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The MioOcean Age Framework: Age Model Database and Chronoinformatics Approach for synchronised Miocene Ocean Temperature, Climate and Proxy Records

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Abstract. Understanding climate evolution depends fundamentally on time: when changes occurred, how rapidly they occurred, and whether changes recorded at geographically disparate locations were synchronous. Palaeoclimate syntheses, which can provide important evidence for broader climate assessments, such as the Intergovernmental Panel on Climate Change (IPCC) Assessment Reports, require chronological frameworks that are sufficiently accurate and comparable between records across both Milankovitch and longer geological timescales. The Miocene Ocean Temperature Synthesis (MioOcean) provides an important test case, compiling upper ocean and bottom water temperature records spanning 23.04–5.333 million years ago. Within MioOcean, the MioOcean Age Model Group (MioAGE) evaluates and harmonises the depth and age models underlying these temperature records and develops a consistent chronological framework for reconstructing and interpreting the evolution of Miocene ocean temperatures across space and time. Here, we present the MioOcean Chronoinformatics approach applied to 69 sites, from which 38 key sites were synchronised into the MioOcean Age Framework through detailed chronological evaluation and harmonisation of the age models using biostratigraphy, magnetostratigraphy, and/or astrochronology. We critically assess published depth and age models, then verify, standardise and, where needed, revise the chronologies within a consistent framework anchored to the Geologic Time Scale 2012. These 38 sites comprise 53 individual age models, all of which required verification and standardisation, with 33 additionally requiring revision. The resulting chronologies are integrated into the open, machine-readable and updateable MioOcean Age Model Database, which preserves depth and age models, chronological tie points, metadata and provenance. Across 10,560 Miocene temperature data points, synchronisation resulted in a mean age change of 28 kyr, demonstrating changes that are important on Milankovitch timescales (18-405 kyr), while the largest offsets reach several million years (up to 7.121 Myr) and can alter the geological interval to which individual proxy observations are assigned. We also present the MioAGE Reliability Grid across all key sites to evaluate differences in Age Model Quality and Reporting Quality among the major chronological approaches, and integrate these into site-level assessments. Together, these developments establish a consistent and reproducible chronological foundation for MioOcean and demonstrate the utmost importance of preserving the underlying sample, depth and chronological information required to reproduce and update palaeoclimate records. More broadly, we introduce Chronoinformatics, an approach for systematically organising, interrogating, evaluating, preserving and updating chronological information that is now available for use across geological intervals, proxy systems and large-scale community syntheses, ultimately feeding into IPCC's Assessment Reports. The MioOcean age compilation is hosted on Zenodo (https://doi.org/10.5281/zenodo.22258616; Drury, Tangunan et al., 2026).

Short summary: Reliable climate histories depend on knowing when changes occurred. We critically evaluated and harmonised the age information underlying global Miocene ocean temperature records, creating a consistent age framework, an open and updateable database, and a new approach for assessing chronological reliability. Our Chronoinformatics approach provides a transferable way to organise, evaluate and update age information for future climate syntheses.

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1 Introduction

Reconstructing Earth's climate evolution depends on when changes occurred, how rapidly they occurred and whether changes at different locations represent the same point in time. Establishing these temporal relationships is fundamental to identifying the mechanisms and feedback driving climate processes. Determining whether changes in atmospheric greenhouse gases, ocean temperature and circulation, ice volume and the carbon cycle lead, lag or occur together underpins our interpretation of interactions within the climate system. Resolving these relationships across geographically distributed records requires sufficiently accurate and synchronised age models; without this temporal alignment, apparent leads, lags or differences between records cannot be confidently interpreted in terms of climate processes and causality (Blaauw, 2012; Westerhold et al., 2024). Palaeoclimate records therefore require age control that is sufficiently accurate, consistent and comparable between locations and within individual records across both Milankovitch (e.g., 18-405 kyr) and longer geological (e.g., >0.5 Myr) timescales. This is particularly important for large-scale palaeoclimate and palaeoecology syntheses, like those incorporated into the Intergovernmental Panel on Climate Change (IPCC) Assessment Reports, where apparent differences between sites may reflect differences in their underlying depth models, age models, chronological approaches or timescales rather than genuine spatial or temporal differences in climate. Age control therefore provides the temporal framework through which geographically distributed palaeoclimate observations should be integrated and interpreted across space and time.

Developing such a consistent chronological framework is challenging because paleoclimate records commonly draw on multiple chronological approaches, including biostratigraphy, magnetostratigraphy, chemostratigraphy, astrochronology, and radiometric dating. These approaches provide chronological constraints at different temporal resolutions and with different sources of uncertainty, and their availability and applicability vary between sites and through time. Individual records may integrate chronological information generated by different studies using different depth scales, numerical calibrations and methodological approaches. Chronological frameworks themselves also evolve as depth models are revised, stratigraphic events are recalibrated and geological timescales are updated. Consequently, the numerical ages originally assigned to a proxy dataset should not be treated as fixed attributes of those observations. Instead, the underlying sample, depth and chronological information must remain traceable if records are to be evaluated, synchronised and updated.

These challenges are particularly important for community syntheses that combine palaeoclimate observations from geographically distributed archives. The Miocene Ocean Temperature Synthesis (MioOcean) provides an important test case for addressing this challenge, seeking to reconstruct global and regional changes in upper ocean and bottom water temperatures (UOT and BWT, respectively) during the Miocene (23.04–5.333 million years ago, Ma), through the compilation of temperature reconstructions generated from marine sediments unified by a consistent age framework (Sosdian, Auderset et al., this volume). These temperature proxy records are based on different paleothermometers, such as TEX_{86} and alkenone $U^{K}_{37'}$ indexes, foraminiferal Mg/Ca, clumped isotopes (Δ_{47}), and stable oxygen isotopes ($\delta^{18}O$) of glassy foraminifera. Each MioOcean proxy group compiled available published proxy records along with their associated metadata

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(for detailed discussion, see Sosdian, Auderset et al., this volume; Sosdian, Kochhann et al., this volume; Auderset, Liu et al., this volume). A central consideration of this effort is that reconstructing temperature change through a key interval of Earth's climate history requires not only well-constrained temperature estimates, but equally well-constrained ages with which to place those observations in time and compare them between locations.

The Miocene provides an important window into a geologically recent warmer world that was characterised by major changes in global temperature, atmospheric carbon dioxide (pCO_2) and ice volume, ultimately resulting in the emergence of conditions recognisable to today (Shackleton et al., 1975; Flower and Kennett 1994; Shevenell et al., 2004a,b; Shevenell et al., 2008; Holbourn et al., 2005; Holbourn et al. 2018; Herbert et al., 2016; Rae et al., 2021; The CenCO_2PIP Consortium, 2023). The Miocene captures significant climatic warming and cooling endmembers (e.g., Billups and Schrag 2003; Shevenell et al., 2004b; Holbourn et al., 2014, 2018; Herbert et al., 2016; Drury et al., 2018a,b; Liu et al., 2022; Meckler et al., 2022; Sosdian and Lear 2020; Westerhold et al., 2020; Steinthorsdottir et al., 2021, The CenCO_2PIP Consortium, 2023). The Miocene Climatic Optimum (MCO, 16.9–14.7 Ma) encompasses the warmest phase of the past 35 million years with consistently elevated pCO_2 values and major ice loss. The MCO ended with global cooling and a major expansion of the East Antarctic ice sheet at ~13.8 Ma during the Middle Miocene Climate Transition (MMCT, 14.7–13.8 Ma). Further cooling to near-modern latitudinal temperature gradients occurred during the Late Miocene Cooling (LMC, 7.0-5.5 Ma), accompanied by evidence for transient Northern Hemisphere Glaciations). The Miocene also saw significant evolutionary and ecological changes, including the rise of terrestrial C4 plants (Cerling et al., 1997; Tauxe and Feakins, 2020; Peppe et al., 2023), the first proposed hominins and earliest evidence for bipedalism in our hominid ancestors (Brunet et al., 2002; MacLatchy et al., 2023), and marked expansion and diversification of the marine biosphere (Boscolo-Galazzo et al., 2021; Crichton et al., 2023). MioOcean's aim to constrain both temperature and age is fundamental to determining how Miocene climate and its biosphere evolved and to assess how the timing and magnitude of these changes varied between ocean basins.

Developing reliable age models for entire geological periods like the Miocene presents several challenges. Over the 18-million-year (Myr) duration of the Miocene the availability, resolution and applicability of different chronological approaches vary considerably. The availability of sediments may be compromised by incomplete sediment recovery and stratigraphic gaps (e.g., hiatuses; Barron and Keller, 1982, Sibert & Rubin, 2021), and intervals of intense carbonate dissolution on a global scale such as the onset of the MCO during the late Early Miocene, and the Middle to Late Miocene Carbonate Crash (e.g. Mayer et al., 1985; Mayer et al., 1986; Lyle et al., 1995; Roth et al., 2000; Preiss-Daimler et al., 2013; Holbourn et al. 2015; Lübbers et al., 2019). Sites sampled by scientific ocean drilling rarely contain a complete Miocene sediment package, and it is even rarer that these sediments are studied with a truly integrated stratigraphic approach that utilises all chronological approaches spanning the entire interval. Consequently, age models often are developed for targeted intervals using different combined chronological approaches. These age model segments subsequently need amalgamating to construct a continuous age framework. Integrating disparate age model segments and verifying the consistency and robustness of chronological information at their boundaries adds substantial complexity, especially when constructing long-term records or comparing between time intervals. Furthermore, these chronological approaches require better

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intercalibration, especially for the Early to Middle Miocene. However, intercalibration remains challenging as there are few locations where all approaches can be applied with confidence. There is a broader limitation in how age models are traditionally reported, archived, and reused. Chronological information is often distributed across publications, supplementary material, expedition reports and data repositories, while the final published proxy dataset may retain only depths and assigned ages. This can make subsequent evaluation, recalibration and updating difficult, particularly for researchers who are not stratigraphic specialists. More broadly, treating chronology primarily as a final age column disconnects proxy observations from the underlying information required to understand how those ages were derived and how they should change as depth models, stratigraphic calibrations and geological timescales evolve.

Here, we therefore present the MioAGE perspective and introduce 'MioOcean Chronoinformatics' as an approach to provide the temporal component of a broader space-time informatics approach, linking geographically distributed proxy observations to structured and reproducible chronological information. 'Chronoinformatics' (chronology informatics) is the systematic organisation, interrogation, standardisation and preservation of the information required to construct and revise/update chronologies. By retaining this information in machine-readable and updateable form, rather than treating published ages as fixed values, the MioOcean Age Framework and Chronoinformatics approach are designed to support increasingly automated approaches to data validation, integration and future updating while preserving the expert stratigraphic interpretation on which the age models depend.

We deliver two interconnected outcomes: (1) a consistent chronological framework for MioOcean temperatures and (2) a broader Chronoinformatics approach for organising, evaluating, preserving and updating chronological information that can be adapted and expanded across geological intervals, proxy systems and community synthesis initiatives, with potential applications to large-scale efforts (e.g., the Time Integrated Matrix for Earth Sciences, TIMES). Within MioOcean, MioAGE has two overarching aims: (1) to identify and critically evaluate the depth and age models underlying the compiled temperature reconstructions, and (2) to ensure that temperature reconstructions from key sites are presented using the best available depth models and within a consistent age framework.

We address these aims using MioOcean Chronoinformatics, which encompasses several interconnected innovations: 1) the MioAGE Survey (Section 2), a community-based approach to evaluating chronologies included in a global synthesis (Lawrence et al., 2021; Sosdian et al., 2024); 2) the MioOcean Age Framework (Section 3), anchored to the Geologic Timescale 2012 (GTS2012) and underpinned by a consistent workflow for recovering, interrogating, verifying, revising and standardising depth and age information and resulting in an open-access, machine-readable and updateable MioOcean Age Model Database that retains the underlying chronological information and provenance; and 3) the MioAGE Reliability Grid (Section 4), a reliability assessment framework that provides a means of evaluating differences in chronological robustness and reporting. The development of the MioOcean Chronoinformatics generated broader governance resources to resolve challenges inherent in large community initiatives, including 1) a curated, machine-readable reference/citation database linking publications to the underlying observations, chronological constraints, interpretations and provenance used in the MioOcean synthesis; and 2) a contributor model that can help inform broader discussions on contribution credit, authorship

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and attribution in community-led research. We provide community guidelines for archiving and updating depth and age models in future publications to ensure reproducibility and updatability by other users (Section 5), evaluate the implications for Miocene chronology and the wider geochronology field and identify key areas where future work is required to match high-quality temperature records with accurate and reproducible chronologies (Section 6). Together, these developments establish a consistent, transparent and reproducible chronological framework for MioOcean, while providing an accessible and transferable Chronoinformatics approach for integrating, evaluating and reusing complex stratigraphic information across large-scale palaeoclimate syntheses.

2 MioAGE Survey - Critical survey and synthesis of published age models used by MioOcean temperature records

2.1 MioAGE Survey rationale and design

Generally, temperature reconstructions are generated from proxy measurements made on samples from a known primary depth within a sediment core or position within an outcrop. At some locations, these primary depth measurements are then converted to a composite depth scale using a depth model that aligns data from different holes (or sometimes nearby sites) so that they can be accurately compared and/or compiled onto a single composite depth scale (IODP-MI, 2011; Drury et al., 2026; see Section 2.1.1 and Table 1). An age model is then created by assigning a numerical age to specific depths using one or more chronological approaches described below (see Section 2.1.2). Some chronological approaches have their calibration to numerical age revised periodically, for instance during major updates to the GTS (see Section 2.1.2). Importantly, both composite depth models and age models may be subject to revision as further research is carried out on both studied sites and on regional/global stratigraphic frameworks. Even stratigraphic data and proxy data generated on the same core material cannot be directly compared in age if their respective age conversions were made using different depth models, age models or correlation to different geological timescales. Thus, the first step towards achieving a consistent MioOcean Age Framework was to critically assess how readily published MioOcean temperature records could be synchronised based on available depth and age information.

This goal was achieved through the MioAGE Survey: a structured critical evaluation of the most recent stratigraphy and chronology available for each MioOcean site, compared with the stratigraphy and chronology underpinning each individual published temperature record from this site. The MioAGE Survey consists of a Site Review and a Proxy Data Review (Table A1). The Site Review evaluated the best available depth and age model available for each site, documenting depth model information, chronological approaches and time scale used for calibration. The Proxy Data Review summarised the proxy records and data points per site and then reviewed each proxy record individually to document number of data points, sample ID availability, depth and age model information, and whether these matched the best available depth model and the Westerhold et al. (2020) timescale respectively. The MioAGE Survey was initially completed for 65 MioOcean sites originating from the Miocene Temperature Portal (Figure F-Survey, map panel; Lawrence et al., 2021; Sosdian et al., 2024). Four MioOcean key sites added during the MioOcean process were surveyed retrospectively using the same approach,

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bringing the total number of surveyed sites to 69 (Figure 1a, 1h; see Section 2). The survey results are presented in Section 2.3 and summarised in Table A2, with the full survey questions and results available in Drury, Tangunan et al., (2026).

Table 1. MioOcean depth model terminology used.

Abbreviation	Full name	Description
MBSF	Meters Below Sea Floor (core depth below seafloor)	The depth below seafloor measured within a single hole as assigned when drilled (e.g., 'shipboard').
MCD	Meters Composite Depth (core composite depth below seafloor)	Depths of individual cores are offset by a specified amount defined in the offsets table (also referred to as 'affine table') to align depth horizons across multiple holes. Data retain their original proportions and are not affected by stretching or compression. The mcd scale is used to stitch together a composite record by splicing the best recovered core intervals to ensure a complete-as-possible sampling path. The offsets and composite often have been determined during the scientific drilling expedition.
RMCD	Revised Meters Composite Depth	RMCD is a composite depth model that has been revised and updated from the initially defined composite MCD based on additionally generated data. Multiple revisions can exist and therefore the source publication has to be identified when reporting the RMCD.
A(R)MCD	Adjusted (Revised) Meters Composite Depth	Depths of core intervals outside the defined composite are adjusted by stretching/squeezing/correlating to the defined composite record. This is a must for any samples taken in sections from a parallel drilled hole that is not part of the defined composite path. It is important to report the source publication of the MCD or RMCD as the mapping pairs are only valid for a given composite record.

2.1.1 Survey design: Sample ID and depth model use

The International Ocean Discovery Program (IODP-2) and its precursor programs (Integrated Ocean Drilling Program [IODP-1], Ocean Drilling Program [ODP], and Deep Sea Drilling Project [DSDP]) have long favoured the drilling of multiple holes at a single site location (e.g. Ruddiman et al., 1985; Hagelberg et al., 1992; Mayer et al., 1992, Drury et al., 2026). This approach was preferred both to reduce the impact of gaps in sediment recovery, which result from the drilling process, and to provide a larger volume of sediment to the research community. As a result, the IODP+ community (from here onwards IODP+ is used to encompass IODP-2, IODP-1, ODP and DSDP) has promoted the use of consistent terminology to describe the different depth models that may be used to convert sample identifiers into depth values. The key depth scales used are summarised in Table 1 (IODP-MI, 2011).

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In our survey of MioOcean sites, we first documented the best available depth model for that site, and then the depth models used by the published temperature datasets, allowing us to identify datasets for which improvements in the depth models could be applied (Table A2; Drury, Tangunan et al., 2026). Published temperature records were also evaluated on whether the full sample ID was reported. It is important to note that without knowing the exact position from which a sample was taken, datasets from the same site cannot be accurately compared and the ages of reported proxy data points cannot be updated, rendering these datasets obsolete. Therefore, it is vital that researchers provide the full original sample identifiers (i.e., reporting site, hole, core, section and the exact top and bottom location of the sample within this section), and the details and/or source of any depth model applied when making their research data available to the community (see Drury et al., 2026 for further discussion).

2.1.2 Survey design: Age model and geological timescale use

We classified the datums used to produce age models for MioOcean sites into three main approaches, with additional approaches considered under Further Remarks. Sites could contain more than one type of chronology (e.g., age model categories), with the classification based on the published age model. This classification was undertaken independently of the age model categories reported for the temperature proxy records (Sosdian, Auderset et al., this volume). The categories and terminology described here reflect those used at the time of the survey; subsequent changes in terminology and categories are reflected in the final MioOcean Age Model Database (see Section 3).

- Biostratigraphy: This most commonly includes data from calcareous nannofossils, planktonic foraminifera, radiolaria, and diatoms and incorporates first (FAD) and last appearance datums (LAD), lowest (LO) and highest occurrences (HO), first and last common or dominant appearances, planktonic foraminifera coiling reversals, and crossovers of dominance (X) between two species.
- Magnetostratigraphy: These datums were generated by identification of changes in the Earth's magnetic field preserved within the sediment (i.e. the pattern of intervals of normal and reverse polarity) which can be correlated to the Geomagnetic Polarity Time Scale (GPTS).
- Astrochronology/Cyclostratigraphy: Depth-age tie-points generated by 1) correlation of records with astronomically paced variability to other well-dated regional or global records (e.g. tying benthic stable $\delta^{18}O$ data to a global composite or stacked record) and 2) direct correlation or "tuning" of proxy variables to astronomical parameters (e.g. tying benthic $\delta^{18}O$ data or elemental ratios from X-ray fluorescence (XRF) core scanning to combinations of eccentricity/obliquity/precession or incoming solar radiation (i.e., insolation) at a specific latitude/season).
- Other: Other types of chronology, such as radiometric dating and chemostratigraphy (e.g., $\delta^{18}O$ and carbon [$\delta^{13}C$] stable isotopes; strontium isotope stratigraphy [SIS]), were also used across the MioOcean sites (8 sites). While they are not considered in detail here, the survey did record where additional chronological approaches were used.

The survey also recorded which GTS the different chronological approaches utilised. Sites with astrochronologies/cyclostratigraphies were considered to have equal accuracy as the Westerhold et al. (2020) timescale.

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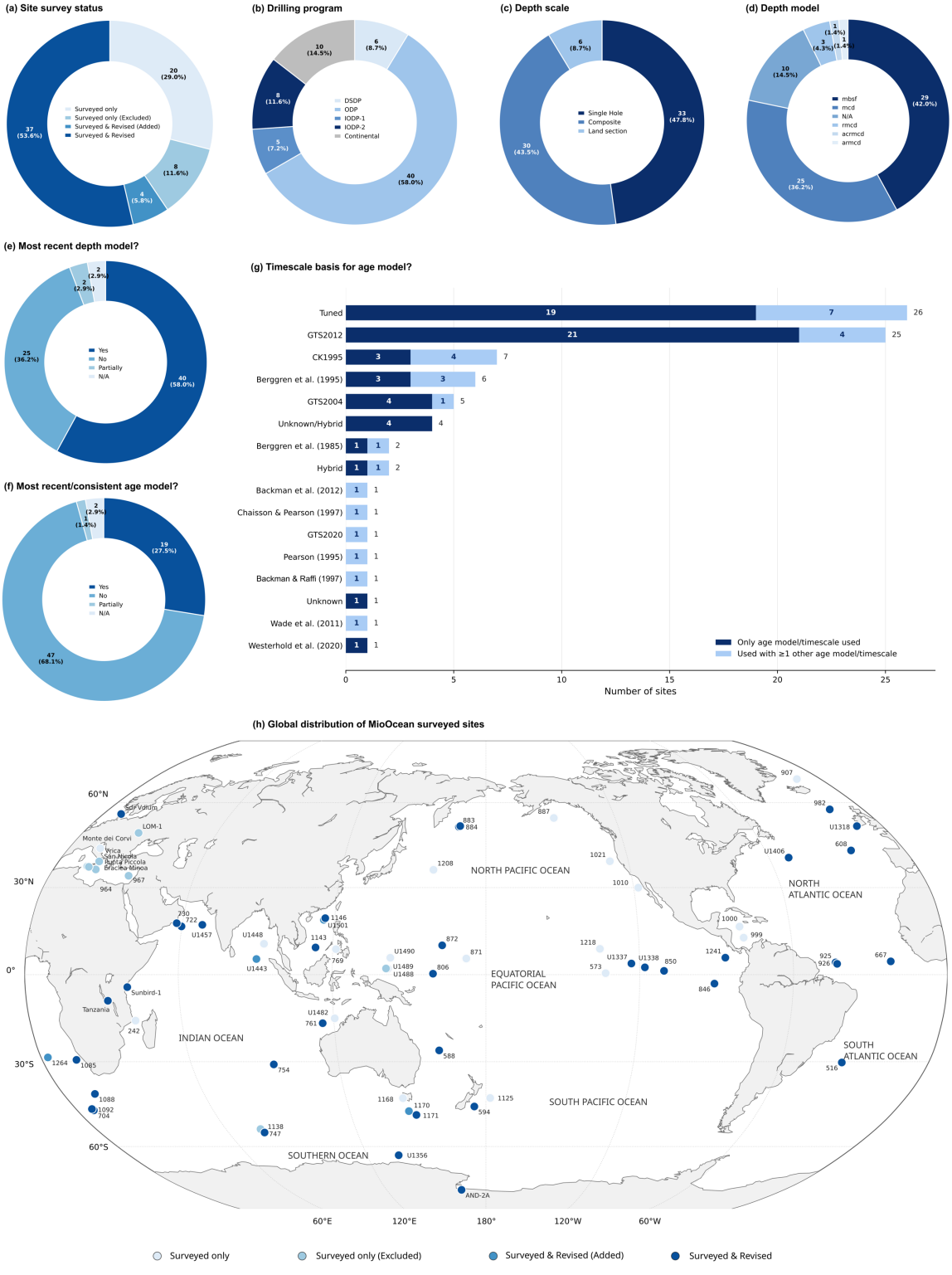
2.2 Critical synthesis of MioAGE Survey results

Fifty-nine of the 69 sites with data in the MioOcean database were collected through scientific ocean drilling from DSDP to IODP-2 (Figure 1b; Table A2; Drury, Tangunan et al., 2026). As these 59 sites were recovered throughout the 50+ year duration of IODP+, there was considerable variation in coring methods, quality of records, associated depth scales, and age models used. The remaining 10 sites were sampled on marine sequences now exposed on land or recovered through continental drilling.

At the outset, 33 of the 69 sites only had the primary mbsf depth model available, as either only a single hole was cored, or multiple holes were cored but not placed on a composite depth model; Figure 1c). Thirty multi-hole sites had composite depth scales and splices available to provide a continuous section for sampling (Figure 1c). Of these 25 used the shipboard composite, three used a revised composite, and two sites had a composite depth model where the off-splice intervals were mapped onto the splice (Figure 1d). The chronological approach used to develop age models varied among the surveyed sites, with approximately half the sites combining more than one approach (35 out of 69 sites). Thirty-four sites use a single approach: 16 used biostratigraphy, 3 used magnetostratigraphy, and 15 used astrochronology/cyclostratigraphy. The remaining 35 sites combined multiple chronological approaches: 31 of which used biostratigraphy, 30 used magnetostratigraphy, 13 used astrochronology/cyclostratigraphy, seven used chemostratigraphy (four of which used Sr stratigraphic correlation), and one used radiometric dating via $^{40}Ar/^{39}Ar$ geochronology (Figure 2; Table A2). Overall, a significant portion of temperature datasets did not utilise the most recent depth and/or age model. For 26 of the 69 sites, the depth model required updating or was inconsistent between studies at the same site (Figure 1e), and for 46 of the 69 sites, the age model required updating or was inconsistent between studies (Figure 1f).

The survey shows that a wide variety of time scales and numerical calibrations were used to provide the numerical ages for different chronostratigraphic approaches (Figure 1g). Because individual sites may have more than one age model approach or chronological framework, a single site may contribute to multiple age model categories; consequently, the total number of counts can exceed the 69 sites that were assessed (85 approach-counts in total). Several sites had hybridized age models that drew on multiple chronostratigraphic frameworks, while for others, the timescale or calibration used could not be explicitly identified in the publication. Astronomically-tuned age models were the most frequently used (26 sites), including those directly tuning to an orbital solution from Laskar et al. (2004, 2011a) or those correlated to other stratigraphies that were directly astronomically tuned. The GTS 2012 (Hilgen et al., 2012) is the most frequently represented GTS, recorded in age models from 25 sites. Other age models used numerical ages from earlier GTS (e.g., Berggren et al., 1985; Berggren et al., 1995; Cande and Kent, 1995; GTS2004, Lourens et al., 2004) or later GTS (Raffi et al., 2020 (GTS2020)), as well as other biostratigraphic frameworks (e.g., Wade et al., 2011; Backman et al., 2012). Less frequently represented frameworks, calibrations and/or timescales included Pearson (1995); Chaisson and Pearson (1997); Backman and Raffi (1997) and Westerhold et al. (2020). Two sites were classified as specified hybrid age models, while the timescale basis was classified as unknown or unknown/hybrid for a further five sites.

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Figure 1. Summary of the MioOcean age model survey across 69 sites. (a) site survey status; (b) drilling programme; (c) depth scale; (d) depth model; (e) use of the most recent depth model; and (f) use of the most recent or consistent age model. Numbers and percentages indicate the proportion of surveyed sites in each category. (g) Timescale basis of the published age models, distinguishing sites that used a single timescale or age model framework from those that used the framework in combination with one or more others. Counts in (g) are not mutually exclusive because individual sites may utilise multiple timescales or age model frameworks. (h) Global distribution of MioOcean surveyed sites. The initial survey included 65 sites, with four additional sites subsequently surveyed, bringing the total to 69. Colours indicate site status, from light to dark blue: Surveyed only; Surveyed only (Excluded); Surveyed and Revised (Added); and Surveyed and Revised. Five of the initially surveyed sites were subsequently excluded from MioOcean.

The outcome of the MioAGE Survey demonstrates the absolute necessity of harmonising and synchronising the MioOcean Temperature records into a unified MioOcean Age Framework. The survey revealed that there is both significant variability in the depth models and chronology underpinning the MioOcean sites, as well as highlighting that 36% of sites (26/69) did not use the most recent depth model and 68% (47/69) did not use the most recent or consistent age model (Figure 1c, 1d). The use of eight different timescales and biostratigraphic frameworks is particularly problematic, as the numerical calibration of bio- and magnetostratigraphic events can vary wildly between timescales (see Section 3.2). These differences mean that harmonisation requires more than simply adopting the published numerical ages. Instead, the depth and chronological information for individual sites must first be evaluated, verified and, where necessary, revised and standardised. The MioAGE Survey therefore provided the basis for identifying where these revisions were required and informed the development of the consistent MioOcean Age Database described in Section 3.

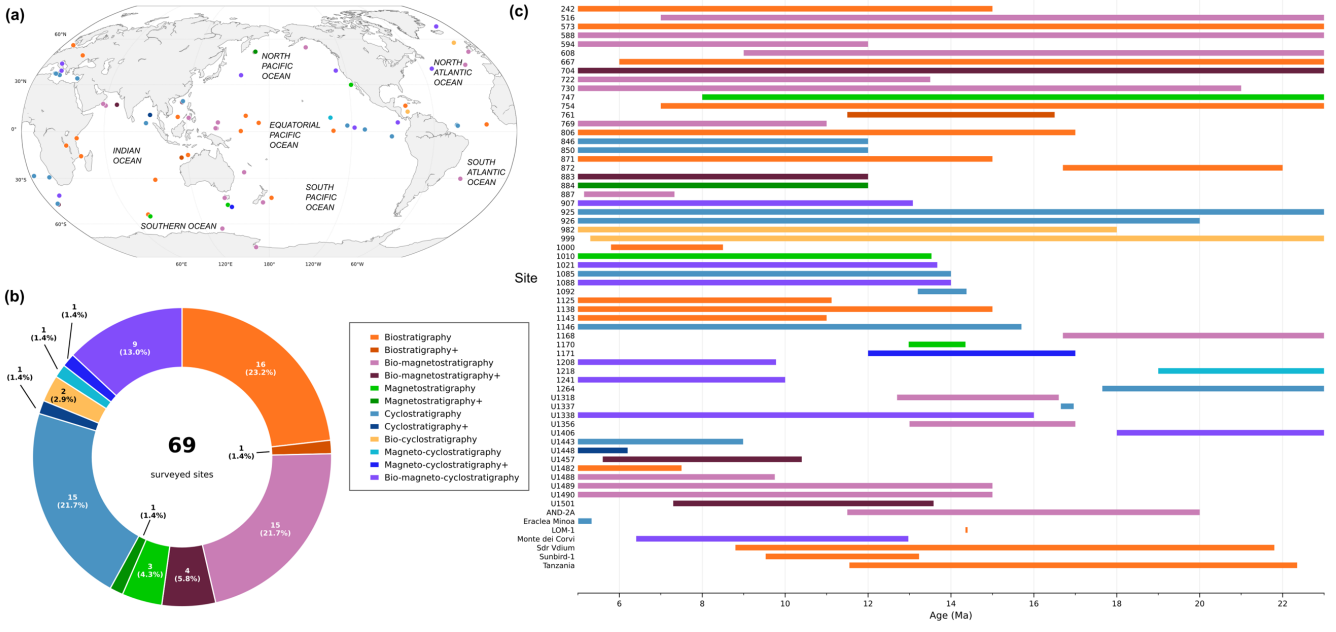


Figure 2. Spatial distribution, frequency and temporal coverage of published age model approaches across the MioOcean surveyed sites. (a) global distribution of the 69 surveyed sites, (b) distribution of age model approaches across the 69 surveyed sites with numbers and percentages indicating the number and proportion of sites in each category, and (c) temporal coverage of the published age model approach for each site across the Miocene. Five out of the 69 surveyed sites are not Miocene.

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3 MioOcean Age Framework and the MioOcean Age Model Database

3.1 Selection of key sites and MioOcean Age Model Database rationale

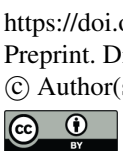
Building on the outcomes of the MioAGE Survey, the next step was to address the identified inconsistencies in depth model, age model, and choice of timescale by developing a consistent age framework for the MioOcean temperature records. All MioOcean proxy and chronological data at a location need to utilise a consistent depth and age model linked to a consistent timescale. The MioAGE Survey (Section 2.2) demonstrated that datasets from the same site rarely utilised the most recent or even the same depth and/or age model available. Following verification, MioAGE revised and standardized existing age and depth information for many sites to the most recent depth model and consistent timescales, allowing subsequent temporal recalibration of MioOcean temperature records.

Due to the scale of the updates needed, 38 key sites were prioritised by the MioOcean proxy groups based on the number of proxies, number of data points and temporal proxy-data resolution at each site, as well as on geographical and temporal coverage. Where possible, this included sites with long, high-resolution proxy records, often using more than one paleothermometer. For MioAGE, our goal was to unify the age models for all key sites into the MioOcean Age Framework underpinned by GTS2012 (see Section 3.2). For each key site, we verified and standardised the age model, additionally revising those age models that did not yet map onto GTS2012. This process involved ensuring that all stratigraphic information had all available sample and chronological metadata available (including full sample ID where available), be updated to the most recent, best available depth model and composite splice (where relevant), and to have its age model recalibrated onto a unified, synchronized framework. We established the MioOcean Age Model Database to collate and harmonise the standardized age models into a machine-readable, updatable and reproducible format that can be applied to the MioOcean temperature database and other datasets. Establishing the MioOcean Age Framework and MioOcean Age Model Database involved an iterative phased process outlined in Section 3.3 and 3.4.

3.2 Geologic Time Scale selection: Rationale for underpinning MioOcean Age Framework with GTS2012

GTS2012 (Hilgen et al., 2012) was chosen as the basis of the MioOcean Age Framework and MioOcean Age Model Database. The MioAGE Survey identified a plurality of key sites that were already calibrated to GTS2012 (18/38 sites; 15 used GTS2012 exclusively and three used it in combination with other timescales). Astrochronologies all used La2004 or La2011 as the astronomical target (16/38 sites; 11 used tuned age models exclusively and five used them in combination with other age model frameworks), which we consider compatible with GTS2012. We therefore prioritised the revision of the age models for those key sites that did not yet sit fully within the GTS2012 framework. Since the 1980s, the polarity time scale has undergone major changes (Figure 3). Chiefly, these were initially underpinned by better constraints on plate pair spreading rates (Berggren 1995 and CK1995) aided by early astronomically age-calibrated reversal ages for the Quaternary (e.g. Hilgen 1991, Shackleton 1990). GTS2004 and GTS2012 mark major improvements from earlier pre-2000s GPTSs, largely due to the astronomical constraints for most of the Neogene reversals. GTS2012 still broadly aligns with later

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refinements and presented in more recent comprehensive GTS like GTS2020 (Raffi et al., 2020) and the integrated CENOGRID astrochronology-GPTS (W2020; Westerhold et al., 2020).

We recognize the significant advances in Miocene biostratigraphy incorporated into GTS2020 (Raffi et al., 2020), as well as the important progress toward astronomical calibrations of magnetic field reversals incorporated into GTS2020 and the CENOGRID GPTS (Kochhann et al., 2016; Liebrand et al., 2016; Drury et al., 2017; Beddow et al., 2018). Some of these astronomically tuned reversal ages have additionally been verified by high-precision U-Pb zircon radioisotopic geochronology (Kasbohm et al., 2023). Although a subset of astronomically tuned Early Miocene magnetic reversal ages were incorporated into the 2020 GPTS (Gradstein et al., 2020), Liebrand et al. (2016) had noted uncertainties in the stratigraphic positions of the reversals identified at Site 1264 and therefore advised caution regarding their use in the geologic time scale (see their Supplementary Fig. S6, for those that are considered an improvement on GTS2012, in grey, and those that were highly unreliable, outside of the grey box).

We chose to ultimately prioritise the scale of the synchronisation MioAGE could achieve by selecting GTS2012 as the basis for the MioOcean Age Framework. The rigorous standardization processes we applied to age models in the MioOcean Age Model Database (see Section 3.3.3) mean that in the future, the MioOcean Age Framework can be easily re-calibrated to other GTS, such as GTS2020, and incorporate future work that addresses outstanding discrepancies.

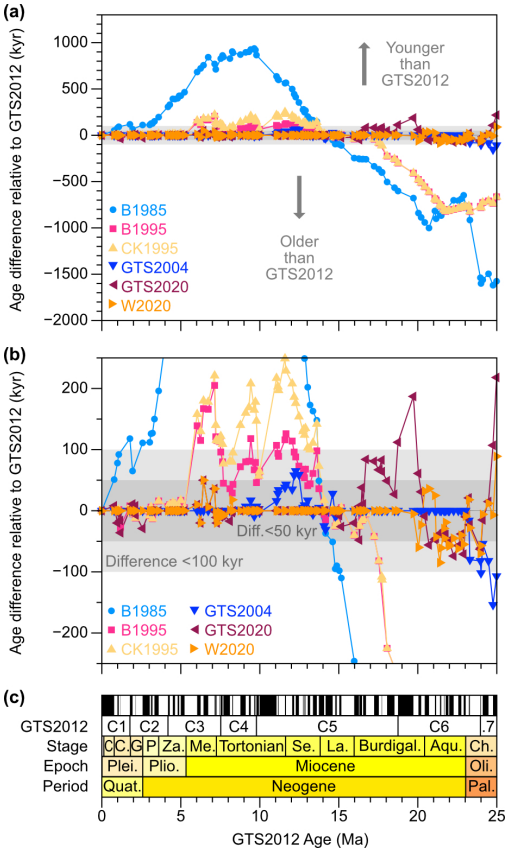


Figure 3: Improvement of the Neogene GPTS as incorporated in progressing studies and compilations since the 1980s. Marine magnetic anomaly profiles and radiometric dating were used to calibrate the GPTS from the 1980s and 1990s, including B1985 (Berggren et al., 1985), CK1992 (Cande and Kent, 1992), B1995 (Berggren et al., 1995) and CK1995 (Cande and Kent, 1995). There is an order-of-magnitude reduction in absolute age-errors between these pre-2000s GPTS and GTS2004. Astronomical age calibration of reversal boundaries substantially contributed to this significant reduction (Hilgen, 1991a,b; Hilgen et al., 1995; Lourens et al., 1996; Krijgsman et al., 1999; Hüsing et al., 2007). This progression is depicted through comparison with the Geological Time Scale (GTS) 2012 (Hilgen et al., 2012, in Gradstein et al., 2012). The large Early Miocene age difference between GTS2020 (Raffi et al., 2020) and GTS2012 is due to the inclusion of uncertain reversal boundary ages at Site 1264 (Liebrand et al., 2016; see their supplementary information figure S6). We therefore recommend using either the GTS2012 (Hilgen et al., 2012) depicted here, or W2020 (Westerhold et al., 2020) compilations, the latter of which we consider most accurate to date. Here we present the age difference against GTS2012 ages because W2020 presented an updated GPTS but did not reinterpret the GTS (see Figure B1). Panel (b) presents a zoomed-in version of panel (a). In panel (c), we abbreviate Chibanian as C (following GTS2020 nomenclature, unofficially referred to as "Ionian" in GTS2012), Calabrian as C., Gelasian as G, Piacenzian as P, Zanclean as Za., Messinian as Me, Serravallian as Se., Langhian as La., Burdigalian as Burdigal., Aquitanian as Aqu., Chattian as Ch., Pleistocene as Plei., Pliocene as Plio., Oligocene as Oli., Quaternary as Quat., and Paleogene as Pal. See Hilgen et al. (2012) in Gradstein et al. (2012) for G(P)TS, Stage, Epoch, and Period definitions. The GPTS shown are summarised and archived in Drury, Tangunan et al. (2026). The GPTS was used as the foundation of this comparison as comparing bioevents between timescales can be additionally complicated by changes in species names.

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3.3 MioOcean Age Model Workflow: revise, verify, standardise

Building on the outcomes of the MioAGE Survey, the next step was to address the identified inconsistencies in depth model, age model, and choice of timescale by developing a consistent age framework for the MioOcean temperature records. All MioOcean proxy and chronological data at a location need to utilise a consistent depth and age model linked to a consistent timescale. The MioAGE Survey (Section 2.2) demonstrated that datasets from the same site rarely utilised the most recent or even the same depth and/or age model available. Following verification, MioAGE revised and standardized existing age and depth information for many sites to the most recent depth model and consistent timescales, allowing subsequent temporal recalibration of MioOcean temperature records. Having established GTS2012 as the basis of the MioOcean Age Framework, we implemented a comprehensive workflow to revise the age model and/or age calibration where needed, verify appropriate depth model use and then standardise the finalised age model in the MioOcean Age Model Database (Figure 4). This workflow consisted of three interconnected components: revision, verification, and standardization, which together ensured that age models for all 38 key sites are aligned within the GTS2012-based MioOcean Age Framework and consistently standardised and harmonised in the MioOcean Age Model Database (see Section 3.3.3 for details).

Revise component: For key sites with astrochronologies or age models that were already calibrated to GTS2012 (25 total), we critically evaluated the age models to ensure there were no issues (e.g., ages implying stratigraphic reversals, missing metadata, etc.). For selected key sites, we chose to apply a recently published astrochronology, based on direct tuning to orbital parameters, rather than updating the age model from the original publication even where this utilised GTS2012. For the remaining key sites where all depth-age tie-points were based on bio- and magnetostratigraphy, we used the calibrated GTS2012 ages for datums, isotope stages, and geomagnetic polarity reversals. For a handful of sites, updating the bio-, chemo- and/or magnetostratigraphic datums was complex, so new chronologies were developed using astrochronology and/or chemostratigraphy (Sites 846, U1337). In parallel with these age model revisions, the depth scale was updated where needed to the most recent available depth models to ensure that each site was presented on a unified depth scale. Additionally, a revised composite depth model and composite splice was developed for one site (Site 846).

Verify component: As part of updating the depth scale to the most recent available depth models during the update and revision phase, the depth scale terminology was standardised following the nomenclature in Table 1. However, to ensure that each site was presented on a unified depth scale, the relationship between each sample ID, depth and depth model source was verified once the update and revision phase was complete. This verification process included checking that the sample ID for each tie point matched their assigned primary depth value (e.g., mbsf). The application of the most recent composite depth model to the sample ID and primary depth was then verified and corrected where issues occurred. Where possible, the age model was assessed to confirm whether it followed the composite splice associated with the applied composite depth scale. Finally, for those sites with an a(r)mcd scale (Table 1), the composite depths of off-splice samples were then correctly mapped to the composite splice. Where major changes in depth occurred, the age model was revisited to ensure that its integrity was retained.

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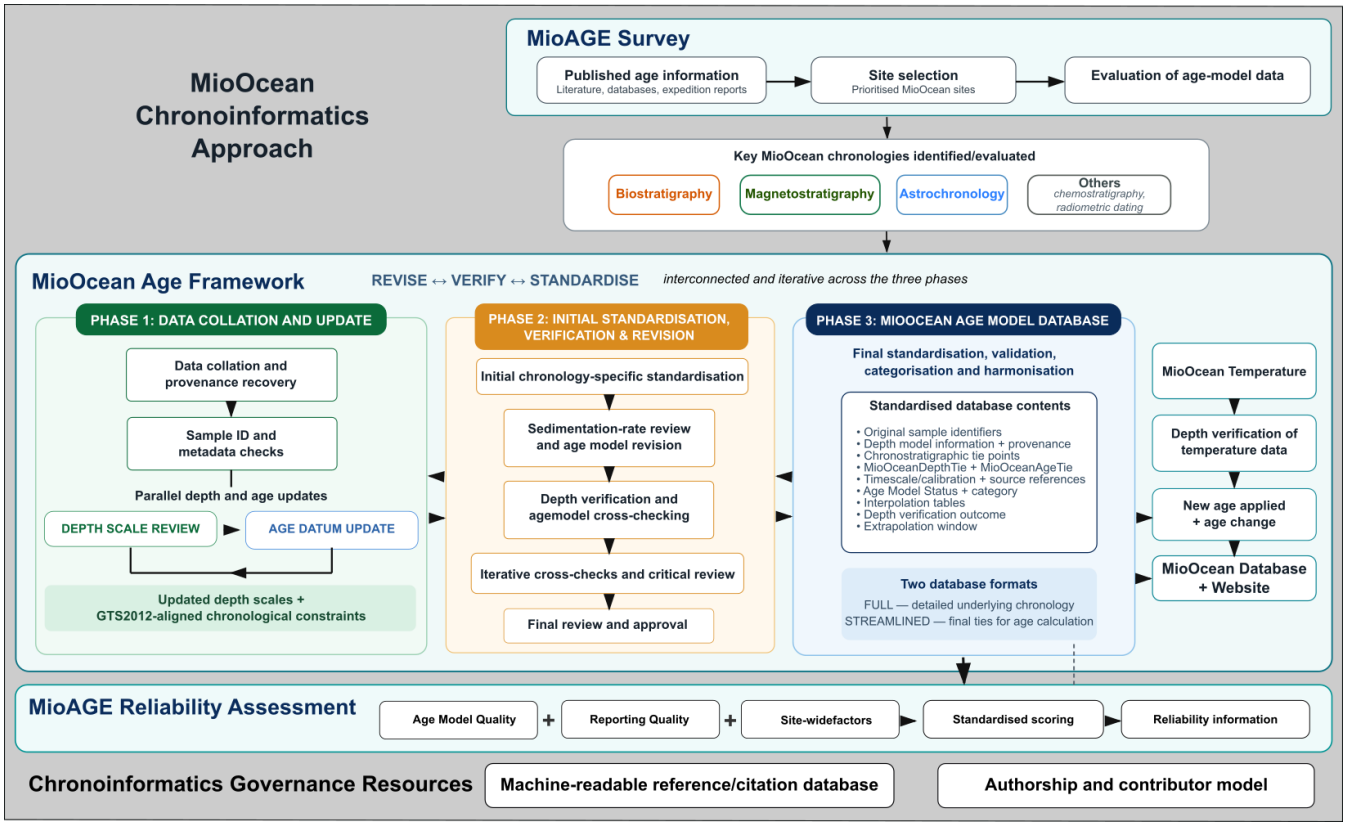


Figure 4. MioOcean Chronoinformatics Approach. Overview of the integrated MioAGE approach, from the evaluation of published chronologies through the iterative revision, verification and standardisation of age-depth information within the three-phase MioOcean Age Framework, culminating in the MioOcean Age Model Database and its application to temperature and other proxy datasets. The MioAGE Reliability Assessment provides a methodological framework for evaluating chronological robustness and reporting, while the machine-readable reference/citation database and authorship and contributor model support provenance, reproducibility and transparent community contribution.

Standardise component: Throughout the process, the age models were iteratively standardised to ensure consistent reporting of sample and chronological metadata and source information across all key sites. Additionally, MioOcean-specific information was provided, including the applicable range of the age model, age model category, age model status, and depth verification outcome. This ensured that the finalised age models and their associated information were consistently structured for integration into the MioOcean Age Model Database.

These 'revise', 'verify' and 'standardise' components were implemented through iterative phases: Phase 1 focused on data collation and provenance recovery, integration of information from multiple sources, and updating depth scales and age calibrations where required; Phase 2 focused on initial standardisation, verification, and iterative critical review and revision of the depth and age models; and Phase 3 focused on construction of the MioOcean Age Model Database, including final standardisation, validation, categorisation and harmonisation of the chronological information. Although discussed sequentially, the phases were iterative, with depth and age information revisited if verification identified inconsistencies. The implementation of these interconnected components and phases is described below and shown schematically in Figure 4.

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3.3.1 Phase 1: Data collation and update

Data collation and provenancing. Stratigraphic data and age models were collated from multiple primary sources. For some sites, we utilised age models that had previously been collated or previously published astrochronologies. For other sites, we used the information gathered during the MioAGE Survey to collate stratigraphic information from multiple sources to create a new age model. All references and citations associated with the depth models, stratigraphic information and chronological constraints were systematically recorded to preserve traceable age-model provenance. These records were subsequently curated into the machine-readable reference/citation database (Appendix C; Drury, Tangunan et al., 2026), linking the underlying chronological information used in the synthesis to its original published sources. Though MioOcean focusses on the Miocene, the age model was revised, verified and standardised for the entire site even where the relevant data extended beyond the boundaries of the Miocene. For a select few sites the choice was made not to incorporate younger or older sections where the integration involved significant complexity.

Sample ID and metadata checks. To update both depth and age models, it was imperative that all sample IDs and depth scale information was reported for both temperature records and individual stratigraphic information (e.g., datums/magnetic field reversals). For all age models and proxy datasets lacking sample IDs, we either contacted the authors of the original publication, or found missing sample IDs in the shipboard and/or core repository records. Full sample identifiers and primary mbsf were recovered as much as possible. We therefore highlight the importance of reporting complete sample IDs and depth models in **Section 4** recommendations below.

Depth scale review and update. For key sites that required age model updates to GTS2012, the initial step was to verify whether the existing datums were placed on the most recent or appropriate depth scale. As all key sites are part of IODP+, the depth scales used for the sites were either the original primary depth of the hole (mbsf/CSF), or a composite depth record (shipboard: mcd/CCSF; revised: rmcd/revised CCSF; Table 1). If the depth scale was in mbsf or CSF, or if no revision had been made to the composite depth or splice, no further adjustments were necessary regarding the depth scale. However, in cases where the composite depth and/or splice were revised, such as for ODP Sites 925 and 926 (Wilkens et al., 2017) or IODP Site U1338 (Wilkens et al., 2013, Kochhann et al., 2016), different age model intervals were published on different versions of the composite depth and/or splice. As such, the depth scale of these age models needed unifying and updating using the most recent revised offsets. When a composite depth scale and splice are used, samples and data that is collected "offsplice" can be temporarily distorted relative to the splice (see Wilkens et al. (2022) and Drury et al. (2026) for details). This off-splice material can be 'mapped' or aligned with the splice by using the a(r)mcd depth scale (Table 1). Where possible, any off-splice stratigraphic data was placed on the a(r)mcd depth scale. The depth scale review and update process was also applied to the MioOcean Temperature database, which is described in Section 3.4 and in Sosdian, Auderset et al. (this volume). For Site 846, depth scale issues were identified, and an updated composite depth scale and splice were developed. These are discussed in greater detail in Appendix B and in Drury, Tangunan et al., 2026.

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Age datum calibration to GTS2012: update and verification. In parallel with the depth scale review, the age datums were updated to the GTS2012 calibration. As discussed in Section 2, 19 sites used datums, reversals or events that were already calibrated to GTS2012 and 18 sites used astrochronology, while 28 sites required updates to the GTS2012 calibration. For the 11 sites requiring calibration to GTS2012, the age datums, reversals and events for these sites were calibrated to the appropriate sources in GTS2012, such as Appendix 3 (Anthonissen and Ogg, 2012) for calcareous nannofossil and planktonic foraminiferal datums, and Chapter 5 (Ogg, 2012, derived from Hilgen et al., 2012) for geomagnetic reversal ages. The 19 sites that were already calibrated to GTS2012 were verified to ensure the age calibrations were correct. On occasion, age models utilised regional GTS2012 or species that were not calibrated in GTS2012. These bioevents and magnetic reversals were critically evaluated by MioAGE biostratigraphers and palaeomagnetists respectively, to determine their suitability for inclusion in the age model. Where appropriate, some bioevents/reversals were excluded from the age model, for instance because a bioevent was unreliable, or to prioritise one of two closely-spaced bioevents. For most bioevents and palaeomagnetic reversals, we applied the 'centre point' or midpoint approach to determine the depth-location of the tie point (see Section 4). However, in some cases this approach caused unrealistic changes in sedimentation rates, or even age reversals with adjacent bioevents/reversals. For these stratigraphic tie points (mostly bioevents, occasionally reversals), we applied a curated approach where we used a depth point other than the midpoint in a given depth range to prefer a more parsimonious estimation of sedimentation rates and temporal progress through the interval (see Section 4 for details).

3.3.2 Phase 2: Initial standardisation, verification, and iterative critical review and revision

Following data collation and the initial depth scale and GTS2012 updates in Phase 1, the age models were initially standardized to enable consistent critical review and verification across the key sites. The standardization process varied in complexity depending on the chronological approaches and issues identified at individual sites. For some age models, this involved chronology-specific standardization, such as updating biostratigraphic taxonomy and standardising event terminology to Base (B) and Top (T), or consistently using the base of a chron for magnetostratigraphic events. For others, standardisation identified issues that required more extensive review and revision of datum depths and the age model itself, including GTS2012 recalibration, tie point-depth curation, and the exclusion of events that resulted in unrealistic sedimentation rates. Standardisation was therefore an iterative process, with newly identified issues addressed and the resulting age models subsequently re-evaluated and modified where needed.

Sedimentation rate review, curated depth approach and age model revision: The sedimentation rates based on linear interpolation (38 sites) or polynomial fits (2 Sites: U1338, U1356) were reviewed for all key sites to identify unrealistic variability or negative sedimentation rates. Where needed, bio-, magneto-, chemo-, astro- events were reviewed, depth-curated and/or excluded to address sedimentation rate issues. Top of Core (Recent) and Base of Site tie points were also added where appropriate to improve the usability and application of the age models across the full relevant site interval (Top of Core: 17 sites; Base of Site: 7 sites; Drury, Tangunan et al., 2026). Where any revision altered the depth–age relationship, the resulting age model and sedimentation rates were re-evaluated iteratively. MioOcean age models were generally

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extrapolated by ±10m in the depth domain from the topmost and lowest ties. The depth-extrapolation was set to ±0m adjacent to 'Top or Core'/'Base of Site' tie points or where there was strong evidence that a ±10m extrapolation would lead to erroneous application (e.g., Site U1406). For two sites (Sites 754, 850) the extrapolation window was increased marginally to cover all temperature data available.

Depth verification and age model cross-checking. As part of the iterative review and revision process, the agreement of the sample ID and primary depth, as well as the application of the most recent depth model was verified and corrected where issues occurred. The depth verification process utilised standardised excel templates coupled with open access code that supports sample ID and depth scale verification: Code for Ocean Drilling Data (CODD; Wilkens et al., 2017) and the Ocean Drilling Composite Tracker (ODCT; Pälike and Westerhold, 2025). Where depth verification resulted in substantial changes to the depth of samples or reversed the chronological order of tie points, the age model was revisited to determine whether further revision was required. Revised age models were subsequently cross-checked and reviewed before finalization.

3.3.3 Phase 3: MioOcean Age Model Database

Following revision of the depth models and recalibration of age datums, all updated chronological information was standardised and integrated into the MioOcean Age Model Database, providing a consistent and reproducible chronological framework for Miocene temperature records. The database serves as the chronological backbone of the MioOcean initiative by harmonising depth models, age models, sample and chronological metadata, and chronostratigraphic tie points into a common structure that can be applied consistently across all proxy datasets. The age model database contains tie type, sample ID, depth information, GTS type and age event information, depth and age source information, and MioOcean classification (depth verification, age model status, age model category, extrapolation window). The database was designed around a standardised architecture that preserves both the provenance of the original published information and the revisions and evaluations applied within the MioOcean Age Framework.

For each site, the database archives the original sample identifiers, depth model information, age-model tie points, interpolation tables, and associated metadata required to reproduce or update the chronology. Where multiple versions of depth models exist (e.g., shipboard and revised composite depth scales), the source and version of the depth model used are documented to ensure transparency and reproducibility. For each site, the recommended depth was mirrored in the clearly labelled 'MioOceanDepthTie' column, with both the source column and associated MioOcean temperature database depth column recorded. Similarly, 'MioOceanAgeTie' records the associated numerical age for each 'MioOceanDepthTie', along with the chronostratigraphic framework used to calibrate each age model, including the numerical timescale and source references, is retained alongside the updated and/or revised MioOcean chronology. As part of the final database standardization, an Age Model Status was assigned to each site to document the level of evaluation and modification undertaken by MioAGE. Finalised age models were classified as either 'MioOcean – Revised, Verified and Standardised Age Model' where revision of the existing chronology was required, or 'MioOcean – Verified and Standardised Age Model' where the existing chronology was retained but verified and standardised for inclusion in the database (Drury, Tangunan et

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al., 2026). Supplementary information lists the MioOcean Age Model Database content and the standardized fields and categories used (Drury, Tangunan et al., 2026).

Depth and age calculations were carried out using either standardised templates and code utilising Code for Ocean Drilling Data (CODD; Wilkens et al., 2017) and IGOR Pro that calculate mbsf, (r)mcd and a(r)mcd to generate consistent depth-age relationships for each site. These templates or codes facilitated a uniform approach to the recalibration of each site's depth-age relationship, ensuring that the depth-age model is aligned with the GTS2012 time scale across all key sites. The resulting depth-age models are stored in a uniform format that facilitates direct application to the MioOcean Temperature Database, as well as other proxy data generated at key MioOcean sites. A key component of the database is the preservation of the underlying chronostratigraphic information rather than only the final age model. Each age model retains the depth-age tie points, together with their source information, allowing future recalibration as stratigraphic frameworks evolve. By preserving the original sample identifiers, depth model references, and tie-point metadata, the MioOcean Age Database remains updateable rather than representing a static compilation.

The MioOcean Age Model Database is provided in two formats: Full and Streamlined (Drury, Tangunan et al., 2026). The full database provides detailed stratigraphic information, full depth and age metadata and MioOcean classification for all ties (including excluded ones). The full format provides individual entries for all samples pertaining to a tie point (e.g., Top-Centre-Curated-Base). The streamlined database provides only the final ties used to calibrate depth to age, which is reported with a subset of the full format metadata (e.g., excluded tie points are not reported). The full format is recommended for anyone either looking to improve an age model or who wants to learn more about the underlying age model underpinning data. The streamlined age model is most suitable for calculating age.

The database has been developed to maximise interoperability with the wider MioOcean infrastructure and existing palaeoclimate repositories. Standardised metadata fields and consistent formatting enable straightforward integration with the MioOcean Temperature database. As part of the final integration, the harmonised age models were cross-checked against the MioOcean Temperature Database to ensure that the appropriate age-depth relationships could be consistently applied to the temperature records. The MioOcean Age Model Database ultimately provides a harmonised fully traceable chronostratigraphic framework for Miocene temperature records, as well as other proxy records available at the MioOcean key sites, enabling reproducible integration, inter-site comparison and future updating as new stratigraphic constraints become available.

3.4 Critical review of MioOcean Age Model database

The MioOcean Age Framework delivers a consistent chronological framework across all key MioOcean sites, presented in the machine-readable and updatable MioOcean Age Model database (Figure 5). Age-depth plots for all 38 key sites are provided in Drury, Tangunan et al., 2026, documenting the chronological tie points, approaches and final harmonised age-depth relationships for each site. In terms of the temporal range of the age models revisited for the 38 MioOcean key sites, 13 completely spanned the Miocene (Sites 806 and 872 are included with near-complete coverage), with the remaining 26

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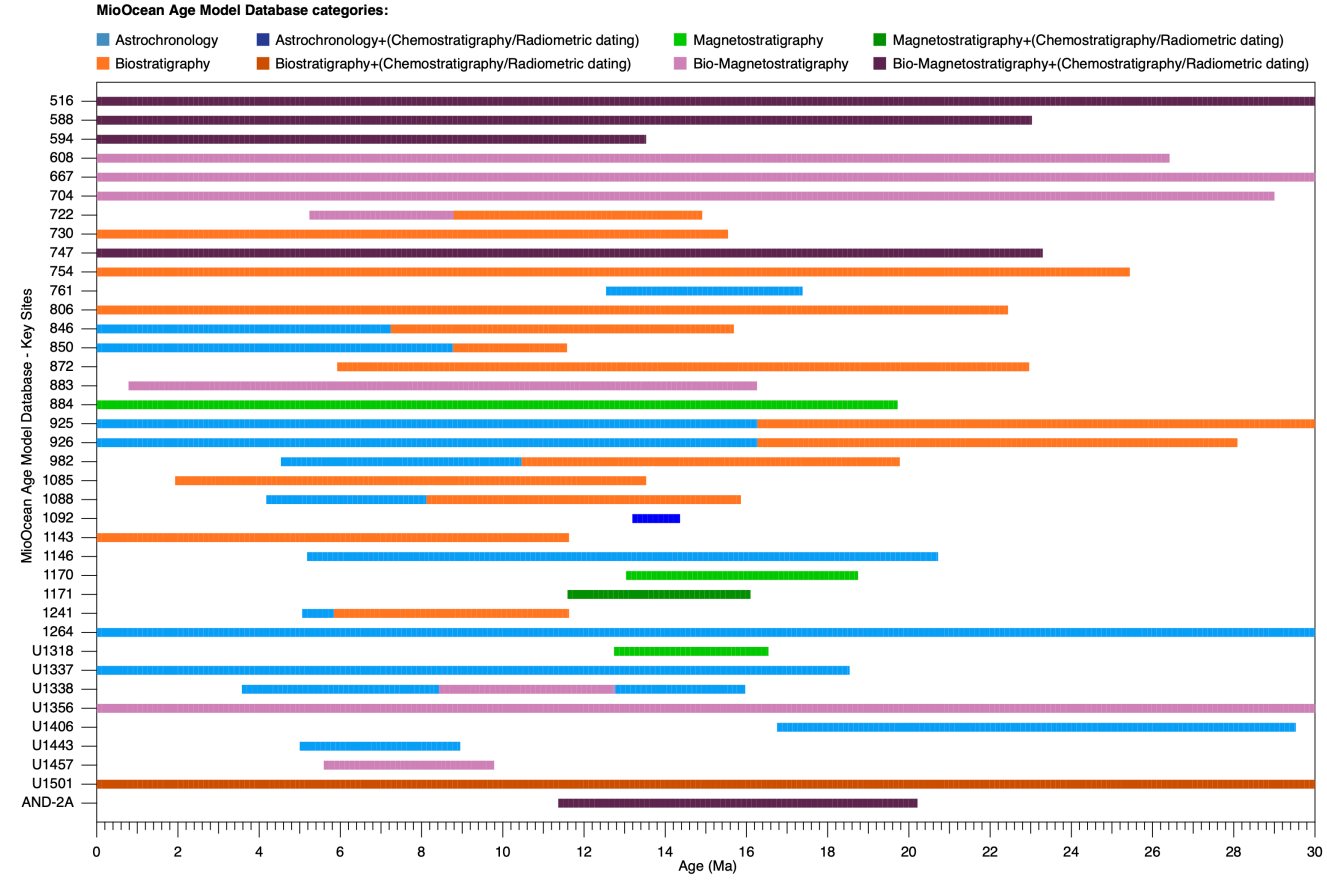


Figure 5. Age range of all MioOcean key site age models ([revised], verified and standardised) available in the MioOcean Age Model Database for the interval 0-30 Ma. The colour indicates the type of age model approach used for each interval. Sites 722, U1356, U1406 and AND-2A contain intervals with hiatuses and/or slumps (not shown). An equivalent figure spanning 0-67 Ma is provided in Figure B2.

key sites only partially spanned the Miocene. Breaking this down further, 24 key sites (partially) spanned the Early Miocene (Aquitanian: 15; Burdigalian: 24), 32 key sites (partially) spanned the Middle Miocene (Langhian: 30; Serravalian: 32) and 31 key sites spanned the Late Miocene (Tortonian: 31; Messinian: 30). Though the MioOcean focus was on the Miocene, in some cases the age model for the entire site was revised, verified and standardised. The age models from 24 key sites were revisited for the Plio-Pleistocene (20 full; 4 partial; records that stop before 5 Ma were not considered to have Pliocene coverage). The age model updates for 11 key sites extend older than the Miocene, with all spanning at least part of the Oligocene, and three extending older: Site 516 spans ~0-67.8 Ma; Site 926 spans ~0-40.2 Ma; Site U1356 spans ~0-55.5 Ma. For certain sites, the age model relied on a different means of calibration, where the age model had to unify either multiple chronological approaches, or multiple strategies within the same approach (Figure 5). For instance, Site U1338 had an astronomically calibrated age model between 3.578-8.301 Ma (Drury et al., 2016, 2018b) and 12.735-15.968 Ma (Holbourn et al., 2014, 2022). The intervening portion of the U1338 record (8.301-12.735 Ma) was calibrated via multi-hole bio- and

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magnetostratigraphy (Expedition 320/321 Scientists, 2010; Backman et al., 2016), using a polynomial fit as U1338 was a rare case with large, often multi-hole, datasets from both siliceous (diatoms, radiolarians) and calcareous (nannofossils, planktic foraminifera) microfossils and palaeomagnetic data. In the case of Site U1337, the entire age model was based on astrochronology, however multiple individual studies made up the Recent to Early Miocene record, namely Lyle et al., 2019 (0-5.939 Ma; partially derived from Drury et al., 2018b), Drury et al., 2017 (5.939-8.301 Ma), a new MioOcean tuning (8.301-14.949 Ma; based on data from Tian et al., 2013, 2018), Holbourn et al., 2024 (14.949-17.194 Ma; originally based on Holbourn et al., 2015) and Hilgen, 2025 (17.194-18.541 Ma). So, while the MioOcean Age Model Database encompasses harmonised age models for 38 key sites, these age models unify 53 individual age models that all needed verification and standardisation, with 33 individual age models additionally requiring revision (Drury, Tangunan et al., 2026).

We identify eight age model categories in total. These categories are organised around four main approaches: astrochronology ('A'), biostratigraphy only ('B'), magnetostratigraphy only ('M') and integrated bio-magnetostratigraphy ('BM'). Each main category can have further constraints from additional 'other' chronological approaches (see also section 2.1.2), which is denoted by a '+' added to the main category. Astrochronology (A) was utilised as the sole approach at 14 sites. Twenty-nine key sites utilised Biostratigraphy (B) in some capacity, with 15 using biostratigraphy only. Magnetostratigraphy (M) was utilised by 18 key sites, though only 4 sites utilised it as the sole chronological approach. Thirteen sites utilised an integrated bio-magnetostratigraphic approach for age calibration. Eight sites used some additional chronological input denoted by the +, encompassing the use of oxygen and/or carbon isotope chemostratigraphy (Sites 588, 747, 1171), Sr-isotope stratigraphy (Sites U1501, AND-2A), radioisotopic dating (Site 516, AND-2A) or other chemostratigraphic markers (Sites 516, 594). One site (1092) was categorised as an A+ approach to denote a benthic isotope stratigraphy anchored to an astronomically tuned target.

When broken down into the 53 individual records, it was more common for a sole means of age control (37 instances) to be used for a given portion of the record. This was particularly pronounced in astrochronology. In the 19 individual records based on astrochronology 18 applied orbital tuning as the sole means of age control, compared to half (14 of 28 records) for biostratigraphy and 5 of 14 records for magnetostratigraphy.

Within a site, it was most common for the age tie point data to utilise a combination of shipboard and postcruise data sources (28 of the 38 primary sites), including where astrochronologies were informed by shipboard and postcruise data. Within these 22 sites, it was most common for the biostratigraphic data to be based partly or entirely on original shipboard data that had not been revisited. Only three sites (sites 730, 872, and 884) had age models based wholly on shipboard data.Overall, this indicates that while the use of shipboard data remains pervasive, in most instances it is critically revisited (at least in part) in subsequent publications.

The finalized age models in the MioOcean Age Model Database also provided the standardized chronological information required for the development and testing of the MioAGE Reliability Grid. During the harmonisation process, we identified substantial differences in the robustness and reporting of the chronological information available across sites, highlighting the need for a consistent means of assessing age model reliability. We therefore developed the MioAGE Reliability Grid to

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evaluate differences in Age Model Quality and Reporting Quality across different chronological approaches (Biostratigraphy, Magnetostratigraphy, Astrochronology), with an integrated stratigraphic assessment of overall reliability at the site level. The development, criteria, and application of the MioAGE Reliability Grid are described in detail in Section 4.

3.5 Calculating MioOcean Depths and Ages for the MioOcean Temperature Database

Once all MioOcean temperature data had a validated sample ID (see Sosdian, Auderset et al., this volume; Section 3.3.1), new MioOcean depths were calculated using the most recent depth models to ensure consistency with those used in the MioOcean Age Model Database.

The temperature data at all MioOcean sites (e.g., not only MioOcean key sites) received a new MioOcean interval and primary mbsf depth value, with 44 sites additionally receiving a new (r)mcd depth value and 13 sites receiving a new a(r)mcd depth value, along with relevant depth model source information. The depth-verification process was completed using CODD and ODCT (Wilkens et al., 2017; Pälike and Westerhold, 2025). The finalised age-depth relationships in the MioOcean Age Model Database were then applied to the entire MioOcean temperature database. For all key sites, the age-depth ties from the MioOcean Age Model Database were applied to the matching MioOcean depth column to create MioOcean Age (Ma). All temperature data within the extrapolated depth range of the MioOcean Age Model for that site will have a MioOcean Age (Ma), with information concerning the MioOcean Age Model Category, Status and original age data source information reported in dedicated columns. The only exception where MioOcean Age (Ma) is not calculated is when the input MioOcean depth could not be calculated (e.g., was reported as a NaN) or when the age assignment occurred during a hiatus/slump and was deemed highly uncertain. The limited datapoints matching these criteria are excluded, and MioOcean Age (Ma) is reported as NaN. MioOcean Age (Ma) is also reported as NaN for temperature data that occurred outside the extrapolated depth range of the MioOcean Age Model, as well as temperature data from MioOcean sites that were not included as key sites. For these ‘out of range’ and ‘non-key site’ temperature data, the original published age should be used for further analysis.

A MioOcean Recommended Age (Ma) column is provided to facilitate the analysis of MioOcean temperature records irrespective of whether there is a matching MioOcean age model. MioOcean Recommended Age (Ma) integrates MioOcean Age (Ma) or published age depending on several factors. At MioOcean key sites, MioOcean Recommended Age (Ma) reports MioOcean Age (Ma) within the applied age model range. MioOcean Recommended Age (Ma) will therefore also be NaN where MioOcean Age (Ma) is NaN because of depth- or age-verification concerns. For ‘out of range’ and ‘non-key site’ temperature data, MioOcean Recommended Age (Ma) reports the published age used by the original proxy study. Users should refer to the published age source information compiled within the temperature database for further information about the published ages.

This application of the MioOcean Age Model database to the MioOcean temperature database ensures that new MioOcean ages are available for the MioOcean temperature records at all key sites where the required depth information could be verified. The provision of MioOcean Recommended Age (Ma) facilitates data use. Overall, this structure also allows future

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revisions to individual site chronologies without requiring reconstruction of the entire database, supporting version-controlled updates as new stratigraphic information becomes available. The resulting impact of these updates on the ages assigned to the MioOcean temperature data is assessed in Section 3.6.

3.6 Impact of MioOcean age model harmonisation on MioOcean temperature data - underlying factors of age change

Of the total 14,559 temperature data points available at the 38 key sites, 13,104 temperature datapoints were assigned a new MioOcean Age (Figure 6; Drury, Tangunan et al., 2026). Of these, 1,532 MioOcean temperature points have a MioOcean Age that remains unchanged relative to the original published age (12%). A total of 1,305 temperature data points were out of range of the MioOcean Age Model age model for the site so report the originally published age in the MioOcean recommended age column (Sites 516, 722, 982, 1085, 1088, 1146, 1241). For four of these sites (Sites 722, 982, 1088, 1241), an age reversal occurs at the transition from MioOcean Age to published age. These intervals should be treated with extreme care;the age model will require extending before data can be used across these transitions (Drury, Tangunan et al., 2026). No age (MioOcean or published age) is reported for a further 141 temperature data points because the relevant MioOcean depth could not be verified or they occurred in an interval where the age assignment was highly uncertain. At Site U1406, six data points occur in a coring disturbance or slump and at Site U1338, the sample ID was incomplete for 135 datapoints, precluding the calculation of MioOcean depths, and accordingly, MioOcean Age.

The average age change for all new MioOcean Ages is 0.027 Myr, with a median and mode of 0.000 Myr, and interquartile range of 0.101 Myr (IQR; denoting the difference between the 25% and 75% confidence interval of the box plot in Figure 6A). When only the Miocene aged datapoints are considered (11,182 in total) the mean mode and median remain unchanged, as well as the percentage of changed ages (87.8%), while the IQR is 0.099 Myr. Overall, the age changes are <0.5 Myr, which is significant on Milankovitch timescales (Figure 6B). However, when considering the full dataset, the largest positive change (a younger age becoming older) is 7.121 Myr in ODP Site 730 and the largest negative change (an older age becoming younger) of -2.695 Myr in ODP Site 747, although only including Miocene aged datapoints the largest negative change decreases to -1.877 Myr at DSDP Site 516.

When broken down into cases where there is a single type of age control (14 of the 38 primary sites and 9,083 datapoints) the original age changed in 99.3% of the data points where biostratigraphy was used and 98.1% for magnetostratigraphy in both the overall and Miocene aged samples. For astrochronology, the original age changed for 84.1% for the overall database and 83.3% for Miocene aged samples. The average change in age for the whole dataset is 0.034 Myr for astrochronology, -0.030 Myr for magnetostratigraphy and 0.020 Myr for biostratigraphy. The IQR is highest in biostratigraphy (0.287 Myr), followed by astrochronology (0.062 Myr) and lowest in magnetostratigraphy (0.053 Myr). When only Miocene aged datapoints are considered, the mean and IQR are unchanged for magnetostratigraphy (mean: -0.030 Myr and 0.053 Myr), while biostratigraphy (mean: 0.022 Myr, IQR: 0.338 Myr) and astrochronology (mean: 0.044 Myr, IQR: 0.074 Myr) change slightly.

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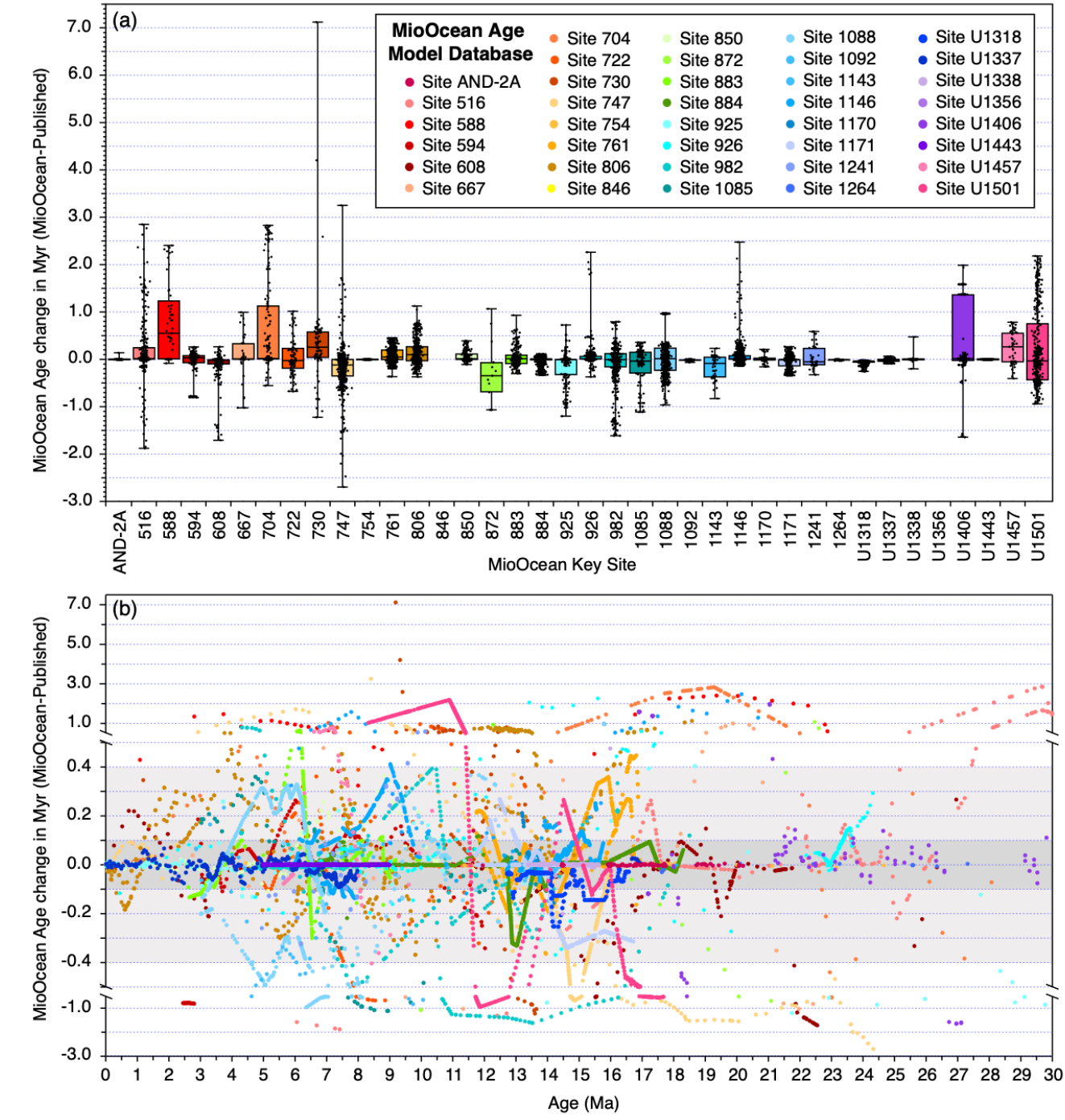


Figure 6. Impact of age-model changes on MioOcean temperature data across time and sites. (a) Change in age in Myr (MioOcean-Published Age) shown as box-whisker plots (with median-line) for each MioOcean key site (full data range shown). (b) Change in age in Myr (MioOcean-Published Age) over time for 0-30 Ma, separated by key site. The shaded areas indicate age changes of ±100 kyr (dark grey) and ±400 kyr (light grey) respectively. Panel b is reproduced for the full 0-67 Ma in Figure B3.

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Where combined methods of age control are applied (3,601 overall and 3,049 Miocene aged datapoints), magnetostratigraphy+ has the lowest percentage change in age (56.8% for the full and Miocene-only dataset). The age changed for the entire biostratigraphy+ category, which also has the highest mean change (0.237 Myr) and IQR (1.195 Myr). The lowest average change for the whole dataset is the Bio-magnetostratigraphy+ category (-0.014 Myr) and astrochronology+ for the IQR (0.019 Myr), while for the Miocene the astrochronology+ category has the lowest mean (-0.016 Myr) and IQR (0.019 Myr). Where the type of age control changes through the record, namely Astrochronology to Biostratigraphy (372 datapoints) and Bio-magnetostratigraphy to Biostratigraphy (7 datapoints), the age changed in 100% of the datapoints, the mean age change is 0.159 Myr and -0.285 Myr respectively.

When each primary site is considered individually, Site 1146 has the largest number of datapoints both overall and for Miocene-only aged samples, while Site 872 (13) and 1264 (10) have the fewest number of datapoints in the overall and Miocene aged breakdowns respectively. Site U1443 has the lowest percentage of age change in both the overall and Miocene with 30.9%, as well as the lowest mean and IQR (both 0.000 Myr) and overall range (0.006 Myr). With respect to the largest differences, in a number of sites, 100% of the original ages changed in both the overall and Miocene datapoints (sites 594, 667, 722, 730, 846, 850, 872, 1085, 1088, 1241, 1264, U1318, U1406, U1457 and U1501) while Site U1337 also changed entirely in the Miocene samples. In terms of mean change, DSDP Site 588 had the largest overall change (0.778 Myr), ODP Site 704 had the highest IQR (1.690 Myr) and the range was highest in 730 (8.343 Myr) in both datasets.

Several factors within the MioAGE workflow could drive changes between the original published ages and the harmonised MioOcean ages. These include changes to the age model itself, for example through the selection of different stratigraphic information or prioritization of a different chronological approach; changes to the depth axis of the age model following an update to the depth model; and changes in the numerical calibration of stratigraphic information to GTS2012. Age changes also arise independently of changes to the age model if the depths assigned to the original temperature proxy data are updated to a more recent depth model. The magnitude of an age change therefore reflects the combined effects of the original depth and age information, subsequent stratigraphic revisions, and the harmonisation undertaken by MioAGE, rather than simply the chronological approach used. The MioOcean Age Model Database can be explored in greater detail through the interactive [Streamlit interface; https://mio-ocean.streamlit.app/Age_models], where users can examine the harmonised age-depth relationships, chronological tie points, metadata and provenance for individual sites (see Sosdian, Auderset et al. (this volume) for further information about the MioOcean Streamlit). The application of these harmonised chronologies to the individual MioOcean proxy compilations is described in Section 3.5 and in the associated MioOcean Output 1 studies (Sosdian, Auderset et al., this volume, Sosdian, Kochhann et al., this volume, Auderset, Liu et al., this volume).

3.7 Challenges and problems encountered during depth and age model harmonisation

Development of the MioOcean Age Framework and MioOcean Age Model Database highlighted several recurring challenges in recovering, reconstructing, and harmonising published depth and age information. Age-depth models were only partially complete at most sites. Sample IDs were often not provided in full, and age-depth tie points were missing or

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without full depth information. Where possible, these deficiencies could be addressed by 1) contacting the lead author(s) for raw data files; 2) converting available information (e.g., mbsf / CSF-A of a specific hole) to full sample depth information (core, section, interval); and 3) identifying the original sample request(s) and retrieving full sample depth information from the request to tie to the temperature data points. However, these solutions were harder to apply to older ODP and DSDP sites, where it was common to report shipboard bio-/magneto-events against mbsf only, without reporting full sample ID.

Our standardized approach to documenting age model information also uncovered inconsistencies and clerical errors that were not always apparent from the published age models alone. These included, for example, correct numerical ages associated with incorrect magnetochron event names, Bayesian age calibrations reported as GTS2012 age calibrations, inconsistent event terminology, and chronological information reported on anomalous or poorly documented depth scales. Such issues could propagate into subsequent studies when published age-depth information was reused without access to the underlying sample and stratigraphic metadata. One of the most significant problems encountered involved the use of anomalous or unreferenced depth scales combined with missing sample ID information. For instance, Site 594 presented a major challenge where sample ID information was difficult to impossible to trace, especially as two holes were drilled at the Site (Hole 594* and Hole 594A). Although a MioOcean Age Model is presented for Site 594, we recommend it is not used until a more in depth age model study can be done at this location. Depth-related issues were also identified at Sites 704, 883 and 884, where there were systematic mismatches between the primary depth derived from the core catcher (CC) sample ID and the reported primary depths in the shipboard reports, requiring detailed evaluation of the underlying sample and depth information (Figure 7; Figure B4). Ultimately, the reported primary depths for bioevent CC samples were reported at the top depth of 1-2 cores below the actual core the CC originated from, resulting in offsets of up to 15 m between the depth reported in shipboard tables and the depth derived from the actual sample ID. This sample ID-depth discrepancy likely accounts for much of the change in age observed at Sites 704, 883 and 884 (Figure 6; Figure 7).

In most cases there was sufficient information to reconstruct the age-depth models of each site based on the chronological methods described in the original publications and the (updated) age-depth model information. The changes in age between data on the original age model and data on the revised age model were typically relatively small; however, in some cases the offsets were more significant, going up to several million years (Figure 6). For instance, Figure 7 highlights two sites, ODP Sites 982 and 704, that experienced some of the most drastic age model updates and focuses on how the MioAGE standardization efforts update our understanding of temperature data coverage across the Miocene Climate Optimum (Sosdian, Auderset et al., this volume; Sosdian, Kochhann et al., this volume; Auderset, Liu et al., this volume). For Site 982, while proxy data from Herbert et al. (2016) and Mejia et al. (2025) required updates of 100s of kyr, data from Super et al. (2020) were in some cases offset by over 1 Myr. This discrepancy may stem from the fact that the study apparently used linear interpolation between only the first and last tie points of the original age-depth table, rather than between each of the tie points listed in the table. As a result, when the updated age model was applied to these data, the revised ages for the proxy data substantially differed from the original published ages, even though the changes to the depth and age model for that site were minor. At Site 704, some proxy data from Auderset et al. (2022) were also offset by up to 1.5 Myr. Site 704 was used

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as a high-latitude tracker in Auderset et al. (2022), and it originally appeared to provide high-resolution data across the MCO. However, critically, our MioOcean age updates show instead that the high-resolution data spans 20–18 Ma in the Early Miocene, an interval that has been infrequently targeted for detailed proxy studies (Woodhouse and Kasbohm, 2026). This change will significantly impact the initial interpretation. These examples demonstrate that chronological harmonization is important not only for improving numerical age consistency, but also for correctly identifying the temporal coverage and resolution of existing proxy records. The MioAGE standardization thus provides a clearer basis for identifying which intervals of the Miocene are well represented by available temperature records and where important temporal gaps remain.

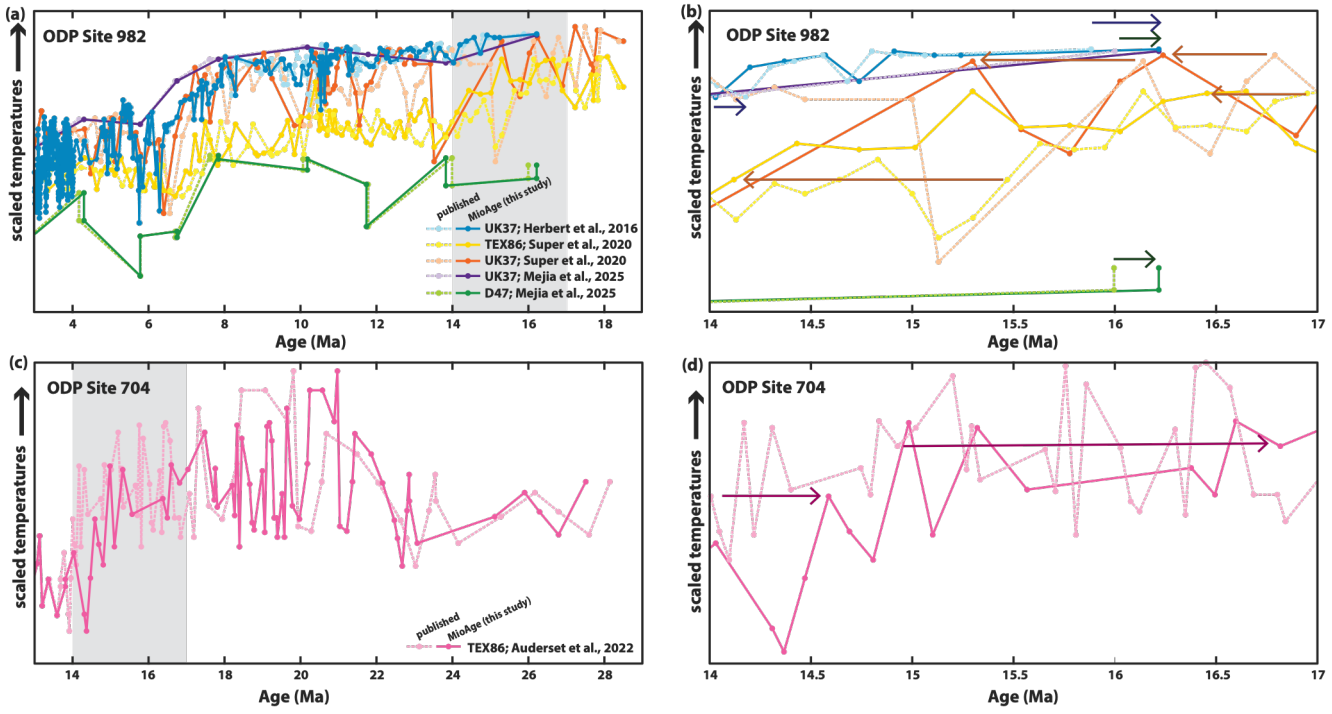


Figure 7. These plots highlight the effect of MioAGE updates on scaled temperature data from ODP Sites 982 (a and b) and 704 (c and d). Bold colors show updated time series, and pale colors show scaled data on original age models. Plots b and d zoom into the Miocene Climate Optimum interval (17–14 Ma, highlighted in grey in plots a and c). Arrows indicate the time difference between the same data point.

4 MioOcean reliability assessment and age model uncertainties

4.1 Why a reliability assessment is needed

Accurately identifying the chronostratigraphy of each MioOcean temperature record to facilitate correlation across regions is a key goal for MioOcean. The stratigraphic framework used to construct any paleoenvironmental reconstruction is its foundation, though a truly synoptic global reconstruction is an impossibility. Accurate determination of a single point in time in a marine sediment core, for example, is often complicated by low accumulation rates where 1 cm may equal several

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740 hundred years and by bioturbation or other sediment disturbance that can distort or disguise the temporal signal. Correlation across ocean basins can be further complicated by differences in timing and expression of benthic oxygen isotope signals between sites, reflecting combined influence of global ice volume, deep-water temperature, and regional oceanographic processes.

Despite these inherent complications, global paleoenvironmental syntheses of other intervals of Earth history have been 745 successfully attained (Imbrie et al., 1984; Martinson et al., 1987). These early reconstructions provide valuable lessons on how best to avoid or reduce the impact of stratigraphic complications. Stratigraphic correlation among samples to attain a global paleoclimate reconstruction was first attempted by the Climate Long Range Mapping and Investigations Project (CLIMAP). CLIMAP's last interglacial reconstruction (CLIMAP, 1984) and the USGS Pliocene Research, Interpretation and Synoptic Mapping project's mid-Piacenzian reconstructions (PRISM; Dowsett et al., 2016, and references therein) 750 illustrate the complexity of correlating records from across the globe to a single time period and comparing temperature data from different proxies. More recently, the Pliocene Climate Variability over Glacial-Interglacial Timescales (PlioVar) initiative synthesized Late Pliocene marine and terrestrial records with particular focus on integrating records with robust stratigraphic frameworks (McClymont et al., 2017; McClymont et al., 2020; McClymont, Ho et al., 2023). PlioVar primarily utilised published age models, with chronologies revised where the original publication pre-dated the LR04 benthic isotope 755 stack (Lisiecki and Raymo, 2005) or the GPTS published in GTS2012 (Ogg, 2012; Gradstein et al., 2012) but did not undertake a formal reliability assessment of individual age models. As part of PRISM, stratigraphic fidelity was considered for the first time through a rubric, as a means to provide a standardised and uniform measure of age model fidelity (Dowsett et al., 2017). Here we build on the knowledge gained from these past efforts.

We discuss the inherent uncertainties in constructing age models for Miocene temperature records, and we establish 760 chronostratigraphic standards for the inclusion of various types of age models into the MioOcean Age Framework and Database. We propose a new reliability assessment that considers a range of general and chronology-specific uncertainties (e.g., sampling resolution, signal mixing etc). The MioOcean Age Model Reliability Grid reviews the reliability of the age model based on reporting quality and inherent age model quality for each of the main chronological approaches individually (biostratigraphy, magnetostratigraphy, astrochronology), which are then integrated and considered alongside site-wide 765 factors to provide a reliability indicator for each age model category available per site.

4.2 Sources of MioOcean age model uncertainties

Our new reliability assessment record considers age model uncertainties due to universal aspects such as sampling resolution and signal mixing (Section 4.2.1), as well as those specific to different chronological approaches (Sections 4.2.2-4.2.4). We also consider the impact that incoherent reporting can have on age model uncertainty (Section 4.2.5). Because sample 770 density and sedimentation rate, as well as the uncertainties related to the different chronological approaches, may change over the length of a time series, age models should be assessed as individual records specific to a time interval and not as a single record over the length of the time series. This discussion is limited to the characterization of the chronostratigraphic

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utility of the MioOcean age models, focussing on the three main chronological approaches identified (biostratigraphy, magnetostratigraphy and astrochronology). Chemostratigraphy and radiometric dating (the use of radioisotopic decay to calculate numeric age) were the two other main chronological approaches observed in the MioOcean Age Model Database, Chemostratigraphy can provide additional chronological constraints through the identification and correlation of characteristic foraminiferal $\delta^{18}O$ and $\delta^{13}C$ events or features, or through Sr isotope stratigraphy, which derives age constraints by correlating measured seawater $^{87}Sr/^{86}Sr$ ratios to the established seawater Sr isotope curve. Radiometric dating is one of the few approaches that can provide direct numeric age constraints. Due to the paucity of use within the MioOcean database, these chemostratigraphic tools and radiometric dating are not discussed in detail. Here, we point readers to a Themed Issue of *GSA Bulletin* on "Reporting and Interpretation of Geochronologic Data", including Schaen et al. (2021) and Condon et al. (2024) for more discussion on the uncertainties impacting radiometric dating in particular. However, the general processes that can influence age model uncertainty will also be relevant to these approaches.

4.2.1 General sources of age model uncertainty

Sampling resolution: Sampling resolution is a fundamental consideration for all chronological approaches because it determines the temporal resolution at which stratigraphic events and signals can be identified and what their associated depth uncertainty is. Capturing paleomagnetic reversals or biostratigraphic events requires sufficiently high-resolution sampling, although there is no universal minimum sampling resolution that ensures the detection of transitional directions at reversals or bioevents. Similarly, astrochronological approaches require sufficient resolution to distinguish the cycles being interpreted; for example, resolving precession is important to avoid aliasing higher-frequency variability as lower-frequency orbital cycles. More broadly, the appropriate sampling resolution depends on the temporal scale of the signal being investigated and the questions being addressed, and practically, the amount of material required for different chronological approaches. Several short-lived, intense glacial features in Miocene isotopic records, for example, would require sampling on the order of 1.5-5 kyr to capture them (Westerhold et al., 2020). As continuous records with sub-orbital resolution remain uncommon for many Miocene proxies, the resolution and limitations of both the chronological information and the associated proxy records need to be considered when interpreting and correlating records.

Continuity, sedimentation rates and signal mixing: Regardless of sampling density, the effective temporal resolution of a stratigraphic record is also influenced by sediment accumulation rate, hiatuses, bioturbation and other post-depositional processes, as well as the continuity and integrity of the recovered geological material, including disturbance or gaps introduced during drilling. Awareness of how continuous a sequence is critical for accurate application of most chronological techniques. Poorly constrained hiatuses or coring gaps can for instance mask missing palaeomagnetic reversals, and for astrochronology could lead to misidentification of the astronomical source of observed cycles or an incorrect correlation to an astronomical target. Low sedimentation rates increase the amount of time represented by a given thickness of sediment and can therefore limit the temporal resolution at which chronological signals can be resolved. Bioturbation further mixes sediment upward and downward within the sediment column, potentially displacing signal

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carriers from their original stratigraphic positions and smoothing or offsetting stratigraphic signals. These effects become increasingly important at low sediment accumulation rates. Other taphonomic and diagenetic processes, including physical abrasion and breakage, dissolution and other chemical alteration, redox processes and biological activity, can further modify the signal carriers preserved within the sediment. Together, these processes influence the resolution and fidelity of the stratigraphic information available for constructing an age model.

4.2.2 Biostratigraphy

Uncertainties in age models based on chronostratigraphic marker species relate to the completeness of the biostratigraphic framework, the quality of the reporting, the sampling resolution, the paleogeographic applicability of bioevents and zonal schemes, and the preservation and identification of the microfossils being analysed. Biostratigraphic zonal schemes are sometimes heavily dependent on calibrations from only a few locations, making them very useful in those locations but perhaps less applicable globally. The applicability of biostratigraphic zonations varies geographically, as many marker species have latitudinally restricted distributions, with tropical markers becoming less common or absent at higher latitudes as meridional temperature gradients increase (e.g. Wade et al., 2011). Some bioevents are also diachronous between low, temperate and high latitudes and between ocean basins (Wade et al., 2011; Lam et al., 2022). It is also important to consider the reliability of events, as some are more reliable than others, both in time and in different geographic regions. The location of the record and the zonal scheme used by the authors should therefore be considered when assessing the reliability of the published bioevents.

A wide range in the quality of biostratigraphic documentation is available in the literature, with some authors reporting presence vs. absence data rather than species counts and others reporting only coarse resolution data (e.g., common in shipboard reports). There is also the consideration of some authors' taxonomic clarity or lack of experience and expertise on certain species. Inconsistent terminology is common across the literature, for instance with LO used to define both 'last occurrence' and 'lowest occurrence'. These refer to distinctly different events: 'last occurrence' refers to the stratigraphically highest occurrence of a species, whereas 'lowest occurrence' refers to its stratigraphically lowest occurrence (Backman et al., 2012; Wade et al., 2011). This ambiguity is why, during the standardisation process, we standardised bioevent terminology to B for base and T for top occurrences throughout the MioOcean Age Model Database. It is also important to consider the date of original publication for biostratigraphic information, since taxonomic concepts, as well as the GTS, have changed over time. Furthermore, microfossil zonal schemes have also evolved following taxonomic and biostratigraphic updates. For example, Miocene planktonic foraminiferal Zone M4 was divided into Subzone M4a and Subzone M4b by Berggren et al. (1995) and followed by Wade et al. (2011), based on the FAD of the marker *Globorotalia birnageae*. However, subsequent taxonomic and biostratigraphic studies indicated that *Globorotalia birnageae* belonged in the genus *Paragloborotalia* and evolved much earlier in the late Oligocene (Leckie et al., 2018). Thus, the subdivision of Zone M4 is invalid (King et al., 2020). Similarly, calcareous nannofossil biozonations have been progressively refined; Backman et al. (2012) introduced a

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new Miocene CNM zonation (CNM1–CNM20), incorporating updated bioevent definitions and age calibrations and providing an alternative to the earlier NN zonation of Martini (1971).

Finally, large stratigraphic errors can occur around events when small or poorly preserved microfossils hinder confident species identifications, or when low microfossil abundances hamper consistent detection of occurrence ranges. These factors can obscure the placement of bioevents and increase uncertainty in their use as chronological constraints. Careful evaluation of the literature by an expert is therefore necessary to account for the plethora of caveats outlined here.

4.2.3 Magnetostratigraphy

The most fundamental problem in magnetostratigraphic age models is that the polarity record may be incomplete or ambiguous. Core gaps, drilling disturbance, sediment deformation, and redeposition can lead to missing or duplicated intervals, while very short polarity chrons may not be resolved, particularly at low sedimentation rates. Consequently, an observed polarity sequence may not always represent a complete and undisturbed record of geomagnetic field reversals. In addition, paleomagnetic data must be placed within some geochronological foundation. Some uncertainties in magnetostratigraphic age models are further bound to fundamental choices such as the reliability of the initial age control (e.g., biostratigraphic events or radiometric dates) guiding the correlation of a local magnetic polarity reversal stratigraphy to a GPTS, as well as the reliability and applicability of the GPTS itself for the time interval. These uncertainties propagate into the construction of the age model.

Palaeomagnetic data themselves also introduce uncertainties. The clarity and strength of the magnetic signal controls the robustness of a local geomagnetic reversal stratigraphy, including whether it is possible to identify every single known chron. First, geomagnetic field intensity generally decreases during reversals, making the magnetic directions within reversal intervals weaker and less straightforward. Second, magnetic grains can still re-align in unconsolidated muddy sediments after deposition, depending on grain size, shape and magnetic properties. Therefore, the recorded remanence may be acquired sometime after deposition, resulting in a delayed lock-in of the magnetic signal and an apparent reversal age that is younger than the actual deposition age of the sediment (e.g., Suganuma et al., 2011). Third, not all magnetic minerals provide equally reliable records: iron oxides such as magnetite, maghemite, and hematite are generally considered robust magnetic carriers, whereas iron sulphides such as greigite and pyrrhotite may form or alter during diagenesis and therefore potentially can record secondary signals. Rock magnetic analyses are consequently important for identifying the magnetic carriers and assessing the reliability of the palaeomagnetic record. To account for all uncertainties, we consider sedimentation rates, sampling resolution, and magnetic-mineral characteristics key aspects for the evaluation of magnetostratigraphic age models.

It should further be noted that geomagnetic reversals are not instantaneous in the geologic record. Complete reversals take time: geodynamo models estimate that it takes ~5-10 kyr for a full reversal to take place and the duration is also latitude-dependent (e.g., Clement, 2004). All recent GPTS's, however, assign a numerical age to a polarity boundary with a nominal resolution of ~1 kyr. They represent reference ages for the polarity boundaries, not a claim that the field switched polarity

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instantaneously at that time. GPTS ages commonly originate from astronomical tuning of a (high-resolution) stratigraphy to an astronomical solution or insolation curve, with the actual reversal commonly identified at the midpoints between samples with different polarities. The sedimentary record of the reversal interval can be further expanded by bioturbation and delayed magnetization lock-in. Thus, the apparent 1-kyr precision of the GPTS should not be interpreted as 1-kyr accuracy for the timing or duration of an individual reversal.

4.2.4 Astrochronology

In building age models based on chronostratigraphy and astrochronology, the quality and resolution of these data are crucial. Low-resolution magnetic susceptibility, for example, can mimic obliquity although precession is present. Within the scope of MioOcean, all astrochronologies were numerical rather than floating astrochronologies calibrated to numerical age. As such, we only consider the uncertainties relating to numerical astrochronologies on Miocene timescales here. For a broader discussion of uncertainty in cyclostratigraphy, see Sinnesael et al. (2019). Broadly, the main categories of uncertainties in astrochronology relate to 1. the signal clarity in the data used to tune, 2. the choice of astronomical solution as the tuning target, 3. the tuning technique, and 4. the initial age constraints used to guide the tuning. As with biostratigraphy, expertise and experience can also impact the fidelity of an astrochronology, as the Cyclostratigraphy Intercomparison Project (CIP) also demonstrated that researcher experience with a specific archive and/or time period leads to systematically more accurate cyclostratigraphies (Sinnesael et al., 2019).

Signal clarity: section 4.2.1 discussed the impact that sample resolution, sedimentation rates and signal mixing can have on the quality of the geological data being used to create an age model. These aspects can significantly impact clarity and integrity of cycles recorded in a stratigraphic dataset underpinning an astrochronology. To address these potential uncertainties, we consider the sedimentation rate, sample resolution, data quality, cycle amplitude, and cycle quality of these data. The sample resolution criteria of at least 4 samples per targeted-cycle is defined based on the recommendations from Martinez et al. (2016).

Tuning target: Due to the chaotic behaviour of the inner planets and main asteroids Ceres and Vesta, calculating accurate numerical astronomical solutions back in time is limited to about 50-60 Ma (Laskar et al., 2011a,b; Zeebe and Lourens, 2019). Ceres and Vesta thus appear to be the main limiting factors for any precise reconstruction of the Earth orbit (Laskar et al., 2011b, Laskar 2004). For the Miocene, where numerical solutions can provide accurate target curves, most uncertainties stem from so far unknown changes in tidal dissipation and dynamical ellipticity (Figure 21.7 in Lourens et al., 2004). The effect on precession and obliquity back to 12 Ma do not significantly affect orbital tuning (Zeeden et al. 2014). Beyond 12 Ma, tuning to precession and obliquity will contain an increased uncertainty that still needs to be resolved through collaboration between astronomers and geoscientists (e.g., Farhat et al., 2022). However, the orbital solutions for short (~100 kyr cycle) and long eccentricity (~405 kyr cycle) can be considered reliable for the entire Miocene. Short eccentricity is stable constrained back to 40-50 Ma and long eccentricity is considered a stable metronome back to the Late Cretaceous

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(Laskar et al. 2004; Laskar et al., 2011a,b; De Vleeschouwer et al., 2024). Therefore, for early Miocene astrochronologies, the uncertainty related to tuning to a target curve containing precession and obliquity remain poorly constrained.

Tuning technique: Cyclostratigraphy and astrochronology is an iterative process that can be achieved through a range of visual and/or numerical numerical approaches (see Sinnesael et al., 2019 for recommended guidelines). The process of tuning, i.e. identifying the phase relationship between the geological data and tuning target, as well as the location and number of tie points, can add uncertainties due to a dampened response to astronomical forcing, unknown phasing between forcing and proxy response (e.g., Miocene ice volume response to insolation forcing), and changes in the phase-relationship over time. Sometimes no appropriate tuning target is available, or there is no constant relationship between the tuning target and the dataset for an entire interval (e.g., Drury et al., 2021 had to apply four tuning relationships between 0-30 Ma). Correlating single isotope events only (e.g., TG, CM, Mi-events; more commonly used within chemostratigraphy) can lead to a high risk of misidentification, especially when working with low resolution records. Age models developed through identifying and correlating all events or cycles within a record are less likely to have this issue occur.

Initial age constraints: Converting a cyclostratigraphy to a numerical astrochronology requires initial age constraints to firstly identify the most appropriate astronomical parameters to tune to, as well as identify initial anchor points to tie a cyclostratigraphy to an astronomical solution. Initial age constraints guiding the tuning can bear the largest error leading to misidentification of cycles (e.g., obliquity instead of precession) or by providing a misleading starting point. An erroneous biostratigraphic framework, for example, can lead to a misidentified paleomagnetic reversal. The use of astronomically calibrated bio- or magnetoevents to act as anchor points could also lead to circular reasoning if these are not ground-truthed with additional independent constraints. Integration of regionally available records through high-resolution stratigraphic correlation is recommended to ground truth the reliability of the initial age tie points.

4.2.5 Impact of incomplete reporting

For all chronologies, the utility of an age model is determined by the quality of the reporting and whether the chronology can be reproduced and revised. As discussed in Section 2.1.1, all stratigraphic information in an age model must be reported alongside full sample ID and depth model type and source information. Additionally, an age model should report information relevant to the age calibration (e.g., the GTS or astronomical target curve used). Depth and age uncertainty should be reported as much as possible. Each chronological approach additionally has specialist reporting requirements that underpin and validate the reliability of the stratigraphic information in an age model (i.e., a clear taxonomic framework, well-documented demagnetisation protocols, the phase relationship used for tuning). A high-quality age model is documented in detail in a table that is updatable when different aspects of an age model change. Though the uncertainty related to incomplete reporting is difficult to quantify numerically, it can have a significant impact on the perceived reliability of an age model, as it is simply impossible to verify an age model's foundations.

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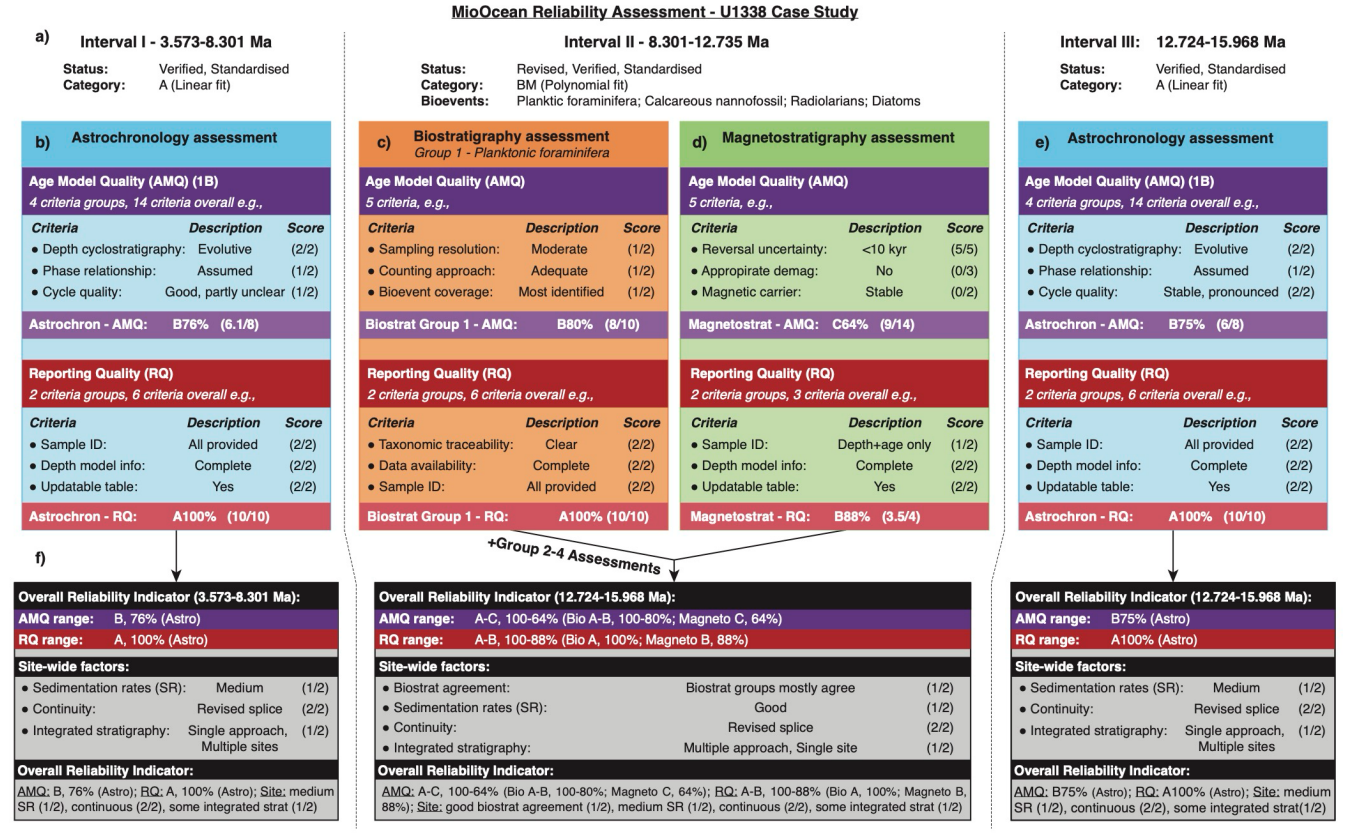


Figure 8. Site U1338 Reliability Assessment case study. a) Denotes the three age model segments, each spanning a different interval and with a different age model status and category. b) the first astrochronology assessment of Age Model Quality (AMQ) and Reporting Quality (RQ) for the first age model segment based on an astrochronology (Drury et al., 2018b, 2016). c) the biostratigraphy and d) magnetostratigraphy assessment of Age Model Quality (AMQ) and Reporting Quality (RQ) for the second age model segment based on bio-magnetostratigraphy (Expedition 320/321 Scientists, 2010). e) the second astrochronology assessment of Age Model Quality (AMQ) and Reporting Quality (RQ) for the first age model segment based on an astrochronology (Holbourn et al., 2022, 2014). f) the integrated overall reliability indicator for each age model segment, considering the range of Age Model and Reporting Quality, as well as site-wide factors.

4.3 MioOcean age model reliability indicator

Effectively addressing the range of universal and chronology-specific factors impacting age model uncertainty is a complex task. Integrated stratigraphy involves combining multiple stratigraphic and chronological approaches to improve the confidence and reduce the uncertainty of an individual approach applied on its own (Hilgen et al., 2015; Sinnesael et al., 2019). We designed the MioOcean Age Model Reliability Grid to qualitatively assess the reliability of age models incorporated into the MioOcean Age Framework using an integrated approach considering the range of factors impacting age model uncertainty discussed in Section 4.2. The Reliability Grid consists of a robust semi-quantitative framework to assess the quality and consistency of the age models at each site by assessing both age model- and reporting-quality criteria for each of the major chronological approaches used in MioOcean. Crucially, the Reliability Grid then integrates the individual

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chronological reliability assessments (Section 4.3.1: biostratigraphy; Section 4.3.2: magnetostratigraphy; Section 4.3.3: astrochronology) into an overall Site-wide reliability indicator to synthesise all available chronological information along with site-wide factors, such as sedimentation rates and whether an integrated approach was considered (Section 4.3.4). These Reliability Grids ultimately offer a comprehensive and integrated stratigraphic assessment of age model reliability. For the discussion below U1338 was chosen as a case study, as the integrated age model contains three distinct intervals (Figure 8a) using biostratigraphy and magnetostratigraphy (between 8.301-12.724 Ma; (Figure 8c, d) and astrochronology (two independent chronologies between 3.573-8.301 (Figure 8b) and 12.724-15.968 Ma (Figure 8e)). Each interval was assessed separately and received its own overall reliability indicator (Figure 8f). Assessments were made based on the information collated in the MioOcean Age Model Database, supplemented by additional information provided in the source literature. The grids also provide space for the assessor to add notes and additional references relevant to the assessment.

4.3.1 Biostratigraphy assessment criteria

The biostratigraphic reliability assessment considers the uncertainties associated with both the scientific quality of the biostratigraphic framework and the quality of its reporting (Figure 8c). The assessment therefore separates these into Age Model Quality and Reporting Quality criteria, with each criterion assigned a score from 0 to 2.

The Age Model Quality criteria assess the scientific quality and reliability of the biostratigraphic framework. These consider sampling resolution and sample thickness, stratigraphic integrity (e.g. bioevent reversals or stratigraphic inconsistencies), whether the counting approach is appropriate for the bioevents used, and the coverage of appropriate bioevents expected at the site or latitude. Bioevent coverage is assessed relative to the bioevents that can reasonably be expected at a given site, rather than simply rewarding a greater number of bioevents. This accounts for paleogeographic differences in the distribution and applicability of biostratigraphic markers. Similarly, the counting approach is assessed according to whether it is appropriate for the selected bioevents, recognising that quantitative counts may be necessary for abundance-based events, whereas qualitative approaches may be sufficient for other bioevents.

The Reporting Quality criteria assess how well the data, methods and associated metadata are documented and made available. General reproducibility criteria consider whether the age model is provided in a table with sufficient sample, depth and age information, and whether the source and details of the depth model are reported. Biostratigraphy-specific reporting criteria assess taxonomic traceability, availability of the underlying species count, distribution or occurrence data, methodological traceability (including the bioevents or zonations, calibration/GTS used, assumptions and formulas), and accessibility of supporting datasets. For taxonomic and methodological traceability, the emphasis is on whether the approach used can be clearly identified and traced; established taxonomic concepts or methodologies may therefore be appropriately referenced rather than described in full.

For each criterion, the assessor selects the description that best reflects the available evidence, generating an individual score of 0, 1 or 2. The individual scores are combined to provide separate Age Model Quality and Reporting Quality scores. These are subsequently assigned to five reliability categories: A (9-10; highly reliable), B (7 to <9; moderately reliable), C (5 to <7;

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reliable), D (3 to <5; limited reliability), and E (0 to <3; unreliable, use with caution). Assessor judgement is retained for borderline cases, and a brief summary records the rationale for the assessment.

In the example shown in Figure 8c, the biostratigraphic reliability assessment was applied separately to four microfossil groups used for constructing the Site U1338 age model between 8.58-11.79 Ma: calcareous nannofossils, planktonic foraminifera, radiolarians and diatoms (please note, only the planktonic foraminifera assessment is shown in Figure 8c, the remaining grids are shown in full in Drury, Tangunan et al., 2026). Site U1338 is located in the eastern equatorial Pacific and occupied an equatorial to near-equatorial setting during the Miocene, where high biological productivity and changes in carbonate and biosiliceous sedimentation produced a rich but environmentally variable microfossil record Expedition 320/321 Scientists (2010). The assessment captures this variability among fossil groups. Calcareous nannofossils and diatoms achieved the highest Age Model Quality scores (10/10, 100%; Category A), reflecting high sampling resolution, consistent sampling, appropriate counting approaches and identification of most or all expected bioevents. Planktonic foraminifera and radiolarians scored 8/10 (80%; Category B), principally because of lower sampling resolution and semi-quantitative counting, although the majority of appropriate bioevents were identified. These differences illustrate how the reliability of biostratigraphic constraints can vary among microfossil groups at the same site as a consequence of sampling, the availability and abundance of appropriate marker taxa, preservation, and the nature of the bioevents used. In contrast, all four microfossil groups received the maximum Reporting Quality score of 10/10 (100%; Category A), indicating strong reporting, methodological and taxonomic traceability, and data availability and accessibility. This demonstrates that high Reporting Quality does not necessarily correspond to equally high Age Model Quality.

The reliability scores for individual microfossil groups are therefore retained separately rather than combined or averaged into a single biostratigraphic score. Averaging could obscure important differences in the quality and applicability of the individual age frameworks; for example, a particularly strong record from one microfossil group could compensate numerically for a weaker or poorly resolved record from another. Instead, the individual assessments are considered together at the integrated stage, where agreement and complementarity among independent microfossil groups can contribute additional information on the overall reliability of the site chronology. This approach preserves the strengths and limitations of each biostratigraphic dataset while allowing their collective contribution to the overall age model to be evaluated.

4.3.2 Magnetostratigraphy assessment criteria

Age Model Quality criteria for magnetostratigraphic models include sampling density, demagnetization protocols, assessment of remanence carriers, presence of hiatuses, and comparison with other types of chronological information (e.g., biostratigraphy) when correlating reversals to the GPTS. Reporting Quality criteria include whether sample IDs and sampling uncertainty are included with the ages and depths of reversals (so that age-depth models can be updated), and detail provided about the depth modelling approach. We scaled our criteria such that a typical shipboard workup would merit an average score of C, corresponding to 6-9 points out of a possible 14 (43-64%; Figure 8d).

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We also show our evaluation of the Site U1338 magnetostratigraphic age model information between 8.58-11.79 Ma. Because the magnetostratigraphy was ascertained only with shipboard work (Expedition 320/321 Scientists, 2010), there was no assessment of magnetic mineralogy, and only two alternating field demagnetization experiments were performed. However, a high measurement resolution of 2.5 cm, a lack of hiatuses at the site, consideration of integrated biostratigraphy, and replication of reversals in multiple holes were all favourable. Sample IDs were provided but depth uncertainties were not retained. As expected, this site's shipboard work therefore merited a C score for magnetostratigraphy.

4.3.3 Astrochronology assessment for independent astrochronologies and astronomically-based stable isotope correlations

The Astrochronology reliability assessment is relevant for both independent astrochronologies and astronomically-based stable isotope correlations. Although astrochronologies regularly rely on biostratigraphic and/or magnetostratigraphic information as part of their initial age constraints (see Section 4.2.4), the reliability of this stratigraphic information is not assessed independently using the bio- or magnetostratigraphy assessments, but is instead assessed as part of the Age Model Quality criteria. The astrochronology reliability assessment considers the uncertainties associated with both the scientific and reporting quality of the astrochronology-derived age model (Figure 8a, 8e). The assessment therefore separates these into Age Model Quality and Reporting Quality criteria, with each criteria group averaged to assign an overall score from 0, 1 or 2. The assessor selects the criteria description that best reflects the available evidence. The individual criteria group scores are combined to provide separate Age Model Quality and Reporting Quality scores assigned to five reliability categories ranked as A, B, C, D or E. Assessor judgement is retained for borderline cases, and a brief summary records the rationale for the assessment, which feeds into the integrated assessment indicator (see Section 4.3.4).

The Age Model Quality criteria assess the scientific quality and reliability of the astrochronology-derived age model. biostratigraphic framework. The Age Model Quality score is informed by separate assessments for an astronomically-based stable isotope correlation (Grid 1A) and an independent astrochronology (Grid 1B). The '1A - stable isotope correlation grid' should be used where a stable isotope record is correlated to an astronomically tuned global stable isotope reference record (e.g., LR04 or CENOGRID; Lisiecki and Raymo, 2005; Westerhold et al., 2020). The 1A grid provides a streamlined assessment that considers the quality of both the stable isotope data used for the correlation, as well as the quality of the target used to correlate to. The '1B - independent astrochronology' should be used for astrochronologies developed by directly correlating geological data to a numerical astronomical solution.

The 1B grid evaluates an astrochronology on four criteria groups: Geological Data Quality; Reliability of the Foundation; Astronomical Target and Relationship to the Target Curve. The Geological Data Quality criteria group assesses how well the geological data used for the astrochronology can resolve the relevant Milankcovitch cyclicity. These criteria consider sedimentation rates, the smallest cycle resolvable with the average sampling resolution, data quality (e.g., signal to noise ratio), cycle amplitude and how well the cyclicity is imprinted in the geological data. The Reliability of the Foundation criteria group assesses the quality of the initial age control (including whether it is solely based on shipboard analysis or also

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involves in-depth post-cruise revision), and whether the geological data was evaluated using a depth-based cyclostratigraphic analysis with Milankovitch cyclicity ground-truthed using the initial age constraints. The Astronomical Target criteria group assesses which target curve was used and whether it is reliable for the target cyclicity (e.g., obliquity and precession for 0-10 Ma; eccentricity for 0-23 Ma). The publication age of the astronomical target curve is considered here (see Section 4.2.4), with target curves preceding La2004 identified as requiring an update to a more recent curve. Finally, the Relationship to the Target Curve evaluates the evidence or logical arguments defining the phase relationship between the geological data and the astronomical target, the degree of tuning (e.g., whether an astrochronology is minimally tuned, fine-tuned or overtuned) and whether the astrochronology was independently validated through statistical testing, multi-proxy approaches or by comparison to an independent chronology.

The Reporting Quality criteria assess how well the astrochronology and associated metadata are documented and archived through Reproducibility and Revisability criteria groups. The Reproducibility criteria group considers whether the astrochronological tie points are reported in a detailed table with full sample information, depth and target curve information, as well as whether the depth model type and source is recorded. The Revisability criteria group considers whether sufficient information (e.g., sample ID, primary and composite depths) is provided to ensure that the astrochronology could be updated to accommodate revisions to the depth model.

U1338 has two independent astrochronologies spanning 3.573-8.301 Ma (Drury et al., 2018b, 2016) and 12.724-15.968 Ma (Holbourn et al., 2022, 2014; Kochhan et al., 2016), and as such required an astrochronology assessment for each interval (Figure 8b, 8e). The respective astrochronology age model quality assessments capture the difference in climate variability between the Middle Miocene (generally high amplitude eccentricity-driven variability) and the Late Miocene (generally lower amplitude obliquity-driven variability). The Age Model Quality category for the Late Miocene astrochronology was B-76% (6.1/8.0) largely because there were intervals with a low signal to noise ratio leading to some uncertainty in the tuning (Figure 8b). The Age Model Quality category for the Middle Miocene astrochronology was B-75% (6.0/8.0): the geological data is of exceptional quality, however, tuning to obliquity and precession remains very complex beyond the Late Miocene (Figure 8e), as the phase of the obliquity and precession tuning target is less well constrained in the 10-20 Ma interval (e.g., Zeeden et al., 2014). Both age models applied fine tuning rather than minimal tuning approaches. Both astrochronologies have a Reporting Quality category of A-100%, as they are recorded with full sample ID, depth and tuning target information in the MioOcean Age Model Database and in the most recent published versions of these age models compared to their first publication. This illustrates the ongoing improvements in age model reporting by the community.

4.3.4 Integrated reliability assessment

The most reliable age models are constructed through the integration of multiple stratigraphic frameworks, i.e., using integrated stratigraphy. Integrated stratigraphy can increase confidence in age model accuracy and reliability. Palaeomagnetic age models, for instance, are considerably strengthened when interpreted alongside complementary datasets rather than as standalone chronologies. Integration of independent chronological approaches can provide complementary

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constraints and allows agreement or inconsistencies between different stratigraphic frameworks to be identified. For each MioOcean age model segment with a distinct age model category, our integrated reliability assessment table (Figure 8f) combines individual age model assessments from a single site into an integrated site-level assessment and considers these alongside site-wide factors that influence the reliability of the overall age model. Because sample density and sedimentation rate, as well as the uncertainties related to the different age model components, may change over the length of a time series, age models compared in this way should be limited to specific time intervals. As the maximum scores vary among chronological approaches, Reporting Quality and Age Model Quality scores are converted to percentages to enable comparison between approaches. The individual chronological biostratigraphic, magnetostratigraphic and astrochronologic assessments are retained separately rather than combined into a single average, thereby preserving differences in the strengths and limitations of each chronological approach. Finally, to form an overall reliability indicator, we consider site-wide factors such ashe continuity and average sedimentation rates of the site or hole and the degree of integrated stratigraphy used along with the Reporting Quality and Age Model Quality score range. Site-wide factors considered include sedimentation rate, stratigraphic continuity, the presence of hiatuses or core gaps, recovery across multiple holes, and the extent to which independent chronological approaches have been integrated. The highest site score is reserved for multiple-cored records of continuous high sedimentation rates, where splices cover the core gaps. Records that consider multiple sites and multiple stratigraphic approaches to attain their age models score higher than those that consider either multiple sites or multiple approaches, or consider neither. The integrated assessment therefore provides an overall site-level reliability indicator while retaining the individual chronology-specific assessments needed to identify the sources of strength or uncertainty within each age model. For instance, at Site U1338, the three overall reliability indicators have similar site-wide scores as all three intervals had comparable sedimentation rates and continuity, and all used a degree of integrated stratigraphy. The main difference in reliability indicator therefore derives from the differences in chronological approach underpinning the age model (Figure 8f).

4.4 Application to MioOcean sites

The MioAGE Reliability Grid was applied to all 38 MioOcean key sites to assess the reliability of the age models incorporated into the MioOcean Age Framework. For each site, the relevant chronology-specific assessments were undertaken according to the age model approaches used, with separate evaluation of Age Model Quality and Reporting Quality (note that when an astrochronology assessment was completed, any initial age constraints from bio-magnetostratigraphy were only assessed within the astrochronology grid and did not undergo assessment using the bio- or magneto-grids). Where multiple chronological approaches were available, these individual assessments were subsequently considered together with site-wide factors in the integrated reliability assessment described in Section 4.3.4. The reliability assessment was undertaken per site and, where applicable, separately for each age model category interval. The completed reliability assessments for all MioOcean key sites are provided in Drury, Tangunan et al., 2026.

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The 38 sites encompass a wide range of chronological frameworks, allowing the Reliability Grid to be applied across age models based on astrochronology, biostratigraphy, magnetostratigraphy, integrated bio-magnetostratigraphy, and combinations incorporating additional chronological approaches. Several sites also contain more than one Age Model Category, reflecting changes in the chronological approach used through different intervals of the record. In addition, individual chronological approaches may have been assessed separately for different time intervals where the underlying chronology was derived from different studies or workers. Application across this range of age models demonstrates the importance of retaining the chronology-specific and, where appropriate, interval-specific assessments: the factors controlling reliability, and the quality and availability of the information required to assess them, differ among chronological approaches and among the underlying studies from which they were derived. The integrated assessment therefore provides a consistent basis for comparing overall age model reliability across the MioOcean key sites while retaining the individual assessments needed to identify the specific strengths and limitations of each chronology.

5 Guidelines for archiving and updating age-depth models

5.1 General Reporting Guidelines

The workflow implemented in MioOcean (Figure 4) highlights both the feasibility and the challenges of harmonising age models across large, heterogeneous datasets. Based on the experience gained from harmonising and revising 38 age models for MioOcean, we propose a set of best-practice guidelines for reporting, updating and archiving depth-age models. This will ensure that they are reproducible and can be updated by future refinements or modifications.

Firstly, it is important to recognise that the depth and age models used for geological data can be subject to change. Age models can be modified based on new observations and revisions of chronostratigraphic tie points. Similarly, depth models can change, particularly for scientific ocean drilling records at a given location where a composite depth scale has been constructed from multiple holes. Post-cruise high-resolution measurements, such as XRF core scanning, for example, allow the original shipboard composite sediment splice to be verified and corrected if necessary (e.g., Evans et al., 2004; Westerhold et al., 2007; Wilkens et al., 2013; van Peer et al., 2017a; Drury et al., 2018a). It is important to note that age models are only valid when used in conjunction with the specific depth model that was employed during their construction. Only by using the original depth model can multiple proxy datasets be reliably compared and meaningfully interpreted for testing hypotheses.

For ocean drilling samples, data are usually obtained from individual samples or measurements taken at set intervals in sediment cores. Each sample or measurement can be uniquely identified by its full sample label, independently of any core depth or age model. This sample ID number provides the basic information from which depth and age can be calculated. In scientific ocean drilling, sample IDs consist of the site number, followed by the hole identification, the core number, the section number and the depth at which the sample was taken (e.g. 925C-12H-1, 20-22 cm). Data should not only be reported

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against a depth value (e.g. 122.34 mbsf) because, if the depth model changes, the sample depth cannot be reconstructed or updated without the associated sample ID. For scientific ocean drilling data from multiple holes in particular, it is crucial to report sample IDs in order to specify which hole a data point originated from and to allow the depth to be updated, if there is a change in the splice (Drury et al. 2026).

Age models are usually presented in straightforward two-column tables showing depth versus age. However, if the depth needs to be recalculated due to a change in the composite depth scale, the age tie points become unusable. To reliably archive published age models, the following must be reported: sample IDs for the depth values, and the source of the depth model for the composite depth (e.g. 'rmcd [Wilkens et al., 2017]'). In order to update the age value, the source of the age and the GTS version to which it is calibrated must be reported (e.g. 'Age Ma [Chaisson and Pearson, 1997]' or 'Age Ma [GTS2012]'). Age tie points from bio- and magnetostratigraphy are often given as the mean of two samples. To allow this value to be updated, the full sample ID for both samples must also be reported. Sample IDs are required for reporting and archiving proxy data in order to calculate depths and respective ages, as well as for future updates.

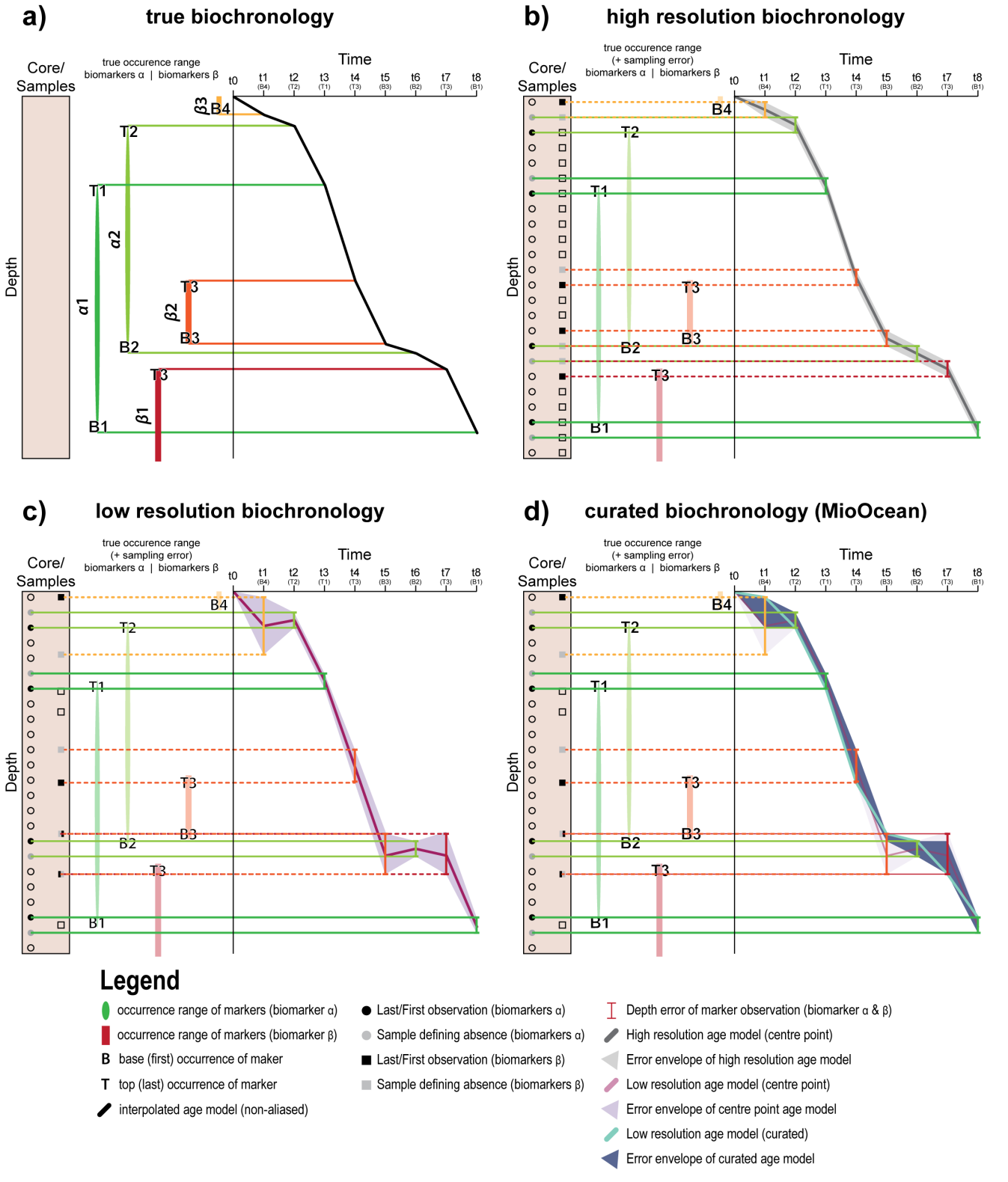
5.2 Biostratigraphy Guidelines

For biostratigraphic data, it is crucial to unequivocally record the samples bounding the first and last stratigraphic observations of a taxon at each biostratigraphic tie point, prior to calibrating them to absolute ages based on geochronological and astrochronological compilations (e.g., Wade et al., 2011; Backman et al., 2012; Agnini et al., 2014; Raffi et al., 2020).

For biostratigraphic age models, it is also highly recommended that evolutionary and extinction patterns be considered within the context of their unique unidirectional temporal progression (Gradstein et al., 2020; Petrizzo et al., 2026). For instance, in the absence of other independent age control, base occurrences of a biostratigraphic marker should conservatively be interpreted as younger than the published "global" age calibration of the event. This stems from the fact that calibrated ages can be regarded as the closest approximation to the true evolutionary FAD or LAD of distinct morphospecies in time. However, in marine settings such as those underpinning MioOcean, the expression and recognition of these evolutionary transitions can be resolved with sufficient sampling resolution and well-defined taxonomic criteria used to distinguish ancestral and descendant morphospecies (e.g., Petrizzo et al., 2026). Morphological transitions may be resolved in detail particularly in high sedimentation rate records. Occurrences of a specific taxon at a given geographic location can, therefore, only be younger than this evolutionary FAD, or older than its LAD. Local diachroneities are to be considered a consequence of biogeography, leading to diachronous species distribution/extinction patterns due to differing ecological conditions. Detecting such biogeographic differences in bioevent chronology, however, require integrated age modelling with other stratigraphic approaches, and do not constitute a typical use of biostratigraphy, but rather the process of developing a robust biostratigraphy. The sample spacing of the biostratigraphic record subsequently further mitigates the detection accuracy of biostratigraphic events (Figure 9).

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Figure 9. Example of potential pitfalls with depth sampling and 'centre point' approaches in biostratigraphy. Time is shown as *t1* to *t8* representing the accepted calibrated timing of each bioevent. a) Idealized biostratigraphic age model example with no sampling bias is introduced to local biochronological events. All recorded depths correspond to the true base (B) or top (T) occurrence of each biostratigraphic marker in both example fossil groups [α] and [β]. b) Example of the additional depth uncertainty introduced by discrete high resolution sampling (i.e., post-cruise biostratigraphic data) including the resulting age-depth error and its error envelope using the "centre point" approach for interpolation. Data of such quality generally results in low age model bias using a center-point approach. c) Example of increased age-depth error propagation with variable and/or low resolution (i.e., shipboard) biostratigraphic sampling using a centre point approach. Such low resolution age-depth models may even contain time reversals due to uncertainties introduced due to large sampling biases. d) Example of the curated approach developed for updating age models in the MioOcean Age Model Database compared to the classical centre-point approach shown in panel c when it is applied to variable- and/or low resolution (i.e., shipboard) biochronologies. The curated approach applied by MioOcean can improve age constraints by observing biostratigraphic principles such as co-occurrence and evolutionary patterns within the full taxonomic and evolutionary framework of all available biostratigraphic markers.

Crucially, at a given location, the 'true' local stratigraphic first occurrence of a biostratigraphic marker takes place between the biostratigraphic sample where the base (B) of a marker was found and the sample immediately preceding it (i.e., the sample below it), where the marker had not yet been found. Conversely, the local last occurrence of a marker takes place between the sample where the top (T) of that marker is found and the sample succeeding it (i.e., above it), where the marker was no longer found. Therefore realistically, base occurrences can only have a downward stratigraphic error and top occurrences can only have an upward stratigraphic error associated with a marker's local observation. This has important implications for the final construction of age models using biostratigraphic datums, particularly in cases where only low-resolution (i.e. shipboard) biostratigraphic data is available. In these cases, the commonly used 'centre' or 'mid-point' approach leads to a considerable loss of critical information for biostratigraphy, especially when only a single depth value is given. The occurrences of overlapping or even inverted biostratigraphic age tie-points is an example of this loss of information.

Therefore, we recommend that both the marker sample and absence sample ID and depth information should always be archived for any biostratigraphic datum: 1) the sample information (ID + depth) for a marker's base or top observation and 2) the sample information for the preceding (for base) or succeeding (for top) sample where the marker was not observed. It should further always be clearly noted in which of these two samples the actual first or last observation of the bioevent was made. This reporting approach facilitates subsequent re-construction and updates of biostratigraphic age models. The archived data thus accurately represents and preserves both local sampling biases, as well as all evolutionary and biogeographic considerations underpinning the biological organisms at the root of biostratigraphy.

5.3 Magnetostratigraphy Guidelines

Magnetostratigraphic records should be archived in a way that preserves the distinction between interpreted polarity patterns and chronological assignments, allowing age models to be updated without losing the underlying palaeomagnetic evidence. Raw palaeomagnetic and rock-magnetic measurements, sample metadata, demagnetization data, magnetic-mineral information, and the original depth scale should be retained, together with the criteria used to assign polarity and identify polarity boundaries. This section summarises several data archiving standards from the paleomagnetic community (Koymans

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et al., 2020). See Section 4.2.3. Magnetostratigraphy for details on how magnetostratigraphic uncertainties could propagate into the quality of a magnetostratigraphic record.

For magnetostratigraphic tie points, it is essential to archive the sampling-dependent depth range within which each event is constrained, reflecting the discrete nature of palaeomagnetic sampling. Magnetostratigraphic tie points are defined by a detected change in remanent magnetic declination and/or inclination between two consecutive analysed samples of opposite polarity. The reversal boundary is conventionally assigned to the midpoint between these two samples. To accurately capture the depth uncertainty associated with each geomagnetic reversal, both bounding samples must therefore be archived, together with their individual depths and polarity interpretations. The resulting depth interval between the two samples provides the minimum sampling-related uncertainty of the reversal and should be retained alongside the calculated midpoint. This approach ensures that the reported precision of magnetostratigraphic tie points reflects the actual sampling resolution rather than implying an artificially precise event depth.

Revised interpretations or age models should be versioned and traceable, with a clear record of changes and justification. This approach ensures that future updates to the GPTS, or new palaeomagnetic interpretations, can be incorporated while preserving the original observations and the full uncertainty associated with each magnetostratigraphic event.

5.4 Astrochronology Guidelines

For astronomically tuned age models, we suggest referencing the orbital solution that was utilized as a target curve (e.g., 'La2004, Laskar et al., 2004'). The rationale behind the tuning approach must also be explained, providing evidence or logical arguments for the applied phase relationship between these data and the target curve (e.g., 'The $\delta^{18}O$ minima were tuned to the eccentricity (E) maxima (from 15-10 Ma) and to eccentricity-tilt (ET) maxima (from 10-7 Ma). No phase shift was applied following the approach of Shackleton and Crowhurst (1997) and Holbourn et al. (2007)'). To avoid transposing the target curve characteristics into geological data, we recommend using as few tie points as possible (see Zeeden et al., 2015). The final astronomical age model should include the full sample ID, depth information and age for tie point, similar to the advice for reporting sample data. Additionally, the origin of the depth model employed must be reported.

5.5 FAIR recommendations

The long-term value of palaeoclimate proxy data hinges on the transparency and reproducibility of the chronological information on which it is based. We therefore recommend that future age and depth models adhere to the FAIR (findable, accessible, interoperable and reusable) data principles (Wilkinson et al., 2016). Proxy data from Earth system research, together with their associated depth and age models, are increasingly archived, published and distributed through large community databases such as PANGAEA and the National Oceanic and Atmospheric Administration (NOAA). However, proxy datasets are commonly reported against a single depth column, while full sample IDs are not always retained and the underlying information required to reconstruct the depth and age models is often incomplete or absent. Although sufficient

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for displaying the published data, this format limits the ability of both researchers and computational tools to evaluate the consistency, provenance and subsequent application of the underlying chronology.

All published proxy records and chronologies should be therefore accompanied by complete and machine-readable stratigraphic and chronological metadata, including original sample identifiers, the source and version of the depth model, fully referenced depth model provenance (see Drury et al., 2026 for recommendations for reporting sample ID and depth model information), chronostratigraphic tie points, interpolation methods, and the GTS used. For age tie points, the source of the numerical age should also be retained, including the origin and version of the GTS and, where applicable, the calibration source. Most importantly, all stratigraphic and proxy data should retain the full sample ID together with the source of the depth model and the age model tie points from which the assigned ages were derived. These metadata collectively ensure that published age models can be independently reproduced, evaluated and updated as stratigraphic frameworks evolve. This approach represents an important component of chronoinformatics: the structured preservation and integration of chronological information in a form that can be interrogated computationally while retaining its geological context and provenance. Standardised metadata and interoperable data formats would enable chronological information to be traced between samples, depth models, age-model constraints and ultimately the ages assigned to proxy observations. This is increasingly important as machine-learning and other computational approaches are used to extract and synthesise palaeoclimate data from large repositories. Without the underlying chronological metadata, such tools may be able to retrieve a published depth or age but cannot determine how that value was derived, whether the appropriate depth and age models were applied, or how it should be updated when those frameworks change.

As the MioOcean initiative demonstrated, considerable effort was required to recover and standardise incomplete chronological information from the published literature. In some cases, the absence of complete sample, depth model or age model information can ultimately make valuable proxy records difficult to reproduce or reinterpret. Adopting FAIR and chronoinformatic reporting practices would substantially reduce the effort required for future synthesis studies, ensuring that chronologies remain reusable, updatable and interoperable as chronological frameworks evolve (Wilkinson et al., 2016). Preserving the links between proxy observations and their underlying sample, depth and age information is therefore essential to realising the full potential of these datasets for future advances in computational science and community-scale palaeoclimate synthesis.

6 The MioOcean Age Framework in Climate Context: implications and road map

The ultimate MioAGE aim was to develop a robust chronoinformatics approach and produce a synchronised MioOcean Age Framework to reliably constrain the evolution of Miocene temperatures (MioOcean UOT and BWT), and facilitate meaningful regional temperature comparisons. The MioAGE survey revealed remarkably different approaches to age models used across the datasets, sometimes even between proxy records from the same site. This lack of congruence underscores

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the need for consistency of age model approaches both within MioOcean and in future research efforts (e.g., Westerhold et al., 2024; Kasbohm et al., 2026). In this section, we discuss how the MioOcean Age Framework and Age Model Database has reduced the congruence in Miocene chronology (section 6.1), and highlight a future roadmap for potential research avenues, both within MioOcean (section 6.2) and beyond (section 6.3).

6.1 MioOcean Age Framework - implications for Miocene chronology

The Miocene was characterised by substantial climate variability across a range of timescales. The MCO represents the last interval when pCO_2 concentrations were consistently higher than the present, with 500 thousand year (kyr)-mean values of 500 parts per million (ppm) around the time of the MCO, declining to ~300–400 ppm by the Late Miocene (CenCO_2PIP Consortium, 2023). Superimposed on these long term climate trends is clear evidence of a highly dynamic climate during the Middle and Late Miocene, with multiple major perturbations of the carbon cycle, including the Monterey event (~16.7–13.5 Ma) and the Late Miocene Carbon Isotope Shift (~7.6–6.7 Ma) (Vincent and Berger, 1985; Keigwin and Shackleton, 1980; Woodruff and Savin, 1991; Holbourn et al., 2007; Drury et al., 2016; Drury et al., 2017; Figure 10a), as well as major cooling during the MMCT and the LMC (Shackleton et al., 1975; Flower and Kennett, 1994; Shevenell et al., 2004b; Shevenell et al., 2008; Holbourn et al., 2005; Holbourn et al., 2013; Holbourn et al., 2018; Herbert et al., 2016; Drury et al., 2017; 2018a, b; Liu et al., 2022; Figure 10a). This latter cooling phase culminated with the onset of transient glaciations in the Northern Hemisphere from 6.0–5.5 Ma (e.g. Krissek 1995; Larsen et al., 1994) before reversing to warmer conditions in the latest Miocene (Herbert et al., 2016). In contrast, less is known about climate evolution in the Early Miocene due to a paucity of records over this extended time interval, although high-resolution stable isotope records indicate a high sensitivity of the climate system and the cryosphere to insolation forcing during the Early Miocene (e.g., Billups et al., 2004; Zachos et al., 2001; Pälike et al., 2006; Liebrand et al., 2016; Liebrand et al., 2017; Liebrand et al., 2024).

The MioAGE places our understanding of Miocene climate evolution within its underlying chronological context and reveals three key features about the current state of Miocene chronology: 1) we have significantly greater chronological coverage in the Middle-Late Miocene compared to the Early Miocene, 2) highly-resolved numerical approaches like astrochronology account for less than 32% of the age models on average, with biostratigraphy remaining a fundamental keystone of Miocene chronology and 3) synchronising the MioOcean temperature records require led to changes in age that are both significant on Milankovitch (18-405 kyr) and Geological timescales (>0.5 Myr).

Both the MioAGE Survey and the MioOcean Age Model Database contain significantly more age models in the Middle to Late Miocene compared to the Early Miocene (Figures 2, 5, 10b). This trend likely reflects the marked interest in key climatic events, such as the MCO, MMCT and LMC. However, prior to the MCO, the number of age models in the MioOcean Age Model Database decreases drastically towards the Oligo-Miocene boundary, with coverage across the OMT less than 50% of the MCO (Figure 10b). This highlights the stark issue that we simply do not have many (well-studied) Early Miocene sedimentary sequences available (e.g., Woodhouse and Kasbohm, 2026).

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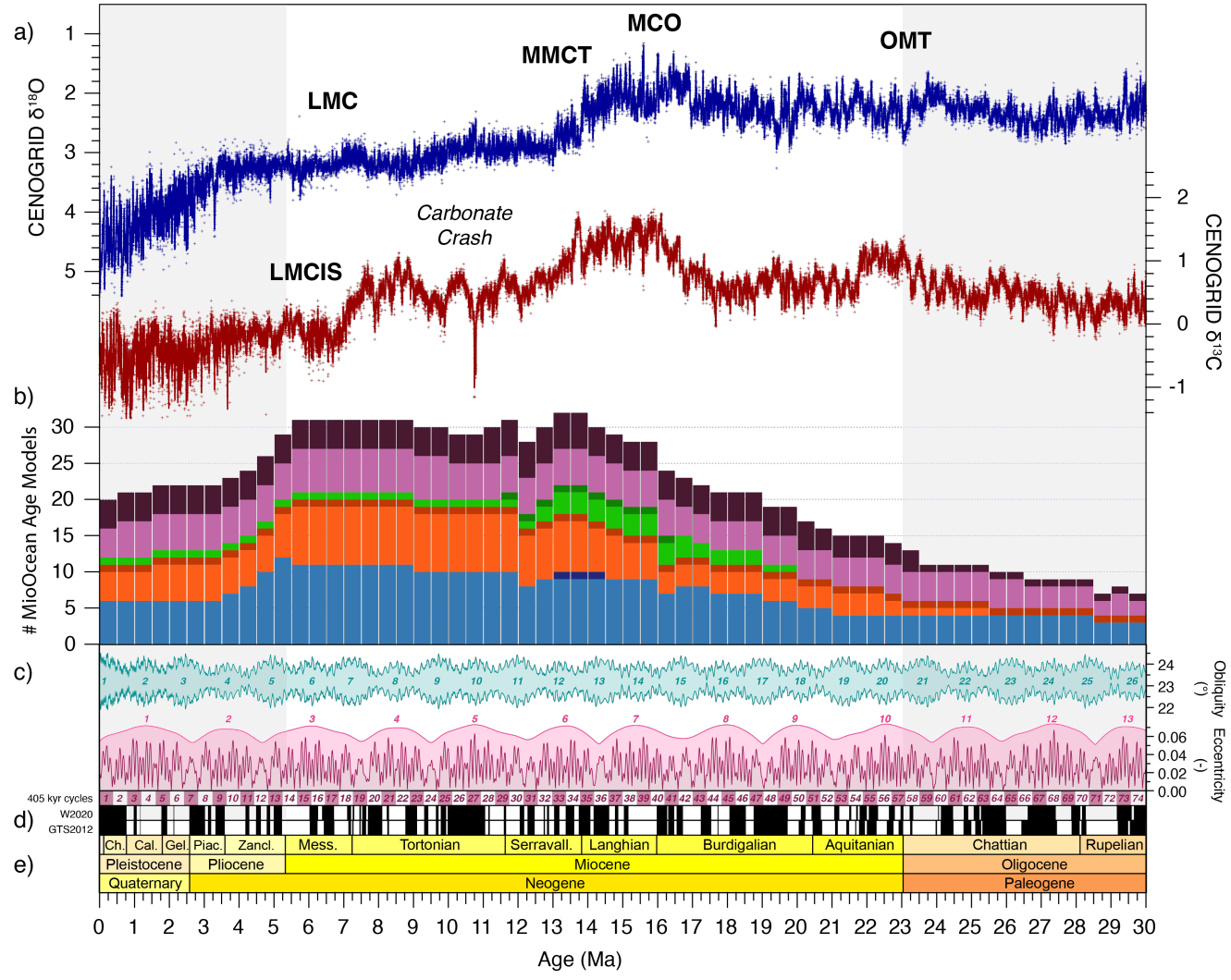


Figure 10. The MioOcean chronologies in climate and stratigraphic context (0-30 Ma). a) CENOGRID benthic foraminiferal $\delta^{18}O$ and $\delta^{13}C$ reference stratigraphy with key climatic events and transitions marked. b) The distribution of MioOcean age models (0.5 Myr bins) separated by category (astrochronology (A): light blue; astrochronology+ (A+): dark blue; biostratigraphy (B): light orange; biostratigraphy+ (B+); magnetostratigraphy (M): light green; magnetostratigraphy+ (M+): dark green; bio-magnetostratigraphy (BM): light purple; bio-magnetostratigraphy+ (BM+): dark purple). c) The La2004 astronomical solutions for obliquity and eccentricity, along with the 405 kyr cycles that can act as astrochronozones. d) The W2020 and GTS2012 GPTS sequences. Note that the W2020 GPTS is consistent with the CENOGRID $\delta^{18}O$ and $\delta^{13}C$ shown in panel a) and the GTS2012 GPTS is consistent with the MioOcean Age Framework. e) The GTS2012 Periods, Epochs and Stages for 0-30 Ma. The intervals older and younger than the Miocene are shaded grey, as they were not the primary focus of MioOcean. Any reduction in age model amounts in these intervals may be an artefact. An accompanying figure spanning 0-67 Ma is shown in Figure B5.

MioAGE demonstrates that Miocene chronology heavily relies on a breadth of chronological approaches, and particularly that fundamental stratigraphic approaches remain highly critical for providing age control for marine sediments (Figure 2, 5, 10b, 11). Astrochronology is a key chronological approach for providing highly accurate and age control for locations that have a demonstrated influence of Milankovitch cycles. Critically, astrochronology can provide the accuracy needed to

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reconstruct Milankovitch-scale climate dynamics by comparing high-resolution proxy records globally (e.g., Westerhold et al., 2024). However, the MioOcean Age Model Database shows that astrochronology only accounts for a maximum of 36% of the age models underpinning MioOcean key sites, though the proportion of astrochronology relatively stable across the Miocene and is not heavily impacted by the reduction in Early Miocene age models (average percentage astrochronology: 35% in Late Miocene; 30% in Middle Miocene; 31% in Early Miocene). In the MioAGE Survey, biostratigraphy and magnetostratigraphy underpinned more than 77% of all surveyed sites (Figure 2). This dominance is mirrored in the MioOcean Age Model Database, with bio-magnetostratigraphy underpinning more than 68% of the age models, and biostratigraphy (62%) contributing for the vast majority of these age model in some way (26% as biostratigraphy only, 35% as part of an integrated bio-magneto age model). When you consider that astrochronology is rarely used in isolation and often uses bio- and magnetostratigraphic datums to provide initial age constraints, the percentage of age model informed by biostratigraphy is likely much higher.

Biostratigraphic and integrated bio-magnetostratigraphic age models can provide robust age control for comparison between sites. However, the bio- and magnetostratigraphic MioOcean age models often have a lower and often uneven, sometimes clustered, distribution of chronological tie points, especially when compared to the MioOcean astrochronologies, which have a near-even tie-point distribution and a much higher tie point frequency, with distinct bands for precession-, obliquity- and eccentricity-based tunings. For samples adjacent to a tie point, reliable bioevents and magnetic reversals with a small depth error can provide an incredibly robust, chronological anchor. The lower tie point frequency and uneven/clustered distribution mean that the temporal uncertainty between individual tie points can be more variable for bio-magnetostratigraphic age models than for high-resolution astronomically tuned records. Importantly, none of the chronological approaches discussed here inherently guarantee a robust chronology. All depend on the quality and suitability of the underlying data, including sufficiently resolved astronomical signals, reliable magnetic polarity records, and well-preserved and ecologically appropriate biostratigraphic markers (Section 4). Where these conditions are not met, uncertainty increases. The MioAGE Reliability Grid provides a means of capturing these differences in Age Model Quality and Reporting Quality and demonstrates why the chronological approach alone should not be used as a proxy for the reliability of an individual age model. These patterns should also be considered in the context of the MioOcean dataset, which specifically comprises sites for which temperature records were available and does not represent an exhaustive assessment of Miocene chronology.

Consequently, even after harmonisation within the MioOcean Age Framework, caution remains essential when comparing temperature records among sites. This is particularly important when comparing records from sites with MioOcean age models that were comprehensively revisited with those with challenging MioOcean age models with limited chronological information, or with those still utilising their originally published age model. For example, an age model constrained primarily by lower-resolution legacy shipboard stratigraphy cannot be expected to provide the same temporal resolution as a high-resolution astrochronology, even where both have been verified and standardised within the same framework. Furthermore, even if two sites share identical bioevents and magnetic reversal tie-points updated to GTS2012, there can be local changes in sedimentation rate between tie points that are not resolved by the age model and can introduce apparent

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lead-lags between locations. These potential age offsets will be largest when the depth-spacing between tie-points is greatest. The full stratigraphic information provided for each age model, together with the Reliability Assessment therefore provides important context for interpreting comparisons between synchronised MioOcean records by retaining information on differences in the underlying chronological quality and reporting.

The impact of chronological harmonisation is evident in the changes to the ages assigned to MioOcean temperature data (Figure 6). Across the MioOcean temperature records assigned new MioOcean Ages, the mean change relative to the published ages is approximately 27 kyr, comparable to the duration of a precession cycle. Although most age changes are relatively small on geological timescales (<0.5 Myr), they are significant on Milankovitch timescales and can therefore influence interpretations of the timing, phasing and apparent leads and lags among palaeoclimate records. At the extremes, age revisions reach several million years and can alter the geological interval to which individual temperature observations are assigned. The implications of synchronisation therefore depend on the temporal scale of the scientific question: differences that appear minor in the context of long-term Miocene climate evolution may become important when resolving orbital-scale climate dynamics or comparing the timing of changes between sites.

These chronological constraints are particularly relevant because the Miocene, and especially the MCO, has been viewed as a possible analogue for aspects of anthropogenic climate change (Steinthorsdottir et al., 2021). Reconstructing global and regional Miocene ocean temperature evolution provides an opportunity to investigate how and where the oceans take up heat and respond to changing forcing in a warmer, higher-pCO_2 world, thereby helping to constrain climate sensitivity and explore the impacts of warm and variable ocean temperatures on other components of the Earth system, including ice sheets, precipitation patterns and life on land and in the oceans. Miocene climate variability also provides the environmental background to several major evolutionary and ecological changes in both the marine and terrestrial realms. In the terrestrial biosphere, the Late Miocene sees the expansion of C4 savannas across the low and mid-latitudes, marking a global shift from C3 to C4 plants (Cerling et al., 1997; Tauxe and Feakins, 2020; Peppe et al., 2023). The first proposed hominins and earliest observed bipedalism observed in hominid ancestors also both evolved in the Miocene (Brunet et al., 2002; MacLatchy et al., 2023). In the marine realm, the oceanic mesopelagic zone substantially expands and diversifies from the Middle Miocene onwards (Boscolo-Galazzo et al., 2021; Crichton et al., 2023). Placing these changes within a consistent chronological framework is fundamental to determining their temporal relationships with changes in the climate system and to distinguishing genuine leads, lags and regional differences from chronological artefacts (Westerhold et al., 2024).

6.2 Future outlook of the MioOcean Age Framework within MioOcean

In this section, we provide recommendations for future research focusing on both improving depth and age models for MioOcean records, as well as on the identification of data gaps and crucial locations for future SST research. The development of the MioOcean Age Framework has highlighted several priorities for future work, both for improving the chronological framework itself and for guiding the development of future temperature records. The current framework provides (revised, verified and standardised) age models for the 38 MioOcean key sites, in many cases extending beyond the

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Miocene where the available chronology and scope permitted but also identifies intervals and locations where chronological or temperature-proxy coverage remains limited. Future development should therefore focus on extending the framework to the remaining MioOcean sites, improving chronological constraints across the temporal ranges represented by these sites, and targeting new temperature records where robust chronology is already available or can be developed.

6.2.1 Incorporating Remaining MioOcean sites into the MioOcean Age Framework

The MioOcean initiative primarily focused on updating or verifying age models for 38 key sites, chosen based on the number of proxy records, data points, and their geographic and temporal significance. However, the remaining 53 MioOcean sites from which 53+ temperature proxy records were generated were not revisited or placed in the MioOcean Age Framework. These sites were not included in the initial effort due to their limited data coverage across extended periods, which did not justify the extensive work required for updating, as they were unlikely to significantly enhance the utility of the existing proxy data compilation. Despite this, these sites hold considerable potential for future high-resolution or regionally focused studies and could merit this effort in the future.

6.2.2 Potential for improvements in Miocene chronology

The next major advance in Miocene chronology will come from more widespread integration of independent chronological constraints. Future work should make better use of the full range of available approaches, combining biostratigraphy, magnetostratigraphy and astrochronology with chemostratigraphy and radiometric dating wherever possible. The development of high-resolution integrated chronologies at multiple sites should be prioritised, particularly where astronomically tuned records can provide well-constrained anchor points for regional and global correlation. At present, more than 58% of surveyed MioOcean sites and 71% of the MioOcean key sites rely on bio- and/or magnetostratigraphy for at least part of the age model. For 76% of the MioOcean key sites age models rely on shipboard data to a certain degree, which has not yet been revisited or verified through subsequent research. Composite depth scales should also be verified at sites where the composite depth model is shipboard mcd (e.g., using core image photos, physical properties data or XRF core scanning). Further work should focus on improving stratigraphic and chronological frameworks of existing archives through the generation of high-resolution bio-, magneto-, and chemo-stratigraphic records, including high-resolution isotope stratigraphy and XRF core scanning. Within the MioOcean Age Model Database, targeted improvements could also extend current chronological control; for example, both Sites 594 and U1501 could benefit significantly from additional detailed investigation. Additionally, sites like 846, 850, 925, 926, 982 and U1338 have astrochronologies that only cover part of the sedimentary sequence, so extending these to span the full site would be beneficial (Figure 11). Aside from the MioOcean key sites now incorporated into the MioOcean Age Model Database, sites that could represent well-suited targets for future chronological research include those that either feature multi-proxy SST records, exceptionally high-resolution data, or finally where existing stratigraphic records represent a major stratigraphic challenge (e.g., ACEX/910; see Sosdian, Auderset et al., this volume) or have potential for further integrated stratigraphy.

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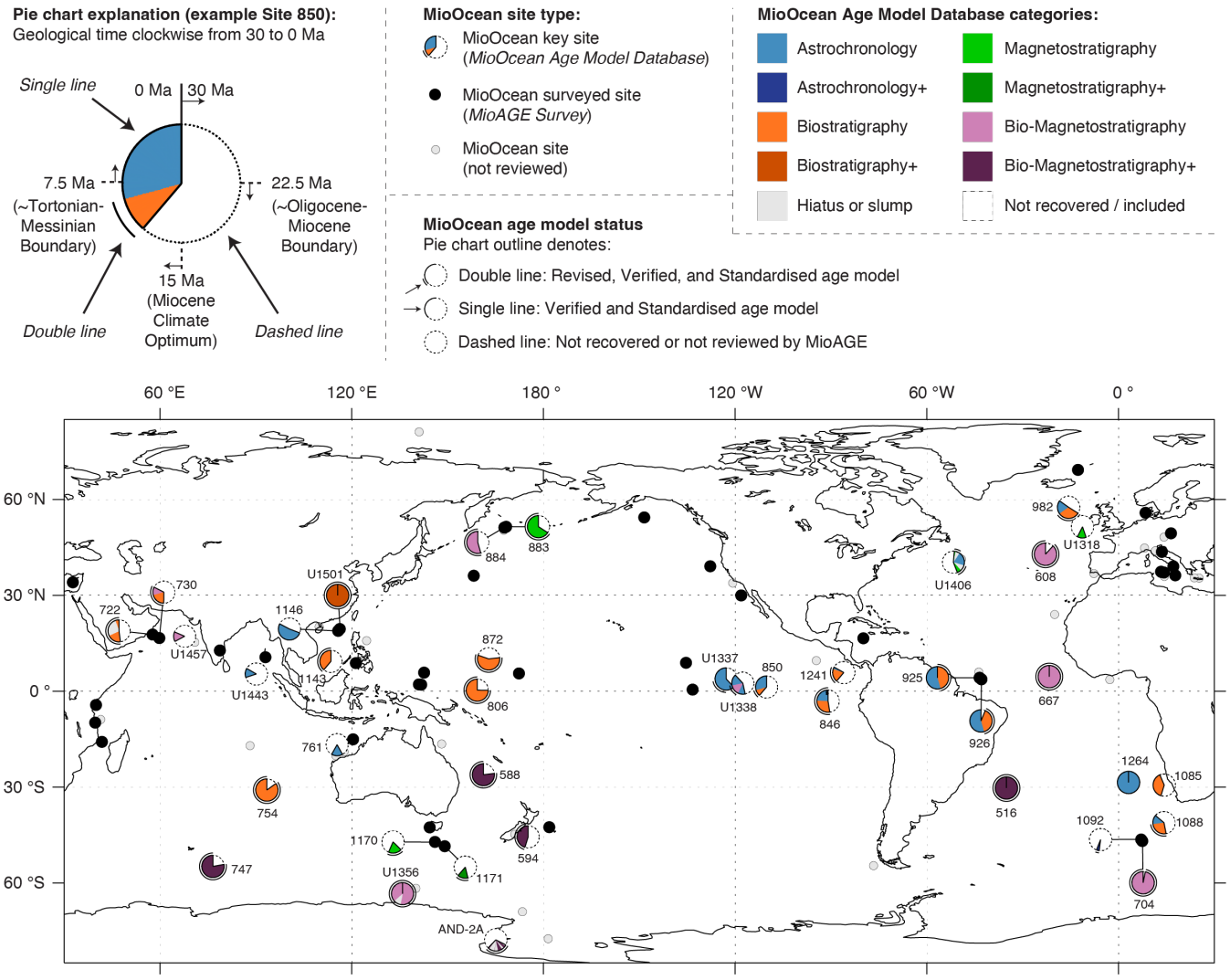


Figure 11. Overview of MioOcean key sites in the MioOcean Age Model Database (pie chart 'clocks'), surveyed MioOcean sites (black), and other MioOcean sites (grey). Pie chart colours represent the different age models categories and which time interval they cover, as a clock counting time down clockwise from 30 to 0 Ma. The outlines of pie charts denote which part of the MioOcean age models has been revised, verified, and standardised (double line), verified and standardised (single line), or not recovered or not reviewed by MioAGE (dashed line). Pie charts of overlapping sites (e.g., ODP Sites 925 and 926, Ceara Rise, equatorial Atlantic Ocean) have been moved for visualisation purposes, with lines connected to their original site location.

Chemostratigraphy and radiometric dating were not assessed as standalone chronologies within MioAGE, so there is significant gain to explore integrating these with other approaches. The availability of high-resolution SIS calibrated at astronomically-tuned sites are expanding for the Miocene (e.g., Stoll et al., 2024; McArthur et al., 2025). Miocene benthic foraminiferal stable $\delta^{18}O$ and $\delta^{13}C$ stratigraphy has improved significantly in the last two decades (see Westerhold et al., 2020 and the references therein), with the event stratigraphy well understood for all major ocean basins for most of the Miocene (broadly other than the carbonate crash, where foraminiferal preservation is badly affected; e.g., Lübbers et al.,

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2019). Many Miocene stable isotope stratigraphies are astronomically tuned, providing a reliable reference framework for chronological correlation for the time interval between 5.3 Ma and ~14 Ma on a global scale (Westerhold et al., 2020) with potential for the Early-Middle Miocene once remaining discrepancies have been explored and addressed (e.g., Hilgen, 2025; McArthur et al., 2025). While recent interspecies benthic foraminiferal $\delta^{18}O$offsets and their relationship to regional and global seawater $\delta^{18}O$ has progressed (e.g., Jöhnck et al., 2021), these remain poorly constrained in the Miocene. Integrating these approaches has the potential to significantly improve the quality of Miocene regional high-resolution benthic $\delta^{18}O$ reconstructions, especially in low-amplitude intervals during the Late Miocene. Moreover, the generation and inter-correlation of high-resolution benthic isotope records across poorly constrained time intervals prior to the MCO (~23-17 Ma) and across the "Carbonate Crash" (~12-8 Ma) remain important targets for future efforts. Additionally, high-precision radioisotopic geochronology is a powerful tool that can provide highly accurate and precise constraints for bio-, chemo-, and magnetostratigraphic data when sediments contain suitable volcaniclastic interbeds. Kasbohm et al. 2024 used high-precision U-Pb zircon geochronology to date ash layers interbedded with MCO carbonates at ODP Site 1000 (Nicaragua Rise) and produced a Bayesian age model for sediments from 19.0-14.0 Ma at this site. This could be an ideal target for integration into the MioOcean Age Framework, especially if the integrated stratigraphy was further enhanced with biostratigraphy

6.2.3 Potential for improvements in Miocene temperature proxy research

In addition to further improvements in Miocene chronology, a complementary priority is to take greater advantage of sites where robust chronological frameworks already exist, but temperature proxy coverage remains limited, or for instance where partial Miocene temperature data exists, which could be extended younger or older. These sites provide opportunities to generate new temperature records that can be placed directly within well-constrained temporal frameworks, avoiding the need to develop chronology and temperature reconstructions independently.

A critical focus for high-resolution temperature reconstructions should be 1) target well-dated sites (e.g., Sites 1264, 926, U1406) capturing intervals such as the O/M boundary, the MMCT or the MCO, which are crucial targets given their relevance to understanding rapid climate transitions and warm climate dynamics, 2) targeting under-represented time intervals, such as 5-13 and 17-23 Ma, again at locations where reliable chronologies are available (e.g., 1092, 1264), and 3) revisiting sedimentary archives from poorly explored geographic ocean regions, such as the Atlantic Ocean for BWT or the Indian Ocean for UOT and the Arctic region in general (Table 2; Figure 11). To assess potential future climatic impacts of the current global warming it is particularly important to reconstruct the changing temperature gradients between high and low latitudes, as well as the magnitude and progression of polar amplification during Miocene warmth. A key target identified through the MioOcean effort as a whole, is the need for additional high-resolution temperature data at well-dated sites to better constrain the Equator-to-Pole thermal gradient, which is essential for providing realistic boundary conditions for climate models (Figure 11). Although a current challenge, improving the stratigraphic resolution of UOT and BWT records to orbital-scale resolution across the Miocene would enhance our understanding of climate variability on a warmer Miocene Earth (Figure 10).

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Table 2. Summary of the temporal and geographic distribution of sites with verified temperature data included in the MioOcean database, showing the availability of Upper Ocean Temperature (UOT) and Bottom Water Temperature (BWT) records across the major ocean basins. UOT refers to temperature estimates derived from sea-surface and/or mixed-layer to thermocline proxies, whereas BWT refers to bottom water temperature estimates reconstructed from deep-ocean proxies. Ocean basins with very sparse data coverage are indicated in italics.

	O/M boundary and Early Miocene (23.04 - 16.9 Ma)	**MCO (16.9 - 14.7 Ma)**	**MMCT (14.7 -13.8 Ma)**	**Middle to early Late Miocene (13.8 - 9 Ma)**	**Late Miocene to M/P boundary (9 - 5.333 Ma)**
Total Sites	**33**	**32**	**36**	**58**	**60**
UOT Total Sites	**31**	**30**	**33**	**55**	**56**
UOT Key Sites	18	22	22	33	26
Basins Missing UOT Information	*Pacific* (East), *Indian* (North) and Arctic Oceans	Arctic Ocean	Arctic Ocean	Arctic Ocean	Southern & Arctic Oceans
Basins with (some) UOT Data	Atlantic, *Indian*, *Pacific*, Southern Oceans	All other basins	All other basins	All other basins	All other basins
BWT Total Sites	**6**	**7**	**8**	**10**	**8**
BWT Key Sites	4	6	6	7	4
Basins Missing BWT Information	Southern hemisphere and high northern latitudes (all basins)	Northern mid/high latitudes (all basins), Atlantic Ocean	Northern mid/high latitudes (all basins)	Northern mid/high latitudes (all basins)	Arctic Ocean
Basins with (some) BWT Data	*Pacific, Atlantic*	*Indian, Pacific, Southern Oceans*	*Atlantic, Pacific, Indian, Southern Oceans*	*Atlantic, Pacific, Indian, Southern Oceans*	All other basins

Some (MioOcean) sites have excellent chronologies, but were not considered as key sites, as they have low-resolution temperature data and/or no multi-proxy temperature data (e.g., Sites 588, 929, 999, 1000, 1237, U1335, U1336). Particularly, Site 588 (Southwest Pacific), Site 1237 (Southeastern Pacific), and Site 1000 (Nicaragua Rise) stand out as ideal targets for future SST work from the perspective that they have excellent age control and could be suitable candidates to target for high-resolution temperature reconstructions.

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Generating high-resolution temperature records at such well-dated sites would improve the spatial and temporal coverage of MioOcean while allowing records from different ocean basins to be compared at increasingly fine temporal resolution. Improved coverage across latitude bands and ocean basins would strengthen reconstructions of equator-to-pole thermal gradients and provide more robust constraints for comparison with climate-model simulations. Where sedimentation rates, preservation and proxy availability permit, developing UOT and BWT records approaching orbital-scale resolution would further improve our ability to investigate the magnitude, timing and regional expression of Miocene climate variability.

6.3 Beyond MioOcean - Wider application of MioOcean Age Framework

Although developed for the MioOcean temperature synthesis, the MioOcean Age Framework and Chronoinformatics approach can be adapted to other proxy systems and geological intervals. Within the Miocene, this could extend beyond temperature to records of the carbon cycle, ocean circulation, productivity and marine ecosystems, enabling different components of the Earth system to be evaluated within a more consistent temporal framework. This would be particularly valuable for investigating the timing and phasing of environmental changes and assessing apparent leads and lags between proxy records.

The same principles can be applied beyond the Miocene, although their implementation will necessitate adaptation between geological intervals, archives and chronological approaches. Different time intervals may require different stratigraphic tools, calibration schemes and reliability criteria; the transferable component is therefore the approach to chronology rather than the specific MioOcean Age Framework or GTS2012 calibration. The approach developed through MioAGE provides a basis from which these interval- and proxy-specific applications can be developed.

In this way, MioOcean provides a test case for the broader Chronoinformatics Approach introduced here. Future applications could build on the knowledge gained through MioAGE to develop interconnected chronological frameworks across different proxy systems and geological intervals, while adapting their structure and assessment to the each applications requirements. This could include broader community initiatives such as the newly launched TIMES, where consistent and interoperable chronological information is fundamental to integrating diverse geological records over the last 100 Myr (Westerhold et al., 2024; Kasbohm et al., 2026). Such development would strengthen the temporal integration of increasingly large community data syntheses and improve our ability to investigate Earth-system change across space and time.

7 Data and code availability

[Note to editors/reviewers: links in this section are not all currently publicly available, as the data compilation is under moratorium until publication of this report. Access can be granted to reviewers at the appropriate stage.]

The MioOcean Age Model database is available as part of the MioOcean database (Sosdian, Auderset et al., this volume) and is openly accessible and can be downloaded directly from: 1) the age model section of the MioOcean website (https://mioocean.com/age-models/); 2) the age model section of the Streamlit dashboard (https://mio-

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ocean.streamlit.app/Age_models); and 3) through Zenodo [Drury, Tangunan et al., 2026, https://doi.org/10.5281/zenodo.22258616;], where the MioAGE Survey, Reliability Assessment, and Citation Database are archived. The palaeolatitude and palaeolongitude estimates used originate from the central MioOcean database (Sosdian, Auderset et al., this volume). Further information pertaining to and templates used during the generation of these MioAGE data products are available in the Appendices and Zenodo. The MioOcean Age Model database compiles the revisited age-depth models for MioOcean key sites in a standardised and harmonised format, including detailed stratigraphic and chronostratigraphic metadata. These age models provide newly updated age for MioOcean temperature records and can be applied to other proxy data generated at the same site. We encourage users to also cite the publications producing the original depth and age model data when using this data product, to provide credit to the data generators. To aid this process, we have included a citation database, which is summarised in Appendix C and archived on Zenodo. The Zenodo record is currently restricted, with direct access available to editors and reviewers via a private link provided to the journal. Anyone interested in participating in the review of the data may request access via Zenodo. Upon acceptance, the record will be made publicly accessible under the same DOI.

8 Conclusions

The MioOcean initiative generates a consistent global synthesis of Miocene UOT and BWT records. Through MioAGE, we provide the consistent chronological foundation required to integrate MioOcean temperature records across sites and through time, while retaining the underlying chronological information and provenance required for future evaluation and revision. We achieve this through the MioAGE Survey, which comprehensively assesses the depth and age information underpinning these temperature records and identifies substantial variability in depth models, chronological approaches, geological timescales and reporting practices across the published literature. Building on the MioAGE Survey, we present the MioOcean Age Framework and integrate revised, verified and standardised chronologies for 38 key sites into the machine-readable and updateable MioOcean Age Model Database. To support the community in systematically assessing age model robustness, we present the MioAGE Reliability Assessment, which considers Age Model Quality and Reporting Quality along with site-wide factors to provide an age model reliability indicator. Finally, we provide recommendations for the reporting and archiving of depth and age models for community use.

Collectively, these developments provide a structured approach for recovering, evaluating, harmonising, preserving and assessing chronological information within a large community synthesis. The broader value of Chronoinformatics, developed through MioOcean, is a demonstrated approach for integrating chronology explicitly into palaeoclimate data synthesis. Although its implementation will vary in different applications, the underlying approach can be adapted beyond MioOcean to other proxy systems (e.g., geochemical, ecological), geological intervals and community synthesis initiatives, including those that provide evidence for broader climate assessments, such as the IPCC Assessment Reports. MioOcean

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Chronoinformatics provides a pathway towards palaeoclimate syntheses in which chronological information remains transparent, reproducible and responsive to future advances in stratigraphy and geochronology.

9 CRedit authorship contribution statement

Contributions are reported using the CRedit taxonomy and are organised into groups reflecting the different roles and modes of contribution within MioAGE. The author contribution model recognises the distinct but complementary contributions required for this community synthesis alongside broader MioOcean Steering Committee guidance. MioAGE leadership (AJD and DNT: 2023-2026; DL: 2022-2023; with guidance from AH) was supported by leadership of specialist subgroups (GA, JK, DJK, TW). All MioAGE members contributed to age model collation, curation, processing and validation with substantial hands-on involvement by AJD, DNT, DL, GA, JK, DJK, TW, AJC, KGDK, WKu, DO, TEvP. All MioAGE members (AJD, DNT, DL, GA, JK, DJK, TW, AJC, KGDK, WKu, DO, TEvP, WKr, MMR, NSS, ECS, BSW, AH) contributed to age model data evaluation, analysis, and interpretation, as well as providing critical specialist expertise, interpretation, and discussion of the MioAGE outputs. This approach is intended to transparently represent the different levels of contribution to MioAGE, with specific contributions for each author detailed below using the CRediT taxonomy. AH authorship location was chosen to represent her significant and active role within MioAGE and the MioOcean Steering Committee.

Conceptualization: AJD, DNT, DL, GA, TW, BSW, AH; **Data Curation:** AJD, DNT, DL, GA, JK, DJK, TW, AJC, KGDK, WKu, DO, TEvP, WKr, MMR, NSS, ECS, BSW, AH; **Formal Analysis:** AJD, DNT, DL, GA, JK, DJK, TW, AJC, KGDK, WKu, DO, TEvP, WKr, MMR, NSS, ECS, BSW, SM, AH; **Investigation:** AJD, DNT, DL, GA, JK, DJK, TW, AJC, KGDK, WKu, DO, TEvP, WKr, MMR, ECS, BSW, SM, AH; **Methodology:** AJD, DNT, DL, GA, JK, DJK, TW, AJC, KGDK, WKu, DO, TEvP, WKr, MMR, NSS, ECS, BSW, SM, AH; **Project Administration:** AJD, DNT, DL; **Supervision:** AJD, DNT, DL, AH; **Resources:** AJD, DNT, TW; **Coding Development:** AJD, TW, NSS; **Validation:** AJD, DNT, GA, JK, DJK, TW, AJC, KGDK, WKu, DO, TEvP, MMR, NSS, ECS, AH; **Visualization:** AJD, DNT, DL, GA, JK, DJK, TW, AJC, KGDK, WKu, DO, TEvP, WKr; **Writing–Original draft preparation:** AJD, DNT, DL, GA, JK, DJK, TW, AJC, KGDK, WKu, DO, TEvP, WKr, MMR, ECS, BSW, AH; **Writing–Review & Editing:** AJD, DNT, DL, GA, JK, DJK, TW, AJC, KGDK, WKu, DO, TEvP, WKr, MMR, NSS, ECS, BSW, SS, AA, SM, AH; **Funding Acquisition:** AJD, DNT, GA, JK, DJK, TW, AJC, KGDK, TEvP, BSW, SS, AA, SM, AH

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10 Declaration of competing interest

This manuscript has not been published or presented elsewhere in part or in entirety and is not under consideration by another journal. We have read and understood your journal's policies, and we believe that neither the manuscript nor the study violates any of these. There are no conflicts of interest to declare.

11 Acknowledgments

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12 Appendix A - MioAGE Survey Information

The following information relates to the MioAGE Survey. The full MioAGE Survey results and associated information is archived on Zenodo (Drury, Tangunan et al., 2026). Please note, although the survey was comprehensive, some chronological information may have been missed and will therefore have been perpetuated into the MioOcean Age Model

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Database. Furthermore, stratigraphic information collated in the survey was not interrogated and vetted to the same degree as the database as it did not go through the full workflow process illustrated in Figure 4.

Table A1. MioAGE Survey template used to evaluate the depth and age models and associated temperature proxy records across MioOcean sites. The survey was conducted in two phases. Phase A (Site Review) assessed the available depth models and chronological frameworks for each site, including the stratigraphic approaches and timescales used. Phase B (Proxy Review) evaluated the associated temperature records, including sample and site information, sample-depth assignments, and whether depth and age models required updating to the best available depth model and chronological framework.

Survey phase	Site Review Questions
Phase A	Is this a DSDP, ODP, IODP-1, or IODP-2 Site? (IODP-1 = Integrated Ocean Drilling Program, IODP-2 = international ocean discovery Program)
	What is the current best available depth model for this site? (mbsf [CSF-A], or a composite depth scale [multiple holes are spliced together into one depth model]) (search the DSDP/ODP/IODP volumes and open literature)
	In case a composite depth is available for this site, provide further information (e.g., data used, references, is the original splice revised [RMCD], are intervals out of the splice adjusted to the splice [i.e., stretching and squeezing of out-of-splice intervals to the splice, ARMCD], other more obscure depth models used [CCSF-B]).
	What is the current best age model for this Site based on? (biostrat, magnetostrat, cyclostrat, bio-magnetostrat, magneto-cyclostrat, bio-magneto-cyclostrat)
	Biostrat explain (planktonic foraminifera, nannofossils, which time scale used to date bio events [cande and kent, GTS2012, GTS2020, other])
	Magnetostrat explain (inclination and/or declination data used, or just reversals?, which time scale is used to date reversals [Cande and Kent, GTS2012, GTS2020, other])
	Cyclostrat explains (what is the tuning signal? [XRF, physical properties, isotopes], what is the tuning target [eccentricity Laskar 2010d, insolation 65 N, Laskar 2004])
	Further remarks regarding this Site and/or records from this site
Phase B	**Proxy Review Questions**
	How many temperature records (i.e., individual entries) from this site are in the database? (see https://bolin.su.se/data/miocene-temperature-portal…, provide number: 1, 2, 3, ...)
	On how many samples (across all records from this site) has temperature data been collected? (e.g. if both TEX86 and UK37 have been measured on the same sample, this counts as 1)
	Name Record 1 to n
	How many samples in Record 1 to n
	For Record 1 to X: Do all samples have DSDP, ODP, IODP sample information provided? (i.e., Leg./Exp., Site, Hole, Core, Type, Section, Halve, top/bottom cm) (explain where necessary)
	For Record 1 to n: Is additional work needed to update the sample depths to current best available depth model

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	For Record 1 to n: Is additional work needed to bring the age model in line with Westerhold et al., 2020 ages? (Sites with cyclostratigraphy are considered of equal accuracy as W2020)
	Further remarks regarding this Site and/or records from this site

Table A2. Summary of all sites surveyed for the MioOcean initiative. The original list of key sites was recommended by the proxy groups based on the number of available proxies and data points and their geographical and temporal coverage. The published records vary in their depth scales and age model approaches (biostratigraphy, B; magnetostratigraphy, M; cyclostratigraphy, C; or combinations thereof; and additional age constraints, such as radioisotopic dating or chemostratigraphy, +), including the geological timescales and calibrations used (Berggren et al., 1985, B1985; Berggren et al., 1995, B1995; Pearson, 1995, P1995; Backman and Raffi, 1997, BR1997; Chaisson and Pearson, 1997, CP1997; Wade et al., 2011, W2011; Backman et al., 2012, B2012; Westerhold et al., 2020, W2020). Most recent depth or age model (*); Excluded from temperature database or non-Miocene data (E); Additional sites after the original survey phase (A). See Drury, Tangunan et al. (2026) for an expanded version of this table.

Program	Site	Depth Scale	Depth Model	Age Category	Timescale basis for Age Model	Site Survey Status
DSDP	242	Single Hole	mbsf*	B	GTS2004	Surveyed only
DSDP	516	Single Hole	mbsf*	BM	GTS2012	Surveyed & Revised
DSDP	573	Single Hole	mbsf*	B	Unknown/Hybrid*	Surveyed only
DSDP	588	Single Hole	mbsf*	BM	GTS2012	Surveyed & Revised
DSDP	594	Single Hole	mbsf	BM	Unknown/Hybrid	Surveyed & Revised
DSDP	608	Single Hole	mbsf*	BM	GTS2012	Surveyed & Revised
ODP	667	Single Hole	mbsf	B	GTS2012	Surveyed & Revised
ODP	704	Single Hole	mbsf*	BM+	GTS2012	Surveyed & Revised
ODP	722	Single Hole	mbsf	BM	GTS2012, GTS2020	Surveyed & Revised
ODP	730	Single Hole	mbsf	BM	GTS2004	Surveyed & Revised
ODP	747	Single Hole	mbsf*	M	B1995	Surveyed & Revised
ODP	754	Single Hole	mbsf*	B	GTS2012*	Surveyed & Revised
ODP	761	Single Hole	mbsf	B+	GTS2012	Surveyed & Revised
ODP	769	Single Hole	mbsf*	BM	B1985	Surveyed only
ODP	806	Single Hole	mbsf*	B	B1985, BR1997, CP1997, Tuned	Surveyed & Revised
ODP	846	Composite	mcd	C	Tuned, Hybrid	Surveyed & Revised
ODP	850	Composite	mcd	C	Tuned	Surveyed & Revised
ODP	871	Single Hole	mbsf	B	Unknown/Hybrid	Surveyed only

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Program	Site	Depth Scale	Depth Model	Age Category	Timescale basis for Age Model	Site Survey Status
ODP	872	Single Hole	mbsf	B	P1995, CK1995, GTS2004	Surveyed & Revised
ODP	883	Single Hole	mbsf*	BM+	GTS2012	Surveyed & Revised
ODP	884	Single Hole	mbsf*	M+	GTS2012	Surveyed & Revised
ODP	887	Single Hole	mbsf*	BM	GTS2012	Surveyed only
ODP	907	Composite	mcd	BMC	Tuned	Surveyed only
ODP	925	Composite	mcd	C	Tuned	Surveyed & Revised
ODP	926	Composite	mcd	C	Tuned	Surveyed & Revised
ODP	964	Composite	mcd	C	Tuned*	Surveyed only (E)
ODP	967	Composite	mcd	C	Tuned*	Surveyed only (E)
ODP	982	Composite	mcd	BC	GTS2012, Tuned	Surveyed & Revised
ODP	999	Single Hole	mbsf	BC	B1995, CK1995, Tuned	Surveyed only
ODP	1000	Composite	mcd	B	CK1995	Surveyed only
ODP	1010	Composite	mcd	M	CK1995	Surveyed only
ODP	1021	Composite	mcd	BM	CK1995	Surveyed only
ODP	1085	Single Hole	mbsf*	C	Tuned*	Surveyed & Revised
ODP	1088	Composite	mcd*	BMC	Tuned*	Surveyed & Revised
ODP	1092	Composite	mcd*	C	Tuned*	Surveyed & Revised
ODP	1125	Composite	mcd*	B	GTS2012	Surveyed only
ODP	1138	Single Hole	mbsf*	B	GTS2004	Surveyed only (E)
ODP	1143	Composite	mcd*	B	B1995	Surveyed & Revised
ODP	1146	Composite	mcd	C	B1995, CK1995, Tuned	Surveyed & Revised
ODP	1168	Single Hole	mbsf*	BM	GTS2012*	Surveyed only
ODP	1170	Single Hole	mbsf	M	GTS2012	Surveyed & Revised (A)
ODP	1171	Single Hole	mbsf	MC+	GTS2012, Tuned	Surveyed & Revised
ODP	1208	Single Hole	mbsf*	BMC	CK1995, Tuned	Surveyed only
ODP	1218	Composite	acrmcd	MC	Tuned	Surveyed only

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Program	Site	Depth Scale	Depth Model	Age Category	Timescale basis for Age Model	Site Survey Status
ODP	1241	Composite	mcd	BMC	Tuned	Surveyed & Revised
ODP	1264	Composite	rmcd*	C	Tuned*	Surveyed & Revised (A)
IODP-1	U1318	Composite	mcd*	BM	GTS2012	Surveyed & Revised
IODP-1	U1337	Composite	mcd	C	Tuned	Surveyed & Revised
IODP-1	U1338	Composite	armcd*	BMC	W2020*	Surveyed & Revised
IODP-1	U1356	Single Hole	mbsf*	BM	GTS2012*	Surveyed & Revised
IODP-1	U1406	Composite	mcd	BMC	Tuned	Surveyed & Revised
IODP-2	U1443	Composite	mcd	C	Tuned	Surveyed & Revised (A)
IODP-2	U1448	Composite	rmcd*	C+	Tuned*	Surveyed only
IODP-2	U1457	Composite	mcd*	BM+	GTS2012	Surveyed & Revised
IODP-2	U1482	Composite	mcd	B	GTS2012	Surveyed only
IODP-2	U1488	Composite	rmcd	BM	GTS2012	Surveyed only
IODP-2	U1489	Composite	mcd	BM	B1995, GTS2012	Surveyed only (E)
IODP-2	U1490	Composite	mcd	BM	Hybrid	Surveyed only
IODP-2	U1501	Single Hole	mbsf*	BM+	GTS2012*	Surveyed & Revised (A)
Other	AND-2A	Single Hole	N/A*	BM	GTS2012	Surveyed & Revised
Other	Eraclea Minoa	Land section	N/A*	C	Unknown*	Surveyed only
Other	LOM-1	Single Hole	N/A*	B	GTS2012	Surveyed only (E)
Other	Monte dei Corvi	Land section	N/A*	BMC	GTS2004*	Surveyed only
Other	Punta Piccola	Land section	N/A*	C	Tuned*	Surveyed only (E)
Other	San Nicola	Land section	N/A*	C	Tuned*	Surveyed only (E)
Other	Sdr Vdium	Single Hole	N/A*	B	Unknown/Hybrid	Surveyed & Revised
Other	Sunbird-1	Single Hole	N/A*	B	W2011, B2012	Surveyed & Revised
Other	Tanzania	Land section	N/A*	B	B1995	Surveyed & Revised
Other	Vrica	Land section	N/A*	BMC	Tuned*	Surveyed only (E)

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13 Appendix B - MioOcean Age Framework and MioOcean Age Model Database Information

The following information relates to the MioOcean Age Model Database. The MioOcean Age Model Database (full and streamlined) itself is available through Drury, Tangunan et al. (2026).

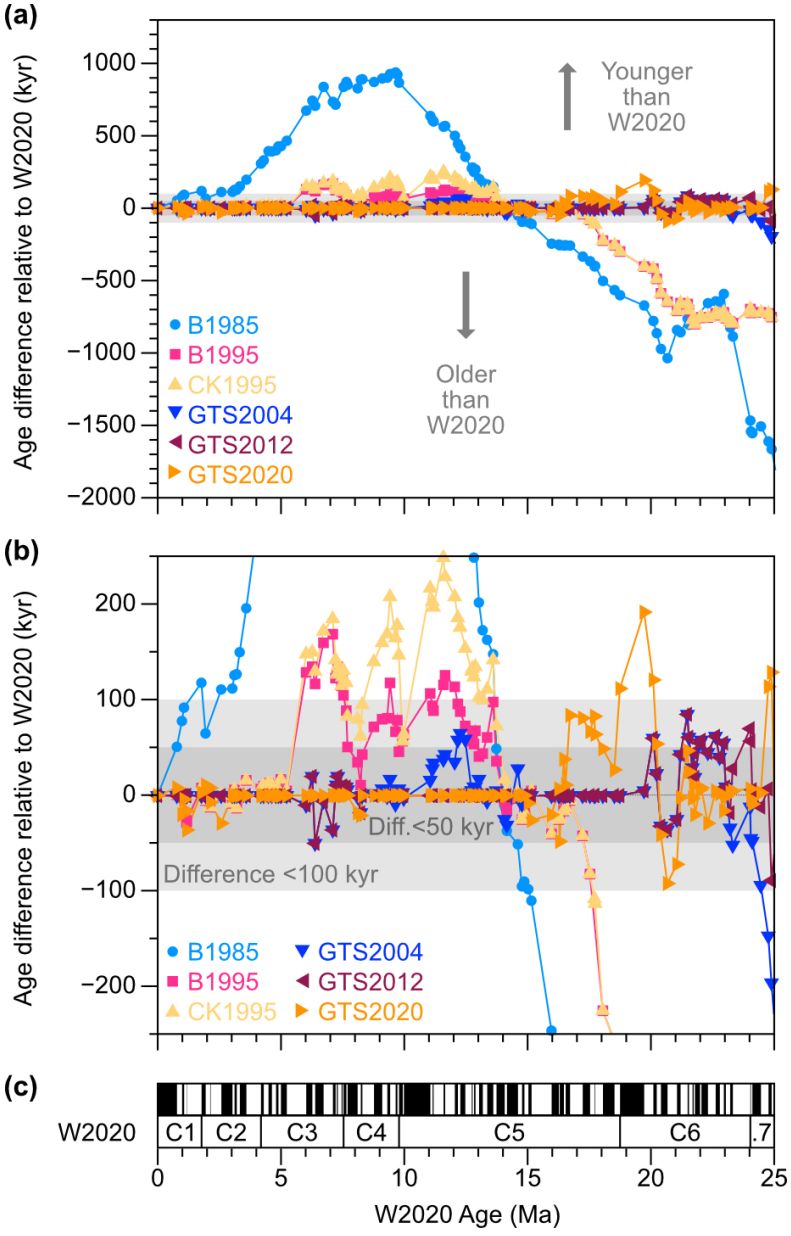


Figure B1. GPTS comparison to W2020 (links to MioAGE Survey). As in main Fig. 2, but here with W2020 as a reference GPTS (see Figure 2 for references) No Stages, Epoch, and Periods are indicated in this figure, as W2020 presented a revised GPTS, but no reinterpreted GTS (Westerhold et al., 2020). Nonetheless, we recommend using W2020 as reference GPTS; however within the

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scope of MioOcean, GTS2012 was preferred as it already underpinned a significant portion of key sites, it remains relatively consistent with W2020 and crucially GTS2012 includes calibrated bioevents.

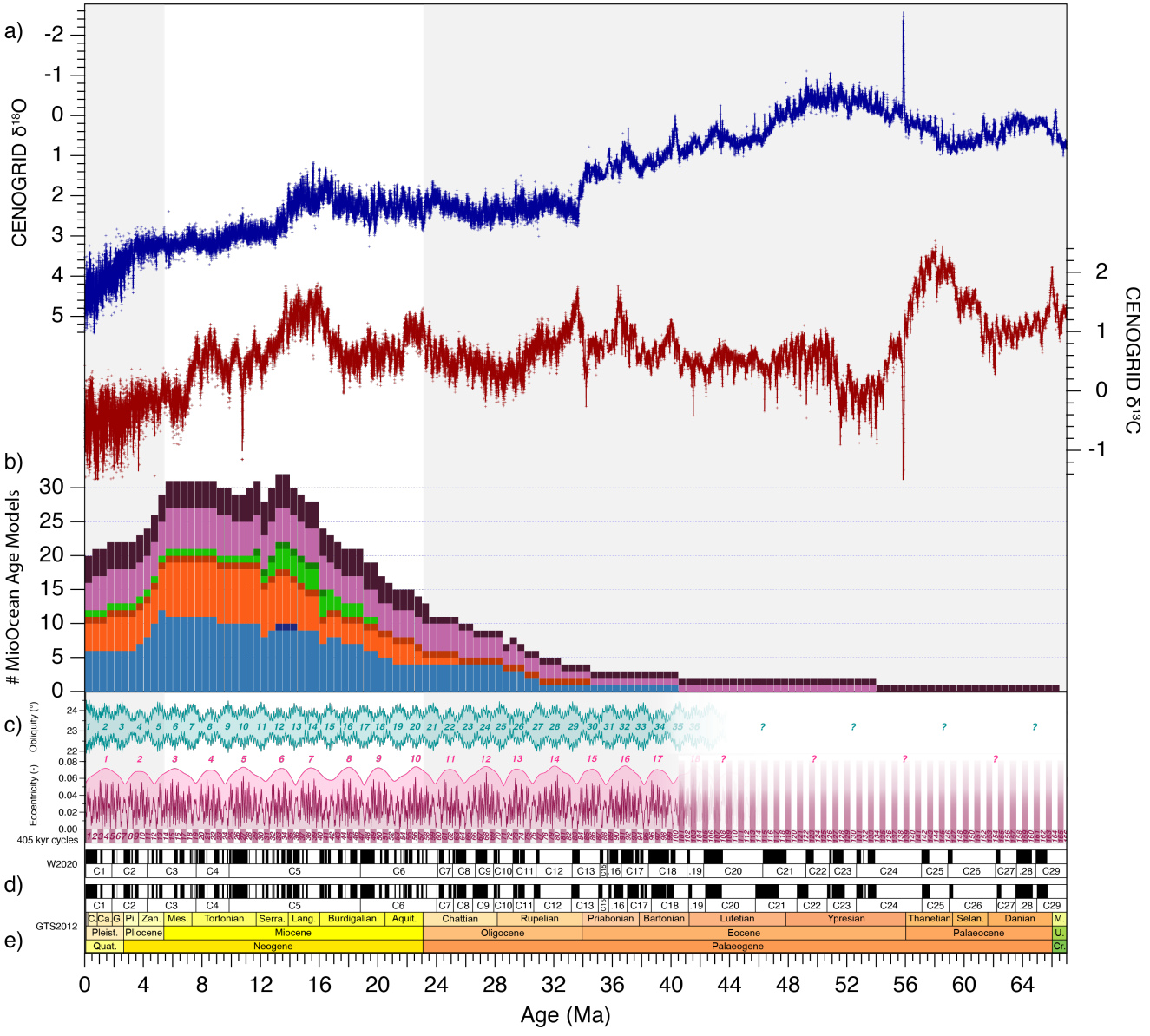


Figure B2. Age range of all MioOcean key site age models ([revised], verified and standardised) available in the MioOcean Age Model Database for the interval 0-67 Ma. The colour indicates the type of age model approach used for each interval. Sites 722, U1356, U1406 and AND-2A contain intervals with hiatuses and/or slumps (not shown).

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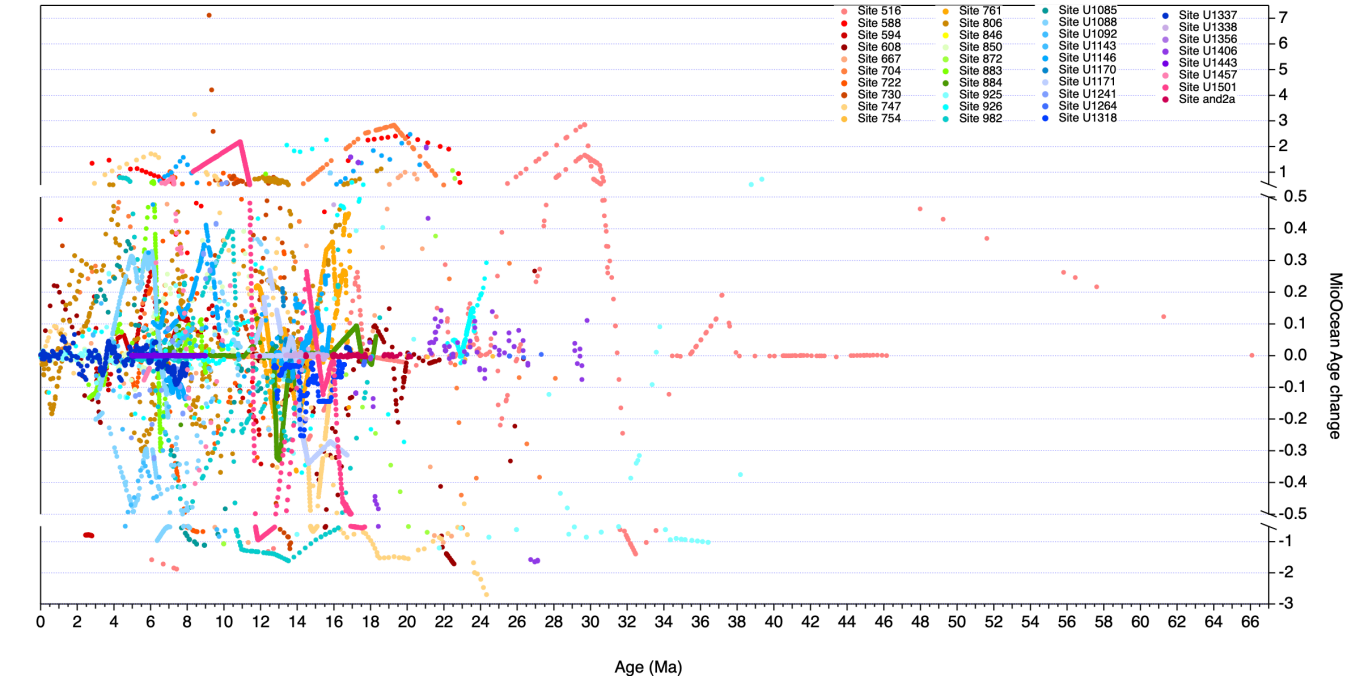


Figure B3. Evolution of the change in age in Myr (MioOcean-Published Age) for the interval 0-67 Ma, separated by key site.

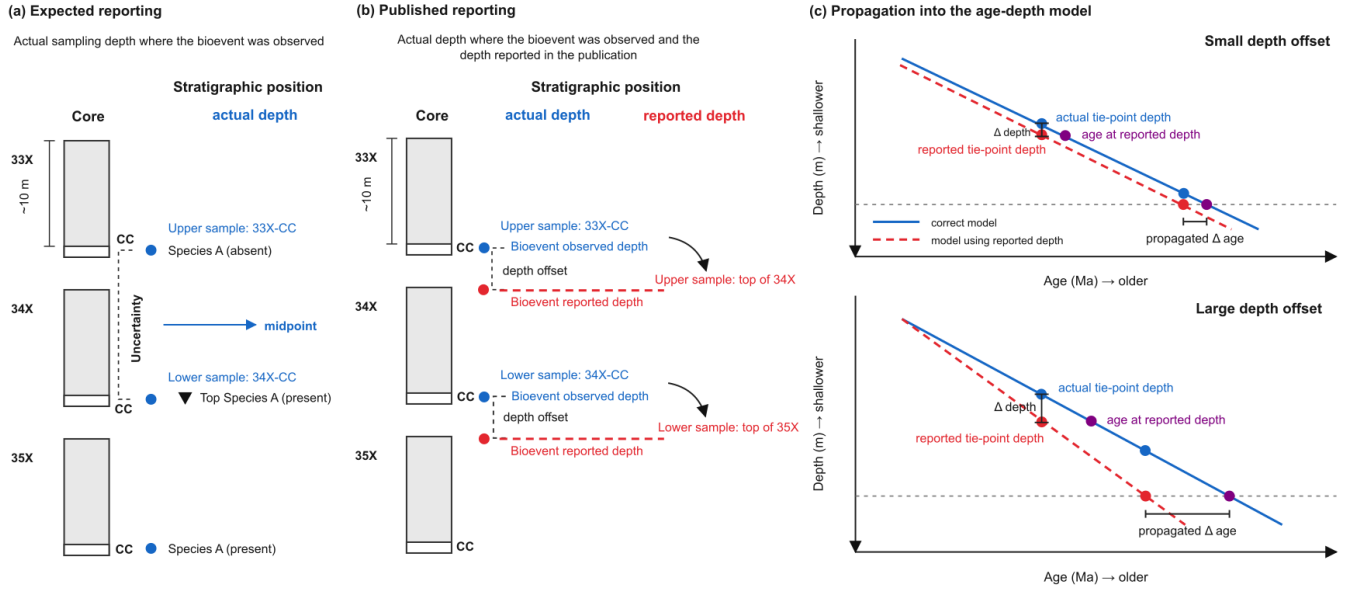


Figure B4. Illustration of how systematic mismatches between the primary depth derived from the core catcher (CC) sample ID and the reported primary depths in the shipboard reports can propagate into age-depth models. a) and b) Primary depths for bioevents identified from CC samples were instead reported at the top depth of one or two cores below the actual core the CC originated from. This issue was identified at three MioOcean key sites (704, 883 and 884) resulting in offsets of up to 15 m between reported depth and actual depth for bioevents. c) Illustration of how incorrect bioevent depths propagate into age-depth models and calculated sample ages.

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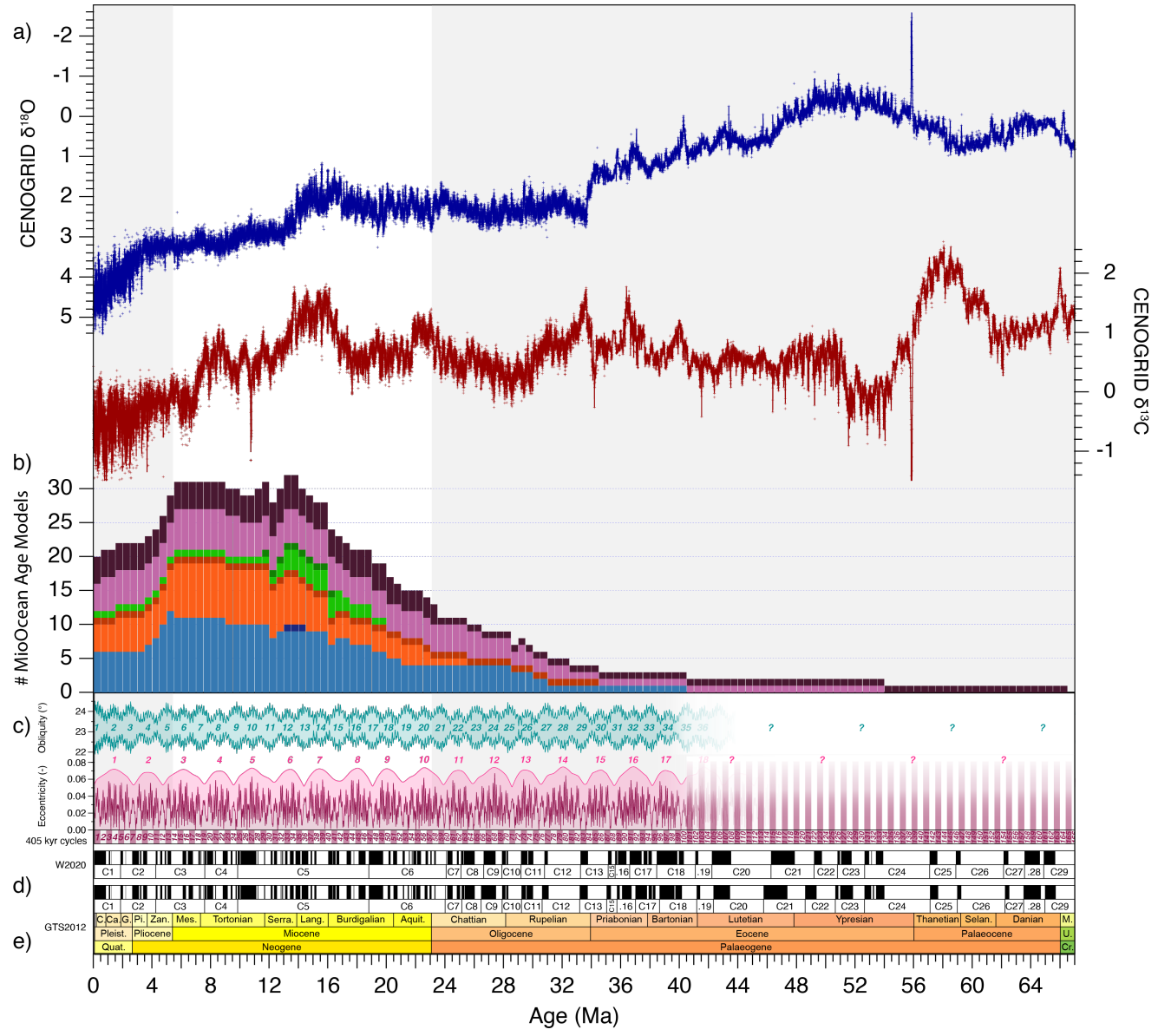


Figure B5. MioOcean Age Model Database in Cenozoic climate and stratigraphic context (0-67 Ma). a) Shows the CENOGRID benthic foraminiferal $\delta^{18}O$ and $\delta^{13}C$ reference stratigraphy with key climatic events and transitions marked. b) shows the distribution of MioOcean age models (0.5 Myr bins) separated by category (astrochronology (A): light blue; astrochronology+ (A+): dark blue; biostratigraphy (B): light orange; biostratigraphy+ (B+); magnetostratigraphy (M): light green; magnetostratigraphy+ (M+): dark green; bio-magnetostratigraphy (BM): light purple; bio-magnetostratigraphy+ (BM+): dark purple). c) the La2004 astronomical solutions for obliquity and eccentricity, along with the 405 kyr cycles that can act as astrochronozones. d) the W2020 and GTS2012 GPTS sequences and chron names. Note that the W2020 GPTS is consistent with the CENOGRID $\delta^{18}O$ and $\delta^{13}C$ shown in panel a) and the GTS2012 GPTS is consistent with the MioOcean Age Framework. e) the GTS2012 Periods, Epochs and Stages for 0-67 Ma. The intervals older and younger than the Miocene are shaded grey, as they were not the primary focus of MioOcean. Any reduction in age model amounts in these intervals may be an artefact. An accompanying figure spanning 0-30 Ma is shown in Figure 10.

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Appendix B - Site 846 composite depth scale, splice revision and mapping pairs

The composite depth scale and composite splice were revised for ODP Site 846 after a mismatch was observed between the Site 846 benthic foraminiferal stable isotope record (Shackleton et al., 1996) and several Pliocene benthic foraminiferal stable isotope reference curves (CR17, Wilkens et al., 2017; LR04, Lisiecki and Raymo, 2005). After the depth scale and splice revision, offsplice material was additionally mapped onto the splice. The Site 846 revised offsets, splice interval table, mapping pairs and explanatory notes are archived on Drury, Tangunan et al. (2026).

14 Appendix C - Citation databases

The MioAGE Citation Database provides a curated, machine-readable record of the publications and other sources underpinning the MioOcean Age Framework, MioOcean Age Model Database, and MioAGE Reliability Grid. It was developed alongside the age model compilation to maintain the connection between individual chronological constraints, age and depth models, and their original sources, and to facilitate consistent and appropriate attribution when these data are subsequently used or reused.

An important principle of the MioAGE Chronoinformatics approach is that use of a compiled or harmonised database should not replace citation of the original publications and data generators on which that resource is built. Users of the MioOcean Age Model Database should therefore cite the relevant original sources associated with the sites, age models and chronological information they use, alongside citation of the MioAGE database and manuscript where appropriate. This is particularly important for community synthesis products, where individual observations and chronological constraints may originate from numerous shipboard studies, post-cruise publications and subsequent stratigraphic revisions. Retaining this citation provenance both recognises the contributions of the researchers who generated the original data and enables users to trace chronological information back to its primary source.

To facilitate this, the complete curated Citation Database is archived with the Drury, Tangunan et al. (2026) assets and can be downloaded and reused alongside the MioOcean Age Model Database. A corresponding EndNote reference library has also been compiled and can be shared or exported for use with other major reference-management software, providing a straightforward means of incorporating the relevant original citations into subsequent studies. All publications contained within the Citation Database are also included in the reference list of this manuscript.

Table C1. Sources of the depth models and age models used for each MioOcean key site.

Site	Depth Model Source	Age Model Source
516		Pujol, 1983; Berggren et al., 1983; Auderset et al., 2022; Florindo et al., 2015; Wei and Wise, 1988; Hess et al., 1989; Bryan and Duncan, 1983; Hamilton et al., 1982

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588		Barton and Bloemendal, 1986; Auderset et al., 2022; Jenkins and Srinivasan, 1986; Berggren et al., 1985; Flower and Kennett, 1993; Hodell and Woodruff, 1994; Oslick et al., 1994; Wright et al., 1992
594	Herbert et al., 2016	Herbert et al., 2016
608		Clement and Robinson, 1987; Krijgsman and Kent, 2004; Gartner, 1992; Pagani et al., 1999; DiStefano et al., 2011
667		Weaver et al., 1989; Shipboard Scientific Party, 1988; Weaver and Raymo, 1989; Miller et al., 1989; Olafsson, 1989
704		Ciesielski et al., 1988; Ciesielski et al., 2005; Auderset et al., 2022
722	Shipboard Scientific Party, 1989	Shipboard Scientific Party, 1989; Bialik et al., 2020
730		Prell et al., 1989; Spaulding et al., 1991
747		Harwood et al., 1992; Scherer et al., 2007; King et al., 2023; Wright and Miller, 1992
754		Peirce et al., 2005; Auderset et al., 2022
761	Holbourn et al., 2004; Holbourn et al., 2024	Holbourn et al., 2024
806		Shipboard Scientfic Party, 1991; Chaisson and Leckie, 1993; Nathan and Leckie, 2009
846	Westerhold this paper	Shackleton et al., 1995; Lisiecki and Raymo, 2005; Westerhold et al., 2020; Raffi et al., 1995
850	Lyle et al., 2019	Wilkens et al., 2017; Lyle et al., 2019; Drury et al., 2018; Drury et al., 2017; Raffi and Flores, 1995; Shackleton et al., 1995
872		Pearson, 1995
883	Keigwin, 1995	Barron et al., 1995; Rea et al., 1995; Herbert et al., 2016
884		Barron et al., 1995; Lyle and OlivarezLyle, 2025
925	Wilkens et al., 2017	Zeeden et al., 2013; Drury et al., 2017; Wilkens et al., 2017; Pearson and Chaisson, 1997; Curry et al., 1995
926	Zeeden et al., 2013; Wilkens et al., 2017; Palike et al., 2005	Zeeden et al., 2013; Drury et al., 2017; Wilkens et al., 2017; Pearson and Chaisson, 1997; Curry et al., 1995; Backman et al., 2012; Fornaciari, 1996

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982	Drury et al., 2018; Shipboard Scientific Party, 1996	Drury et al., 2018; Hodell et al., 2001; Shipboard Scientific Party, 1996; Spiegler, 1999; Lirer and Iaccarino, 2005
1085	Wefer et al., 1998; Westerhold et al., 2003	Wefer et al., 1998; Gastaldello et al., 2024
1088	Gersonde et al., 1999; Tanner et al., 2020; Herbert et al., 2016	Tanner et al., 2020; Marino and Flores et al., 2002; Herbert et al., 2016; Gersonde et al., 1999
1092	Evans et al., 2004	Kuhnert et al., 2009
1143	Shipboard Scientific Party, 2000	Li et al., 2005; Shipboard Scientific Party, 2000
1146	Holbourn et al., 2024	Holbourn et al., 2024
1170		Exon et al., 2001; Shevenell and Kennett, 2004; Shevenell et al., 2008
1171		Stickley et al., 2004; Leutert et al., 2020; Shevenell and Kennett, 2004
1241	Tiedemann et al., 2007	Tiedemann et al., 2007; Groeneveld and Tiedemann, 2005; Mix et al., 2003
1264	Drury et al., 2021	Bell et al., 2014; Drury et al., 2021; Liebrand et al., 2016; Boscolo-Galazzo et al., 2026
AND-2A		Acton et al., 2008; Levy et al., 2016; Florindo et al., 2013
U1318	Expedition 307 Scientists, 2006	Quaijtaal et al., 2018
U1337	Wilkens et al., 2013; Lyle et al., 2019	Drury et al., 2018; Lyle et al., 2019; Drury et al., 2017; Tian et al., 2013; Tian et al., 2018; Holbourn et al., 2024; Hilgen, 2025
U1338	Wilkens et al., 2013; Lyle et al., 2019	Drury et al., 2018; Drury et al., 2016; Drury et al., 2017; Backmann et al., 2016; Pälike et al., 2010; Holbourn et al., 2014; Kochhann et al., 2016; Wilkens et al., 2013; Holbourn et al., 2022
U1356		Bijl et al., 2018; Tauxe et al., 2012; Sangiorni et al., 2018
U1406	van Peer et al., 2017	van Peer et al., 2017a; van Peer et al., 2017b; van Peer et al., 2024
U1443	Clemens et al., 2016; Bolton et al., 2022; Lübbers et al., 2019	Bolton et al., 2022
U1457	Routledge et al., 2019	Routledge et al., 2019; Tauxe and Feakins, 2020
U1501		Sun et al., 2018; Jian et al., 2019; McArthur et al., 2025

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15 Appendix D - MioAGE contributor model

To ensure transparent and equitable recognition of contributions within MioAGE, we developed an authorship and contributor recognition model that extends the standard Contributor Roles Taxonomy (CRediT) model (Table D1). While CRediT provides a widely adopted framework for describing scholarly contributions, many activities essential to collaborative, infrastructure-scale community initiatives are not fully represented by the standard taxonomy alone. The MioAge model combines contributor self-assessment using CRediT with project-specific contribution criteria designed to capture the scientific, technical and organisational activities required to develop the MioOcean Age Framework and its associated products. This includes contributions ranging from the critical evaluation and harmonisation of individual site chronologies to the development and curation of the MioOcean Age Model Database, reliability assessment, workflows and wider synthesis. The model therefore provides a record not only of contributions to the resulting manuscript, but also of the sustained and distributed effort required over the lifetime of MioAge to develop and maintain its community-based chronological framework and associated research infrastructure. In doing so, it recognises that large collaborative synthesis initiatives depend on substantial and diverse contributions that extend beyond the roles traditionally captured through manuscript authorship alone.

Table D1. MioAGE Contributor Model. Framework used to document and recognise contributions to MioAGE, combining standard CRediT contributor roles with MioAGE-specific criteria that capture the scientific, technical and organisational contributions involved in developing the MioOcean Age Framework and its associated products.

MioAGE Contributor Model		
Framework component	**Contribution types / scope**	**How it is recorded**
CRediT contributions	Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Software; Supervision; Validation; Visualization; Writing – original draft; Writing – review & editing	Contributor self-assessment using applicable CRediT roles
MioAGE scientific contributions	Scientific development and interpretation of the MioOcean Age Framework and associated products	Project-specific contribution record
Site chronology assessment and harmonisation	Critical evaluation, verification, revision and/or standardisation of individual site chronologies	Sites and/or age models contributed to
MioOcean Age Model Database	Database development, compilation, curation, integration and maintenance	Project-specific contribution record

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MioAGE Reliability Grid	Development, refinement, assessment and/or application of the Reliability Grid	Project-specific contribution record
Workflow and methodological development	Development of workflows, methods, protocols and associated tools	Project-specific contribution record
Data curation and quality control	Data compilation, checking, validation, standardisation, metadata and provenance	Project-specific contribution record
Community coordination and organisation	Working-group coordination, meetings, community activities and organisational contributions	Project-specific contribution record
Manuscript contribution	Development of manuscript content, figures/tables, writing, review and editing	Recorded alongside relevant CRediT writing roles

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