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Global Acritarch Database (>110 000 occurrences)

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Abstract. Acritarchs, microfossils with an algal affinity, are of great significance for studying the origin and evolution of early life on Earth. Acritarch data are currently dispersed across various research institutions and databases worldwide, lacking unified integration and standardization. Palynodata was the largest database of acritarchs, containing 15 fields, 111 382 entries, 812 238 metadata items, and 7385 references. However, it lacked references post-2007 and excluded geographic data. Here, we collected and organized previous data, adding 24 fields, 4531 entries, 1 882 081 metadata points, and 424 references, to build a "Global Acritarch Database" (GAD). The expanded database now contains a total of 39 fields, covering genera, species, and related geological information (geological timescale, location, modern latitude and longitude, paleolatitude and paleolongitude, stratum, and others), amounting to 115 947 entries, 2 694 671 metadata, and 7816 references. Each entry is associated with fields that facilitate a better understanding of the geographical distribution and changes over geological timescales of acritarchs, thereby revealing their temporal and spatial distribution patterns and evolution throughout the history of the Earth. This article describes GAD version 1.0, which is available at https://doi.org/10.5281/zenodo.13828633 (Shu et al., 2024).

1 Introduction

Acritarchs are organic-walled cysts of unicellular protists, first defined by Evitt (Evitt, 1963) as a group of "*unknown and possibly varied biological affinities consisting of a central cavity enclosed by single or multiple layers of walls, mainly composed of organic materials*" (Yin, 2018). Among these, only a few are related to non-algal origins, possibly representing eggs or exoskeletons of higher crustaceans, plant spores, fungal spores, cyanobacterial remains, and other groups (Butterfield, 2005; Colbath and Grenfell, 1995; Schrank, 2003; Servais et al., 1997). Evitt (Evitt, 1963) also noted that acritarchs are an

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informal, practical classification category with no taxonomic ranks above the genus level, suggesting the use of the International Code of Botanical Nomenclature to name morphological genera and species without assigning them to a specific biological phylum (Wicander, 2002). Morphologically, acritarchs are typically single-celled microfossils ranging in size from a few micrometers to one millimeter. The most common shape is spherical, and they can be either smooth or covered with spines (Mendelson, 1987). The oldest and most well-preserved acritarchs are derived from approximately 1.8 billion years ago in Mesoproterozoic rocks, with evidence suggesting these rocks existed as far back as 2.5 billion years ago (Buick, 2010; Gaucher and Sprechmann, 2009). Due to their abundance, high diversity, and widespread distribution in marine sediments (Lei et al., 2012), acritarchs are valuable for determining chronological ages and biostratigraphic correlations, particularly in Proterozoic and Paleozoic strata, where they are sometimes the only fossils present (Beraldi-Campesi, 2013; Wicander, 2002). Acritarchs have been discovered in sedimentary rocks from marine and terrestrial aquatic environments, with records from all continents, spanning from the Proterozoic to the present. They are particularly valuable when combined with other fossil groups for regional and global paleobiogeography and paleoecology research (Dale, 2023; Lamb et al., 2009; Mudie et al., 2001). Finally, acritarchs represent primary producers at the base of the marine food chain in the Proterozoic and Paleozoic Eras (Wicander, 2002), and played an important role in the evolution of global marine ecosystems（Falkowski and Knoll, 2011）. Given their significance, it is crucial to establish a global database.

Despite advances in acritarch research, several challenges remain. First, the morphological diversity and complex classification of acritarchs have limited our understanding of this group (Agić et al., 2015; Arouri et al., 1999; Bernard et al., 2015; Butterfield and Rainbird, 1998; Javaux and Marshal, 2006; Moldowan et al.,1996; Wang et al., 2022; Williams, 1998). Second, although many acritarchs have been discovered, global spatial and temporal distribution remains uneven, with certain regions experiencing relatively weak research (Gray and Boucot, 1989; Huntley et al., 2006; Jacobson, 1979; Lei et al., 2013; Schreck et al., 2017). Additionally, existing acritarch databases are often limited to specific regions or periods and lack comprehensive, systematic, and complete global coverage (Anderson et al., 2017; Bernardi et al., 2011; Chamberlain et al., 2016; Servais et al., 2003; Williman and Moczydłowska, 2011). These limitations hinder further research on acritarchs in geological history.

Here, we introduced a database that integrates global acritarch data from various geological periods, including genus, geographical distribution, and geological timescales. In the following sections, we provide information regarding data sources and selection criteria, review and clean the definitions behind entries, fields, and metadata, and outline the process. We explored the extensive compiled spatial and temporal trends, discussed the future uses and limitations of the dataset, and addressed the ongoing goals of the database. By leveraging this global database, we can better understand the diversity and evolutionary patterns of acritarchs and reveal the structure and function of biological communities in geological history. It not only provides references for oil and gas exploration but also promotes interdisciplinary research. Through in-depth data mining and analysis, we can explore the acritarchs' stratigraphy, and environmental and ecological issues throughout the history of the Earth, ultimately providing new research ideas across different fields.

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2 Methods

2.1 Compilation purpose

The affinities of acritarchs are primarily linked to algae, suggesting that acritarchs were the main contributors to primary productivity in early oceans, paving the way for the subsequent rise of consumers (Agić, 2016; Daners et al., 2017). This implies that they played a crucial role in early marine environments and were important for maintaining ecological balance and carbon cycling. Quantitative analysis of fossils (e.g., acritarchs) from different strata allows better understanding of past changes in marine environments, including shifts in marine productivity, redox conditions, and carbon cycling. This aids in exploring the evolution of deep-time biological pumps and enhances our understanding of the processes and mechanisms behind the modern marine carbon cycle (Jia et al., 2022). Previous databases (Table 1), such as Palynodata (https://paleobotany.ru/palynodata, last access: 10 December 2024), containing a large number of acritarchs, exhibit several shortcomings: 1) the database only includes literature from 1842 to 2007, with no records for the following 17 years; 2) the numeric ages of strata in the database have not been updated; 3) despite including 15 fields, Palynodata lacks critical information such as latitude, longitude, lithology, stratigraphy, and paleogeography. In contrast, the Paleobiology Database (PBDB, https://paleobiodb. org/, last access: 10 December 2024) only collects a small amount acritarch data (866 entries). In summary, previous databases exhibit issues such as incomplete data, difficulty in addressing fossil sampling biases, and inapplicability for studying spatiotemporal changes. Therefore, we aim to build a global acritarch database (GAD) to advance research in this field.

Table 1. GAD: Comparison of data sources from Palynodata, PBDB, this study.

Data base	N of all entries (i.e., rows)	Proportion	N of all metadata (i.e., cells with content)	Proportion
Palynodata	111 382	96.06%	812 238	30.15%
PBDB	34	0.03%	352	0.01%
This study	4531	3.91%	1 882 081	69.84%
GAD	115 947	100%	2 694 671	100%

2.2 Metadata fields and criterion

GAD data come from PBDB, Palynodata, and published literature. From PBDB, 34 entries and 352 metadata points are sourced from seven studies. The main component of the database was derived from Palynodata (Kroeck et al., 2022; Palynodata Inc. and White, 2008; Strother, 2008) contains 15 fields, 111 382 entries, and 812 238 metadata points, but it has not been updated since 2007 and its location information is limited to textual descriptions. In this study, we searched recent publications through Google Scholar using keywords (such as acritarchs, organic-walled microfossils) and collected 424 additional literature from 2008 to 2023. This collection includes 24 new fields, i.e. geological timescale (with uniform high-to-low levels: Eon, Era, Period, Epoch, and Age), modern latitude and longitude, paleolatitude and paleolongitude, stratigraphy, and lithology, totaling 4531 entries and 1 882 081 metadata points. We have revised and updated the numeric age to the latest International

Chronostratigraphic Chart (2023/09) (https://stratigraphy.org/). Some of the entries that have not been updated include data without temporal information, entries spanning multiple periods, and ambiguously described Precambrian data. The aforementioned three sources together form a new database, GAD, containing 115 947 entries, 39 fields, and 2 694 671 metadata. The database did not include any unpublished data. The metadata primarily originated from original journal articles, supplements, or public repositories containing data tables. The included fields were organized to facilitate future updates of speciation/extinction models, taxonomic nomenclature corrections, data additions, and other research directions such as genus and species information, lithological details, geological timescales, and sampling locations, thereby enabling continual data updates.

2.3 Data cleaning

To maintain clarity and consistency in data description, an "entry" refers to each genus and species along with its related metadata as reported in the literature (i.e., a row), while a "field" refers to the metadata collected for each entry (i.e., a column) (Judd et al., 2022).

To ensure accurate publishing and better utilization of the data, we have cleaned the data using the following steps.

(1) All entries are integrated into a single data table, including entries that lack at least one type of information such as "genus name without species name", "genus and species name without temporal information" or "genus and species name without location information". These were treated as separate entries to preserve them for possible future data replacements. Many acritarch data from Cambrian were compiled by Palacios et al. (Palacios et al., 2009, 2012, 2014, 2017, 2020, 2021), Ordovician data by Le Hérissé et al. (Le Hérissé et al., 2007, 2014, 2015, 2017; Paris et al., 2007; Vecoli and Le Hérissé, 2003), and Silurian and Devonian data by Vavrdová et al. (Vavrdová and Dašková, 2011; Vavrdová and Svobodová, 2010; Vavrdová et al., 1996, 2011). Wherever possible, these compiled datasets were cross-checked with their original publications to ensure completeness, avoid errors, and fill in missing data or applicable fields.

(2) Taxonomic field: the classification of acritarchs was used to name morphological genera and species. During data cleaning, we regulated the representation of "sp." and punctuation marks, such as question marks, commas, parentheses, and minor spacing issues were removed to standardize the naming format and ensure proper characterization (Fig. 1). Considering that this database contained biological fossils, outdated taxonomies or misspellings may have led to analytical errors. We implemented PyRate to check for spelling errors and inconsistencies among the listed species (Silvestro et al., 2014, 2019). The function check_names was utilized, which requires a text file with one species name per line. In the returned file, ranks 0 and 1 indicated the most likely spelling errors, whereas ranks 2 and 3 represented genuinely different names. It is noteworthy

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that this algorithm does not check for synonyms. Ultimately, species data accounted for 90.7% of the database, with 19.4% represented by “sp.”.

(3) Time field: during data integration, several entries lacked temporal information or had insufficient resolution. Therefore, temporal information at the stage level was supplemented to ensure consistent information retrieval (Fig. 2). If precise data were unavailable, the highest possible resolution level was retained, using the stage level as the primary reference, including numeric ages (in Ma), Period, and Stage information to provide relative ages. Ages were assigned by entering a numeric age and automatically matching to fill in relative age information, entering relative age information and automatically matching to fill in numeric age information, or retaining manually entered numeric and relative ages. If the numeric age was not recorded in the literature, it was manually set the age of the top and bottom of its strata using the latest International Chronostratigraphic Chart (2023/09). In the absence of a precise numeric age, a stage position (i.e., early, middle, or late) was used to further define the relative age and match it with the numeric age. Entries with numeric age records accounted for 89.9% of the database, and the remaining 11.1% (11 738 entries) lacked numeric age data (Table 2). Additionally, entries with genus and species names were resolved to the stage level once supplemented, and they accounted for 34.8% of the total data (excluding entries in which the numeric age could not be determined).

(4) Location field: during data integration process, it has been observed that only broad location information was available. To enhance the application of the data in the geospatial field, a minor location information field was added, specifically the “point”（the center point of text location information） determined by latitude and longitude (Fig. 1). After supplementation, latitude and longitude information accounted for 82.0% of the database. Modern latitude and longitude information were derived from detailed references to Google Satellite Electronic Maps. If location information was not recorded in the literature, it was left blank. When it was impossible to determine the precise location, the latitude and longitude information of the center point of the broader location were added to the remarks field, affecting 5972 entries. Paleolatitude conversion primarily relied on G-Plates (https://www.gplates.org/download/, version 2.5), and map alignment was performed using QGIS (https://qgis.org/download/, version 3.32.3). All maps were based on Scotese (Scotese, 2021).

(5) Lithology and stratigraphy information covered only 0.11% and 2.7% of the total entries in the database, respectively, accounting for a very small proportion. The data on lithology and stratigraphy is the next priority for addition. The reference field achieved 100% coverage in the database. It included the main (first) author, publication year, and journal; however, the DOI for each publication was not retained. The corresponding information is expected to be completed in future updates and replacements. Concurrently, for the convenience of machine reading, special characters, and garbled combinations in other applicable fields were deleted.

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Each field was evaluated based on a set of standardized criteria to ensure consistency throughout the process (Fig. 1). Any issues discovered during this process were corrected. A summary of entries by fields is shown in Table 2.

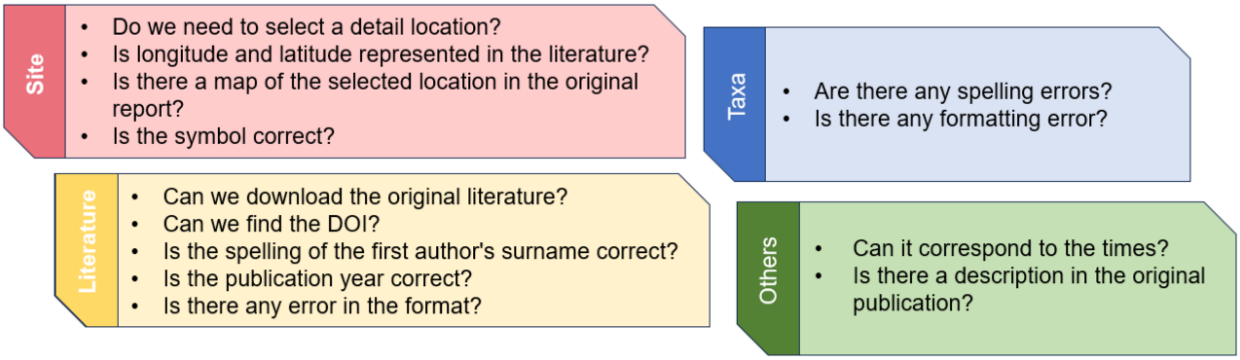

Figure 1. Criteria are used to evaluate whether each entry matches a field.

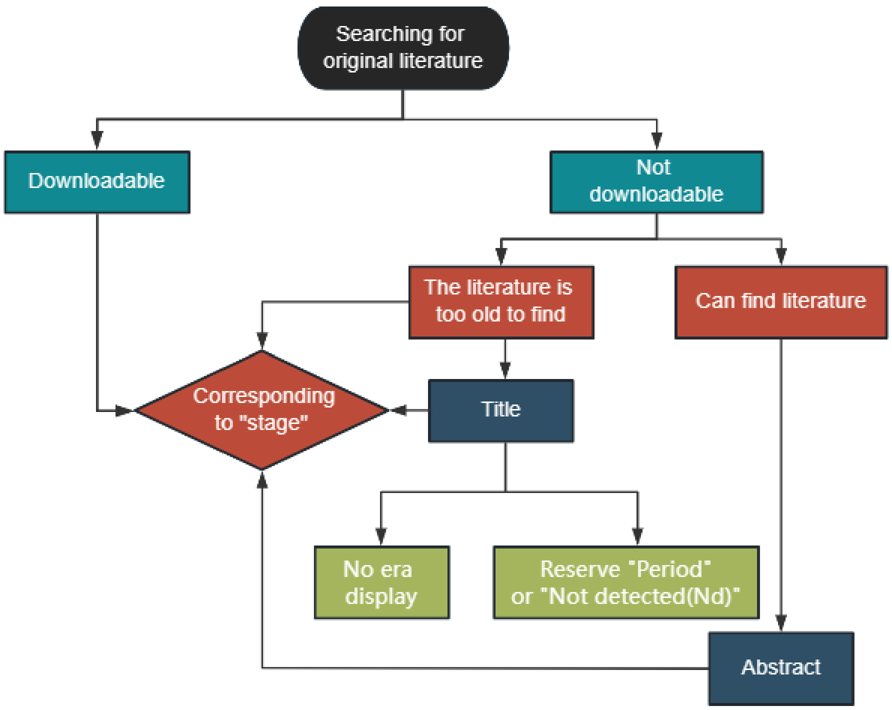

Figure 2. Specific supplementary process for stage level.

Table 2. Summary of entries by fields.

Fields		N of all entries	Proportion	Notes
Taxon filed	With species name	105 191	90.7%	There are 20 395 indefinite species, accounting for 19.4% of "With species name".

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	Without species name	10 756	9.3%	Refers to the genus level.		
Total		115 947				
Time field	With age	104 209	89.9%	Include	Entries	
					N	Proportion
				Eon level	104 209	100%
				Era level	101 224	97.1%
				System level	91 538	87.8%
				Series level	60 325	57.9%
				Stage level	36 233	34.8%
				Substage level	5999	5.7%
	Without age	11 738	10.1%	This includes all entries that cannot detect the numeric age.		
				Include	Entries	
					N	Proportion
				Eon level	2082	17.7%
				Era level	415	3.5%
				System level	12	0.1%
				Cross level	2525	21.5%
				Not detected	7131	60.8%
Total		115 947				
Location field	With modern latitude and longitude records	95 084	82.0%	This contains 1796 entries from oceans or seas, accounting for 1.9%, and 93 288 entries from continents, accounting for 98.1%.		
	Without modern latitude and longitude records	20 863	18.0%	This includes 6264 entries that have location names but cannot determine latitude and longitude, accounting for 30.0%.		
Total		115 947				
Others	Lithological field	128	0.11%			
	Occurrence status: Incomplete	50 311	43.4%	Judgment principle: whether there is a species name, numeric age, and modern latitude and longitude.		
	Occurrence status: Complete	65 636	56.6%			
	Stratigraphic field	3122	2.7%			
	Reference field	115 947	100%			

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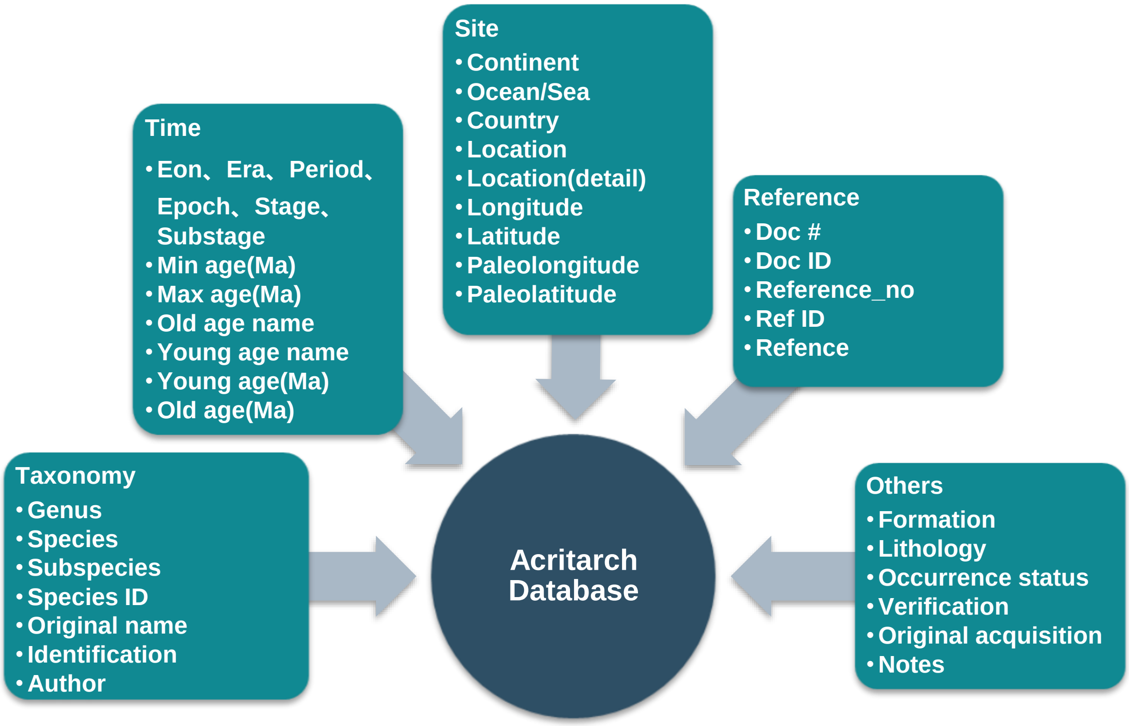
167 **3 Results**

168 **3.1 Data statistics**



169

170 **Figure 3.** Classification of each field in database settings.

171

172 Each entry in the GAD is associated with a set of fields, all of which represent information related to fossils. There are 39
173 fields can be broadly divided into five categories (Fig. 3): (1) taxonomy, (2) time, (3) site, (4) reference, and (5) others. A basic
174 description of these fields can be observed in Table 3, with details on how and why each field was assigned.

175 **Table 3.** Detailed description and notes for each field.

Category name	Description of Category (Individual fields)	Notes
Taxonomy		
Genus	Genus names of biological fossils.	Unified format, all data available.
Species	Species name of biological fossils.	It may contain blank spaces or sp.
Subspecies	Subspecies names of biological fossils.	It may contain blank spaces.
Original name	Record of species name.	
Species ID	The serial number of the species.	
Author	The name of indefinite species.	It may contain blank spaces.

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Identification	Used to explain “aff. /cf. /certain/…”.	
Time		
Eonothem/Eon	The unit of time representing the longest time, typically used to describe geological periods exceeding billions of years.	Source: International Chronostratigraphic Chart (2023/09) (https://stratigraphy.org/)
Erathem/Era	A unit of time under the Eon, typically referring to a large period lasting several hundred million years.	
System/Period	A unit of time under the Era, typically indexed to a period of tens of millions year.	
Series/Epoch	A unit of time under the Period, typically measured in millions to tens of millions of years.	
Stage/Age	A unit of time under the Epoch, each stage typically represents a time span of several million years.	
Substage	A unit of time under the Stage, usually used to describe a shorter period within the stage.	
Min Age (Ma)	Numeric age of the lower boundary of stratigraphic age.	
Max Age (Ma)	Numeric age of the upper boundary of stratigraphic age.	
Old Age Name	The lower boundary of stratigraphic age.	Keep the original division.
Young Age Name	The upper boundary of stratigraphic age.	
Old Age (Ma)	Numeric age of the lower boundary of stratigraphic age.	
Young Age (Ma)	Numeric age of the upper boundary of stratigraphic age.	
Site		
Continent	The continent where the geographical location is located.	
Ocean/Sea	The sea area where the geographical location is located.	
Country	The country where the geographical location is located.	
Location	The major locations where the original data is used.	Including sectors, may be precise to a province or country.
Location (Detail)	Fixed point determined by longitude and latitude.	
Longitude	Longitude determined by location.	If it is not represented in the literature, use the center of the “location” to represent it.
Latitude	Latitude determined by location.	
Paleolongitude	The longitude of a certain period and location in geological history.	According to modern latitude and longitude conversion.

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Paleolatitude	The latitude of a certain period and location in geological history.	
Reference		
Doc #	The serial number of literatures in Palynodata.	Unified format, All data available.
Reference	Literature information includes author, year, title, and journal.	
Ref ID	The serial number of literatures in GAD.	
Doc ID	The serial number of literatures in the database (Supplement for 2008-2023).	
Reference_no	The serial number of literatures in PBDB.	
Others		
Formation	Stratigraphic information of fossils.	Insufficient data volume.
Lithology	Lithological information of fossils.	
Occurrence status	Whether the information records are complete or not.	
Verification	Returning to the original to verify information.	
Original acquisition	Acquisition status of original literature.	
Notes	Other remarks.	
Incidentally, "Nd" represents "Not Detected", it's just that the corresponding information cannot be obtained from the original literature.		

3.2 Statistics of the GAD

The GAD contains 115 947 entries from 7816 references, representing 2993 different sampling locations and records throughout geological history. Among these, 36 233 are marked as "stage level", covering 101 out of the 102 stages in the Phanerozoic. In terms of biological fossil records, the database included 1456 genera and 9863 species (excluding those classified as sp.). During the process of correcting the numeric age, 7131 data points lacked a numeric age due to the inability to obtain geologic age from the original literature. The Paleozoic is the most well-represented, accounting for 70.9% of total entries (Table 4), followed by Mesozoic (13 071 entries) and Neoproterozoic (9043 entries). Regarding the spatial distribution of acritarchs, 93 288 entries originated from the continent, with a small portion from oceanic or marine areas accounting for 1.9%.

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The sections below focus on fossil classification, literature sources, paleogeographic and spatiotemporal distribution trends. These examples illustrate the unique aspects of this compilation method and demonstrate the potential of the database for promoting research in paleoproductivity, paleoenvironment, and biological evolution.

Table 4. Summary of the proportion of entries and sites by geologic era.

Era	All entries		All sites	
	N	Proportion	N	Proportion
Cenozoic	6004	5.9%	5473	6.2%
Mesozoic	13 071	12.9%	11 938	13.5%
Paleozoic	72 074	70.9%	61 767	69.6%
Neo-Proterozoic	9043	8.9%	8165	9.2%
Meso-Proterozoic	1251	1.2%	1167	1.3%
Paleo-Proterozoic	196	0.2%	191	0.2%
Total	101 639	100%	88 701	100%

3.3 Taxonomy statistics

At the genus level, the database included 1456 genera and 9863 species (excluding sp.). The top ten genera, in terms of quantity that account for 36.0% of the total data volume, are *Baltisphaeridium* (7.0%), *Micrhystridium* (6.7%), *Veryhachium* (5.7%), *Leiosphaeridia* (3.9%), *Multiplicisphaeridium* (2.7%), *Cymatiosphaera* (2.7%), *Tasmanites* (2.1%), *Leiofusa* (1.8%), *Acanthodiacrodium* (1.8%), and *Lophosphaeridium* (1.5%), the specific number of entries can be obtained in the Figure 4. *Baltisphaeridium*, the most abundant genus, has been present since the Precambrian (approximately 1600 Ma) and was most prolific during the Paleozoic Era (including 647 species accounting for 8079 entries in the database, with 337 entries having only the genus name and 1050 entries classified as sp.).

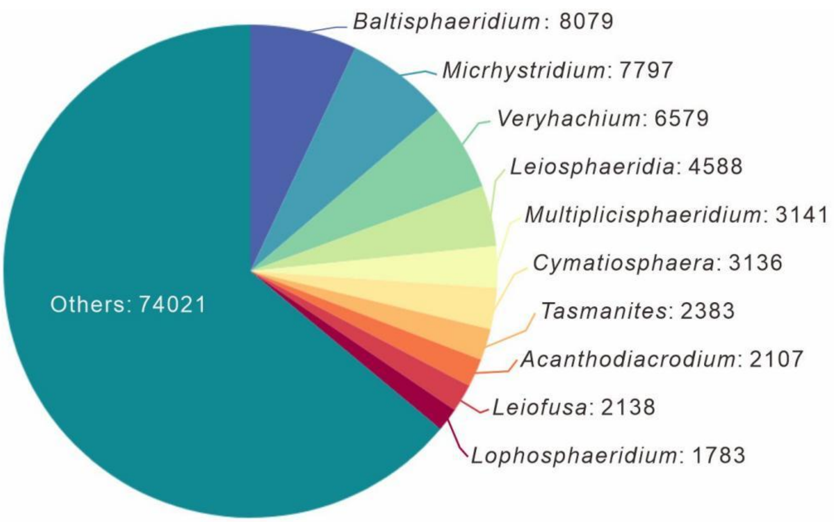

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Figure 4. Statistical pie of the occurrence number of genera in the database.

3.4 Literature sources and statistics

Data in this database were obtained from 7816 references, spanning from 1842 to 2023. The temporal distribution of publication years is presented in Fig. 5. The average number of research outputs after 1930 (83.9 papers/per year) is an order of magnitude greater than that before 1930 (0.12 papers/per year). This difference is not significant in the overall context and was thus not displayed on the graph. Even the relatively lower research outputs of the 1950s and 2020s were more than 2.5fold higher than the total output from the 1930s and 1940s combined over 20 years. More than half of research output occurred in the 1970s and 1980s, with 4322 papers accounting for 55.3% of the total.

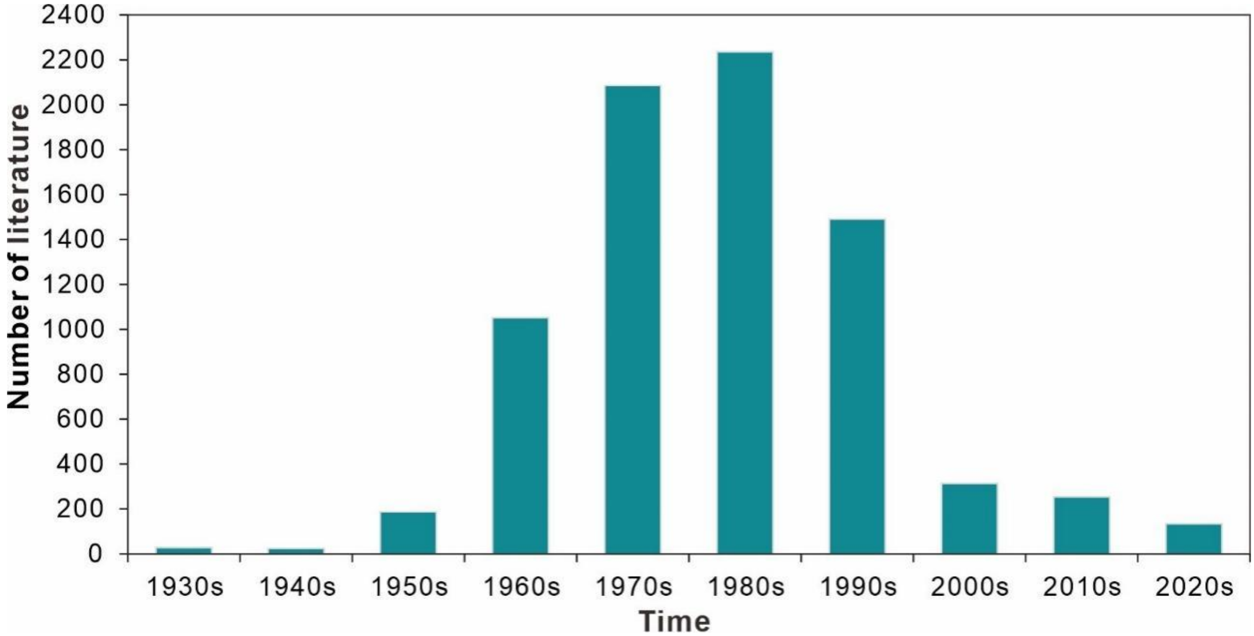

Figure 5. Statistics of publication distributions in the database.

3.5 Temporal distribution

Figure 6a indicates that over a long timescale, data volume steadily increases during the Proterozoic but remains below 5000 entries, peaking in the Ediacaran with 3137 entries. However, there are almost no records for the Paleoproterozoic, accounting for only 1.9% of the Proterozoic data. The Ordovician (Paleozoic) exhibits the highest number of entries at 21 898, followed by a decline to the Carboniferous low point of 1682 entries. Subsequently, a minor peak occurs during the Cretaceous (5984 entries) before the data volume dropped below 5000 entries. Figure 6b presents the maximum data volume of 4442 entries during the Darriwilian (Ordovician), whereas the minimum is zero during the Jiangshanian (Cambrian). Two significant increases in data density occur at the intersections of Stage 10 and the Darriwilian (Cambrian-Ordovician) and between the

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Dapingian and Darriwilian (Ordovician). Four significant decreases occur at the transition between the Darriwilian and Floian (Ordovician), Darriwilian and Sandbian (Ordovician), Lochkovian and Pragian (Devonian), and Famennian and Tournaisian (Devonian-Carboniferous). Such data distribution may be attributed to 1) limited research intensity and 2) low temporal resolution in the study area, both of which constrain the availability of material for analysis.

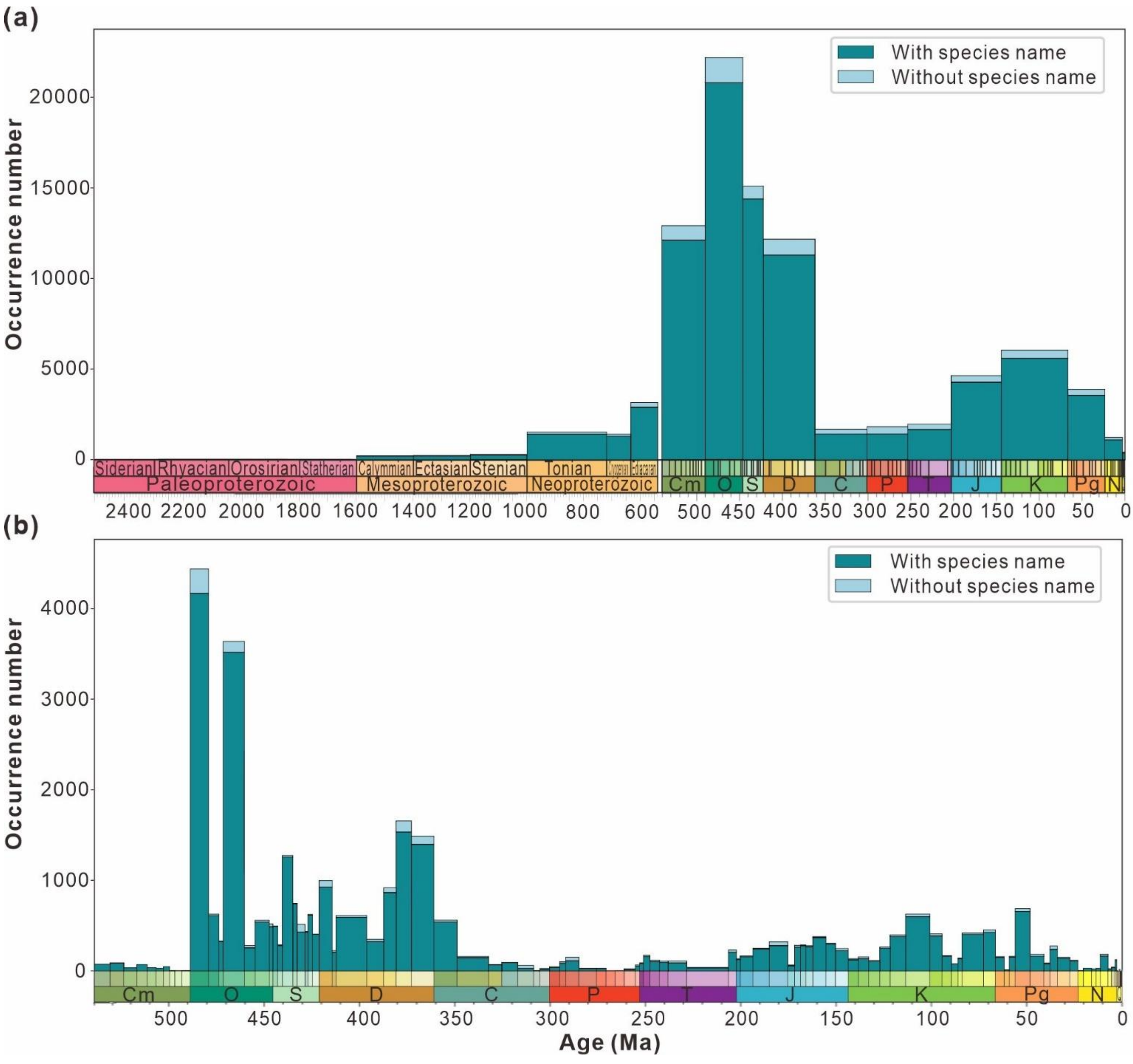

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Figure 6. The number of entries from "have digital age" data split the "timescales include 2500 Ma" **(a)** and Phanerozoic **(b)** and binned by geologic stage. Each stage is divided into data with species name and data without species name for statistics according to the storage type of the genus and species field in the database.

3.6 Spatial distribution

The spatial distribution of data collection was inherently uneven. In terms of its modern distribution (Fig. 7), the peak in the longitudinal distribution lies primarily between -10° to 30°, with a small amount collected between -50° to -90° and 90° to 130°. According to the latitudinal distribution, most of the data are from the Northern Hemisphere, from Europe, China, and North America and predominantly between 25° and 65°, accounting for 82.0% of the GAD. Figure 8 presents the modern geographic distribution by Era. Most Precambrian data, primarily source from China and Europe, accounted for 86.4% of the total, whereas most Phanerozoic data are from North America, Europe, Australia, and China, accounting for 93.2%. The Cenozoic and Paleozoic data exhibit the widest spatial distribution (-176.2° to 176.1°), with the Paleozoic containing the highest quantity of data (61 767 entries, representing 69.6% of the total geographic data).

The paleogeographic distribution of data across periods (Fig. 9) highlights how data are concentrated in different regions over time. The diagram indicates that most of the data from the Cambrian to the Quaternary are from shallow marine environments, favoring continental edges. As the continents migrated northward from the Mesozoic to the Cenozoic, records begin to concentrate in the mid-latitude regions in the Northern Hemisphere. Taking the peak values of each period as examples and starting with the Cambrian, the highest data concentration is observed between -35° and -45° (3688 entries), mainly in Gondwana and the Baltic, which shifted to -25° and -35° (3638 entries) by the Ordovician. In the Carboniferous, the highest data concentration is near 5° to -15° (468 entries) in the North American and Eurasian plates. In the Permian, data are evenly distributed across the mid-latitude regions near the coast of the Tethys Ocean in both hemispheres. Thereafter, fossil records start to tilt towards the mid-latitude regions of the Northern Hemisphere (such as North America, Europe, and Asia) during the Mesozoic and Cenozoic. The highest data concentrations were between 25° and 35° during the Triassic, and moved to between 35° and 45° and between 45° and 55° during the Jurassic-Cretaceous and Paleogene-Quaternary periods, respectively.

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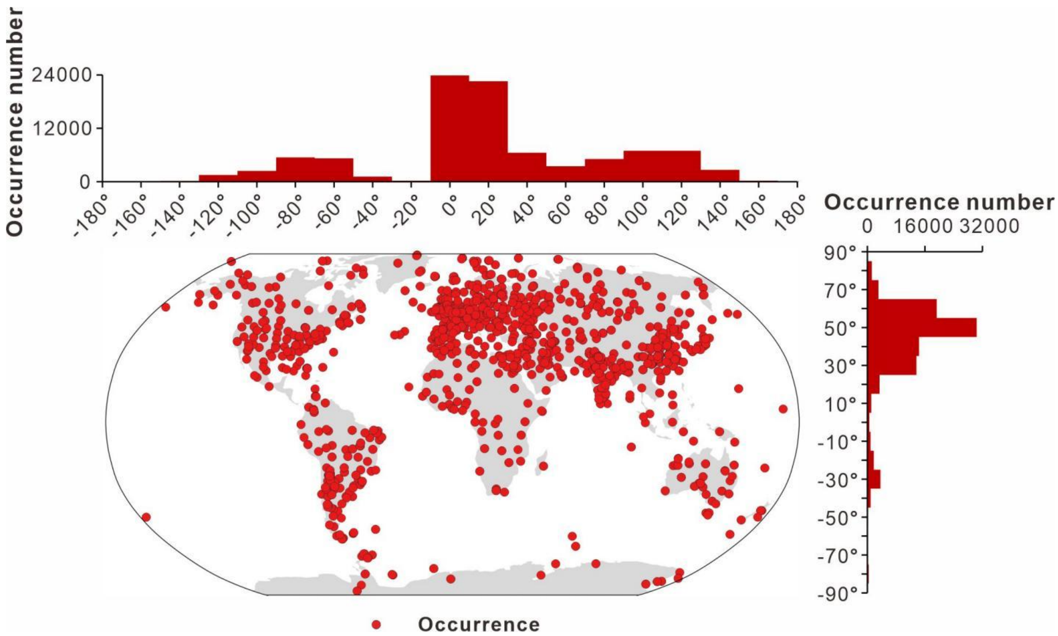

Figure 7. Spatial distribution of all data from the GAD.

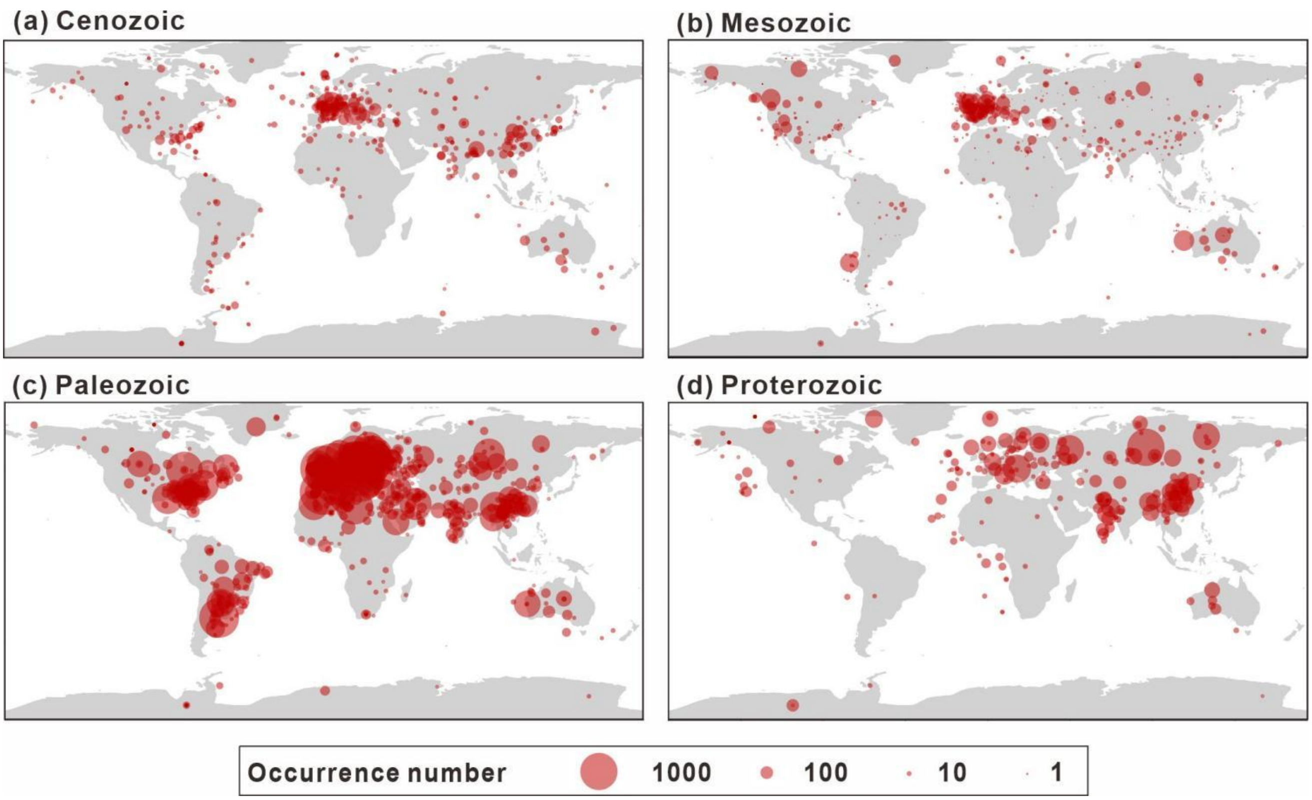

Figure 8. Summary of the spatial distribution of sampling sites by era **(a–d)**, with the size of each point scaled to the number of occurrences at each site. All panels are plotted on the same scale.

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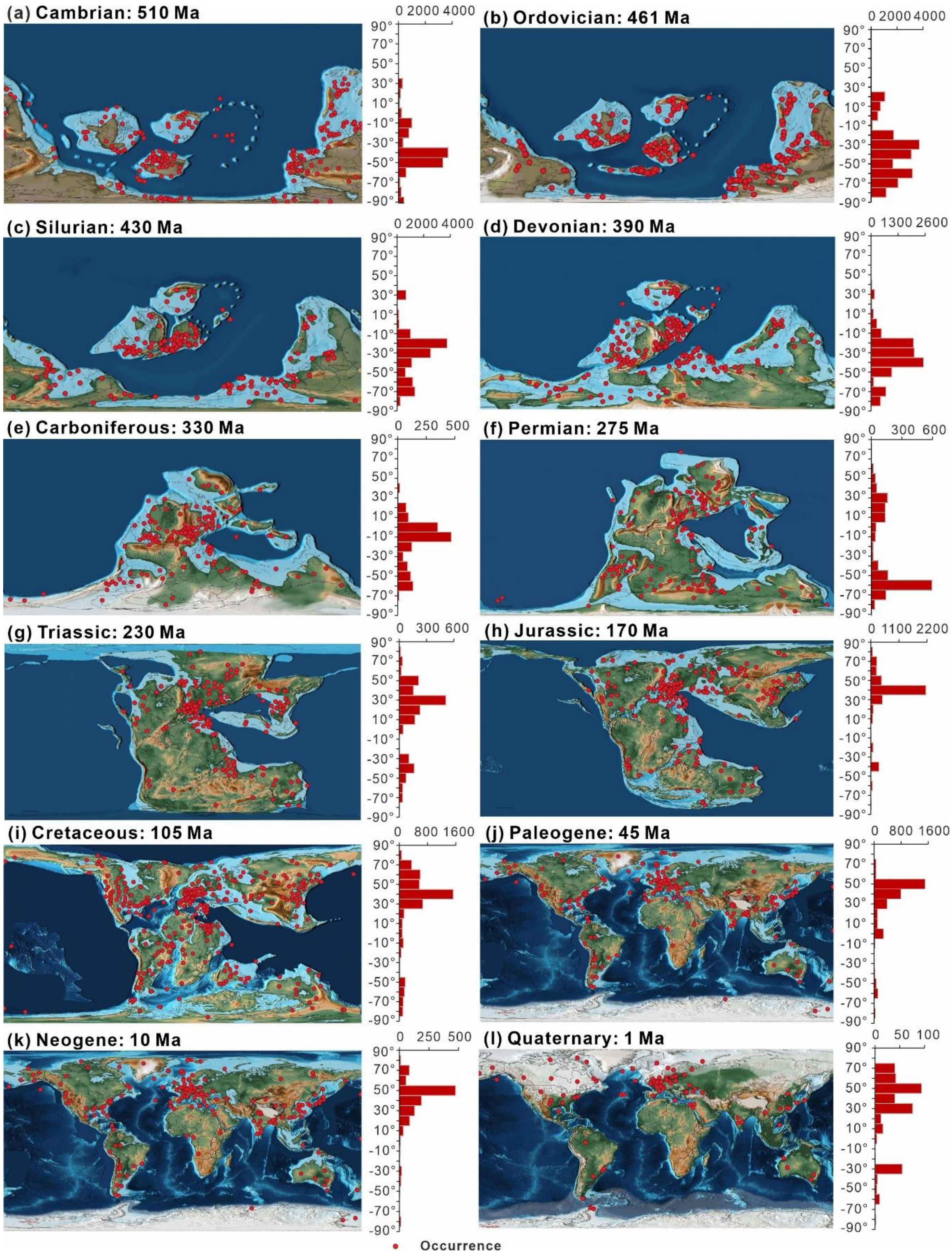

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Figure 9. Summary of the paleogeographic spatial distribution of sampling sites, **(a-l)** separated by geologic period. Histograms to the right of each map show the relative latitudinal distribution of all unique sampling sites within 10° bins, with the horizontal axis representing the number of occurrences. The chronology number indicates the exact point in time for the map selection. For example, Ordovician: 461 Ma, representing the Middle Ordovician. All maps were based on Scotese (Scotese, 2021).

3.7 Spatial-temporal trends in proxy values

The large volume and consistent structure of data in GAD allow for a comprehensive analysis of acritarch evolution over geological timescales. Figure 10 presents heatmaps for each time interval from database entries, where the data is temporally averaged by stage level and spatially into 15° paleolatitude bins. Vertical trends indicate the latitudinal gradient for any given "stage", while horizontal trends indicate the temporal evolution of entries within latitudinal intervals. Notably, the data volume is predominantly observed in the mid-to-low latitudes of the Southern Hemisphere during the Paleozoic, with over 400 entries and peaks reaching above 1400. A clear migration pattern is observed, as the majority of data shift from the Southern Hemisphere to the Northern Hemisphere over time. This is related to tectonic plate movement as since the formation of Pangaea about 250 million years ago, the Gondwana gradually split apart. The plates of South America, Africa, Antarctica, Australia, and India have been drifting northward progressively, affecting the geographical pattern and biodiversity of the Earth (Park, 1988). The heat map (Fig. 10) clearly indicates that all entries exhibited discontinuous spatial and temporal coverage, but the Mesozoic (Cretaceous), Paleozoic (Ordovician and Devonian) generally exhibited good coverage, extending from 30° to -90°. During the Mid-Cretaceous, coverage reached 100%. In contrast, the Paleozoic (Middle to Late Cambrian and Permian), Mesozoic (Jurassic), and Cenozoic exhibited highly discontinuous geographic coverage with a significantly reduced range.

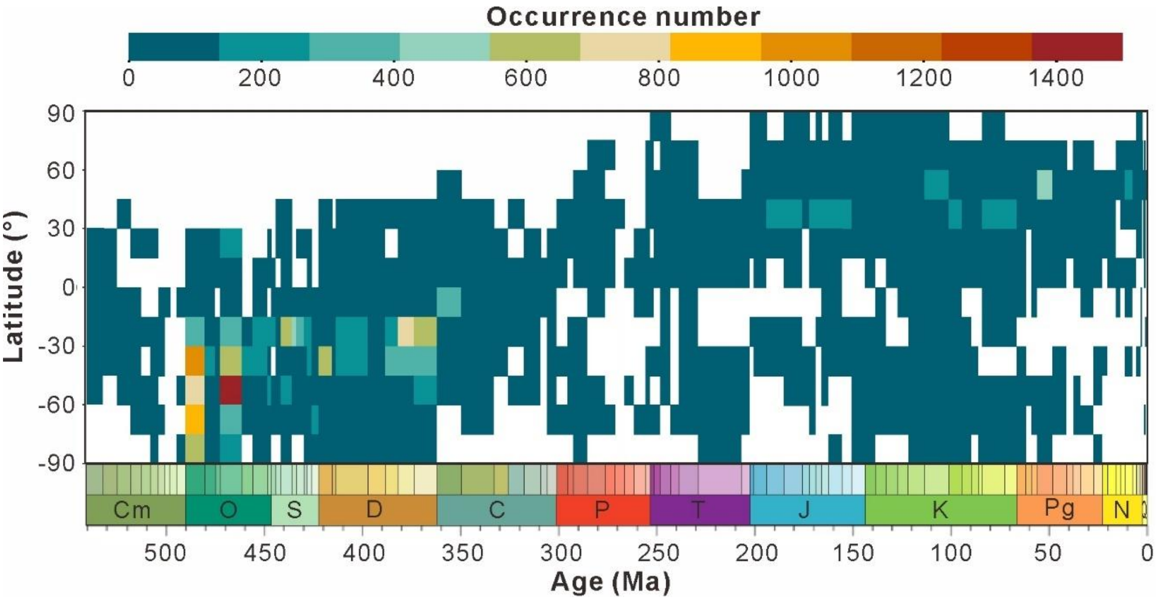

Figure 10. Summary of the spatial-temporal trends binned temporally by stage and spatially by 15° paleolatitudinal bins, cooler colors correspond with lower number of occurrence and vice versa.

4 Data availability

All data for GAD (version 1.0) can be found on Zenodo: https://doi.org/10.5281/zenodo.13828633 (Shu et al., 2024).

5 Code availability

All available example code and auxiliary functions have been uploaded on Zenodo: https://doi.org/10.5281/zenodo.14350992 (Shu, 2024).

6 Conclusions

GAD is a global acritarch database that integrates data from Palynodata and PBDB, and additional published literature not included in previous collections. Building on the foundation of Palynodata, which originally contained 15 fields, 111 382 entries, 812 238 metadata points, and 7385 references, GAD added 24 new fields, 4531 new entries, 1 882 081 new metadata points, and 424 new references, resulting in a database comprising 115 947 entries, 39 fields, 2 694 671 metadata points, and 7816 references. GAD represents records from 2993 different sampling sites spanning geological history from the Precambrian to Phanerozoic. The fossil records include 1456 genera and 9863 species (excluding sp.). Additionally, the database records information related to occurrences such as stratigraphy, lithology, and paleogeography. Among all entries, Paleozoic data are the most abundant, accounting for 70.9% of the total, followed by 13 071 Mesozoic, 9043 Neoproterozoic, 6004 Cenozoic, 1251 Mesoproterozoic, and 196 Paleoproterozoic entries. Regarding the spatial distribution of acritarchs, 93 288 are derived from continents and primarily concentrated in Europe, North America, China, and India, with the remaining 1.9% originating from oceanic or marine regions.

Although substantial efforts have been made, the dataset remains incomplete. For example, information regarding the size dimensions of acritarchs, lithology, and strata are lacking and will be continuously supplemented in the future. Additionally, while meticulous care was taken to ensure accuracy, some errors may have been overlooked due to the sheer volume of data. When reusing GAD, we recommend citing both the GAD and original data sources to ensure proper attribution. Any issues or omissions discovered by the end users can be reported to us, and the relevant information will be updated in future versions of the database. GAD is expected to remain a valuable resource for ongoing and future research.

Author contributions

Xiang Shu: Collected data, conducted database statistical analysis, and drafted a manuscript; Haijun Song, Daoliang Chu, Yuyang Wu, Xiaokang Liu, Enhao Jia, Yan Feng, Yong Du, Wenchao Yu, Huyue Song: They have done a lot of work in expanding and adjusting metadata structures, fields, and other information during the data collection process; Hanchen Song:

Technical guidance on ancient and modern geographic maps; Lai Wei, Xiaokang Liu, Qingzhong Liang, Xinchuan Li, Hong Yao: Technical support for computer language writing, literature collection, semi-automatic data extraction, data cleaning and screening; Haijun Song, Yong Lei, Jacopo Dal Corso, Yuyang Wu, Xiaokang Liu, Enhao Jia: Provided valuable revision suggestions for the manuscript.

Competing interests

The author has declared that there are no competing interests.

Disclaimer

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Review statement

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