THE GEOLOGICAL SOCIETY OF AMERICA®

SedST: An updated chronological database for ocean sediments

Can Cai[1,2], Chao Ma[3,4,†], Bin Hu[1,2], Jiajia Zhang[3,4], Xi Chen[1,2], Dangpeng Xi[1,2], Meinan Shi[1,5], Jun Meng[1,2], Xin Li[6], Tiantian Wang[1,2], He Huang[3,4], Yida Yang[1,2], James G. Ogg[3,7], Mingcai Hou[3,4], Xiumian Hu[8,†], and Chengshan Wang[1,2,†]

[1]*State Key Laboratory of Geomicrobiology and Environmental Changes, Frontiers Science Center for Deep-time Digital Earth, China University of Geosciences (Beijing), Beijing 100083, China*
[2]*School of Earth Sciences and Resources, China University of Geosciences (Beijing), Beijing 100083, China*
[3]*State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Institute of Sedimentary Geology, Chengdu University of Technology, Chengdu 610059, China*
[4]*Key Laboratory of Deep-Time Geography and Environment Reconstruction and Applications of Ministry of Natural Resources, Chengdu University of Technology, Chengdu 610059, China*
[5]*School of Ocean Sciences, China University of Geosciences (Beijing), Beijing 100083, China*
[6]*State Key Laboratory of Palaeobiology and Stratigraphy, Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences, Nanjing 210008, China*
[7]*Department of Earth, Atmospheric and Planetary Sciences, Purdue University, West Lafayette, Indiana 47907-2051, USA*
[8]*State Key Laboratory of Critical Earth Material Cycling and Mineral Deposits, School of Earth Sciences and Engineering, Nanjing University, Nanjing 210023, China*

ABSTRACT

Over the past six decades, the scientific ocean drilling (SOD) programs have collected vast and invaluable data for Earth history research. However, the scattered state of these data across multiple repositories, along with inconsistent standards, methodologies, and terminologies, have increased the complexity of data processing and posed barriers to its effective utilization. While several databases have been developed to consolidate and improve access to SOD data, each has limitations in scope. To address these challenges, we introduce the Sediment Spatial and Temporal Database (SedST, http://sedst.org), a new platform designed to aggregate chronological data from the extensive archives of SOD, including postcruise literature, and provide tools for data accessibility. SedST standardizes biostratigraphic, magnetostratigraphic, and radiometric dating records, aligning them with the latest Geologic Time Scale 2020, to ensure consistency and coherence. Employing the Bchron methodology, SedST establishes age-depth models for >1000 SOD boreholes. Presently, SedST encompasses 37,329 entries from 181 expeditions and 1300 holes, covering the world's ocean basins and including records as old as the Late Jurassic. The platform provides powerful tools for sample ID to depth conversions and individual hole to composite site depth transformation. Accessible via user-friendly graphical interfaces, SedST simplifies data queries and allows the export of search results in CSV format. As a constantly developing platform under the umbrella of the Deep-time Digital Earth program, SedST is committed to enhancing the accessibility and discoverability of marine sediment data, fostering new insights into Earth's geological history.

1. INTRODUCTION

The scientific ocean drilling (SOD) programs are international marine research collaborations that explore Earth's history and dynamics. These projects use oceangoing research platforms to collect samples and data from seafloor sediments and rocks. Several consecutive projects have operated under the SOD initiative, including the Deep-Sea Drilling Project (DSDP, 1968–1983), the Ocean Drilling Program (ODP, 1983–2003), the Integrated Ocean Drilling Program (IODP 1, 2003–2013), and the International Ocean Discovery Program (IODP 2, 2013–2024; Fig. 1). Collectively, these projects have recovered >467 km of core, significantly enriching the comprehensive Earth science data pool.

The SOD projects provide a rich source of data on Earth's past, offering valuable insights into biological, geochemical, and geophysical processes within Earth's surface, crust, and mantle, as well as past climate conditions (Becker et al., 2019). The main accomplishments of these projects include the verification of seafloor spreading and plate tectonics (Becker et al., 2019; Hall and Robinson, 1979; Royer and Coffin, 1992), the exploration of Earth's deep structure beneath the seafloor (Hall and Robinson, 1979; Dick et al., 2000; Wilson et al., 2006; Ildefonse et al., 2007; Rubanik, 2008; Teagle and Ildefonse, 2011; Blackman et al., 2011; Ohira et al., 2018; Voosen, 2023), the unveiling of the global climate history spanning the past ~150 m.y. (Colleoni et al., 2018; Dowsett et al., 2012; Holbourn et al., 2015, 2014, 2005, 2018; Lauretano et al., 2018, 2015; Liebrand et al., 2017, 2016; Pälike et al., 2006; Sexton et al., 2011; Stap et al., 2010; Westerhold et al., 2020, 2018; Zachos et al., 2001, 2010, 2008), the discovery of the diverse and vast amount of life in the deep-sea biosphere (D'Hondt et al., 2004; Lomstein et al., 2012; Heuer et al., 2019), and the development of a robust geological time scale for the past 150 m.y. (Beddow et al., 2018; Billups et al., 2004; Boulila et al., 2018; Drury et al., 2017; Lauretano et al., 2016; Liebrand et al., 2016; Littler et al., 2019; Shackleton et al., 1999; Westerhold et al., 2017, 2014, 2020; Zeeden et al., 2013). These achievements highlight

Chao Ma https://orcid.org/0000-0002-0122-5696
†Chao Ma, machao@cdut.edu.cn; Xiumian Hu, huxm@nju.edu.cn; Chengshan Wang, chshwang@cugb.edu.cn

GSA Bulletin;
Published online 22 July 2025

https://doi.org/10.1130/B37957.1.

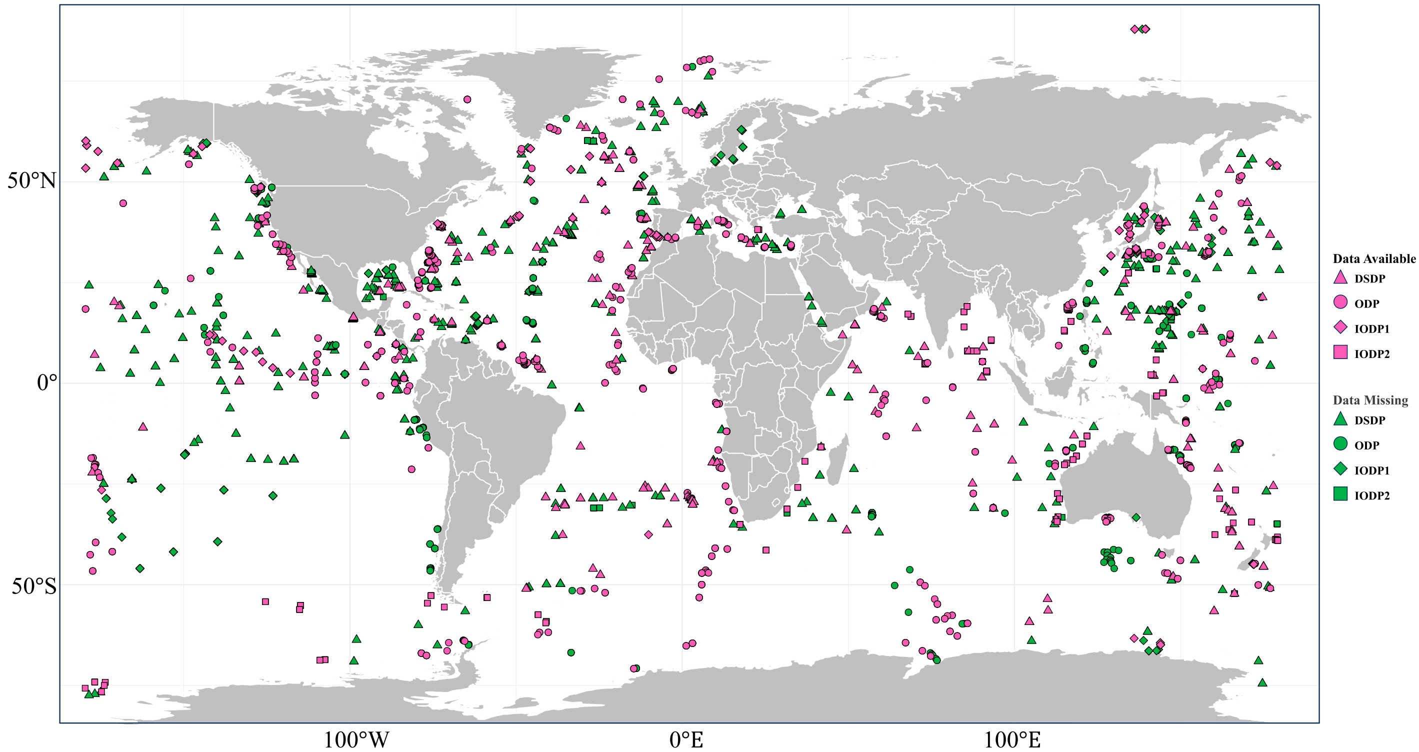

Figure 1. Global distribution of the scientific ocean drilling (SOD) sites, which are color-coded to indicate data availability. Green dots represent sites deficient in sediment or lacking adequate age data, while pink dots denote sites with adequate age data.

the substantial scientific value of the SOD projects. The extensive marine data generated by the SOD projects underscores their lasting impact. With immense potential for data compilation, they serve as a valuable resource for researchers.

Firmly established chronologies are fundamental to exploring Earth science issues using SOD data (Kinsley et al., 2022; Li et al., 2023; Jin et al., 2023; Hou et al., 2023). These chronologies enable researchers to synchronize geological data from different regions into a unified timeline, a critical step for testing causal relationships and understanding Earth's history (Westerhold et al., 2024). Currently, three principal databases host age and age-depth modeling data specific to the SOD project: Neptune Sandbox Berlin (NSB, Lazarus, 1994; Renaudie et al., 2020), Triton (Fenton et al., 2021), and Extending Ocean Drilling Pursuits (eODP, e.g., Sessa et al., 2023). Each database has made significant contributions to the field.

The NSB, conceptualized in 1989, is a comprehensive repository for SOD microfossil occurrences, with chronological data being one of its components (Lazarus, 1994; Renaudie et al., 2020). As of August 2023, NSB housed chronological records from 129 expeditions and 834 holes, which have been extensively utilized by researchers worldwide. Currently, NSB's age model library encompasses >470 drill sites. The development of age models began in the early 1990s with the introduction of the Age-Depth Plot (ADP) program. The ADP program is designed for flexibility, allowing manual adjustments through the addition, relocation, and removal of control points, as well as the incorporation of hiatuses (Lazarus, 1992; Bohling, 2005). The age-depth relationship is constructed as a set of connected straight-line segments to subjectively best fit the chronostratigraphic data in each depth interval. In the 2010s, a systematic review and enhancement effort addressed inaccuracies in existing NSB age models, leading to significant updates. Between 2015 and 2019, 55% of the age models were updated or added, and an additional 24% were formulated between 2020 and 2021. This rigorous evaluation substantially elevated the quality of NSB's age models. However, Renaudie et al. (2020) noted that ~19% of NSB models still fall short of rigorous quality standards, highlighting the need for ongoing refinements. NSB's main strengths include its use of relatively high-quality shore-based data and manual integration of supplementary information—such as sedimentology and seismic stratigraphy to identify hiatuses—to enhance the accuracy of age models. However, its coverage is relatively limited, as NSB was designed to be selective, focusing on higher-quality sites. Additionally, the project has not been updated to include more recent drilling expeditions for several years.

The Triton database, established by Fenton et al. (2021), is a species-level repository for Cenozoic planktonic foraminiferal occurrence records. It compiles data from 174 expeditions covering ~873 ocean drilling holes. When combined with the NSB database, the total coverage extends to ~1213 drill holes. Triton's age models are based on linear interpolation or Generalized Additive Model smoothing, with manual quality checks. However, these models are documented as static images rather than interactive datasets (fig. 4 in Fenton et al., 2021). Although the database is available online as an archive, its lack of a user-friendly web interface makes it challenging for nonprogrammers to use.

The eODP initiative, led by Sessa et al. (2023), aims to enhance the accessibility and interpretation of microfossil and stratigraphic datasets associated with SOD. As of June 2024, eODP includes nearly 86,000 lithologic units from ~1343 drill holes, and 5378 taxonomic entries (Sessa et al., 2023; S. Peters, 2024, personal commun.). Taxonomic information is integrated into the Paleobiology Database (Peters and McClennen, 2016), while lithologic data and age-depth models are housed in the Macrostrat database system (Peters et al., 2018). Despite its extensive data coverage, eODP's age models are relatively coarse, primarily based on shipboard studies. Additionally, eODP currently lacks a public interface, which limits its accessibility and utility for researchers.

In addition to these major databases, several smaller-scale efforts have contributed valuable chronological information. For example, Lyle (2003) developed age models for 144 tropical Pacific sites using polynomial fits, primarily derived from DSDP and ODP Initial Reports, to study carbonate burial in the Pacific Ocean during the Neogene. Similarly, Li et al. (2023) constructed age models for 80 global sites to investigate the Neogene burial of organic carbon in the global ocean, also employing polynomial fits. Westerhold et al. (2020) utilized nine astronomically tuned sites to create a high-resolution benthic foraminifer stable isotope record spanning the entire Cenozoic. While these efforts are significant, they remain limited in scope and accessibility.

Despite the significant contributions of these databases and studies, several challenges persist in the accessibility, usability, and integration of SOD age data. First, while NSB, Triton, and eODP provide valuable archives of downloadable files, extracting and utilizing these data often requires specialized skills. Additionally, the data visualization in these databases is not user-friendly, limiting their accessibility to researchers. Second, high-quality NSB data have limited coverage, whereas eODP provides broader coverage but with lower data quality. Third, the age models in these repositories predominantly rely on linear interpolation or segmentation methods. While these approaches are effective, recent studies on late Quaternary nonmarine sediments have shown that Bayesian age-depth models can yield more reliable results when control point quality is consistent (Blaauw et al., 2018).

In response to these challenges, we introduce SedST (http://sedst.org), a unified repository and open platform designed to enhance the accessibility and usability of SOD chronological data. Developed under the auspices of the Deep-time Digital Earth (DDE) program (Wang et al., 2021), SedST systematically collects and standardizes data from various SOD repositories, including postcruise literature. To construct age-depth models, SedST employs Bayesian techniques using the Bchron package (Haslett and Parnell, 2008). SedST represents a step forward in addressing the limitations of existing databases. Its systematic data collection and standardization efforts provide a supportive foundation for broader initiatives, such as the Time Integrated Matrix for Earth Sciences (TIMES) program (Westerhold et al., 2024).

The structure of this paper is as follows: Section 2 details the source of chronological data and describes the methods used for data collection and recalibration with Geologic Time Scale 2020 standards. This section also covers the implementation of the Bayesian approach in constructing age-depth models. Section 3 provides a concise summary of the age data collected and the age-depth models constructed, along with a comparative analysis with other databases. Section 4 delves into the scientific uses of age data. Section 5 shows the web user interfaces and explains how to search for and download data. Section 6 discusses current limitations and planned future enhancements. Section 7 concludes the paper.

2. MATERIALS AND METHODS

2.1. Data Sources

Throughout the history of SOD, the terminology for research cruises has evolved. They were referred to as legs during DSDP and ODP and as expeditions during IODP. Each leg or expedition visited several sites where drilling was conducted. Each site contains one or more holes. Data from SOD programs are archived in separate repositories (Table 1). DSDP accomplished a total of 96 legs and drilled 1053 holes at 624 sites. A wealth of data can be obtained online through the National Oceanographic and Atmospheric Administration's National Centers for Environmental Information platform. The ODP's Janus database (Mithal and Becker, 2006) includes expeditions from Legs 100–210, totaling 111 completed expeditions that drilled 1797 holes at 669 sites. This includes paleontological, lithostratigraphic, chemical, physical, sedimentological, and geophysical data from ocean sediments and hard rocks. By September 2024, IODP Phases 1 and 2 had successfully conducted 111 expeditions. The corresponding data for these expeditions are archived and accessible through various platforms, including the Laboratory Information Management System (LIMS), the Japan Agency for Marine-Earth Science and Technology (JAMSTEC), and PANGAEA (Felden et al., 2023).

Detailed core material descriptions and scientific data obtained from offshore and postcruise onshore laboratories are documented in SOD publications. Among these five official databases (Table 1), only the Janus repository provides an aggregated collection of chronological data in different fields (Depth-Age Model or Age Profile), readily available for download as online spreadsheet data.

However, the chronological data housed within the Janus database represent but a modest subset of the extensive holdings of the SOD program. The vast majority of the remaining datasets and newly modified data are dispersed across various scientific publications. For example, chronological data from DSDP and ODP cores are recorded in the Initial Reports as text, PDF embedded tables, or figures. Typically, these are located in chapters that offer comprehensive descriptions of each drill site, often within the sections on paleontology. Sometimes, separate chapters dedicated to paleontological studies also contain chronological information. Data from IODP are stored in the Proceedings volume for each drilling expedition. Chronological data from the initial IODP expeditions are primarily recorded as embedded PDF tables. Beginning with Expedition 349, the practice of storing such data transitioned to individual CSV files.

TABLE 1. SCIENTIFIC OCEAN DRILLING DATA REPOSITORIES

	DSDP*	ODP†	IODP1§	IODP2§
Expeditions completed	96	111	54	57
Sites visited	624	669	250	269
Holes drilled	1,053	1,797	649	733
Core recovery (m)	97,056	222,704	66,306	98,187
Repository	NOAA#, Janus**	Janus**	LIMS††, JAMSTEC§§, PANGAEA##	LIMS††, JAMSTEC§§, PANGAEA##
Age data recorded in	Initial Reports, literature	Initial Reports, literature	Proceedings, literature	Proceedings, literature

*Deep-Sea Drilling Project (DSDP) Initial Reports (http://www.deepseadrilling.org/i_reports.htm)
†Ocean Drilling Program (ODP) Initial Reports (http://www-odp.tamu.edu/publications/)
§Integrated Ocean Drilling Program (IODP1) and International Ocean Discovery Program (IODP2) Proceedings (http://iodp.tamu.edu/publications/)
#National Centers for Environmental Information (National Oceanographic and Atmospheric Administration [NOAA], https://www.ncei.noaa.gov/products/international-ocean-drilling-archive)
**Janus database (https://web.iodp.tamu.edu/janusweb/links/links_all.shtml)
††Laboratory Information Management System (LIMS, https://web.iodp.tamu.edu/LORE/)
§§Japan Agency for Marine-Earth Science and Technology (JAMSTEC, https://www.jamstec.go.jp/sio7/)
##PANGAEA is the archive for scientific data resulting from Mission Specific Platform (MSP, https://iodp.pangaea.de/)

Recognizing that numerous researchers have generated new age data or reinterpreted existing age data in their studies using SOD information, significant efforts were undertaken to compile these dispersed, often difficult-to-access but higher-quality age data from postcruise published works. Generally, such chronological information is significantly more detailed and thus gives more precise estimates of biostratigraphic, paleomagnetic, and other chronostratigraphic events than the shipboard data.

2.2. Database Structure

The SedST database consists of nine tables (Fig. 2), with chronological data stored in the table named Stratigraphic_Event. Continuous age models, derived from the primary chronological data using various mathematical techniques and selective data integration strategies, are represented by the Age_Model_SedST developed in this study, along with models sourced from PANGAEA, Triton, and NSB.

To support the functionalities described in section 5.2, three additional tables have been compiled: Sample_to_Depth for converting sample IDs to depth value, IODP_Affine for transforming depths from individual drill holes to a site scale through correlation adjustments, and IODP_Splice for merging data from multiple drill holes into a cohesive dataset. The database also contains a metadata table that stores hole location information, links to the official ocean drilling website (Table 1), and the collected age data range.

The database was developed using MySQL (version 5.7.40), an open-source relational database management system known for high performance, cross-platform compatibility, and scalability.

In this database, chronostratigraphic data and age model data are core components. For the chronostratigraphic data, the greatest importance is placed on the depth and the associated events for each hole (Table 2). Depth data are important, as they facilitate the straightforward integration of chemical, physical, and biological data within a single borehole. This integrative approach is vital for effectively addressing and unraveling complex real-world geological questions. In light of the varied depth representations outlined in the IODP Depth Scales Terminology (IODP-MI, 2011), meters below seafloor (mbsf) has been prioritized as the primary unit of measurement. This decision is rooted in the widespread adoption of mbsf in research (Śliwińska et al., 2022; Davidson et al., 2023; Hess et al., 2023; Jiang et al., 2024; Jørgensen et al., 2024; Moretti et al., 2024) and the fact that mbsf is the only direct measurement, while other methods rely on models that are subject to change. Mbsf is equivalent to the core depth below seafloor-A (CSF-A) scale of IODP. However, the core depth below seafloor-B (CSF-B) and core composite depth below seafloor (CCSF) scales do not correspond to the classical definition of mbsf, as

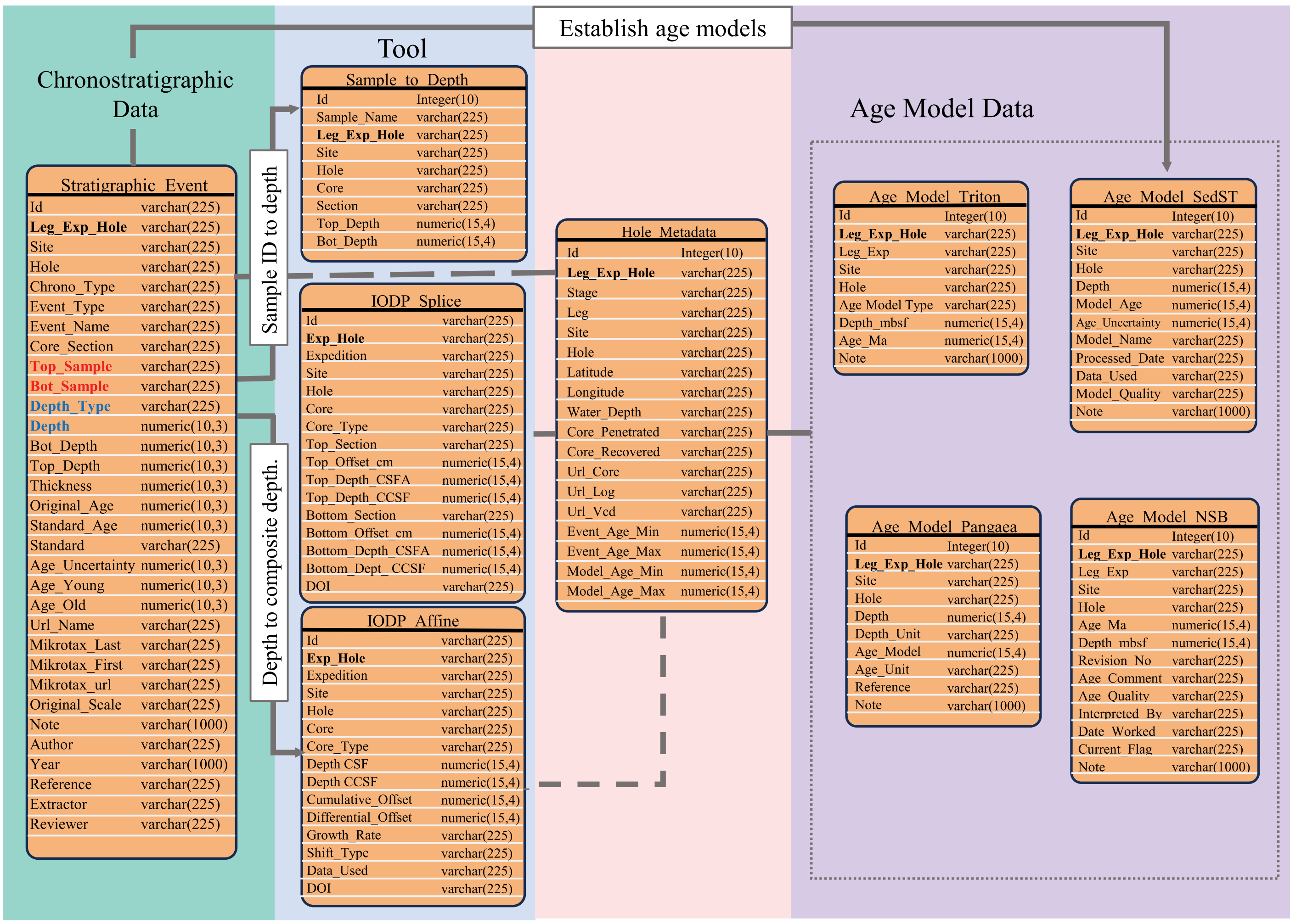

Figure 2. Database structure. Different background colors represent different modules, corresponding to the website functions described in section 5.

TABLE 2. STRUCTURE OF CHRONOLOGICAL DATA

Field	Explanation
Leg_Exp	Identifier or name of the expedition or leg that collected the data
Site	Site name
Hole	Hole name
Chrono_Type	Methodology used to determine age (Bio_R—radiolarian; Bio_F—foraminifera; Bio_N—nannofossil; Bio_D—diatom; Bio_DN—dinoflagellate; I—isotope event; M—magnetic reversal; RD—radiometric dating)
Event_Type	First Appearance Datum/Last Appearance Datum (FAD/LAD)
Event_Name	Specific event or dating system used for age determination
Core_Section	Section being analyzed
Top_Sample	Top sample name
Bot_Sample	Bottom sample name
Depth_Type	Type of depth measurement used (e.g., meters below seafloor [mbsf] and meters composite depth [mcd])
Depth	Depth at which the sample was taken
Top_Depth	The depth of the top boundary of the sample, or the depth of the top sample
Bot_Depth	The depth of the bottom boundary of the sample, or the depth of the bottom sample
Depth_Uncertainty	Represents the depth difference between the top sample and bottom sample
Original_Age	The most likely or average age of the sample indicated in the original resources
Young_Age	Young age for biozone
Old_Age	Old age for biozone
Age_Uncertainty	Uncertainty associated with age determination
Standard_Age	Age value standardized according to criteria
Standard	Reference standard used (e.g., Geologic Time Scale 2020 and Neptune Sandbox Berlin)
Author	Author(s) of the study or publication from which the data was sourced
Year	Year of the publication or study
Note	Information or notes about the data/sample, process, or other relevant context
Reference	Reference to the source material
Processor	Specifies the individual responsible for the collection and processing

Note: See data examples in Table S1 (see text footnote 1).

they account for rescaling or correlation adjustments. Further details can be found in the IODP Depth Scales Terminology.

Chronostratigraphic data are typically acquired through the analysis of core samples. This includes the identification of specific markers, such as the first or last occurrence of certain organisms (Prothero and Schwab, 2013) or a geomagnetic reversal boundary, all of which can serve as indicators of absolute ages. In our database, the methodologies employed to secure numerical age are under Chrono_Type, Event_Type, and Event_Name. The Chrono_Type category includes biostratigraphic event data (Bio), isotope event (I), magnetic reversal data (M), and radioisotopic dating data (RD). Biostratigraphic event data comprise planktonic foraminifer, calcareous nannofossil, radiolarian, diatom, and dinoflagellate event data, with the respective Chrono_Type as Bio_F, Bio_N, Bio_R, Bio_D, and Bio_DN. Event_Type involves First Appearance Datum/Last Appearance Datum (FAD/LAD). Event_Name is carefully recorded, including constraints such as common and organism sizes.

Particular attention has been paid to the uncertainties associated with both age and depth when collecting chronological data, as they are important for the construction of robust age-depth models. Reported age uncertainties, if given, are faithfully recorded. However, primary repositories often lack information on uncertainty. In such instances, if the bottom and top sample depth is provided, the depth uncertainty is calculated as the difference between these two. Since some ages have been stored as zonation when both old and young ages are reported, the median value is taken as the sample's age, with half of the difference serving as the age uncertainty. Reference and Note are documented for the purpose of assessing data quality. Sample information is stored in the Core_Section, with Top_Sample and Bot_Sample fields to ensure depth intercalibration.

In the compilation of age-depth model data, our interest is specifically directed toward age-depth relationships, the methodologies utilized for model construction, and the corresponding references (Fig. 2).

2.3. Data Collection Strategy

In dealing with two types of age data, two parallel methodologies have been developed. The first approach focuses on aggregating the existing age-depth model data, and the second focuses on rebuilding the age-depth model by collecting the chronostratigraphic data from databases and the literature. These chronostratigraphic data are then analyzed and interpreted using the Bchron method to construct age-depth models.

Age-depth model data are stored in published literature and databases. While data in databases are relatively easy to access, extracting information from publications can be more challenging. However, many studies have deposited their data in PANGAEA—an efficient information system dedicated to the management and long-term storage of research data in the earth sciences domain (Diepenbroek et al., 2002; Felden et al., 2023). It hosts a vast array of data from various publications, which are readily retrievable via keyword searches. This efficient search capability makes data extraction from PANGAEA more effective than sifting through individual publications. Alongside PANGAEA, age-depth models were collected from the NSB and Triton, with additional data supplementation from academic papers.

To extract age-depth model data from the PANGAEA database, a targeted search strategy employing four keyword terms—*age-depth*, *chronology*, *age model*, and *age*—was implemented, with a focus on the SOD programs as filters. This approach yielded 188 datasets under age-depth and 377 datasets for chronology. Notably, within the chronology category, 86 datasets are attributed to the Lazarus et al. (1995) revised chronology of Neogene DSDP holes, a majority of which have been incorporated into the NSB. Additionally, 4095 datasets for age model and 12,542 datasets for age were obtained (PANGAEA: Data Publisher for Earth & Environmental Science, https://www.pangaea.de/).

Following the acquisition of unduplicated datasets, our subsequent step involved the extraction of the desired information. Due to the relatively uniform format of PANGAEA's datasets, which integrate metadata with the data, we used a systematic sampling strategy. Specifically, 20% of the data from each of the four datasets retrieved from PANGAEA using the aforementioned four keywords were randomly selected for thorough examination to pinpoint the locations and formats of the necessary information (Fig. S1 in the Supplemental Material[1]).

[1]Supplemental Material. This document provides a detailed description of the age model construction process, examples of data calibration to standard references, and potential research applications of the SedST database. Please visit https://doi.org/10.1130/GSAB.S.29367512 to access the supplemental material; contact editing@geosociety.org with any questions.

Guided by rules established by geoscientists, the computer scientists autoextracted data from separate tables and aligned them in a unified table. Through this process, age-depth model data for 765 holes were successfully extracted from the PANGAEA database. However, slight variations in the table formats within the PANGAEA database occasionally hindered the precision of automated extraction, necessitating manual verification to ensure accuracy. This required substantial time and effort.

In addition to the acquisition of age-depth model data, the SedST database further expands its repository by generating age-depth models from raw chronostratigraphic age data. The primary sources for these chronostratigraphic data are SOD reports and the literature. The challenge posed by unstructured data in publications is addressed through dedicated time and effort. First, relevant publications are downloaded from SOD's official websites, as listed in Table 1, along with additional sources from the Web of Science (Table S1: Reference column). These reports are then reviewed to identify usable tables and figures. Upon locating candidate tables, they are converted from PDF to CSV format using the GeoDeepShovel web tool (Zhang et al., 2023).

2.4. Quality Control

To ensure accuracy, completeness, and consistency, a collaborative team of experts and students (Table S2), along with automated systems, were employed to collect chronostratigraphic age and age-depth model records from published papers and open-access resources. Automated data validation was conducted using Python scripts to ensure that data entries conformed to the correct types and formats, and to verify that depth and age values were within plausible ranges. The validation criteria include requirements that depths should not exceed 3059 m, the maximum drilling depth achieved in Expedition 348, Hole C0002P, and that ages should be younger than 270 m.y. (Müller et al., 2008), consistent with plate tectonic theories. Data identified as exceeding these limits were manually verified before being entered into the database. If the outliers were determined to be accurate rather than errors, they were included in the database. To further enhance data quality, all records underwent a secondary verification process. This involved cross-referencing the leg, expedition site, and hole data against official SOD Hole Summary documentation (downloaded from LIMS Summaries, Hole Summary). For example, a hole in the database listed under Expedition 354 at Site 1542 was not found in the Hole Summary document, as Site 1542 actually belongs to Expedition 383. Review of the official report for Expedition 354 revealed that the information had been incorrectly recorded in the Biostratigraphic Age Datums table for Site 1452 (Fig. S2). Therefore, the record was manually corrected from 1542 to 1452. The architecture of the database was specifically designed to facilitate efficient cross-checking, utilizing fields such as Depth_Top, Sample_Top, Depth_Bot, and Sample_Bot. Additionally, all chronostratigraphic data were converted into age-depth models, thereby providing another layer of verification. Furthermore, each modification to the database is recorded in the system with the responsible individual and time information to prevent human errors and to track changes over time.

A dedicated working group, consisting of 30 members (Table S2) with expertise in micropaleontology, paleomagnetism, chronostratigraphy, stratigraphy, radiometric dating, and computer science, including 12 professors, 6 Ph.D. students, and 11 master's students, is tasked with the ongoing maintenance and management of the SedST database. This team ensures that any modifications to existing records and the integration of new data are documented in subsequent updates. Such an approach guarantees that the database remains current and reliable.

2.5. Data Recalibration

Since the initiation of DSDP in 1968, there have been significant enhancements in the precision of absolute dating, primarily due to ongoing advancements in research methodologies and technological innovations. This period also witnessed a deepening intercorrelation of geomagnetic reversals, biological events, and the astronomical time scale, which has led to numerous revisions in the absolute ages indicated by these events. To ensure comparability across data generated at different times, the ages were recalibrated to align with data in the Geologic Time Scale 2020 (GTS2020; Gradstein et al., 2020) Standard and Supplement by the standard proposed by the NSB database (Renaudie et al., 2020).

The recalibration process begins with standardizing event names across SedST, GTS2020, and NSB to ensure comparability. This involves case normalization and the removal of spaces. Once standardized, each event in SedST is matched to the most similar event name in the standard datasets, namely NSB or GTS2020. If multiple matches exist, the one with the smallest absolute age difference from the original SedST age is selected.

To determine similarity, two matching criteria are used iteratively. The first is absolute matching, where the event name in SedST is identical to a name in the standard dataset. The second is fuzzy matching, where a continuous substring of the SedST event name appears within a standard name. The similarity score is calculated as

$$S = \frac{L_{sub}}{L_{sedst}}. \quad (1)$$

L_{sub} is the length of the longest continuous substring from the SedST event name that appears in the standard event name. L_{sedst} is the length of the SedST event name. S ranges from 0.3 to 1, ensuring that only meaningful partial matches are considered.

Once the best match is identified, the recalibrated event is recorded in the SedST dataset. This includes the matched event name, event type, chrono type (e.g., magnetic reversal and diatom event), age, absolute age difference, and percentage difference. However, some records may contain inconsistencies that require manual verification. These cases fall into three categories: (1) low similarity between the SedST event name and the best-matched standard name; (2) discrepant event types, where the event type in SedST does not match the standard; and (3) significant age discrepancies, where the absolute age difference is >2 m.y., or the percentage difference is $>10\%$.

For cases requiring manual verification, possible causes are first identified, including event annotations, spelling errors, and formatting differences (Table S3). The next step is to find a suitable match, prioritizing GTS2020. If no acceptable match is found, NSB is consulted. If neither dataset provides a suitable match, the original SedST age is retained. Finally, the verified age and its corresponding data source (GTS2020, NSB, or original) are recorded in the SedST dataset.

Of the 37,329 rows of age data in the SedST database, a substantial portion were calibrated using GTS2020 and NSB standards. Specifically, 28,242 rows (75.66%) were recalibrated in accordance with the GTS2020 standard, and 8184 rows (21.92%) used the NSB standard. A smaller portion of the dataset (2.41%) does not conform to the standards being used. These rows were converted to the 2020 standard using the Geomagnetic Polarity Time Scale based on published years. Within this subset, 96 rows are radioactive dating data, which were left unprocessed. The Standard_Age column in the database represents the recalibrated ages, and the Standard column identifies the standards applied (Table 2).

2.6. Age-Depth Modeling

Utilizing the collected and recalibrated age data, age-depth models can be constructed for each drill hole. Commonly used models—including CLAM, OxCal, Bchron, Bacon, and Undatable—have been compared and analyzed (Haslett and Parnell, 2008; Blaauw, 2010; Blaauw and Christen, 2011; Lougheed and Obrochta, 2019).

CLAM (Blaauw, 2010) is a non-Bayesian approach that provides several common types of age models, including linear interpolation, polynomial regression, and cubic, smoothed, or locally weighted splines, with the option to include hiatuses. Researchers must decide on the most appropriate model type. Confidence intervals for predicted ages are calculated using the Monte Carlo approach, where ages are repeatedly sampled with a given probability density function for each depth dated. The single best age-depth model from all iterated models can be obtained by calculating the mean, the medians, the midpoint of the highest posterior density, or other commonly used estimation approaches.

OxCal (Ramsey, 2008) offers five options for depositional models, providing more flexibility: the D-sequence model has fixed time intervals (e.g., tree rings), the V-sequence model has approximately fixed intervals, the U-sequence model assumes a uniform depositional process, the P-sequence model allows for variable sediment accumulation, and the S-sequence model relies solely on age sequences without depth information. In addition to selecting a depositional model, in P_Sequence OxCal requires the choice of an appropriate parameter *k*. A higher *k* value results in a more uniform sediment deposition process, while a smaller *k* value allows for a more variable sediment deposition process. Choosing a reasonable value for *k* can be challenging (Ramsey et al., 2010).

Bchron (Haslett and Parnell, 2008) determines the number of samples between control points using Poisson distribution, employing two gamma distributions to sample increments of time and depth, which ensures monotonicity. Because the depth increments and age increments are independent, Bchron allows for abrupt changes in accumulation rates. These sample points are then connected through piecewise linear interpolation. A large number of samples are generated through Markov Chain Monte Carlo (MCMC) sampling, enabling the calculation of confidence intervals.

Bacon (Blaauw and Christen, 2011) models accumulation rates using a gamma autoregressive process to establish a coherent evolution of deposition, potentially including hiatuses. The corresponding MCMC-sampled integration of this process represents the age-depth model. For Bacon, two prior distributions must be defined: one for the accumulation rate and the other for the autocorrelation of accumulation rates between piecewise linear segments. The length of the linear segments must also be specified. Each of these can influence the model's performance (Trachsel and Telford, 2017).

Undatable (Lougheed and Obrochta, 2019) is designed for sedimentary environments characterized by more fluctuations, such as bioturbation. The bootpc parameter represents the probability of randomly removing an age-depth constraint, making it particularly useful in situations with conflicts among age control points. The xfactor governs the uncertainty in sediment accumulation rates between control points. Both the xfactor and bootpc parameters are subjective and depend heavily on the dataset, requiring users to evaluate whether the chosen values are appropriate.

According to Trachsel and Telford (2017), in the analysis of varved sediment sequences using CLAM, OxCal, Bacon, and Bchron, it was observed that all methods produce similar mean age-depth models, including Undatable in our comparison. The main difference lies in the error estimation. Age uncertainties are usually underestimated by CLAM, while those produced by Bchron are often too large. In OxCal and Bacon, the choice of model-specific parameters influences the estimated uncertainties (Trachsel and Telford, 2017). Undatable is specifically designed to accommodate complex sedimentary processes, allowing larger error estimates based on parameter variations.

Marine sediments are more complex than varved sediments, making CLAM unsuitable because it tends to underestimate sediment uncertainties. Furthermore, simulations show that Bayesian methods are generally more reliable than non-Bayesian methods (Blaauw et al., 2018). Consequently, CLAM was not utilized in our modeling process. Bacon, OxCal, and Undatable all require parameter adjustments based on specific holes, making them less suitable for age-depth modeling across a large number of holes. OxCal is further limited by its inability to provide continuous age models, offering estimates only at control points and selected depths. Undatable exhibits high variability and depends on MATLAB, which is less user-friendly than R for our team's data analysis background. Bacon was found to require a longer runtime under similar conditions (Pfalz et al., 2021). Consequently, Bacon, OxCal, and Undatable were not used. In contrast, Bchron performed moderately in the tests conducted by Trachsel and Telford (2017) and does not require parameter adjustments, making it more scalable across multiple cores. While Bchron may overestimate errors in varved sediments, it may be more suitable for analyzing the complexities of marine sediments. Therefore, we selected Bchron as our primary tool for age modeling.

The Bchron model requires input values for depth, age, one-sigma uncertainty of age (ageSd), and depth uncertainty. Setting the depth uncertainty to zero typically implies identical positions, which can create challenges in the model and also result in inconsistencies with the actual data precision, as stratigraphic event positions in SOD are often determined as the midpoint between the depths of the top and bottom samples. To resolve this issue, data were grouped based on Event_Type, and the average depth uncertainty for each category was calculated in meters: Bio_DN = 5.35 m, Bio_D = 3.98 m, Bio_F = 1.8 m, Bio_N = 3.97 m, Bio_R = 3 m, I = 2.5 m, M = 0.5 m, and RD = 0. These averages were then applied to data lacking depth uncertainty values. In the Bchron model, assigning an ageSd value of zero leads to model failure. Consequently, when primary sources do not report age uncertainty, a conservative error margin of 1% for Cenozoic ages and 2% for Mesozoic ages is adopted as one standard deviation. This is because most Cenozoic chronological data are aligned with the Astrochronological Time Scale, which may have lower uncertainties because it can achieve an unprecedented level of 0.05% (Hinnov, 2018). In contrast, most Cretaceous chronological data may exhibit higher uncertainties because of measurement limitations and interlaboratory variations (Gradstein et al., 2020).

3. CURRENT STATUS OF THE DATABASE

3.1. Chronological Data

The SedST database contains data from 1300 scientific ocean drill holes and 732 sites, which includes a total of 37,329 event data entries that encompass a wide variety of chronological data: 14,052 nannofossil records, 7914 foraminifera records, 4115 radiolarian records, 3718 diatom records, 300 dinoflagellate records, 184 isotope events, and 6942 magnetic reversal records. In addition, the database incorporates valuable data from 96 radiometric dates, which are not documented in other similar databases.

A comparative analysis with the SedST, eODP, NSB, Triton, and Janus databases reveals that SedST contains relatively abundant data across all phases of ocean drilling. It provides the most extensive coverage at the hole level for age data older than the Miocene (23.03 Ma), and the highest coverage at the site level (Fig. 3).

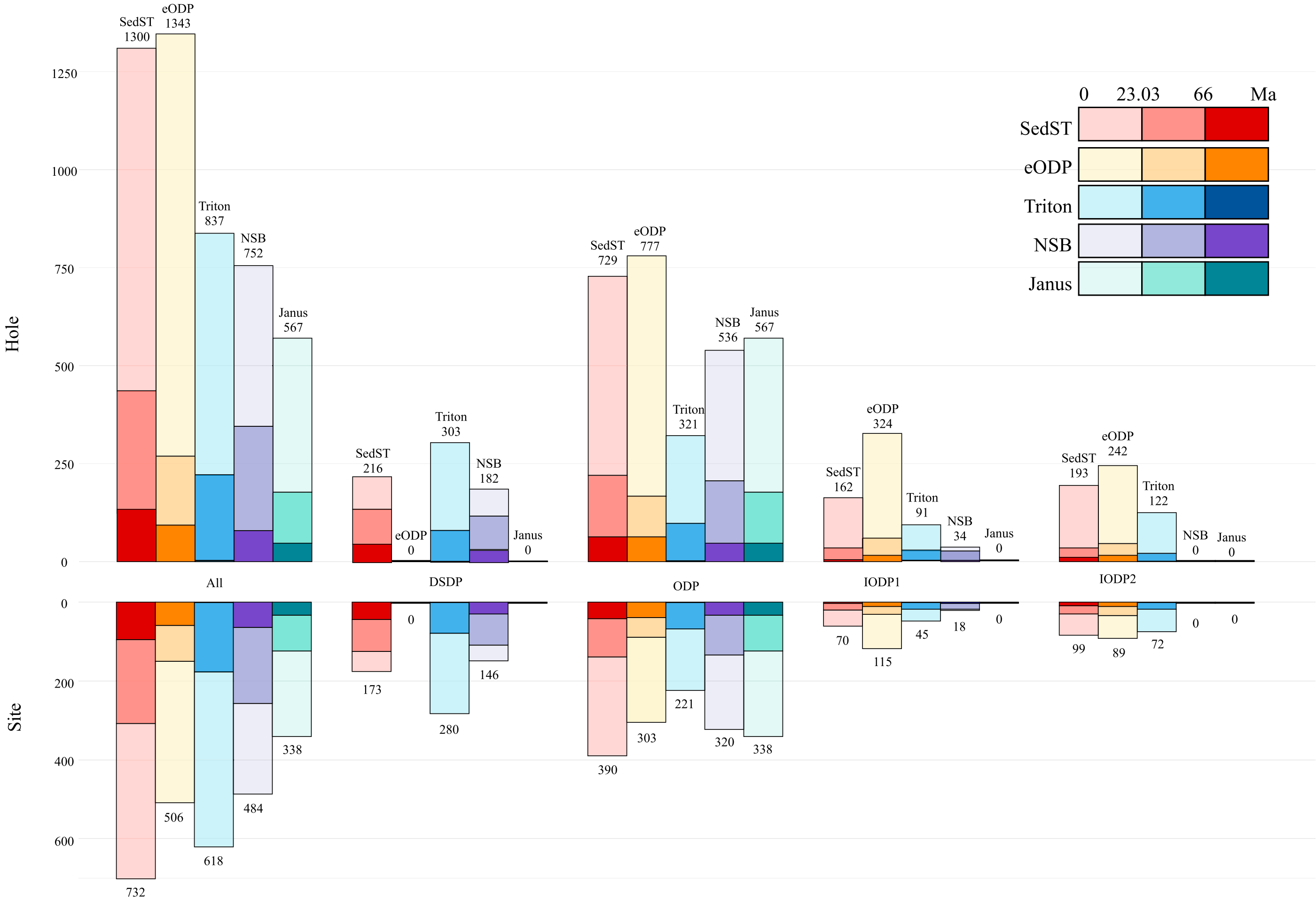

Figure 3. Comparative analysis of site- and hole-level coverage across the Sediment Spatial and Temporal Database (SedST), Extending Ocean Drilling Pursuits (eODP; Sessa et al., 2023), Triton (Fenton et al., 2021), Neptune Sandbox Berlin (NSB; Lazarus, 1994; Renaudie et al., 2020), and Janus (Mithal and Becker, 2006). DSDP—Deep-Sea Drilling Project; ODP—Ocean Drilling Program; IODP1—Integrated Ocean Drilling Program; IODP2—International Ocean Discovery Program.

3.2. Age-Depth Model Data

Comparison of age-depth models from different sources for the same drill hole (Fig. 4) shows that the newly established age-depth models from SedST are generally consistent with other models. NSB's age-depth models exhibit abrupt changes in sedimentation rate because they are constructed from linear segments, while Bchron models are more realistic continuously varying curves. However, NSB age models consider not only data scatter but other sources of information on data quality in choosing where to place age model control points, such as event type (FAD or LAD) and overall data quality for specific fossil groups in specific sites. NSB's age models also explicitly consider evidence of hiatuses in sections, including the alignment of multiple events at depth and reports of hiatuses from the primary drilling reports, as well as other criteria, such as abrupt changes in lithology. Thus, they are generally considered reliable (D. Lazarus, 2025, personal commun.). Triton age models are continuous curves automatically fit to the data points, but some manual adjustments are made as well (Fenton et al., 2021). Bchron only considers local data scatter in evaluating uncertainty, sampling from age and depth probability distributions in each iteration. Consequently, this approach involves an averaging process for determining the best age model. As a result, the Bchron model interprets hiatuses as intervals characterized by extremely slow accumulation (Fig. S3), which is the opposite of the dynamic conditions represented by a hiatus. To aid users in identifying potential hiatuses, we recommend carefully evaluating instances where the model indicates unusually low sedimentation rates. Additionally, we have updated the results to denote the presence of hiatuses, providing users with a basis for assessing the accuracy and reliability of the age models. PANGAEA represents individual research efforts, which utilize different types of methods to construct age-depth models—including linear interpolation, regression, Bayesian models, and cyclostratigraphy—each with different assumptions and associated uncertainties.

4. SCIENTIFIC APPLICATIONS

SedST provides a useful data resource for studying marine sediments and the evolutionary history of Earth that they reflect. When combined with other datasets, SedST can help investigate variations in sedimentation rates, analyze the spatiotemporal evolution of sediments, and explore trends in paleoclimate change.

4.1. Deep-Sea Sediment Accumulation Rate Patterns

Global syntheses of deep-sea sedimentation rates based on SOD data have long been used

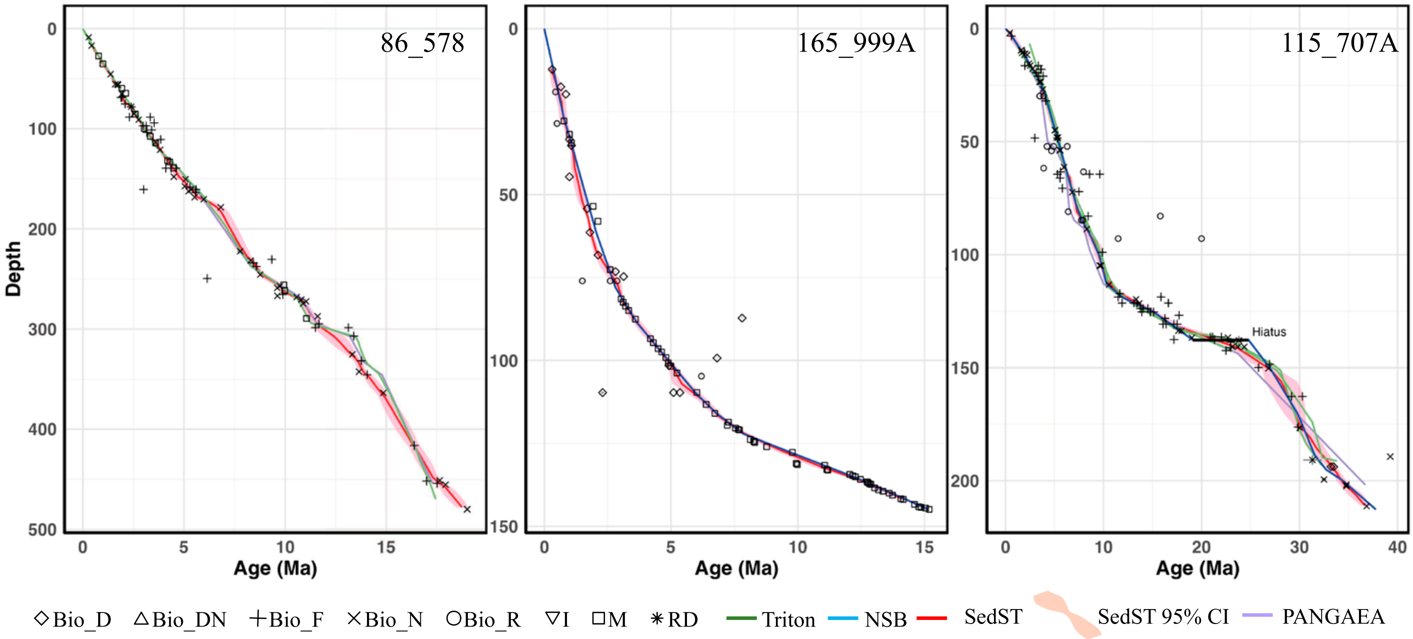

Figure 4. Comparative analysis of age model data of drill holes among Neptune Sandbox Berlin (NSB; Lazarus, 1994; Renaudie et al., 2020), Triton (Fenton et al., 2021), PANGAEA (Felden et al., 2023), and the Sediment Spatial and Temporal Database (SedST). Bio_D, Bio_DN, Bio_F, Bio_N, and Bio_R refer to biostratigraphic events associated with diatoms, dinoflagellates, planktonic foraminifers, calcareous nannofossils, and radiolarians, respectively. I—isotope events; M—magnetic reversal data; RD—radioisotopic dating data; CI—confidence interval.

to study various aspects of Earth's evolving climate and geochemical systems (Davies et al., 1977; Hay et al., 1988; Westacott et al., 2021; Dutkiewicz and Müller, 2022; Renaudie and Lazarus, 2025), using a variety of data compilations. SedST can similarly be used for this type of research. Huang et al. (2024) analyzed Quaternary marine sedimentation rates (SRs) using age-depth data from the SedST database, revealing notable variations in SR across different ocean basins and over time. By selecting 343 high-quality, globally distributed drill sites with closely clustered age data, they identified key trends in SR influenced by distance to continental margins, lithology, and water depth.

Their analysis suggests that SRs have increased across all five oceans since the Quaternary, likely driven by climate-related processes such as the expansion of Arctic ice between 4 Ma and 2 Ma. This glaciation event triggered significant global climate changes, leading to fluctuations in temperature, precipitation, sea levels, and vegetation patterns, which likely intensified weathering and sedimentation. Since the Quaternary, SR evolution has remained consistent in the Atlantic, Pacific, and Indian oceans. However, the Arctic and Southern oceans exhibit distinct variations, likely due to their unique geographical locations and climate conditions. Additionally, lithological and bathymetric data from 99 sites indicate that fine-grained sediments in deeper waters generally exhibit more stable long-term accumulation rates, whereas coarser material near margins shows greater variability.

By integrating these factors, Huang developed a semiquantitative model to estimate SR based on lithology, distance to continental margins, ocean basin distribution, latitude, and water depth. While further refinement may be needed, this study offers new insights into deep-sea sediment dynamics and provides a useful framework for investigating past oceanographic and climate conditions on a global scale.

5. WEBSITE AND INTERFACE

5.1. Main Page Overview

The SedST platform is developed following Agile methodologies (Abrahamsson et al., 2017), integrating a robust MySQL database and a Java backend with a dynamic frontend built using HTML, CSS, Vue.js, ECharts, and JavaScript. The platform is accessible at http://sedst.org. It features a user-friendly interface with intuitive data visualization. The home page displays a global map indicating the spatial locations of SOD holes (Fig. 1), categorized by data availability in the SedST database. A top navigation bar provides access to five main functional sections, covering both collected and generated data as well as analytical tools. Below the map, users can find a summary of the database contents.

5.2. Search Tool Capabilities

Adjacent to the homepage, the Search Stratigraphic Events feature provides users with three optional search parameters, allowing refined queries based on boreholes, standards, and resources, as outlined in Tables 1 and 2. The search results for a selected drill hole are presented as a scatter plot, where different point shapes represent various age data types (Table 2: Chrono_Type). Accompanying the visualization is a detailed table, representing a subset of Table 2. Users may need to use the horizontal scroll bar to view all columns. This table can be downloaded in CSV format.

The Search Age Model feature provides Bchron age models constructed using chronostratigraphic age data from the SedST database, alongside age models obtained from external sources (Fig. 4). Age-depth models and chronostratigraphic age data are displayed together in a single graph to facilitate direct comparison.

The Find Age Range Hole function is designed to assist researchers in identifying drill holes containing data that span user-defined time intervals, thereby streamlining the early stages of research. This tool provides valuable guidance in locating relevant datasets, ultimately enhancing research efficiency.

The Tool tab currently provides two primary features for processing SOD data. First, it allows users to convert sample IDs to depths using the ocean drilling sample numbering protocol (leg/expedition-site-hole-core-section, interval in centimeters; ODP Science Services, 1990). This function is particularly useful when only sample IDs are available and corresponding depth information is lacking. Second, the tool enables conversion from core depth to site composite depth, and facilitates the merging of data from multiple holes within the same site. At present, this functionality supports data from IODP Phase 2, while earlier phases are being organized for future integration.

The Help tab provides detailed information about the SedST database, including its data structure, the types of data it contains, search instructions, known limitations, and contact details for further assistance.

6. LIMITATIONS AND FUTURE ENHANCEMENTS

The SedST database, while well-developed in certain aspects, presents opportunities for further refinement and expansion. A crucial focus is data coverage. While SedST currently provides the highest site-level coverage among individual databases—732 sites, exceeding Triton by 114—it could still benefit from broader integration. The combined coverage of Triton and NSB reaches 815 sites, Triton + NSB + eODP reaches 1010, and eODP includes 43 more holes than SedST. While eODP and Triton operate at a lower precision, these differences highlight areas where SedST can continue to improve its data coverage.

The current age models in SedST are generated using Bchron, which performs well for continuous sedimentation with reliable control points. However, for more complex sedimentary sequences, particularly those involving hiatuses, manual refinement is often required. While the SedST currently annotates significant hiatus locations based on data from NSB and cruise reports, further improvements are needed to better incorporate sedimentary constraints, such as the precise positions and durations of hiatuses.

Another promising area for future development is the integration of astrochronological data. Astrochronology provides continuous, high-resolution age information, which is valuable for refining age models.

Looking to the future, the SedST group plans to enhance the database by opening access to global scientists, addressing issues they encounter, and fulfilling their requests for age data. The immediate focus will be on improving data coverage and quality to ensure that the database is as comprehensive and accurate as possible. Additionally, age models will be manually revised to incorporate not only age data but also additional sedimentary constraints. A longer-term goal is to integrate astrochronological data into the database, which will further enhance the quality and resolution of the age framework. This integration will provide researchers with more robust tools for high-resolution age modeling and stratigraphic analysis.

7. CONCLUSIONS

The SedST database is a continuously updated and quality-controlled resource designed to support research on ocean drilling data. By systematically collecting, curating, and organizing stratigraphic chronological data from SOD programs, SedST provides a unified open platform that facilitates research across different time and space. This resource helps refine the study of past geological and climate events by offering a well-structured chronological framework, allowing researchers to explore potential causal relationships.

Beyond its role in data integration, SedST is designed to lower the barrier to using SOD chronological data by adopting transparent data processing strategies, intuitive data visualization, and user-friendly batch download options. These features make data access and utilization more convenient, enabling both experienced researchers and newcomers to efficiently locate and analyze data. By streamlining the process of working with ocean drilling chronological data, SedST helps make scientific exploration in this field more accessible and efficient.

ACKNOWLEDGMENTS

We gratefully acknowledge the data produced by IODP, ODP, DSDP, and the broader scientific community. We sincerely thank Leah LeVay, David Lazarus, an anonymous reviewer, and the editors for their detailed and constructive suggestions and insightful comments, which significantly improved the quality of this manuscript. We also thank Qingchen Han, Pengcheng Zhang, Yi Zhang, Qi Sun, Xinyi Zhang, Longgang Ye, Shengjian Zhou, Jiajia Zhang, Zhisong Cao, Senhao Ren, Tianyu Huang, and Jingxin Jiang, as well as other colleagues, for their help with data collection, platform construction, and application. This work was financially supported by the National Key Research and Development Program of China (grant 2023YFF0804000), the National Natural Science Foundation of China (grants 42488201 and 42172137), the Sichuan Science and Technology Program (grant 2023NSFSC1986), and the Key Laboratory of Sedimentary Basin and Hydrocarbon Resources of the Ministry of Natural Resources Open Fund (grants cdcgs2023004 and cdcgs2023006). This study is a contribution to International Geoscience Programme Project 739.

REFERENCES CITED

Abrahamsson, P., Salo, O., Ronkainen, J., and Warsta, J., 2017, Agile software development methods: Review and analysis: arXiv:1709.08439, https://doi.org/10.48550/arXiv.1709.08439.

Becker, K., Austin, J.A., Exon, N., Humphris, S., Kastner, M., McKenzie, J.A., Miller, K.G., Suyehiro, K., and Taira, A., 2019, Fifty years of scientific ocean drilling: Oceanography, v. 32, p. 17–21, https://doi.org/10.5670/oceanog.2019.110.

Beddow, H.M., Liebrand, D., Wilson, D.S., Hilgen, F.J., Sluijs, A., Wade, B.S., and Lourens, L.J., 2018, Astronomical tunings of the Oligocene–Miocene transition from Pacific Ocean Site U1334 and implications for the carbon cycle: Climate of the Past, v. 14, p. 255–270, https://doi.org/10.5194/cp-14-255-2018.

Billups, K., Pälike, H., Channell, J.E.T., Zachos, J.C., and Shackleton, N.J., 2004, Astronomic calibration of the late Oligocene through early Miocene geomagnetic polarity time scale: Earth and Planetary Science Letters, v. 224, p. 33–44, https://doi.org/10.1016/j.epsl.2004.05.004.

Blaauw, M., 2010, Methods and code for 'classical' age-modelling of radiocarbon sequences: Quaternary Geochronology, v. 5, p. 512–518, https://doi.org/10.1016/j.quageo.2010.01.002.

Blaauw, M., and Christen, J.A., 2011, Flexible paleoclimate age-depth models using an autoregressive gamma process: Bayesian Analysis, v. 6, https://doi.org/10.1214/11-BA618.

Blaauw, M., Christen, J.A., Bennett, K.D., and Reimer, P.J., 2018, Double the dates and go for Bayes—Impacts of model choice, dating density and quality on chronologies: Quaternary Science Reviews, v. 188, p. 58–66, https://doi.org/10.1016/j.quascirev.2018.03.032.

Blackman, D.K., et al., 2011, Drilling constraints on lithospheric accretion and evolution at Atlantis Massif, Mid-Atlantic Ridge 30°N: Journal of Geophysical Research: Solid Earth, v. 116, https://doi.org/10.1029/2010JB007931.

Bohling, G.C., 2005, Chronos Age-Depth Plot: A Java application for stratigraphic data analysis: Geosphere, v. 1, p. 78–84, https://doi.org/10.1130/GES00009.1.

Boulila, S., Vahlenkamp, M., De Vleeschouwer, D., Laskar, J., Yamamoto, Y., Pälike, H., Kirtland Turner, S., Sexton, P.F., Westerhold, T., and Röhl, U., 2018, Towards a robust and consistent middle Eocene astronomical timescale: Earth and Planetary Science Letters, v. 486, p. 94–107, https://doi.org/10.1016/j.epsl.2018.01.003.

Colleoni, F., De Santis, L., Siddoway, C.S., Bergamasco, A., Golledge, N.R., Lohmann, G., Passchier, S., and Siegert, M.J., 2018, Spatio-temporal variability of processes across Antarctic ice-bed–ocean interfaces: Nature Communications, v. 9, 2289, https://doi.org/10.1038/s41467-018-04583-0.

Davidson, P., Koppers, A., and Konter, J., 2023, Rapid formation of the Ellice and Osbourn basins and Ontong Java Nui breakup kinematics: Geochemistry, Geophysics, Geosystems, v. 24, https://doi.org/10.1029/2022GC010592.

Davies, T.A., Hay, W.W., Southam, J.R., and Worsley, T.R., 1977, Estimates of Cenozoic oceanic sedimentation rates: Science, v. 197, p. 53–55, https://doi.org/10.1126/science.197.4298.53.

D'Hondt, S., et al., 2004, Distributions of microbial activities in deep subseafloor sediments: Science, v. 306, p. 2216–2221, https://doi.org/10.1126/science.1101155.

Dick, H., et al., 2000, A long in situ section of the lower ocean crust: Results of ODP Leg 176 drilling at the Southwest Indian Ridge: Earth and Planetary Science Letters, v. 179, p. 31–51, https://doi.org/10.1016/S0012-821X(00)00102-3.

Diepenbroek, M., Grobe, H., Reinke, M., Schindler, U., Schlitzer, R., Sieger, R., and Wefer, G., 2002, PANGAEA—An information system for environmental sciences: Computers & Geosciences, v. 28, p. 1201–1210, https://doi.org/10.1016/S0098-3004(02)00039-0.

Dowsett, H.J., et al., 2012, Assessing confidence in Pliocene sea surface temperatures to evaluate predictive models: Nature Climate Change, v. 2, p. 365–371, https://doi.org/10.1038/nclimate1455.

Drury, A.J., Westerhold, T., Frederichs, T., Tian, J., Wilkens, R., Channell, J.E.T., Evans, H., Johns, C.M., Lyle, M., and Roehl, U., 2017, Late Miocene climate and time scale reconciliation: Accurate orbital calibration from a deep-sea perspective: Earth and Planetary Science Letters, v. 475, p. 254–266, https://doi.org/10.1016/j.epsl.2017.07.038.

Dutkiewicz, A., and Müller, R.D., 2022, Deep-sea hiatuses track the vigor of Cenozoic ocean bottom currents: Geology, v. 50, p. 710–715, https://doi.org/10.1130/G49810.1.

Felden, J., Möller, L., Schindler, U., Huber, R., Schumacher, S., Koppe, R., Diepenbroek, M., and Glöckner, F.O., 2023, PANGAEA: Data Publisher for Earth & Environmental Science: Scientific Data, v. 10, 347, https://doi.org/10.1038/s41597-023-02269-x.

Fenton, I.S., Woodhouse, A., Aze, T., Lazarus, D., Renaudie, J., Dunhill, A.M., Young, J.R., and Saupe, E.E., 2021, Triton, a new species-level database of Cenozoic planktonic foraminiferal occurrences: Scientific Data, v. 8, 160, https://doi.org/10.1038/s41597-021-00942-7.

Gradstein, F.M., Ogg, J.G., Schmitz, M.D., and Ogg, G.M., 2020, Geologic Time Scale 2020: Elsevier, https://doi.org/10.1016/C2020-1-02369-3.

Hall, J., and Robinson, P., 1979, Deep crustal drilling in the North Atlantic Ocean: Drilling shows that the uppermost half kilometer of North Atlantic oceanic crust is unexpectedly complex: Science, v. 204, p. 573–586, https://doi.org/10.1126/science.204.4393.573.

Haslett, J., and Parnell, A., 2008, A simple monotone process with application to radiocarbon-dated depth chronologies: Journal of the Royal Statistical Society Series C: Applied Statistics, v. 57, p. 399–418, https://doi.org/10.1111/j.1467-9876.2008.00623.x.

Hay, W.W., Sloan, J.L., and Wold, C.N., 1988, Mass/age distribution and composition of sediments on the ocean floor and the global rate of sediment subduction: Journal of Geophysical Research: Solid Earth, v. 93, p. 14,933–14,940, https://doi.org/10.1029/JB093iB12p14933.

Hess, A.V., Auderset, A., Rosenthal, Y., Miller, K.G., Zhou, X., Sigman, D.M., and Martínez-García, A., 2023, A well-oxygenated eastern tropical Pacific during the warm Miocene: Nature, v. 619, p. 521–525, https://doi.org/10.1038/s41586-023-06104-6.

Heuer, V.B., Lever, M.A., Morono, Y., and Teske, A., 2019, The limits of life and the biosphere in Earth's interior: Oceanography, v. 32, p. 208–211, https://doi.org/10.5670/oceanog.2019.147.

Hinnov, L.A., 2018, Cyclostratigraphy and astrochronology in 2018, *in* Montenari, M., ed., Cyclostratigraphy and Astrochronology: Elsevier, Stratigraphy & Timescales Series, v. 3, p. 1–80.

Holbourn, A., Kuhnt, W., Schulz, M., and Erlenkeuser, H., 2005, Impacts of orbital forcing and atmospheric carbon dioxide on Miocene ice-sheet expansion: Nature, v. 438, p. 483–487, https://doi.org/10.1038/nature04123.

Holbourn, A., Kuhnt, W., Lyle, M., Schneider, L., Romero, O., and Andersen, N., 2014, Middle Miocene climate cooling linked to intensification of eastern equatorial Pacific upwelling: Geology, v. 42, p. 19–22, https://doi.org/10.1130/G34890.1.

Holbourn, A., Kuhnt, W., Kochhann, K.G.D., Andersen, N., and Meier, K.J.S., 2015, Global perturbation of the carbon cycle at the onset of the Miocene Climatic Optimum: Geology, v. 43, p. 123–126, https://doi.org/10.1130/G36317.1.

Holbourn, A.E., Kuhnt, W., Clemens, S.C., Kochhann, K.G.D., Joehnck, J., Luebbers, J., and Andersen, N., 2018, Late Miocene climate cooling and intensification of southeast Asian winter monsoon: Nature Communications, v. 9, 1584, https://doi.org/10.1038/s41467-018-03950-1.

Hou, S., Lamprou, F., Hoem, F.S., Hadju, M.R.N., Sangiorgi, F., Peterse, F., and Bijl, P.K., 2023, Lipid-biomarker-based sea surface temperature record offshore Tasmania over the last 23 million years: Climate of the Past, v. 19, p. 787–802, https://doi.org/10.5194/cp-19-787-2023.

Huang, T., Ma, C., Jin, S., Yang, Y., Hu, X., and Hou, M., 2024, Quaternary sedimentation rate revealed by semi-quantitative analysis in global ocean: Marine and Petroleum Geology, v. 166, https://doi.org/10.1016/j.marpetgeo.2024.106900.

Ildefonse, B., Rona, P.A., and Blackman, D., 2007, Drilling the crust at mid-ocean ridges: An "in depth" perspective: Oceanography, v. 20, p. 66–77, https://doi.org/10.5670/oceanog.2007.81.

Integrated Ocean Drilling Program Management International (IODP-MI), 2011, IODP depth scales terminology: https://www.iodp.org/policies-and-guidelines/142-iodp-depth-scales-terminology-april-2011/file (accessed November 25, 2021).

Jiang, X., Zhao, X., Sun, X., Roberts, A.P., Sluijs, A., Chou, Y.-M., Yao, W., Xing, J., Zhang, W., and Liu, Q., 2024, Iron fertilization–induced deoxygenation of eastern equatorial Pacific Ocean intermediate waters during the Paleocene–Eocene thermal maximum: Geology, v. 52, p. 276–281, https://doi.org/10.1130/G51770.1.

Jin, H., et al., 2023, Evolution of silicate weathering in South China since 30 Ma: Controlling factors and global implications: Global and Planetary Change, v. 223, https://doi.org/10.1016/j.gloplacha.2023.104095.

Jørgensen, B.B., Egger, M., and Canfield, D.E., 2024, Sulfate distribution and sulfate reduction in global marine sediments: Geochimica et Cosmochimica Acta, v. 364, p. 79–88, https://doi.org/10.1016/j.gca.2023.11.015.

Kinsley, C.W., Bradtmiller, L.I., McGee, D., Galgay, M., Stuut, J., Tjallingii, R., Winckler, G., and deMenocal, P.B., 2022, Orbital- and millennial-scale variability in Northwest African dust emissions over the past 67,000 years: Paleoceanography and Paleoclimatology, v. 37, https://doi.org/10.1029/2020PA004137.

Lauretano, V., Littler, K., Polling, M., Zachos, J.C., and Lourens, L.J., 2015, Frequency, magnitude and character of hyperthermal events at the onset of the Early Eocene Climatic Optimum: Climate of the Past, v. 11, p. 1313–1324, https://doi.org/10.5194/cp-11-1313-2015.

Lauretano, V., Hilgen, F.J., Zachos, J.C., and Lourens, L.J., 2016, Astronomically tuned age model for the early Eocene carbon isotope events: A new high-resolution δ^{13}C benthic record of ODP Site 1263 between ∼49 and ∼54 Ma: Newsletters on Stratigraphy, v. 49, p. 383–400, https://doi.org/10.1127/nos/2016/0077.

Lauretano, V., Zachos, J.C., and Lourens, L.J., 2018, Orbitally paced carbon and deep-sea temperature changes at the peak of the Early Eocene Climatic Optimum: Paleoceanography and Paleoclimatology, v. 33, p. 1050–1065, https://doi.org/10.1029/2018PA003422.

Lazarus, D., 1992, Age depth plot and age maker: Age modelling of stratigraphic sections on the Macintosh series of computers: Geobyte, v. 2, p. 7–13.

Lazarus, D., 1994, Neptune: A marine micropaleontology database: Mathematical Geology, v. 26, p. 817–832, https://doi.org/10.1007/BF02083119.

Lazarus, D., Spencer-Cervato, C., Pika-Biolzi, M., Beckmann, J.P., von Salis, K., Hilbrecht, H., and Thierstein, H., 1995, Revised chronology of Neogene DSDP holes from the world ocean: Ocean Drilling Program Technical Note 24, https://doi.org/10.2973/odp.tn.24.1995.

Li, Z., Zhang, Y.G., Torres, M., and Mills, B.J.W., 2023, Neogene burial of organic carbon in the global ocean: Nature, v. 613, p. 90–95, https://doi.org/10.1038/s41586-022-05413-6.

Liebrand, D., et al., 2016, Cyclostratigraphy and eccentricity tuning of the early Oligocene through early Miocene (30.1–17.1 Ma): *Cibicides mundulus* stable oxygen and carbon isotope records from Walvis Ridge Site 1264: Earth and Planetary Science Letters, v. 450, p. 392–405, https://doi.org/10.1016/j.epsl.2016.06.007.

Liebrand, D., et al., 2017, Evolution of the early Antarctic ice ages: Proceedings of the National Academy of Sciences of the United States of America, v. 114, p. 3867–3872, https://doi.org/10.1073/pnas.1615440114.

Littler, K., Westerhold, T., Drury, A.J., Liebrand, D., Lisiecki, L., and Pälike, H., 2019, Astronomical time keeping of Earth history: Oceanography, v. 32, p. 72–76, https://doi.org/10.5670/oceanog.2019.122.

Lomstein, B.Aa., Langerhuus, A.T., D'Hondt, S., Jørgensen, B.B., and Spivack, A.J., 2012, Endospore abundance, microbial growth and necromass turnover in deep sub-seafloor sediment: Nature, v. 484, p. 101–104, https://doi.org/10.1038/nature10905.

Lougheed, B.C., and Obrochta, S.P., 2019, A rapid, deterministic age-depth modeling routine for geological sequences with inherent depth uncertainty: Paleoceanography and Paleoclimatology, v. 34, p. 122–133, https://doi.org/10.1029/2018PA003457.

Lyle, M., 2003, Neogene carbonate burial in the Pacific Ocean: Paleoceanography, v. 18, https://doi.org/10.1029/2002PA000777.

Mithal, R., and Becker, D.G., 2006, The Janus database: Providing worldwide access to ODP and IODP data, *in* Rothwell, R.G., ed., New Techniques in Sediment Core Analysis: Geological Society, London, Special Publication 267, p. 253–259, https://doi.org/10.1144/GSL.SP.2006.267.01.19.

Moretti, S., et al., 2024, Oxygen rise in the tropical upper ocean during the Paleocene-Eocene Thermal Maximum: Science, v. 383, p. 727–731, https://doi.org/10.1126/science.adh4893.

Müller, R.D., Sdrolias, M., Gaina, C., and Roest, W.R., 2008, Age, spreading rates, and spreading asymmetry of the world's ocean crust: Geochemistry, Geophysics, Geosystems, v. 9, https://doi.org/10.1029/2007GC001743.

ODP Science Services, 1990, Shipboard Scientists' Handbook: Ocean Drilling Program: Texas A&M University Technical Note 3, p. 55–60, https://doi.org/10.2973/odp.tn.3.1990.

Ohira, A., Kodaira, S., Moore, G.F., Yamashita, M., Fujiwara, T., Kaiho, Y., Miura, S., and Fujie, G., 2018, Active-source seismic survey on the northeastern Hawaiian Arch: Insights into crustal structure and mantle reflectors: Earth, Planets, and Space, v. 70, https://doi.org/10.1186/s40623-018-0891-8.

Pälike, H., Frazier, J., and Zachos, J.C., 2006, Extended orbitally forced palaeoclimatic records from the equatorial Atlantic Ceara Rise: Quaternary Science Reviews, v. 25, p. 3138–3149, https://doi.org/10.1016/j.quascirev.2006.02.011.

Peters, S.E., and McClennen, M., 2016, The Paleobiology Database application programming interface: Paleobiology, v. 42, p. 1–7, https://doi.org/10.1017/pab.2015.39.

Peters, S.E., Husson, J.M., and Czaplewski, J., 2018, Macrostrat: A platform for geological data integration and deep-time Earth crust research: Geochemistry, Geophysics, Geosystems, v. 19, p. 1393–1409, https://doi.org/10.1029/2018GC007467.

Pfalz, G., Diekmann, B., Freytag, J.-C., Syrykh, L., Subetto, D.A., and Biskaborn, B.K., 2021, Improving age-depth correlations by using the LANDO model ensemble: Geochronology, v. 4, p. 269–295, https://doi.org/10.5194/gchron-2021-40.

Prothero, D.R., and Schwab, F.L., 2013, Sedimentary Geology: An Introduction to Sedimentary Rocks and Stratigraphy: New York, W.H. Freeman, 593 p.

Ramsey, C.B., 2008, Deposition models for chronological records: Quaternary Science Reviews, v. 27, p. 42–60, https://doi.org/10.1016/j.quascirev.2007.01.019.

Ramsey, C.B., Dee, M., Lee, S., Nakagawa, T., and Staff, R.A., 2010, Developments in the calibration and modeling of radiocarbon dates: Radiocarbon, v. 52, p. 953–961, https://doi.org/10.1017/S0033822200046063.

Renaudie, J., and Lazarus, D.B., 2025, Cenozoic pelagic accumulation rates and biased sampling of the deep-sea record: Biogeosciences, v. 22, p. 1929–1946, https://doi.org/10.5194/bg-22-1929-2025.

Renaudie, J., Lazarus, D., and Diver, P., 2020, NSB (Neptune Sandbox Berlin): An expanded and improved database of marine planktonic microfossil data and deep-sea stratigraphy: Palaeontologia Electronica, 23, https://doi.org/10.26879/1032.

Royer, J.-Y., and Coffin, M.F., 1992, Jurassic to Eocene plate tectonic reconstructions in the Kerguelen Plateau Region, *in* Schlich, R., Wise, S.W., et al., Proceedings of the Ocean Drilling Program, Scientific Results, Volume 120: College Station, Texas, Ocean Drilling Program, p. 917–930.

Rubanik, N.K., 2008, Deep sea drilling in the oceans: History and potentials (to 40th anniversary of the International

Ocean Drilling Program): Stratigraphy and Geological Correlation, v. 16, p. 678–682, https://doi.org/10.1134/S0869593808060075.

Sessa, J.A., Fraass, A.J., LeVay, L.J., Jamson, K.M., and Peters, S.E., 2023, The Extending Ocean Drilling Pursuits (eODP) project: Synthesizing Scientific Ocean Drilling data: Geochemistry, Geophysics, Geosystems, v. 24, https://doi.org/10.1029/2022GC010655.

Sexton, P.F., Norris, R.D., Wilson, P.A., Paelike, H., Westerhold, T., Roehl, U., Bolton, C.T., and Gibbs, S., 2011, Eocene global warming events driven by ventilation of oceanic dissolved organic carbon: Nature, v. 471, p. 349–352, https://doi.org/10.1038/nature09826.

Shackleton, N.J., Crowhurst, S.J., Weedon, G.P., and Laskar, J., 1999, Astronomical calibration of Oligocene–Miocene time: Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, v. 357, p. 1907–1929, https://doi.org/10.1098/rsta.1999.0407.

Śliwińska, K.K., Coxall, H.K., Hutchinson, D.K., Liebrand, D., Schouten, S., and de Boer, A.M., 2022, Sea surface temperature evolution of the North Atlantic Ocean across the Eocene-Oligocene transition: Climate of the Past Discussions, v. 2022, p. 1–24.

Stap, L., Lourens, L.J., Thomas, E., Sluijs, A., Bohaty, S., and Zachos, J.C., 2010, High-resolution deep-sea carbon and oxygen isotope records of Eocene Thermal Maximum 2 and H2: Geology, v. 38, p. 607–610, https://doi.org/10.1130/G30777.1.

Teagle, D., and Ildefonse, B., 2011, Journey to the mantle of the Earth: Nature, v. 471, p. 437–439, https://doi.org/10.1038/471437a.

Trachsel, M., and Telford, R.J., 2017, All age–depth models are wrong, but are getting better: The Holocene, v. 27, p. 860–869, https://doi.org/10.1177/0959683616675939.

Voosen, P., 2023, Ocean drillers exhume a bounty of mantle rocks: Science, v. 380, p. 876–877, https://doi.org/10.1126/science.adi9899.

Wang, C., et al., 2021, The Deep-Time Digital Earth program: Data-driven discovery in geosciences: National Science Review, v. 8, https://doi.org/10.1093/nsr/nwab027.

Westacott, S., Planavsky, N.J., Zhao, M.-Y., and Hull, P.M., 2021, Revisiting the sedimentary record of the rise of diatoms: Proceedings of the National Academy of Sciences of the United States of America, v. 118, https://doi.org/10.1073/pnas.2103517118.

Westerhold, T., Roehl, U., Paelike, H., Wilkens, R., Wilson, P.A., and Acton, G., 2014, Orbitally tuned timescale and astronomical forcing in the middle Eocene to early Oligocene: Climate of the Past, v. 10, p. 955–973, https://doi.org/10.5194/cp-10-955-2014.

Westerhold, T., Röhl, U., Frederichs, T., Agnini, C., Raffi, I., Zachos, J.C., and Wilkens, R.H., 2017, Astronomical calibration of the Ypresian timescale: Implications for seafloor spreading rates and the chaotic behavior of the solar system?: Climate of the Past, v. 13, p. 1129–1152, https://doi.org/10.5194/cp-13-1129-2017.

Westerhold, T., Röhl, U., Donner, B., and Zachos, J.C., 2018, Global extent of early Eocene hyperthermal events: A new Pacific benthic foraminiferal isotope record from Shatsky Rise (ODP Site 1209): Paleoceanography and Paleoclimatology, v. 33, p. 626–642, https://doi.org/10.1029/2017PA003306.

Westerhold, T., et al., 2020, An astronomically dated record of Earth's climate and its predictability over the last 66 million years: Science, v. 369, p. 1383–1387, https://doi.org/10.1126/science.aba6853.

Westerhold, T., Agnini, C., Anagnostou, E., Hilgen, F., Hönisch, B., Meckler, A.N., Pälike, H., Wade, B., Sosdian, S., and Kasbohm, J., 2024, Timing is everything: Paleoceanography and Paleoclimatology, v. 39, https://doi.org/10.1029/2024PA004932.

Wilson, D., et al., 2006, Drilling to gabbro in intact ocean crust: Science, v. 312, p. 1016–1020, https://doi.org/10.1126/science.1126090.

Zachos, J., Shackleton, N., Revenaugh, J., Pälike, H., and Flower, B., 2001, Climate response to orbital forcing across the Oligocene-Miocene boundary: Science, v. 292, p. 274–278, https://doi.org/10.1126/science.1058288.

Zachos, J.C., Dickens, G.R., and Zeebe, R.E., 2008, An early Cenozoic perspective on greenhouse warming and carbon-cycle dynamics: Nature, v. 451, p. 279–283, https://doi.org/10.1038/nature06588.

Zachos, J.C., McCarren, H., Murphy, B., Roehl, U., and Westerhold, T., 2010, Tempo and scale of late Paleocene and early Eocene carbon isotope cycles: Implications for the origin of hyperthermals: Earth and Planetary Science Letters, v. 299, p. 242–249, https://doi.org/10.1016/j.epsl.2010.09.004.

Zeeden, C., Hilgen, F., Westerhold, T., Lourens, L., Röhl, U., and Bickert, T., 2013, Revised Miocene splice, astronomical tuning and calcareous plankton biochronology of ODP Site 926 between 5 and 14.4 Ma: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 369, p. 430–451, https://doi.org/10.1016/j.palaeo.2012.11.009.

Zhang, S., Jia, Y., Xu, H., Wen, Y., Wang, D., and Wang, X., 2023, GeoDeepShovel: A platform for building scientific database from geoscience literature with AI assistance: Geoscience Data Journal, v. 10, no. 4, p. 519–537, https://doi.org/10.1002/gdj3.186.

Science Editor: Wenjiao Xiao
Associate Editor: Yue Cai

Manuscript Received 12 August 2024
Revised Manuscript Received 14 May 2025
Manuscript Accepted 16 June 2025