OneDZ: A Global Detrital Zircon Database and Implications for Constructing Giant Geoscience Database

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Abstract. The amount of detrital zircon U-Pb geochronology data and Lu-Hf isotopic data has doubled in the past two decades with the continuous improvement of analytical methods, and has developed into the most closely integrated research field in earth science with big data methods. However, how to effectively construct giant databases in geoscience has become a challenge. Here, we present OneDZ, a global comprehensive detrital zircon U-Pb geochronology and Lu-Hf isotope database, which includes diverse samples with data source, location, stratigraphy, depositional age, and various elemental and isotopic information. OneDZ collected corresponding regions, stratigraphic and lithological information to facilitate quick access for users. Comparing with current zircon databases, OneDZ complies 1,925,687 grains of detrital zircon U-Pb and 275,971 grains of detrital zircon Lu-Hf records from 275,971 publications. Furthermore, the construction of OneDZ leverages artificial intelligence (AI) and programming scripts and offers insights into managing large-scale unstructured data in geosciences. This paper further discusses the perspective of applying big data methods in the research of zircon-related areas. This database

exemplifies the power of big data in Earth sciences, providing a platform for investigating zircon data in deep time. It serves as a springboard for research, offering new insights in understanding Earth's past, present, and future. The database (Li and Hu, 2025) is freely available via Zenodo at 10.5281/zenodo.17407937. All code snippets in this research are accessible via https://github.com/KeranLi/Global-Detrital-Zircon. The OneDZ web platform is accessible via https://onedz.top/.

1 Introduction

The advent of high-precision U-Pb geochronology has revolutionized our understanding of Earth history. Isotope-dilution thermal-ionization mass spectrometry (ID-TIMS; Krogh, 1973) remains the benchmark for highest accuracy and precision (≤0.1 %), but its destructive, time-intensive protocol limits statistical throughput for large detrital suites. Laser-ablation inductively-coupled-plasma mass spectrometry (LA-ICP-MS) and secondary-ion mass spectrometry (SIMS) now provide rapid, in-situ analyses with 1 - 3 % precision, which is ideal for analyzing the hundreds to thousands of concordant ages required for robust detrital-zircon provenance and maximum depositional-age studies (e.g., Jarvis and Kym, 1988; MacRae and Neil, 1995; Belu et al., 2003; Muzikar et al., 2003; Yergey et al., 2013). Together, these complementary techniques extend high-precision geochronology from single crystals to entire sedimentary systems. Zircon, a robust and ubiquitous mineral found throughout the continental crust, serves as a reliable recorder of geological events due to its high closure temperature and resistance to weathering and metamorphism (Pupin, 1980). Primary zircons from magmatic or metamorphic rocks are commonly fragmented, transported, and ultimately deposited as detrital zircons.

Typical analyses of detrital zircons include U-Pb and Lu-Hf isotopic systems. Chemical formula of detrital zircon can be represented as [$ZrSiO_4$]. The ionic radius of [Zr^{4+}] is 0.87 Å, which can be easily replaced by [U^{4+}] and [Th^{4+}] because of similar ionic radius of 1.05 Å and 1.10 Å (Jaffey et al., 1971). Two isotopes of [U^{4+}] (^{238}U and ^{235}U) generate ^{206}Pb and ^{207}Pb isotopes following the decay processes: $^{238}U \rightarrow ^{206}Pb+8\alpha+6\beta^-$ (half-life: 4468 million years, Jaffey et al., 1971), $^{235}U \rightarrow ^{207}Pb+7\alpha+4\beta^-$ (half-life: 703.8 million years, Jaffey et al., 1971) and $^{232}Th \rightarrow ^{208}Pb+6\alpha+4\beta^-$ (half-life: 1400 million years, Jaffey et al., 1971). Based on triple decay processes, the detrital zircon ages can be obtained via consisted $^{206}Pb/^{238}U$, $^{207}Pb/^{235}U$ and $^{208}Pb/^{232}Th$ decayed ages.

In addition to U-Pb geochronology, the Lu-Hf isotopic system has become an indispensable tool for understanding crustal evolution and mantle differentiation (Patchett and Tatsumoto, 1983). The [Lu^{3+}] is the heaviest rare earth element (REE) and are easily enriched in detrital zircon. The ^{176}Lu decays to ^{176}Hf via $^{176}Lu \rightarrow ^{176}Hf+\beta^-$ (half-life: 37.1 billion years, Kinny and Mass, 2003). Except for the geochronological applicat ion, the Lu-Hf isotopic data can be used to gain the original information (Scherer et al., 2001; Söderlund et al., 2004). The Lu-Hf isotopic data are noted by ε units by $\varepsilon Hf(0)=10000\times[(^{176}Hf/^{177}Hf)_{sample}/(^{176}Hf/^{177}Hf)_{CHUR,0}-1]$ and $\varepsilon Hf(t)=10000\times\{[(^{176}Hf/^{177}Hf)_{sample}-(^{176}Lu/^{177}Hf)_{sample}\times(e^{\lambda t}-1)]/[(^{176}Hf/^{177}Hf)_{CHUR,0}-(^{176}Lu/^{177}Hf)_{CHUR}\times(e^{\lambda t}-1)]-1\}$. t is the crystallization age. $^{176}Hf/^{177}Hf$ and $^{176}Lu/^{177}Hf$ can be measured from detrital zircons. λ is the decay constant and equals to 1.867×10^{-5} million years (Söderlund et al., 2004). CHUR denotes the isotopic results of the chondritic uniform reservoir.

In the past two decades, it is estimated that millions U-Pb geochronological data of detrital zircons have been internationally reported. As the amount of data increases, it’s possible to use detrital zircon data with big data methods for analyzing significant scientific problems. For instance, the compilation of detrital zircon big data is used for the reconstruction of continental arcs (McKenzie et al., 2016; Cao et al., 2017), tectonic history (Cawood et al., 2012; Barham et al., 2022; Zhang et al., 2023; Malone et al., 2024; Odlum et al., 2024), crustal evolution (Cheng, 2017; Barham et al., 2019; Cawood, 2020), paleo-geographic (Xue et al., 2022; Jian et al., 2022) and provenance analysis (Wang et al., 2024). Along with data-driven analysis, several analytical tools (Ludwing, 2003; Vermeesch, 2018; Saylor et al., 2017; Sharman et al., 2018) and professional databases have been established (Voice et al., 2011; Puetz, 2019; Martin et al.,2022; Puetz, 2024; Wu et al., 2024). However, the existing databases are not primarily designed for the needs of sedimentological researches and the reported data are usually mixed with magmatic and metamorphic rocks. With the rapid accumulation of detrital zircon data, existing databases are difficult to effectively cover detrital zircon data in sedimentary rocks.

In addition, the current database construction mainly focuses on reporting data, lacking discussion on the problems that exist in the database construction process. Several previous reported databases tend to store data by Microsoft Excel software (Voice et al., 2011; Puetz, 2019; Martin et al.,2022; Puetz, 2024; Wu et al., 2024). However, the Excel software can only store limited raw data (n=1048576). Some researches split the data sheets into several Excel files like Wu et al. (2022). The split data sheets hinder fast data searching and the huge amount of data results in excessively low access efficiency in Excel software. Therefore, the construction of giant earth science databases represented by detrital zircon data urgently needs to shift towards the use of more professional database software. Such curated compilations, like Earth Chemistry (EarthChem), Geochemistry of Rocks of the Oceans and Continents (GEOROC), EarthBank and Geochron, with convenient and user-friendly data query - download websites have been developed. These platforms all utilize database software and front-end and back-end to retrieve and download data on web pages. Convenient operation on the web page will guarantee continuously data updating, providing powerful and sustainable data sources for future research.

In order to address the challenges in current geological research based on detrital zircon big data, we have established a detrital zircon database that covers both English and Chinese literature worldwide. Presented here is the OneDZ database, an extensive compilation of zircon U-Pb geochronological and Lu-Hf isotopic data, encompassing over 1925687 U-Pb and 275971 Lu-Hf records from approximately 275971 publications. This database spans nearly the entire history of earth's sediments, offering valuable insights into the timing and nature of geological events. The compilation includes data from various analytical techniques, host rock lithologies, stratigraphic information, and other original records. OneDZ records the lithology, stratigraphic, spatial, and testing information of detrital zircons as much as possible. In the construction of OneDZ database, the Excel software was abandoned, and instead, professional database management software such as MySQL was adapted. In addition, several AI modules and code snippets were introduced to demonstrate how artificial-intelligence tools can improve database construction. To facilitate access, OneDZ has been fully deployed as a web-based platform. Global and regional interdisciplinary research can be conducted simultaneously on OneDZ. At the same time, the enormous data also makes OneDZ a natural laboratory for discussing data analysis methods in Earth science. OneDZ provides a foundation for research in multiple aspects, including data provision, database construction, and discussion and analysis of data analysis methods in earth science.

2 Database construction

One of the most unique features in OneDZ is the systematic construction workflow (Fig. 1). Firstly, the knowledge graph (Hu et al., 2024) was adopted and guided the header design by identifying the most frequent words related to detrital zircon. With the knowledge graph, the words to describe the sample location, sedimentary or stratigraphic descriptions and the isotopic results are the most relevant information associated with detrital zircon studies. Previous research rarely summarized the difficulties in collecting data sources. Guo et al. (2024) summarized current geoscience data compilation challenges include non-repeatability, uncertainty, multi-dimensionality, computational complexity, and frequent updates, which pose significant obstacles to the efficient collection and management of geological information. In practice, constantly switching potential literature search engines and manually downloading potential articles one by one actually occupies the main time of database construction. In this project, AI-assisted tools, including DataExpo and GPT Agent (Supplement 1), were employed to check specific online resources like Pangea (https://pangaea.de/), Google Scholar, and CNKI to search potential papers containing data. Following the AI tools, manual verification was conducted, and publication information were passed to several volunteering experts based on their interest regions. These experts extracted and cleaned data using the computer-vision tool, DeepShovel (Zhang et al., 2023), and Python/SQL scripts. These validated data were imported into the OneDZ database. Table 1 provides a detailed comparison with other detrital-zircon databases.

2.1 Crowdfunded construction

In the era of data explosion, crowdfunding has become an efficient method for building mega databases. Inspired by this cooperative construction, the OneDZ database was established by dividing different regions and quickly organizing a group of experts in detrital zircons. The crowdfunding approach ensures that each scientist is familiar with the contributed data, maximizing efficiency and accuracy within the same framework following a standard. This method also facilitates dynamic database updates and promotes sustained growth in data volume. The crowdfunded construction is anchored by several regional detrital zircon databases mainly in China which published in a special issue of the journal of Geosciences Data Journal (see Yang et al., 2023), including those from the North China Block (Yang et al., 2023; Dong et al., 2023), the Eastern Central China Orogenic Belt (Chai, 2023), the Songpan-Ganzi and Western Qinling terranes (Pan et al., 2023), the Central Asian Orogenic Belt (Wang, 2023), South China (Luo et al., 2023; Xia, 2023), the Qilian-Qaidam-Kunlun collage (He, 2023), the South China Sea (Huang et al., 2023), the Tarim-West Kunlun-Pamir-Tajik-Tianshuihai terranes (Zhang et al., 2023), the Middle East (Chen et al., 2023; Sun et al., 2023), and samples from Quaternary sediments (Chen et al., 2023).

2.2 Facility from AI tools

One of the fundamental challenges in constructing a database lies in data collection. Although the crowdfunded approach ensures that geologists participating in database development are experts in their research area, their expertise does not guarantee familiarity with every publication. To find potential metadata, this study introduced a data parsing system integrated with deep learning technology. The data parsing tool is named DataExpo (Lu et al., 2023) and employs deep learning for metadata extraction (Figure S1-S2 in the Supplement), performing automatic semantic tagging, classification, and structured information extraction from web pages. DataExpo automatically crawls web pages related to detrital zircon research. Using a multidimensional web page ranking strategy, retrieval results for different queries are sorted. Finally, based on natural language processing (NLP) and convolutional neural networks (CNNs), DataExpo adjusts the ranking of retrieval results and determines whether to push them to experts. Another AI tool, a GPT Agent (chatGPT, https://chatgpt.com), was created through prompt engineering to analyze characters from specific websites and find potential titles about detrital zircons. Details on using DataExpo and GPT Agent in the OneDZ database construction are provided in the Supplement 1.

In addition to integrating data sources, data extraction poses another major challenge. While most online articles store data in Excel tables as attachments, a considerable number of detrital zircon data is stored in the main text in the article either in table or in text form. To accelerate construction, the interactive computer-vision AI tool DeepShovel (Zhang et al., 2023) was utilized to automatically split tables via optical character recognition. Details on using DeepShovel can be found in Figure S3 in the Supplement.

2.3 Automatic data process

In the era of exponential data growth, the construction of domain-specific earth-science databases is becoming the norm. Yet existing zircon and broader geoscience repositories overwhelmingly emphasize data quality, while the critical step of data cleaning has received little systematic attention. In the construction of large scientific databases, beyond ensuring the quality of the original data, it is also essential to trace and maintain the quality of different versions of data formed during the database construction process, a procedure known as data cleaning. Hellerstein et al. (2013) and Chu et al. (2016) identified the key steps in the data cleaning process including (1) Data review and understanding; (2) Missing value processing; (3) Outlier detection and handling; (4) Data format and type conversion; (5) Data consistency and normalization; (6) Data de-duplication. Following the standard data cleaning process, Python and MySQL scripts were designed for detecting missing key items, checking for conflicting content, detecting format anomalies, and Supplementing duplicate data entries (see Supplement 2 for details). Python scripts are more flexible while MySQL scripts have higher running efficiency (Figure S4 in the Supplement).

3 Database

The OneDZ database is structured around three core tables: main, age, and geography, which are interconnected via the primary key zircon_id (varchar 100). The main, age and geography tables store basic information about each zircon grain, including its reference, depositional age and geographical location (Figure 2). Two geochemistry tables contain detailed U-Pb and Lu-Hf isotopic data, linked to the main table via zircon_id (Figure 2). This structure ensures data integrity and facilitates efficient querying and analysis. In the OneDZ database we have compiled 1925687 detrital zircon grains with U-Pb ages and 275971 grains with Lu-Hf isotope data. From multiple dimensions such as region, literature, and samples, OneDZ is currently the most comprehensive database for global detrital zircon data records (Table 2). The U-Pb geochronological data are spatially distributed across 142 geographic regions (Figure 3a). The Lu-Hf data are primarily distributed across China, South Africa, India, and Australia (Figure 3b). Periodic statistics indicate that ancient zircons (over 1000 Ma) predominantly contribute to this database in both U-Pb and Lu-Hf data (Figure 3c-f). The content and completeness of sample metadata, spatial data, and stratigraphic information in OneDZ are summarized in Tables 3–6 (expressed as the ratio of valid entries to total entries).

3.1 Reference information

The reference information in OneDZ includes the principal investigator, publication year, journal name, volume, pagination, article title, and a direct weblink to the original publications. Figure S5 in the Supplement provides a temporal overview of the geographic distribution of these scholarly works. OneDZ aggregates a comprehensive total of 742,832 papers from 1995 to 2022 (Figure S5a Supplement), which includes 52,604 English-language papers and 203,326 Chinese-language papers in the U-Pb datasets. For the Lu-Hf datasets, the compilation consists of 65,420 English-language papers and 8,762 Chinese-language papers from 2004 to 2022 (Figure S5b in the Supplement). Additionally, publicly available master's and doctoral dissertations have been incorporated into the dataset. To ensure accessibility and inclusivity, Chinese-language papers on detrital zircons have been meticulously translated into English. In the U-Pb age dataset, journals such as Precambrian Research, Geological Society of American Bulletin, and Gondwana Research predominantly contribute to the database (Figure S6a-b in the Supplement). The Lu-Hf analyses in OneDZ are drawn entirely from the same journal pool that provided the U-Pb data (Figure S6c-d in the Supplement). Comparing with previous databases (Puetz et al., 2024; Wu et al., 2023), OneDZ surpasses existing repositories in volume and in journal diversity (Figure S6a-b in the Supplement).

3.2 Sample, spatial and strata information

OneDZ contains the published sample ID, country or state, region, continent, major and minor geographic or geological description of the sediments. In geological research, geological bodies, sedimentary basins, or specific strata are usually studied as research objects. Recording the samples position solely based on spatial coordinates cannot meet the needs of scientific research. While relying exclusively on high-precision latitude–longitude coordinates is insufficient for rigorous spatial analyses, such attributes are nevertheless the only consistently available resource in most databases and thus remain the primary handle for sample positioning. The decimal format of latitude and longitude coordinates has been considered the most suitable recording format in the previous zircon databases (Puetz et al., 2021, 2024a, 2024b). However, a considerable number of research papers report coordinates in the DMS (Degree-Minute-Second) format. To expedite the standardization of these diverse DMS notations into a decimal format, we have crafted and implemented a Python code snippet, as detailed in

Supplement 3. Another challenge arises from the absence of coordinate reports in some papers. Traditionally, papers lacking specific coordinates have been excluded from databases. However, directly exclusion could exacerbate the spatio-temporal bias. To enhance the data richness, a spatial coordinate estimation method was applied during the database construction process. This method, based on a plane graph and implemented in Python, swiftly estimates coordinates for articles missing these details while striving to maintain accuracy (Supplement 3).

Given the significance of detrital zircons in geological research, the strata information schema within our database has been designed to encapsulate a wide array of sedimentary data. It documents the strata age according to the period-epoch-stage stratigraphic system, as well as the maximum, estimated, and minimum depositional ages. Further details regarding the stratigraphic data points are outlined in Table 4.

Although maximizing the utilization of research papers can mitigate spatial bias to a certain extent, the spatial-strata information visualized in both the U-Pb (Fig. 3) and Lu-Hf (Fig. 4) datasets continues to exhibit significant spatial skew. A majority of the records are concentrated in East Asia, with a particular focus on China.

Despite this concentration, all indicators suggest a substantial global representation within our datasets. The visualization tools employed highlight the areas of high research activity while also underscoring the need for further research in underrepresented regions to achieve a more balanced global perspective.

3.3 U-Pb isotopes database

The geochronological records include full analytical-method metadata: the technique used (e.g., LA-ICP-MS, SHRIMP or ID-TIMS), the analytical institution's spot location (rim vs core), and the spot diameter. For the chronological data, the isotopic ratios $^{206}Pb/^{238}U$, $^{207}Pb/^{235}U$, $^{207}Pb/^{206}Pb$, and $^{208}Pb/^{232}Th$ were recorded with corresponding 1σ uncertainties. A limited number of papers have reported uncertainties at the 2σ level. Where a preferred age was not explicitly reported by the original authors (≤0.5 % of records), OneDZ estimated the most reliable date using 1σ/2σ uncertainty and the 1200 Ma/1600 Ma thresholds of Gehrels et al. (2008). These rare "estimated ages" are flagged as EstAge = 1 so users can readily distinguish them from author-specified values.

Furthermore, the database also archives the discordance ratio, concentrations of U, Th, and Pb, as well as the U/Th and Th/U ratios, providing a comprehensive set of parameters for geochronological analysis.

3.4 Lu-Hf isotopes database

The Lu-Hf isotopic data within OneDZ are fundamentally anchored in U-Pb chronological results. Alongside the age determinations, we have meticulously documented the basic analytical results, including the $^{176}Yb/^{177}Hf$, $^{176}Lu/^{177}Hf$, and $^{176}Hf/^{177}Hf$ isotopic ratios, each accompanied by their corresponding 2σ uncertainties, which reflect the precision of the measurements.

In addition to the raw isotopic data, OneDZ encompassed several calculated parameters derived from these ratios. These include the calculated ratios of f(Lu/Hf), the hafnium isotope composition εHf(t) with their respective 2σ uncertainties, and the model ages TDM1 (Ma) and TDM2 (Ma). These calculated results provide further insights into the isotopic evolution and the crustal residence history of the samples analyzed.

4 Data characteristics

4.1 Rock types statistics

Clastic sediments are vital geological archives to offer deep insights into the sedimentary provenance and evolutionary history of the continental crust (Taylor, 1985). In preparation for studies on sedimentary provenance and related geological inquiries, the OneDZ database collected petrological contexts from original articles. OneDZ categorized rock types into the widely accepted hierarchical granularity system, with Class-1 encompassing clastic, meta-clastic, and pyroclastic rocks. These categories reflect the diverse origins of sediments. Specifically, Class-2 and Class-3 types provide a more nuanced classification based on grain size, which is crucial for understanding sedimentary processes and environments. Class-2 further subdivided the rocks, serving as a supplement to the macroscopic rock classification of Class-1. Class-3 adopts the particle size classification scheme for detrital sedimentary rocks proposed by Udden (1918), Wentworth (1922), and Krumbein (1938), and provides the most detailed classification of rock types. In the U-Pb datasets, Class-1 rock types are predominantly clastic (50%, Figure 6a). Meta-clastics are the second lithological source (36.3%, Figure 6a). Pyroclastic takes up a little ratio (13.8%, Figure 6a). For Class-2 rock types, the major component is sandstone (53.6%, Figure 6b). The breccia, shale, mudstone equally allocated the remaining proportion (13%, 15.7%, 17.8%, Figure 6b). For Class-3 rock types, the distribution of particle sizes is quite uniform, with the proportions ranging from 1.8% to 16.0%. Specifically, fine sand and very coarse sand are the predominant types, accounting for 16.0% and 12.5% of the total, respectively (Figure 6c).

In the Lu-Hf datasets, relatively little rock records were provided in the original article. Clastic rock types contributed the most data to the dataset, comprising 38.9% of the total (Figure 6d). Meta-clastic offered 28.4% of the data and pyroclastic provided 32.7% of the data (Figure 6d). For Class-2 rock types, the major component is sandstone (66.8%, Figure 6e). The breccia, shale, mudstone equally allocated the remaining proportion (9.2%, 11.3%, 12.8%, Figure 6e). In the Class-3 rock types, the distribution of grain sizes is dominated by fine sand, which accounts for 37.5% of the total, making it the most prevalent grain size (Figure 6f). Very coarse sand is also a significant component, comprising 9.3% of the dataset. Other grain sizes contribute with percentages ranging from 1.4% to 8.0%, indicating a relatively balanced but varied composition across the different grain sizes.

4.2 Data uncertainty

The data uncertainty in the OneDZ database is stemmed from methodological errors, dating uncertainties, and potential biases associated with analytical instruments. Methodological errors are primarily attributed to variations in decay constants and half-lives among different isotopic systems. Dating uncertainties and potential biases have more to do with data processing. Figure 7 illustrates the relationships between isotopic ratios, calculated ages, and their corresponding 2σ uncertainties. The $^{206}Pb/^{238}U$

isotopic system adheres to a first-order linear regression model (Figure 7a), demonstrating a relatively consistent uncertainty across a wide range of ages. However, for samples with depositional ages exceed approximately 2000 Ma, the 2σ uncertainty of ages increases to around 300 Ma. This trend suggests that approximately 67% of samples may be associated with a temporal uncertainty of approximately 600 Ma. In contrast, the ^{207}Pb/^{235}U and ^{207}Pb/^{206}Pb isotopic systems are characterized by second-order polynomial regressions (Figure 7b-c). The complex regression models suggest a 2σ uncertainty of 500 Ma emerging at around 3000 Ma in ^{207}Pb/^{235}U and ^{207}Pb/^{206}Pb isotopic systems. The age uncertainty becomes significantly pronounced when analyzing samples over 3000 Ma. Because the uncertainties in ^{207}Pb/^{235}U and ^{207}Pb/^{206}Pb isotopic systems accumulate with time and become significant only in very old samples, these systems are best suited for dating ancient rocks. (between 1000 and 3000 Ma). The relatively low uncertainties suggest ^{207}Pb/^{235}U and ^{207}Pb/^{206}Pb isotopic systems are particularly valuable for studying the early history of the earth's crust.

In addition to the intrinsic variability of isotopic systems, dating uncertainty in OneDZ database is significantly influenced by the selection of the best age. Figure 8 provides a visual representation of the discrepancies between calculated isotope ages and the best ages selected from the raw data extracted directly from published papers. Dating uncertainties grow with increasing best ages across all isotopic systems (Figure 8a-c). To address this, we employed advanced statistical techniques, including Monte Carlo resampling (Figure 8d-f) and Bootstrap resampling (Figure 8g-i), coupled with locally weighted scatter plot smoothing (LOWESS) to estimate and visualize the dating uncertainties. The LOWESS trend lines indicate that potential thresholds of uncertainty may lie around 1000 Ma and 3000 Ma. Samples younger than 1000 Ma exhibit minimal bias, suggesting that the choice of isotopic system and the application of resampling methods have a limited impact on data uncertainty. However, isotopic uncertainties compound with time and reach ~500 Ma by ages of 3000 Ma, limiting reliable dating to still older samples. While commonly employed strategies such as filtering samples based on acceptable 2σ uncertainty or utilizing resampling techniques aim to mitigate the adverse effects of selecting the best age, the analysis presented in Figure 8 suggests that filtering alone does not significantly reduce uncertainties associated with the best age. Notably, in all isotopic systems, filtered results often reveal substantial gaps in the best age, indicating that the filtering process may not be sufficient to address the underlying uncertainties. The resampling methods, however, demonstrate a capacity to alleviate these gaps, particularly in the ^{207}Pb/^{206}Pb isotopic system, where they prove effective in reducing the best age discrepancies (Figure 8i).

For analytical techniques, the LA-ICP-MS has become the preferred method for sedimentary research due to its efficiency in yielding geochronological data. Figure 9 illustrates the variation in discordance ratios over time for different analytical instruments. The SHRIMP method, known for its precision, demonstrates a consistently low discordance ratio (Figure 9a). Remarkably, even samples with elevated age uncertainties maintain discordance ratios below 0.5%, indicating SHRIMP's reliability in dating. LA-ICP-MS displays an increase in age uncertainty for samples exceeding 1000 Ma but maintains a discordance ratio below 0.5% for these samples (Figure 9b). However, LA-ICP-MS exhibits a notable disadvantage for samples with low age uncertainties dating from approximately 800 to 1200 Ma, where the discordance ratio can be relatively high, occasionally exceeding 1%. This underscores the need for particularly careful data interpretation in these specific age ranges. The ID-TIMS method, while less commonly utilized in sediment dating, exhibits low discordance ratios (Figure 9c).

This suggests that ID-TIMS, despite its limitations, offers robust results for the most precision of dating requirements. Samples analyzed by SIMS appear to exhibit a potential linear relationship between age uncertainty and discordance ratio (Figure 9d). The original uncertainty associated with the Lu-Hf dataset predominantly pertains to the analytical outcomes obtained from isotopic measurements. Across all geological periods, the 2σ errors for the isotopic ratios ^{176}Hf/^{177}Hf, ^{176}Lu/^{177}Hf, and ^{176}Yb/^{177}Hf typically fluctuate around 2×10^{-5}, as depicted in Figure S7 in the s Supplement. The measurement ranges for these three isotopes are approximately 2×10^{-2}, indicating a high level of precision in the analytical process (Figure S7 in the Supplement). The uncertainties for the Lu-Hf isotopic system are notably an order of magnitude lower than the analytical results, suggesting that the system is inherently more precise than the measurements themselves. This stability in Lu-Hf uncertainties is maintained even at high resolutions, highlighting the robustness of the dataset in providing reliable isotopic age estimates. Other uncertainty in Lu-Hf datasets are the εHf(0) and εHf(t) errors (Figure S8 in the Supplement). The high-quality isotopic results obtained from the Lu-Hf dataset contribute to the stable and low 2σ errors observed in both εHf(0) and εHf(t), as depicted in Figure S8 in the Supplement. These parameters reflect the hafnium isotope composition at the time of zircon crystallization (εHf(0)) and at a specific time in the past (εHf(t)), exhibiting a consistency in error magnitude that underscores the reliability of the dataset. Similar to the isotopic uncertainty observed in the Lu-Hf system, the uncertainties associated with εHf(0) and εHf(t) are considerably larger than their corresponding 2σ errors. This discrepancy highlights the precision of the isotopic measurements relative to the calculated uncertainties of the hafnium isotope ratios. The stability of the error over the timescale is particularly noteworthy, suggesting that εHf(0) and εHf(t) values are independent and robust indicators of the isotopic evolution of the samples. This temporal stability further reinforces the reliability of these parameters in geochronological and geochemical analyses.

4.3 Spatial and temporal distributions of samples

Spacial distribution biases are evident within the OneDZ database (Figure 4-5). To delve into the effects of biased distributions, the U-Pb age data was segmented according to geological time sequences and visualized (Figure 10). Temporal slices reveal that the Qinghai-Tibet Plateau, Alps, Cordillera and Andes mountains are the main sampling areas in the Cenozoic (Figure 10a-c). In the Mesozoic, the main sampling regions are similar to areas from the Cenozoic (Figure 10d-f). In the Paleozoic, East Asia is obviously over-sampled relative to other regions (Figure 10g-l). In the pre-Cambrian period, East Asia, Europe and Australia contributed the majority of samples (Figure 10m-n)

In this study, we also present the first visualization of the temporal distributions of uranium, thorium, and lead concentrations in detrital zircons (Figure 11). The concentrations of these elements exhibit temporal stability, with uranium ranging from approximately 100 ppm to 300 ppm, thorium from 100 ppm to 200 ppm, and lead from 0 ppm to 200 ppm. Notably, there are differences in the estimation of temporal distributions of element concentrations when using Bootstrap and Monte Carlo methods (Figure 11). Furthermore, beyond elemental concentrations, the Th/U ratio in zircon is a crucial indicator for determining the provenance of zircon. It is widely accepted that a Th/U ratio below 0.1 suggests zircon may have experienced metamorphism and recrystallization, while a ratio above 0.4 is indicative of magmatic zircon. The resampling methods displays from all time spans, that the Th/U is larger than 0.4, indicates magmatic zircon dominants the detrital zircon (Figure S9 in the Supplement).

For Lu-Hf isotopes, the $^{176}Hf/^{177}Hf$ isotope decreases with the $^{176}Lu/^{177}Hf$ and $^{176}Yb/^{177}Hf$ isotopes showing periodic fluctuations (Figure 12). The εHf(0) displays a continuous decline, while the εHf(t) peridocially fluctuates (Figure 13).

5 Discussion

5.1 Evaluate the paleo-spatial reconstruction

Despite the OneDZ database compling comprehensive information about detrital zircon data, obvious oversampling bias exists in regions such East Asia due to disparities in research intensity and focus. This oversampling creates an imbalance and potentially leads to overrepresentations of regional samples.

For instance, the spatial analysis of the global zircon oxygen isotope record has shown that the temporal anomalies in zircon oxygen isotopes were predominantly attributed to regional samples' imbalance (Sundell et al., 2024). To address the issue of regional disparities in global zircon data analysis, Puetz et al. (2024) introduced a method to assess global representativeness. This method involves overlaying a grid across the Earth's surface, dividing it into discrete cells. The degree of global representativeness is then calculated by determining the ratio of the number of cells containing zircon data to the total number of cells in the grid. This approach allows for a quantitative measure of how well the zircon data cover different geographical regions worldwide. However, this evaluation approach is predicated on the present-day distribution of land and sea. In geological time scales, current geographical pattern does not accurately reflect the samples' spatial positions during the depositing period. To enhance the analysis of the spatiotemporal representativeness, we undertook a reconstruction based on the spatial distribution of detrital zircon U-Pb data. Utilizing tools such as pyGplate (Müller et al., 2018; Mather et al., 2024) and in situ block reconstruction methods (Jian et al., 2022), samples were reconstructed following the geohistorical spatial distribution. As shown in Figure 14, the scatter plot of reconstructed data shows that OneDZ covers almost all major continents in various periods of Earth's evolution. However, the spatial kernel density map in Figure 14 re-evaluated the global representativeness of the data. In fact, as we delve into more ancient geological periods, the sampling locations tend to cluster around one or two ancient tectonic plates. This pattern is due to the fact that older zircon grains, which have undergone multiple episodes of sedimentary recycling (where the age difference between the zircon and the time of deposition exceeds 150 Ma), have been subject to significant transport and thus may not accurately represent the original paleogeographic context. Consequently, after approximately accounting for the effects of sedimentary recycling, the data from these ancient times are predominantly sourced from a limited number of locations, lacking global representativeness. Therefore, the evaluation of results based on OneDZ, indicate that the global scope of zircon big data research needs further assessment.

Following the new paleo-spatial reconstruction evaluating methods, the temporal globality of OneDZ detrital zircon U-Pb data was visualized in Figure 15. The visualization in Figures 14c-e demonstrates that the U-Pb data has achieved spatial coverage across paleo-continents. A notable rise (14%) in paleo-spatial reconstruction and valuable stability were observed when the grid size was enlarged from 6° to 10°. As the grid size increases, the spatial resolution of globality gradually decreases, resulting in a continuous increase in the calculated global representative values. The global representative value loses a significant amount of spatial detail when calculated at an excessively large scale. Similarly, small-scale grid calculation results in computational bias towards local detail information, leading to underestimation of the globality. After considering both local and global information, 6° is deemed suitable for evaluating the global representativeness of U-Pb data in the OneDZ database. Figures 14c-e also show periodic peaks in globality coincides with specific geological eras. This phenomenon might be correlated with the heightened research interest in these periods. Samples from these periods are more likely to stimulate scientific inquiry due to the dynamic geological processes occurring at those times. Despite the large volume of data in OneDZ, the calculated paleo-spatial reconstruction does not fully represent global features for most geological times, as the reconstruction does not account for 100 percent of the spatial details. For example, the sample distribution reconstructed for 250 Ma (as shown in Figure 14g-h) appears to have global coverage. However, the calculated paleo-spatial reconstruction for this period only accounts for approximately 30% to 60% of the actual spatial distribution. Consequently, we recommend that regional data be handled with greater caution when interpreting global geological events. It is particularly important to employ spatial kernel density evaluation methods to ensure a more accurate representation of the data.

5.2 Compare the resampling methods

The temporal evolution of zircon U-Pb data is often analysed through big data methods and plays a crucial role in understanding the development of orogenic belts and crustal thickness. Big data methods with zircon U-Pb offer insights into Earth system evolution based on anomalies in time series data. Usually, the fluctuations in the curve are explained as the evolution of the Earth system. Not only is there a risk of data not being globally representative, but the zircon U-Pb curves obtained from big data analysis may also be statistically biased due to inconsistent data volumes. Some resampling statistical tools like Bootstrap and Monte Carlo methods are applied in zircon big data analysis (Keller & Schone, 2012; Yang et al., 2024; Yang et al., 2025). These methods have usually been assumed to be effective in previous studies. However, these resampling methods have not been systematically tested. The zircon U-Pb data in OneDZ, as the world's largest multidimensional imbalanced spatiotemporal dataset, provides a data foundation for comparing the effects when applying different resampling methods.

Firstly, we selected the best age data from zircon U-Pb data for time resampling experiments. In addition to comparing Bootstrap and Monte Carlo resampling methods, we assessed the impact of data sparsity using the 2σ error to identify potential outliers and quantify the uncertainty. The experiment focuses on the sparsity of samples generated within the time range of zircon U-Pb ages exceeding 2500 Ma, with a threshold of 400 Ma. After time resampling using Monte Carlo (Figure 8d-f) and Bootstrap methods (Figure 8g-i), the overall trend of zircon best age data is consistent. Even on time series after 2500 Ma, there was no significant difference in the characterization of evolutionary trends between the two resampling methods. However, there is a significant difference between the two methods in characterizing the details of a time series. In the ^{206}Pb/^{238}U isotope system, four periodic fluctuations were observed in the Monte Carlo resampling results over the time period of 0-1000 Ma (Figure 8d). The Bootstrap method only shows a slight increase around 500 Ma on the same time scale (Figure

8g). The rest of the time scales show a slow increase. In the ^{207}Pb/^{235}U isotope system, the Monte Carlo resampling results showed four small amplitude periodic fluctuations in the 0-2000Ma time period under a generally slow rising background (Figure 8e). The Bootstrap method showed a significant decrease around 1500 Ma on the same time scale (Figure 8h). In the ^{207}Pb/^{206}U isotope system, the Monte Carlo resampling results showed a significant decrease around 1500Ma (Figure 8f). In contrast, the Bootstrap method shows a periodic decrease (Figure 8i), which differs from the more substantial decrease observed with other methods. Although Figure 8 overall depicts the magnitude of age error over time in different systems and does not have practical geological significance, the significant differences in the time curves after resampling using Monte Carlo and Bootstrap methods indicate the need for caution in interpreting data after applying resampling methods. Furthermore, we compared the results of time resampling methods for zircon U-Pb and Lu-Hf system time series data in OneDZ. In the analysis of zircon U-Pb data, the Bootstrap method demonstrates greater consistency over time (Figure 11a-c), meaning that the results obtained using this method exhibit less variation across different time periods compared to other methods. The Monte Carlo method is more sensitive to local data fluctuations than the Bootstrap method (Figure S7 in the Supplement). The Monte Carlo method also shows significant oscillations on relatively sparse εHf(0) and εHf(t) and corresponding errors data (Figure S7a-c in the Supplement). The difference between Bootstrap and Monte Carlo methods will also disappear as the amount of data increases. In the ^{176}Yb/^{177}Hf 2 σ error time series, due to the significant increase in data volume, the significant difference in the results of resampling methods is relatively small (Figure S8 in the Supplement). The above experimental time series data density statistics show that different resampling methods are actually controlled by data density and the areas where significant oscillations occuring in the Monte Carlo method coincide with areas with high data density (Figure 11-12, S7-S7). Since standard Monte-Carlo time-resampling assumes that the underlying process is stationary (often approximated by normality or local uniformity, by Rubinstein & Krose (2016)), it can yield biased estimates when the data density evolves sharply within the chosen window—a situation common in high-frequency zircon datasets. Consequently, more flexible, density-aware resampling strategies are preferred for zircon big-data analysis.

Spatial over-sampling introduces another potential bias that has gained attention in the field (Keller et al., 2018). Addressing this issue often involves spatial resampling methods, which were employed in this research using the OneDZ database. Initially, Monte Carlo spatial resampling was used to assess the frequency at which samples are selected (Keller et al., 2018). Ideally, a balanced spatial sampling should achieve equal total sampling frequencies across regions, increasing the likelihood of sampling from underrepresented areas. Our findings suggest that direct application of the Monte Carlo method does not mitigate sampling bias. Samples from East Asia, particularly China, remain overrepresented due to the large volume of available data from this region, skewing the overall data distribution and leaving other regions sparsely represented, similar to the observed sample sparsity in the temporal domain (Figure 16a). To counteract the hypothesis, we explored data augmentation methods to generate new data points in under-sampled regions. This study introduces the Synthetic Minority Over-sampling Technique (SMOTE, Chawla et al., 2002) to create synthetic data points from regions other than China while preserving the same data features. Applying SMOTE led to a significant increase in resampling frequency in these regions (Figure 16b). Inspired by grid-based methods, we also pre-processed the data by averaging the U-Pb age signals before applying SMOTE. This novel approach enhanced resampling frequency in previously under-sampled regions, resulting in the sampling differences in different regions to significantly reduce (Figure 16c). Direct spatial resampling methods may not adequately resolve spatial imbalances. However, combining these methods with data enhancement techniques and grid-based approaches can significantly mitigate spatial biases.

5.3 Implications for database construction and future developments

The construction of the OneDZ database, which employs a crowdfunding approach, has the potential to significantly broaden data coverage (comparison with other databases can be seen in Figure S10). However, crowdfunding introduces challenges, such as inconsistencies in data formatting and the risk of human errors. To address these issues, a series of Python and MySQL scripts for automated data cleaning and inspection were developed. These scripts have successfully replaced labor-intensive manual inspections, reducing both labor costs and the potential for data errors. From the OneDZ construction process, crowdfunding with automatic data cleaning by Python and MySQL code snippets is feasible and greatly improved the efficiency of database construction.

Moreover, AI tools have played a pivotal role in the data collection and extraction process. Unlike traditional web crawlers, which can pose privacy risks, AI models can predict whether an article may contain the required database features based on publicly available text information, such as titles and abstracts. The integration of AI models into the database construction process eliminates the need for manual screening of potential articles, significantly improving efficiency. Additionally, computer vision tools like DeepShovel are crucial, as a considerable amount of article data is stored in PDF image files in the form of tables. Manual reading and data storage are not sustainable approaches for handling such large volumes of data. Computer vision-based AI models show great promise in reducing labor costs and increasing efficiency.

Furthermore, the limitations of traditional tools like Excel in storing and managing large datasets, especially given the .xlsx format's known data storage caps and issues with formatting errors, have become increasingly apparent. The need for rapid data retrieval in super large databases also renders Excel inefficient for this purpose. In contrast, MySQL offers both unlimited storage capacity and extremely low retrieval latency, making it a superior tool for constructing super large databases in the Earth sciences.

In the OneDZ database, users can quickly retrieve detrital zircon data based on regional search criteria. Regional retrieval is quickly completed through latitude and longitude ranges. Although previous datasets have achieved certain milestones, OneDZ significantly enhances the utility of detrital zircon data by incorporating comprehensive information on lithology, stratigraphy, and depositing age, thereby greatly expanding the scope of analysis. Meanwhile, in conjunction with other Earth science datasets, it is possible to further explore the temporal and spatial evolution patterns of the Earth.

The construction of super large databases in Earth science, utilizing AI and automated scripts, is still in the experimental phase. However, with the rapid advancement of AI, particularly large language models like GPT, we anticipate the development of even more capable models to handle such text-intensive tasks. Additionally, establishing an automated processing platform and designing a user-friendly graphical interface for experts involved in the crowdfunding construction could further reduce labor costs. Progress is being made in developing such a platform and interface, which will be instrumental in advancing the field.

Data availability

The database (Li et al., 2025) is freely available via Zenodo at https://doi.org/10.5281/zenodo.17407937. All code snippets in this research are accessible via https://github.com/KeranLi/Global-Detrital-Zircon. The OneDZ web platform is accessible via https://onedz.top/.

Conclusion

In this study, we introduce a ground-breaking global detrital zircon U-Th-Pb geochronology and Lu-Hf isotope database, which serves as a critical resource for advancing Earth science research. This database includes 1925687 U-Pb and 275971 Lu-Hf records, offering a broad sampling range from global detrital rocks. The database offers an extensive and diverse collection of data, including various types of stratigraphic information, a broad range of sedimentary ages, comprehensive isotope geochemical datasets, and data from multiple analytical techniques such as LA-ICP-MS, SHRIMP, SIMS, and TIMS.

Based on this database, we have characterized the uncertainties associated with zircon dating, compared the efficacy of different analytical techniques, proposed an evaluation method that assesses the deep-time global coverage of the data and discussed the challenges and potential solutions related to spatiotemporal sampling methods. Although the data is globally sourced, variations in spatial and temporal distribution can affect its global representativeness. Therefore, when conducting big data analyses on spatial or temporal distributions, reconstructing data's paleo-points is necessary. In imbalanced spatiotemporal data resampling methods, Bootstrap methods and SMOTE data augmentation methods may be more suitable.

The development of OneDZ demonstrates that leveraging crowdfunding and automated code cleaning processes is essential for the rapid assembly of a comprehensive database. Furthermore, integrating AI tools with MySQL enhances both the construction and usability of such databases, making them more efficient and accessible.

Author contributions

KL, XH, RC, JH, WX, YP, AM, HH, QG, WY, LH, LQ, GC, GS, SZ, TD, KL, JS and BG compiled the data. KL, RC and WX merged the data, formatted the data, performed the analyses, standardized the reference materials, organized the database, managed the publication of the database in the Zenodo repository, and drafted and revised the manuscript. KL designed the code snippets. TL and CF developed the web platform. HX initiated and supported the data compilation.

Competing interests

The contact author has declared that none of the authors has any competing interests.

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Zhang, S., Jia, Y., Xu, H., Wen, Y., Wang, D., and Wang, X.: Deepshovel: An online collaborative platform for data extraction in geoscience literature with ai assistance, arXiv preprint arXiv:2202.10163, https://doi.org/10.48550/arXiv.2202.10163, 2022b.

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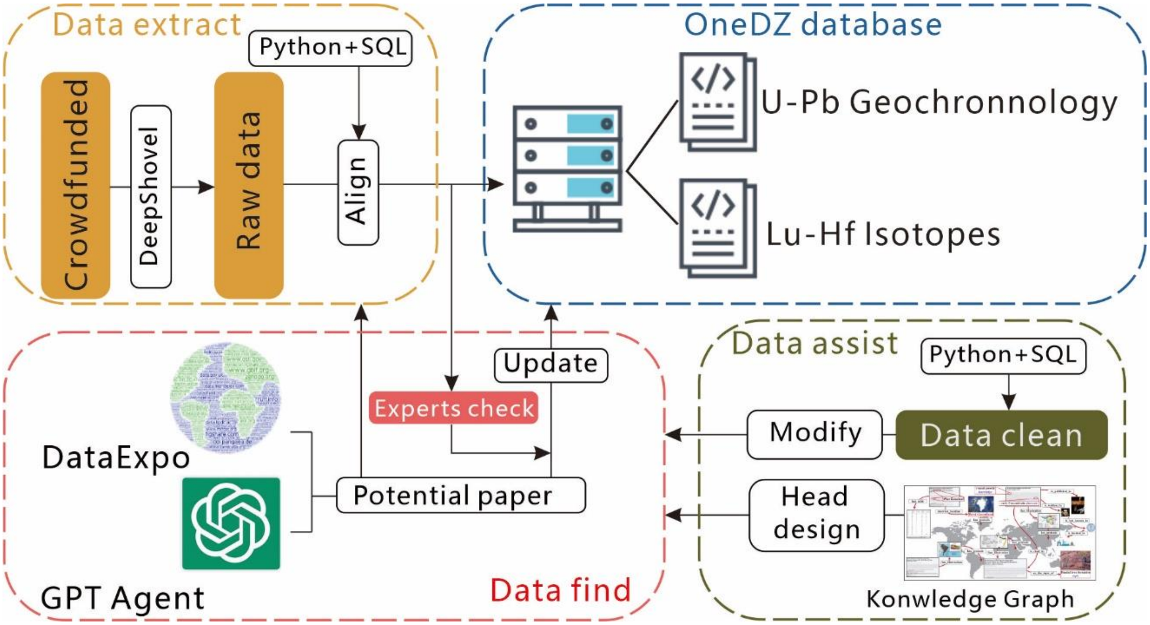


Figure 1: Workflow of constructing the OneDZ database (DataExpo was adopted from Lu et al., 2023, the DeepShovel tool was developed by Zhang et al., 2023, and the knowledge graph was based on Hu et al., 2024).

Figure 2: Schematic of the OneDZ relational schema. The three core tables (blue) and two geochemical tables are linked by the primary key zircon_id (varchar 100). Black underlines indicate primary keys; arrows denote foreign-key relationships.

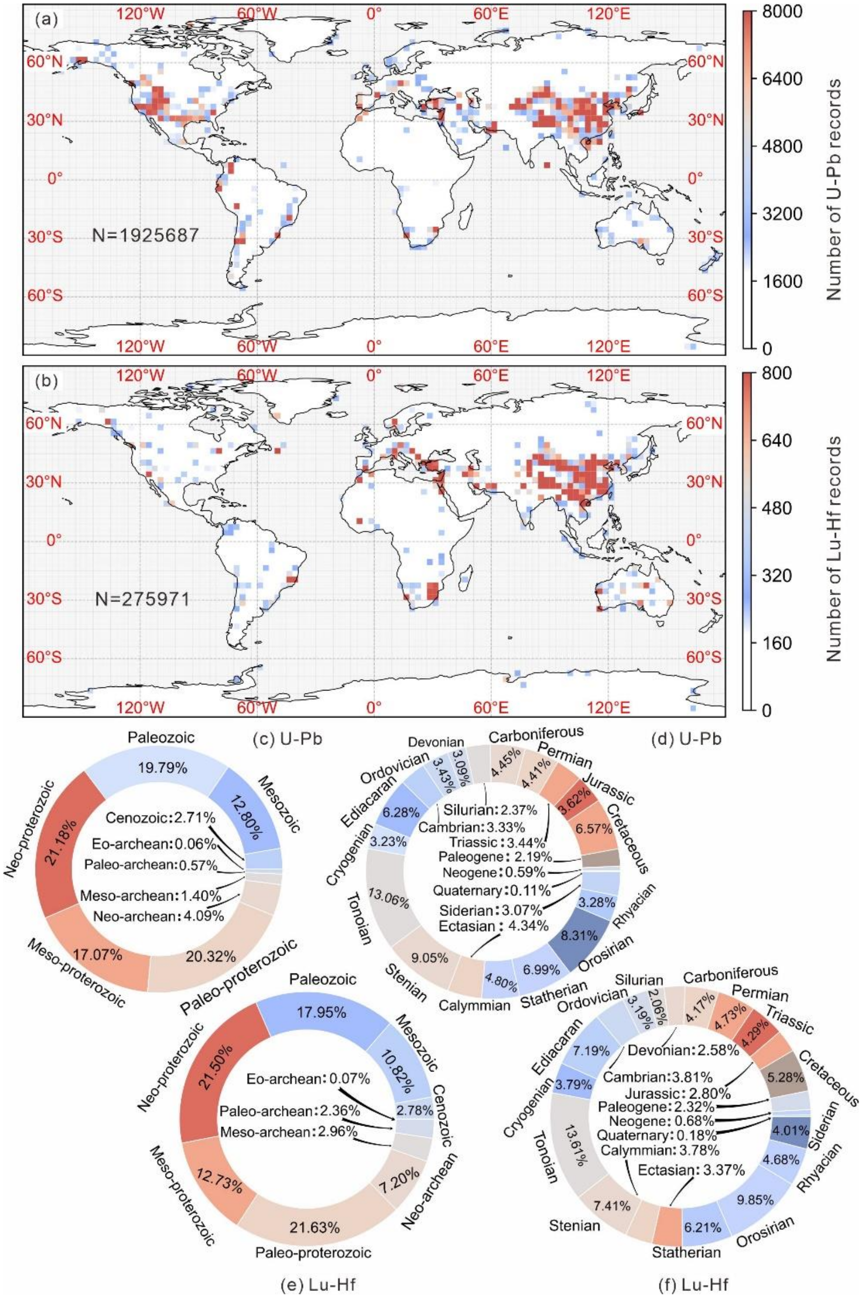


Figure 3: Spatial and temporal distributions of U-Pb and Lu-Hf isotopic records. (a) Kernel density estimate map of U-Pb records (the spatial resolution is 1°×1°); (b) Kernel density estimate map of Lu-Hf records (the spatial resolution is 1°×1°); (c) Era-based distribution of U-Pb samples; (d) Period-based distribution of U-Pb samples; (e) Era-based distribution of Lu-Hf samples; (f) Period-based distribution of Lu-Hf samples.

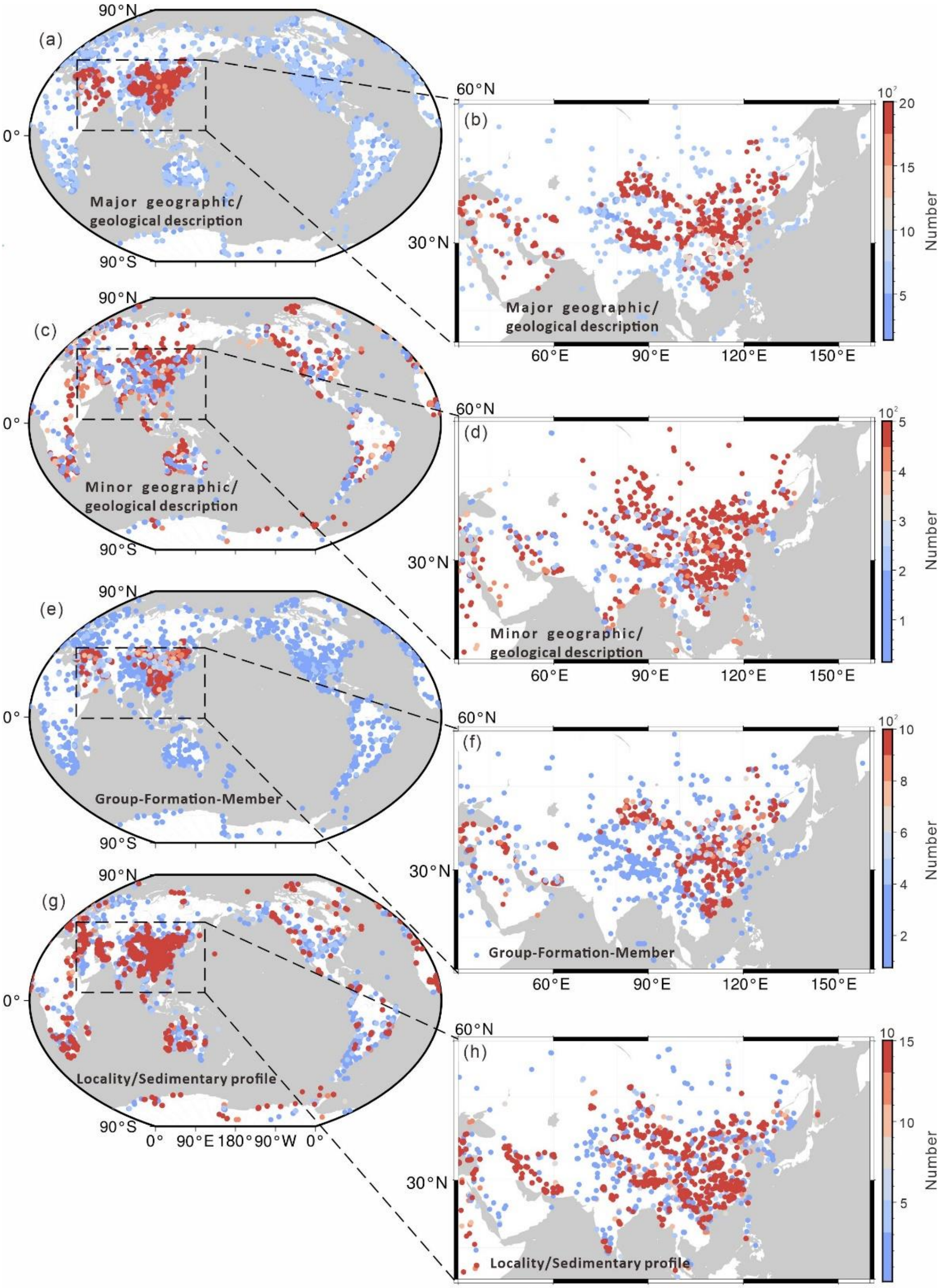


Figure 4: Visualizations of the spatial, temporal and strata information in U-Pb dataset. (a)-(b) Major geographic/geological description; (c)-(d) Minor geographic/geological description; (e)-(f) Group-Formation-Member records; (g)-(h) Locality/Sedimentary profile.

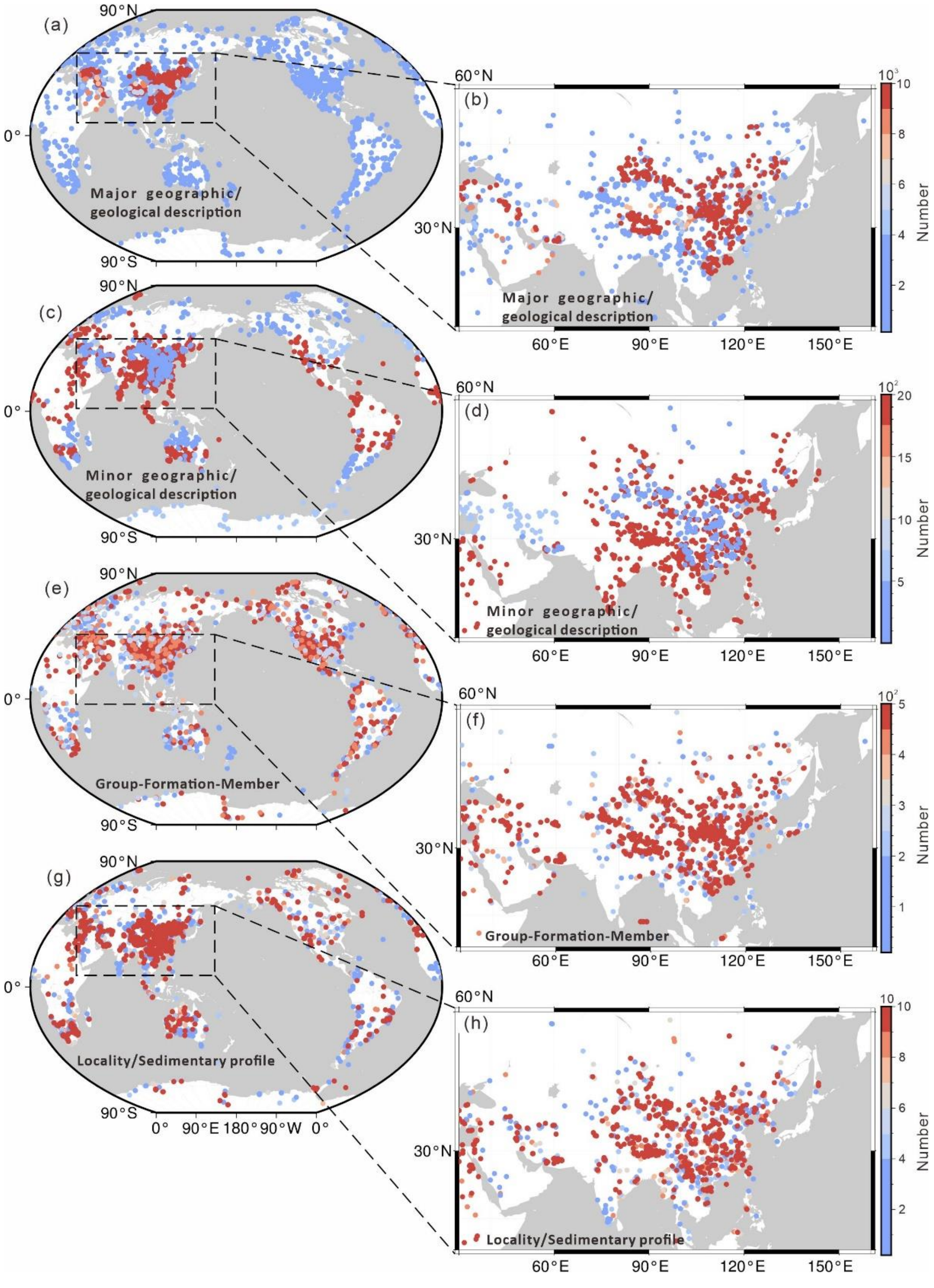


Figure 5: Visualizations of the spatial, temporal and strata information in Lu-Hf dataset. (a)-(b) Major geographic/geological description; (c)-(d) Minor geographic/geological description; (e)-(f) Group-Formation-Member records; (g)-(h) Locality/Sedimentary profile.

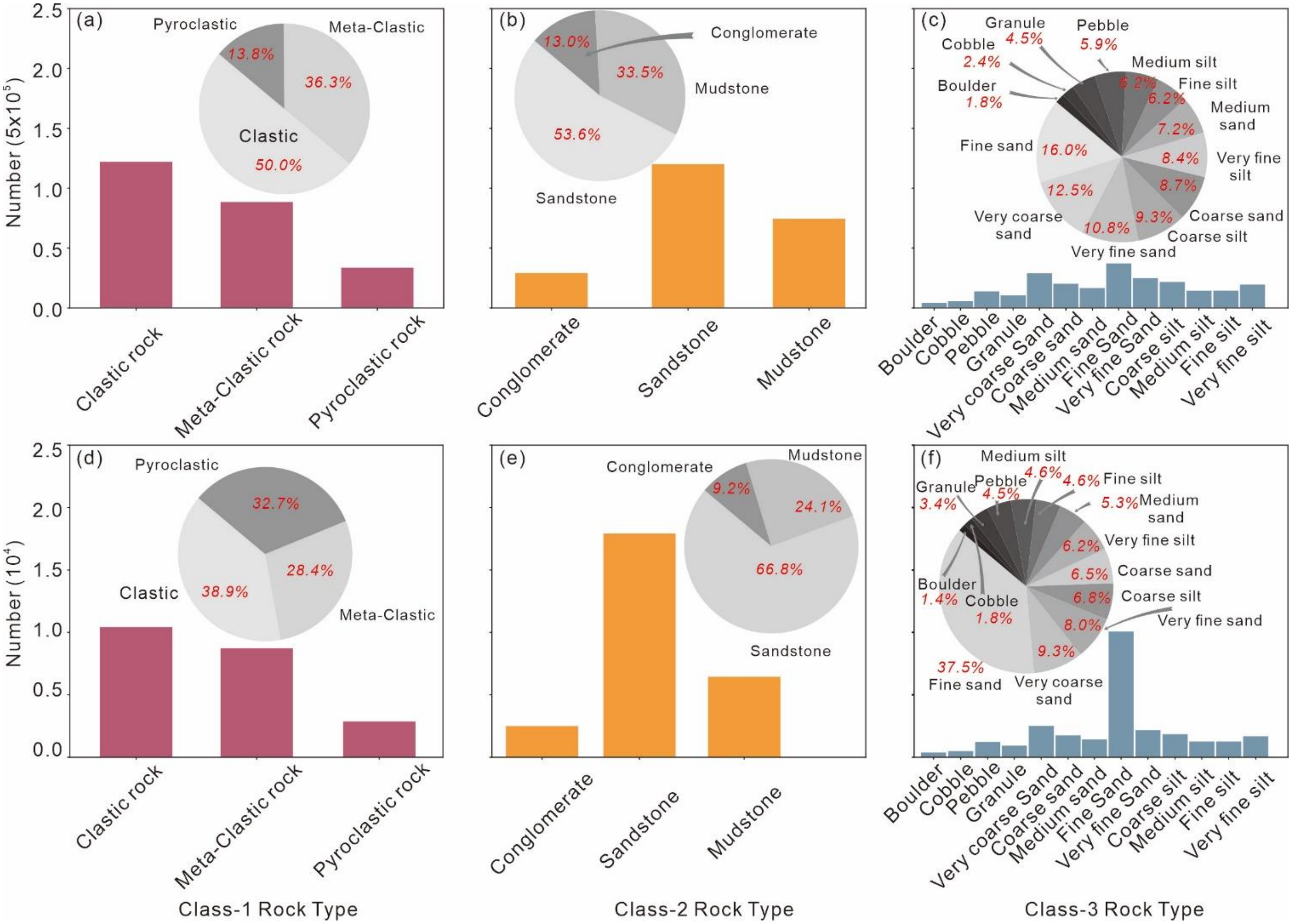


Figure 6: Statistics of the rock types. (a) Class-1 type in U-Pb database; (b) Class-2 type in U-Pb database; (c) Class-3 type in U-Pb database; (d) Class-1 type in Lu-Hf database; (e) Class-2 type in Lu-Hf database; (f) Class-3 type in Lu-Hf database.

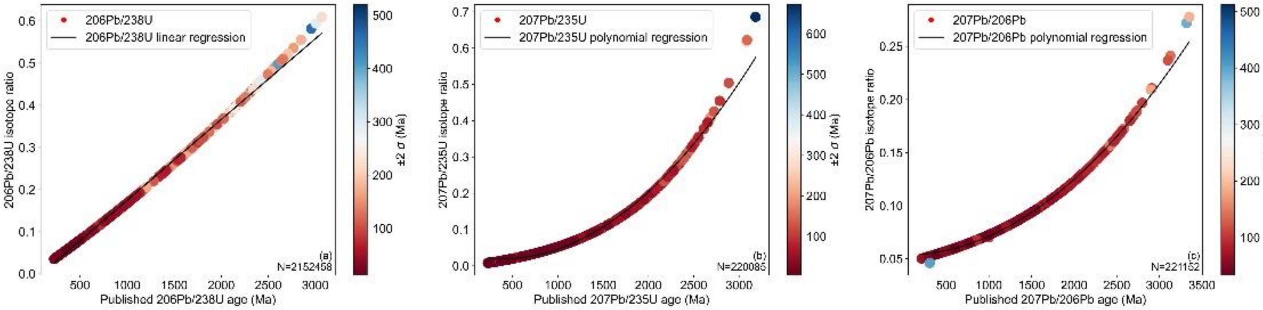


Figure 7: Ages errors of different isotopic systems. (a) ^{206}Pb/^{238}U; (b) ^{207}Pb/^{235}U; (c)^{207}Pb/^{206}Pb.

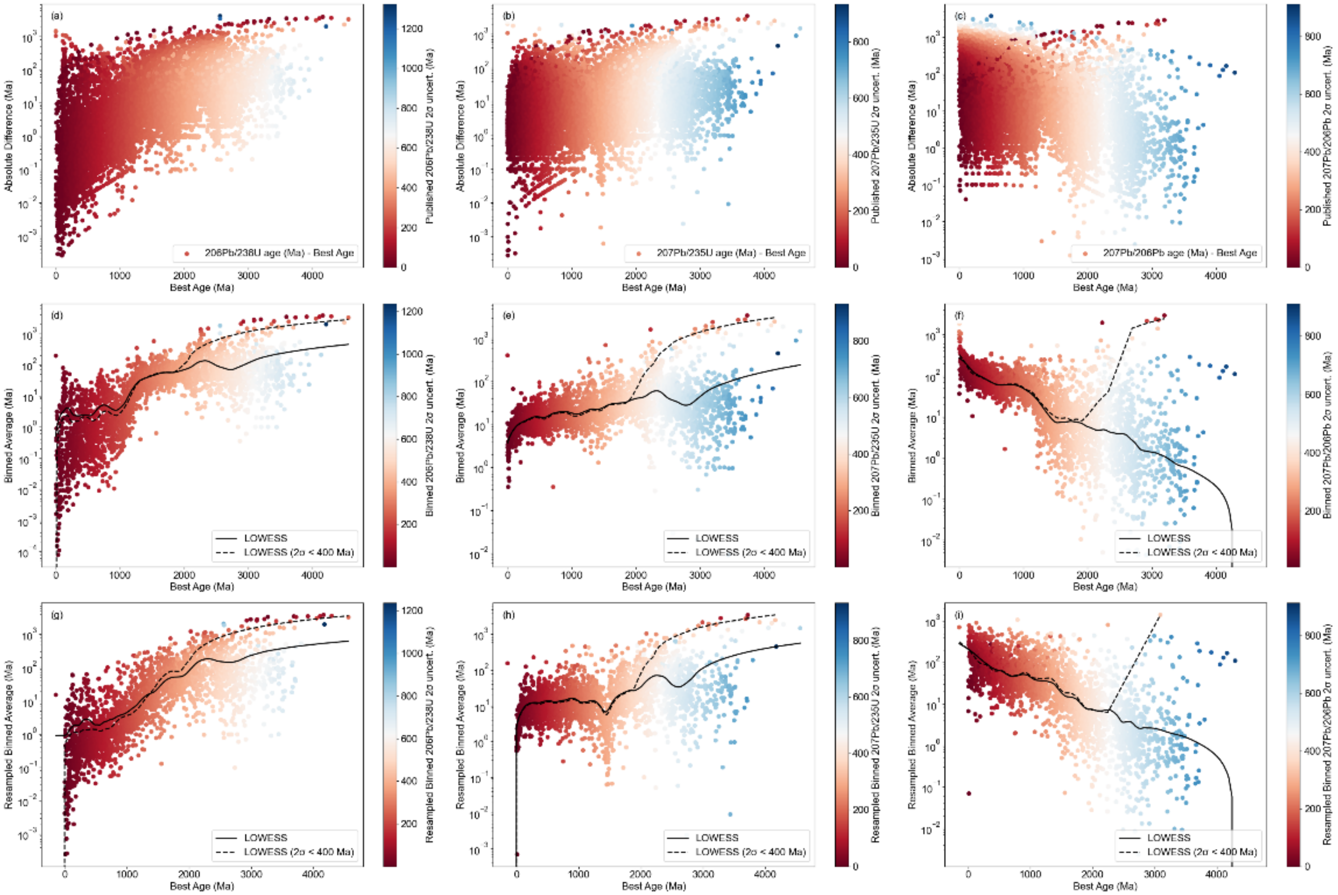


Figure 8: Time-series of dating error via different isotopes. (a)-(c) Original data distribution; (d)-(f) Resampled by Monte-Carlo method; (g)-(i) Resampled by bootstrap method.

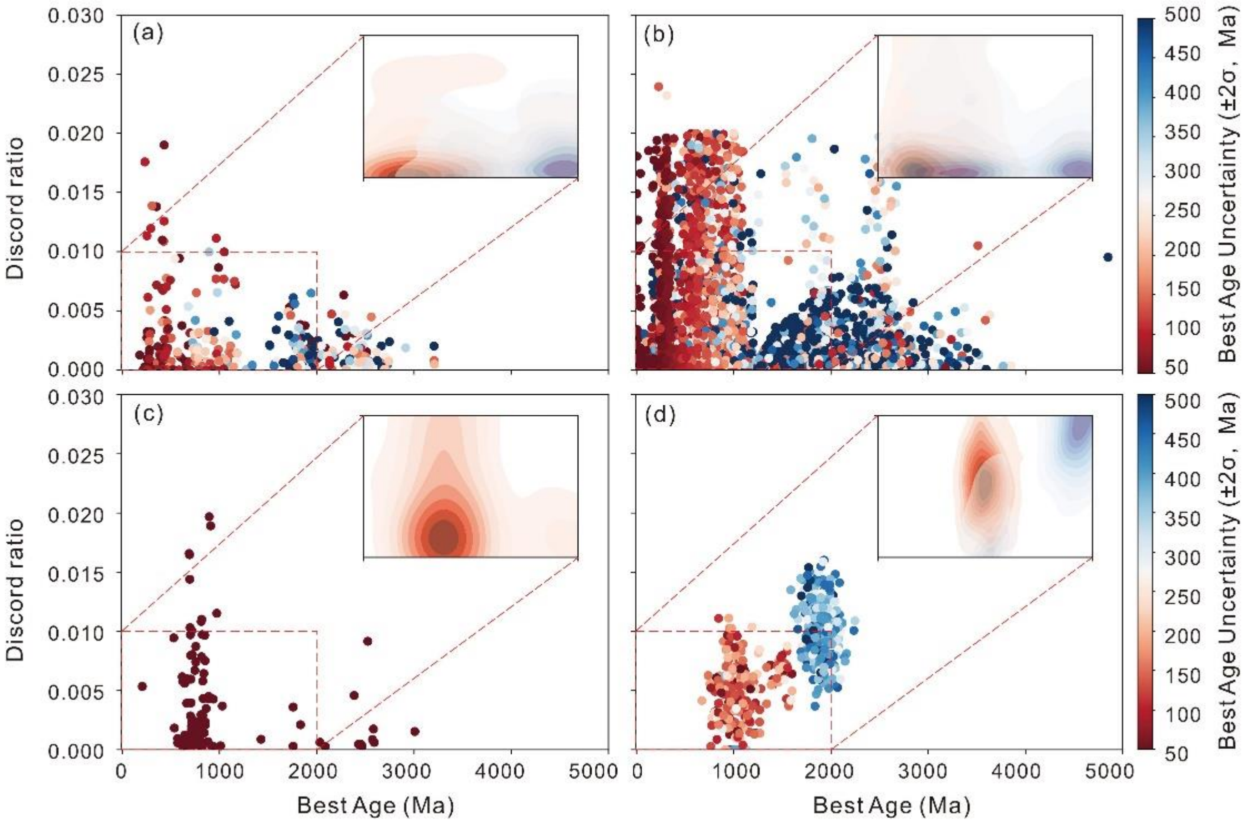


Figure 9: Discordance ratio varying with time by different instruments. (a) SHRIMP; (b) LA-ICP-MS; (c) ID-TIMS; (d) SIMS.

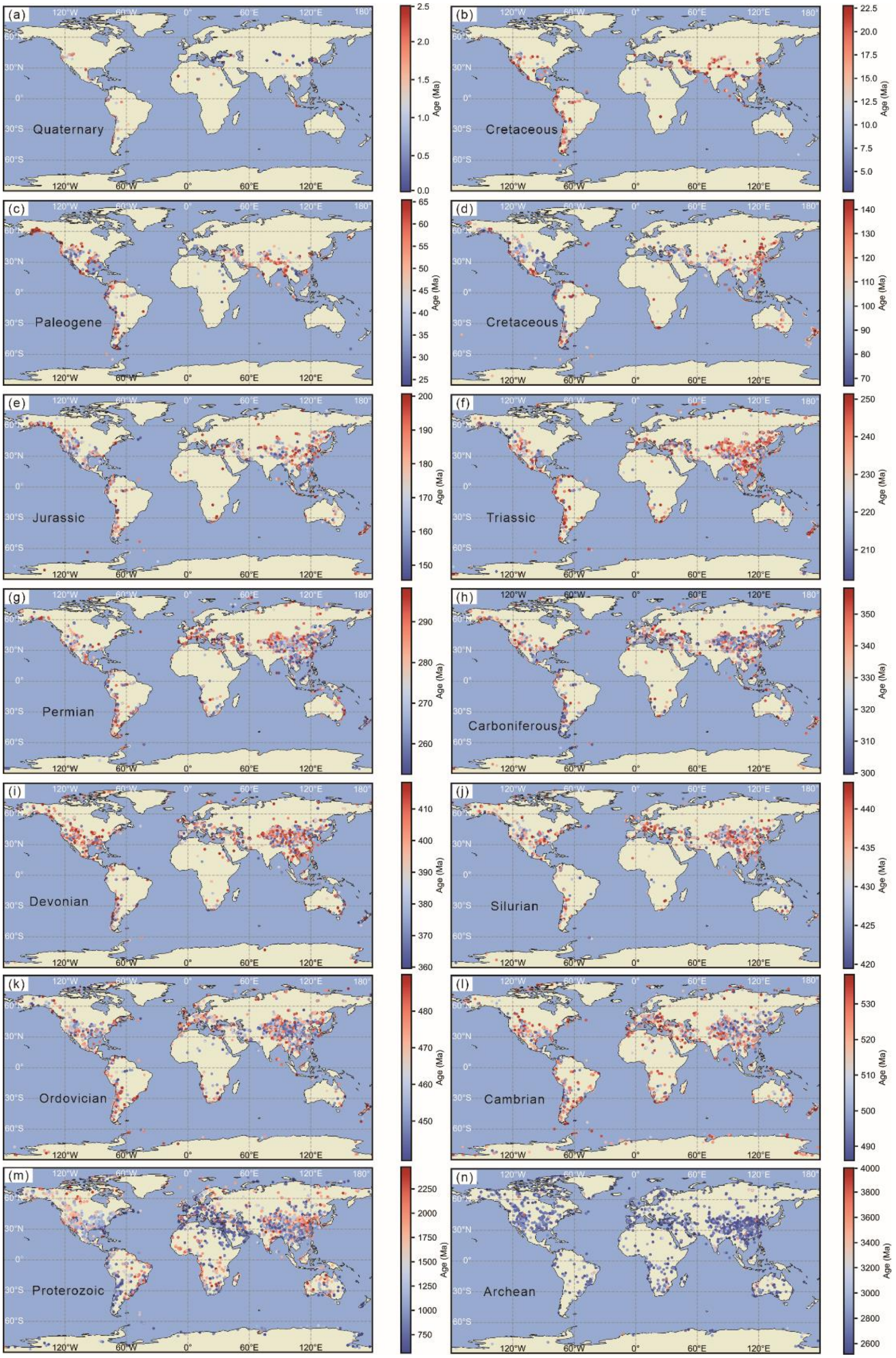


Figure 10: Spatial-temporal distribution of the single U-Pb age record.

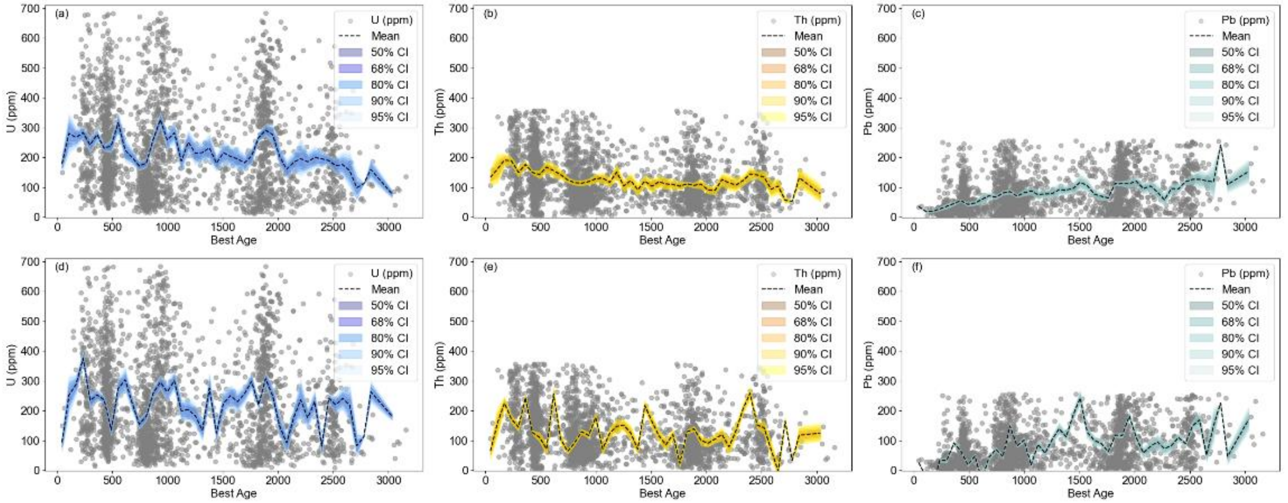


Figure 11: Discordance ratio varying with time by different instruments. (a) SHRIMP; (b) LA-ICP-MS; (c) ID-TIMS; (d) SIMS.

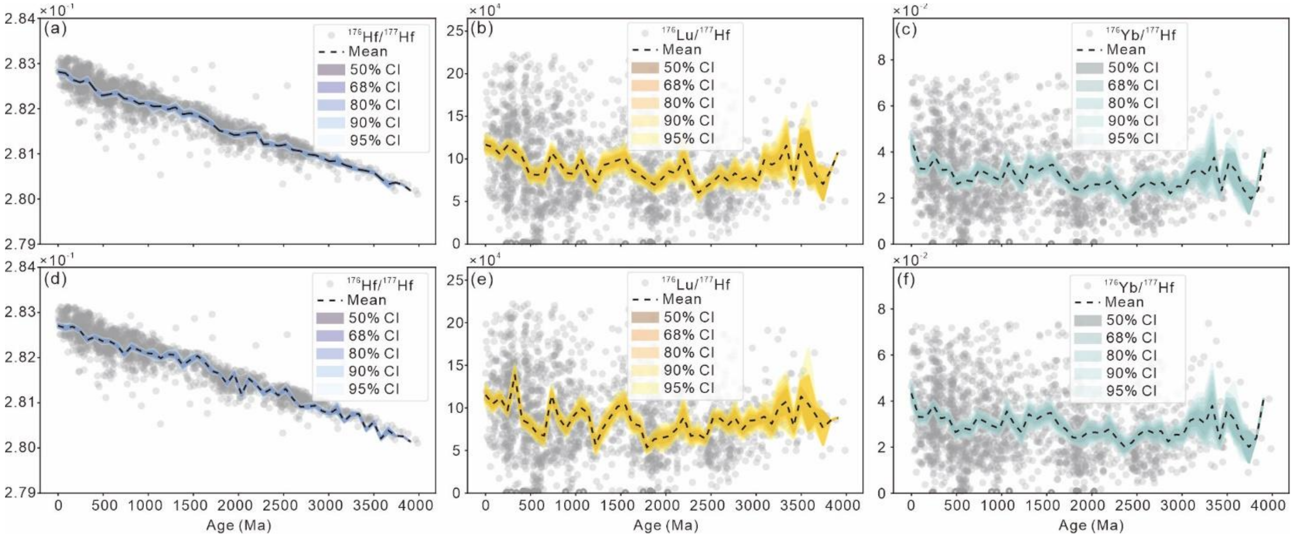
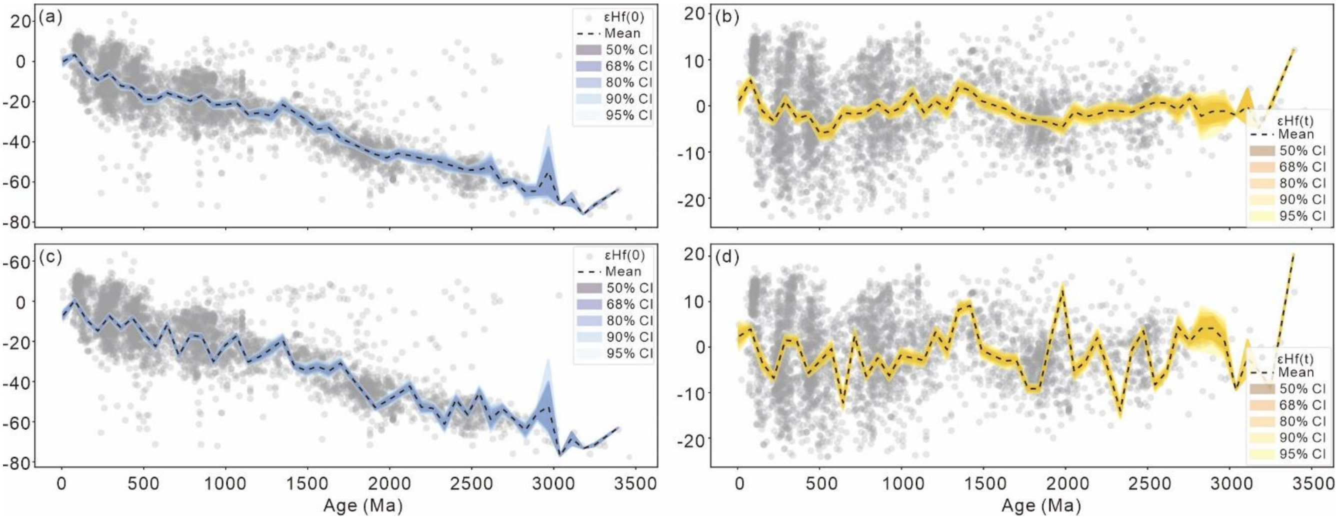


Figure 12: Temporal variations of isotopic uncertainties in Lu-Hf dataset. (a) ^{176}Hf/^{177}Hf with bootstrap resampling; (b) ^{176}Lu/^{177}Hf with bootstrap resampling; (c) ^{176}Yb/^{177}Hf with Monte-Carlo resampling; (d) ^{176}Hf/^{177}Hf with Monte-Carlo resampling; (e) ^{176}Lu/^{177}Hf with Monte-Carlo resampling; (f) ^{176}Yb/^{177}Hf with Monte-Carlo resampling.



655 **Figure 13: Temporal variations of εHf uncertainties in Lu-Hf dataset. (a) εHf(0) with bootstrap resampling; (b) εHf(t) with bootstrap resampling; (c) εHf(0) with Monte-Carlo resampling; (d) εHf(t) with Monte-Carlo resampling.**

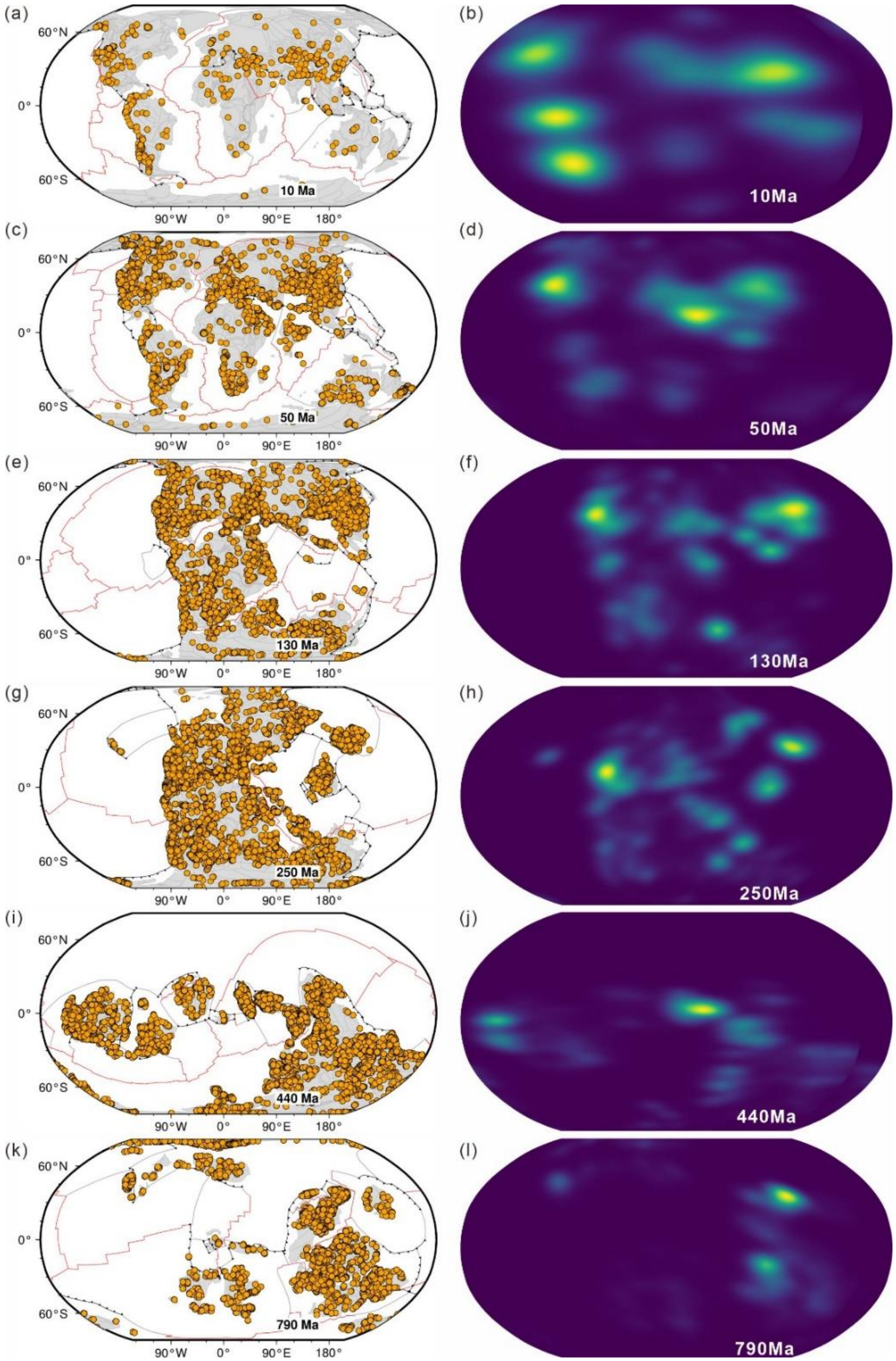


Figure 14: Paleo-distributions and spatial kernel density estimate of U-Pb records (the tectonic model was from Merdith et al., 2021 and the temporal resolution is 1˚×1˚). (a)-(b) Paleo-distribution and density of 10Ma; (c)-(d) Paleo-distribution and density of 50Ma; (e)-(f) Paleo-distribution and density of 130Ma; (g)-(h) Paleo-distribution and density of 250Ma; (i)-(j) Paleo-distribution and density of 440Ma; (k)-(l) Paleo-distribution and density of 790Ma.

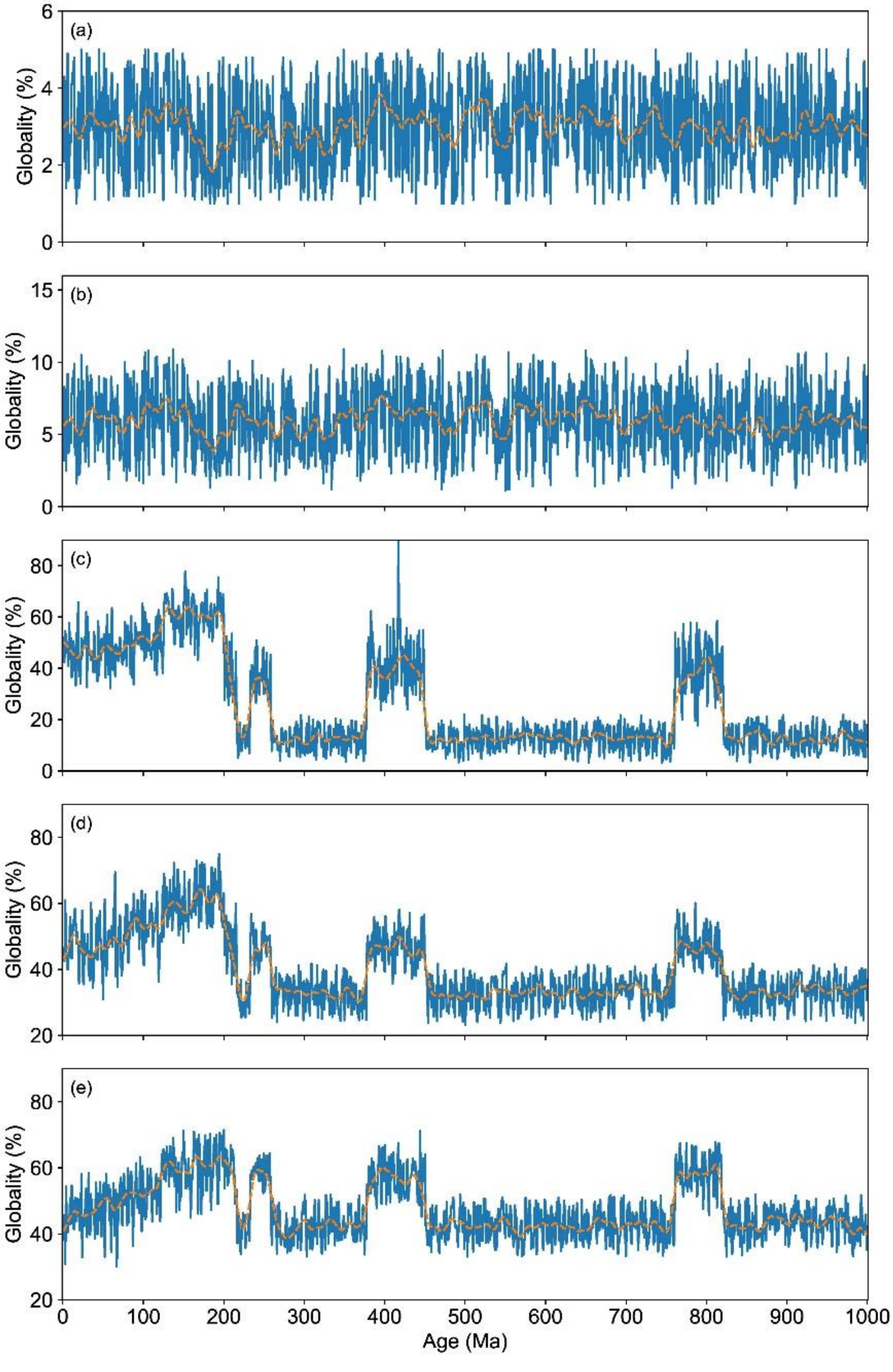


Figure 15: Global evaluation of U-Pb data with different grid sizes. (a) 2°; (b) 4°; (c) 6°; (d) 8°; (e) 10°.

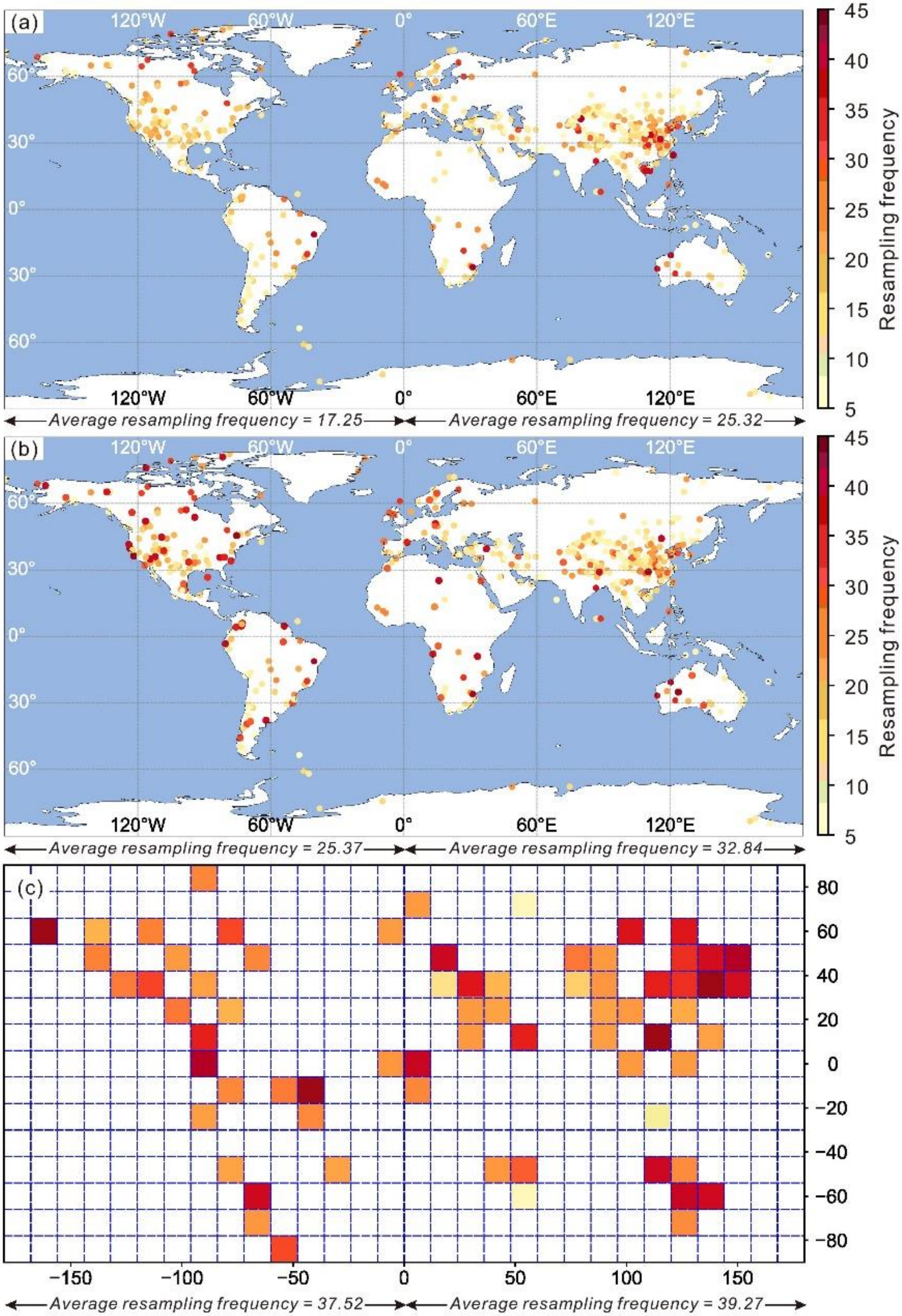


Figure 16: The resampling frequency of different methods. (a) Monte-Carlo method; (b) SMOTE-Monte-Carlo method; (c) 12°×12° grid-SMOTE-Monte-Carlo method.

Table 1: Construction methods comparison of three typical zircon databases

Dataset	Methods	Information types	Data cleaning	Adapting AI tool	Manage data
OneDZ	Crowdfunding	Data origin, Spatial information, Stratigraphic information, Isotopic information	Python and MySQL scripts and artificial checking	Yes	MySQL
Wu et al., 2024	Directly collecting	Data origin, Spatial information, Isotopic information	Artificial checking	Not mentioned	Excel
Puetz et al., 2024	Directly collecting	Data origin, Spatial information, Stratigraphic information, Isotopic information	Artificial checking	Not mentioned	Excel

Table 2: Data comparison of three typical zircon databases

Dataset	Field number of U-Pb	Field number of Lu-Hf	Reference (10^4)	Sample (10^4)	Region	Geological unit	Valid U-Pb age with GPS (10^6)	Valid Lu-Hf data with GPS (10^5)
OneDZ	**71**	**86**	**5.4**	**31**	**215**	**1348**	**1.8**	**2.7**
Wu et al., 2024	24	/	3.4	2.8	208	1347	0.5	/
Puetz et al., 2024	34	26	4.2	20	215	1305	0.6	2.1

Note: the bolded number represents the largest number in different items. Only statistic the detrital zircon from Wu et al., 2024 and Puetz et al., 2024.

Table 3: Data specifications of the reference information (the proportion was calculated by number of valid items divided the number of total items)

Dataset	Field Name	Corresponding field in Puetz et al., 2024	Corresponding field in Wu et al., 2024	Proportion
U-Pb	Lead_Author	Lead_Author	Author_surname and Author_given_name	100.00%
	Year	Year	Year_publication	100.00%
	Journal	Journal	Journal	100.00%

	Vol.	Vol.	Volume	96.99%
	Pages	Pages	First_page and Last_page	95.93%
	Title	Title	Title	100.00%
	Web_Link	Web_link	DOI	54.50%
Lu-Hf	Lead_Author	Lead_Author	Lead_Author	100.00%
	Year	Year	Year	100.00%
	Journal	Journal	Journal	100.00%
	Vol.	Vol.	Volume	96.48%
	Pages	Pages	Pages / Article No.	96.48%
	Title	Title	Title	100.00%
	Web_Link	Web_Link	Web Link	100.00%

Table 4: Data specifications of the sample, spatial and strata information (the proportion was calculated by number of valid items divided the number of total items)

Dataset	Parameter	Corresponding field in Puetz et al., 2024	Corresponding field in Wu et al., 2024	Proportion
U-Pb	Published_Sample_ID	Smaple_ID	Sample_number	26.88%
	Country_State	Country/Small Region		26.91%
	Region	Large Region		79.75%
	Continent	Continent		75.96%
	Major_Geologic_Description	Major Geographic-Geologic Description		26.90%
	Minor_Geologic_Description	Minor Geologic-Geographic Unit		21.45%
	Group			9.97%
	Formation			20.94%
	Member			11.30%
	Locality	Locality		66.10%
	Sedimentary profile			4.61%
	Latitude	Latitude	Latitude	96.23%
	Longitude	Longitude	Longitude	96.23%
	Depos. Age (Period)			11.31%
	Depos. Age (Epoch)			10.95%
	Depos. Age (Age)			10.14%

	Max. Depos. Age (Ma)	Max. Stratigr. Age (Ma) (detrital only)		10.15%
	Est. Depos. Age (Ma)	Est. Stratigr. Age (Ma) (detrital only)		11.51%
	Min. Depos. Age (Ma)	Min. Stratigr. Age (Ma) (detrital only)		9.14%
Lu-Hf	Published_Sample_ID	Ref. No.	Published Sample_ID	21.47%
	Country_State		Country/Small Region	75.85%
	Region			78.76%
	Continent		Continent	73.99%
	Major_Geologic_Description		Major_Geologic_Description	68.78%
	Minor_Geologic_Description		Minor_Geologic_Description	67.01%
	Group			5.05%
	Formation			10.05%
	Member			0.80%
	Locality		Locality	80.86%
	Sedimentary profile			1.82%
	Latitude		Latitude	99.03%
	Longitude		Longitude	99.03%
	Depos. Age (Period)			12.28%
	Depos. Age (Epoch)			8.09%
	Depos. Age (Age)			3.92%
	Max. Depos. Age (Ma)			8.85%
	Est. Depos. Age (Ma)		Est. Strat. Age (Ma)	46.17%
	Min. Depos. Age (Ma)			6.99%

Table 5: Data specifications of the U-Pb isotopic system (the proportion was calculated by number of valid items divided the number of total items)

Field Name	Corresponding field in Puetz et al., 2024	Corresponding field in Wu et al., 2024	Proportion
Mass_Spectrometer	Mass Spectrometer	Instrument	57.02%
Spectrometer_Location	Spectrometer Location		58.42%
Institution	Institution		61.09%
U_Pb_Record_Count	Accepted records		60.97%

Grain_ID	Sample&Grain		98.16%
Spot	Spot		75.95%
Spot_diam	Spot diam. (µm)		12.14%
206Pb_238U_isotope_ratio	206Pb/238U ratio	isotope206Pb/238U	69.16%
206Pb_238U_isotope_uncertainty_1sigma	206Pb/238U 1σ uncert	isotope206Pb/238U_σ	63.26%
206Pb_238U_isotope_uncertainty_2sigma			63.26%
207Pb_235U_isotope_ratio	calculated 207Pb/235U ratio	isotope207Pb/235U	21.31%
207Pb_235U_isotope_uncertainty_1sigma	207Pb/235U 1σ uncert	isotope207Pb/235U_σ	17.06%
207Pb_235U_isotope_uncertainty_2sigma			17.06%
207Pb_206Pb_isotope_ratio	207Pb/206Pb ratio	isotope207Pb/206Pb	6.77%
207Pb_206Pb_isotope_uncertainty_1sigma	207Pb/206Pb 1σ uncert	isotope207Pb/206Pb_σ	5.00%
207Pb_206Pb_isotope_uncertainty_2sigma		Optional	5.00%
208Pb_232Th_isotope_ratio	isotope208Pb/232Th	Optional	3.09%
208Pb_232Th_isotope_uncertainty_1sigma	isotope208Pb/232Th_σ	Optional	3.09%
208Pb_232Th_isotope_uncertainty_2sigma		Optional	3.09%
Published_206Pb_238U_age	206Pb/238U age (Ma)	age206Pb/238U	97.94%
Published_206Pb_238U_age_uncertainty_1sigma		age206Pb/238U_σ	90.93%
Published_206Pb_238U_age_uncertainty_2sigma	206Pb/238U 2σ uncert		90.93%
Published_207Pb_235U_age	207Pb/235U age (Ma)	age207Pb/235U	90.94%
Published_207Pb_235U_age_uncertainty_1sigma		age207Pb/235U_σ	90.94%
Published_207Pb_235U_age_uncertainty_2sigma	207Pb/235U 2σ uncert	Optional	90.94%
Published_207Pb_206Pb_age	207Pb/206Pb age (Ma)	age207Pb/206Pb	93.38%

Published_207Pb_206Pb_age_uncertainty_1sigma	age207Pb/206Pb_σ	93.38%
Published_207Pb_206Pb_age_uncertainty_2sigma	207Pb/206Pb 2σ uncert	93.38%
Best_Age		99.99%
Best_Age_uncertainty_1sigma		95.56%
Best_Age_uncertainty_2sigma		95.56%
Discord_ratio		25.12%
U_ppm		21.56%
Th_ppm		21.56%
Pb_ppm		21.56%

Table 6: Data specifications of the Lu-Hf isotopic system (the proportion was calculated by number of valid items divided the number of total items)

Field Name	Corresponding field in Puetz et al., 2024	Proportion
Mass_Spectrometer		10.26%
Spectrometer_Location		14.28%
Institution		3.83%
Lu_Hf_Record_Count		9.57%
Grain_ID		20.66%
Spot		5.77%
Spot_diam		3.87%
U_Pb_Age	U-Pb Age (Ma)	99.86%
U_Pb_Age_uncertainty_1sigma		13.02%
U_Pb_Age_uncertainty_2sigma		13.02%
176Hf_177Hf	176Yb/177Hf sample ratio	99.67%
176Hf_177Hf_uncertainty_1sigma		13.82%
176Hf_177Hf_uncertainty_2sigma	176Yb/177Hf 2σ	13.82%
176Lu_177Hf	176Lu/177Hf sample ratio	99.86%
176Lu_177Hf_uncertainty_1sigma		55.40%
176Lu_177Hf_uncertainty_2sigma	176Lu/177Hf 2σ	55.40%
176Yb_177Hf	176Hf/177Hf sample ratio	76.34%
176Yb_177Hf_uncertainty_1sigma		41.67%
176Yb_177Hf_uncertainty_2sigma	176Hf/177Hf 2σ	41.67%

178Hf_177Hf		4.72%
178Hf_177Hf_uncertainty_1sigma		0.23%
178Hf_177Hf_uncertainty_2sigma		0.23%
180Hf_177Hf		75.24%
180Hf_177Hf_uncertainty_1sigma		75.24%
180Hf_177Hf_uncertainty_2sigma		75.24%
176Hf_177Hf_initial		9.75%
176Hf_177Hf_initial_uncertainty_1sigma		0.24%
176Hf_177Hf_initial_uncertainty_2sigma		0.24%
εHf(0)		13.77%
εHf(0)_uncertainty_1sigma		4.26%
εHf(0)_uncertainty_2sigma		4.26%
εHf(t)	εHf(t) calc	99.90%
εHf(t)_uncertainty_1sigma		86.54%
εHf(t)_uncertainty_2sigma	εHf(t) 2σ calc	86.54%
TDM1	TDM1 (Ma) calc	95.49%
TDM1_uncertainty_1sigma		8.42%
TDM1_uncertainty_2sigma		8.42%
TDM2	TDM2 (Ma) calc	95.31%
TDM2_uncertainty_1sigma		4.54%
TDM2_uncertainty_2sigma		4.54%
176Hf_177Hf_Chur		6.21%
176Hf_177Hf_DM		4.10%
176Lu_177Hf_Chur		0.28%
176Lu_177Hf_DM		2.15%