



Deep-time Sediment Sulfur Isotopes (DSSI): a database of sedimentary sulfur isotopic records through Earth history

Wenyi Guo¹, Huyue Song¹, Yong Du², Thomas J. Algeo^{1,3,4}, Jing Li¹, Hui Zhang¹, Junjie Xue¹, Jianwei Peng¹, Xiangpeng Ke¹, Haijun Song¹, Daoliang Chu¹, Li Tian¹

¹State Key Laboratory of Geomicrobiology and Environmental Changes, School of Earth Sciences, China University of Geosciences, Wuhan 430074, China

²YU-CUGW Joint Research Center on Deep Earth and Surface Dynamic Coupling, College of Resources and Environment, Yangtze University, Wuhan 430100, PR China

³Department of Geosciences, University of Cincinnati, Cincinnati, OH 45221-0013, USA

⁴State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Chengdu University of Technology, Chengdu 610059, China

Correspondence to: Huyue Song (hysong@cug.edu.cn)

Abstract. Sedimentary sulfur isotopic records constrain reconstructions of seawater sulfate evolution, pyrite burial, microbial sulfur metabolisms, ocean redox, anoxia, and Earth-system feedbacks. These reconstructions require isotopic values to remain linked to sulfur phase, age, locality, and source context. Here, we present the Deep-time Sediment Sulfur Isotopes database (DSSI), a compilation of marine sedimentary sulfur isotopic records in which each isotopic value remains linked to its sulfur phase and associated geological context, spanning 4,061–0 Ma. The released v1.0 datasheet (Guo et al., 2026; <https://doi.org/10.5281/zenodo.21675881>) contains 78,070 rows and 136 public fields; 64,990 rows contain at least one numeric sulfur isotopic value. Sulfur isotopic values are stored in unified isotopic fields and linked to a hierarchical phase classification comprising sulfur category, sulfur component, and sulfur carrier. The release also preserves stratigraphic age, modern and reconstructed paleogeographic coordinates, lithology, depositional setting, analytical method, and auxiliary geochemical information, where available. This structure supports source-traceable spatial and temporal synthesis that distinguishes sulfur phases without separating isotopic values from the geological metadata needed to interpret them.



1 Introduction

Sedimentary sulfur isotopic records represent the intersection of microbial metabolism, ocean redox, sulfate availability, pyrite burial, and the long-term carbon cycle. Sulfate reduction, sulfur disproportionation, sulfide oxidation, and pyrite formation redistribute sulfur among oxidized, reduced, organic, and mineral reservoirs, and these transfers leave isotopic signals that can persist in marine sediments (Canfield, 2004; Paytan and McLaughlin, 2004; Fike et al., 2015; Jørgensen et al., 2019; Fakhraee et al., 2025b). Conventional sulfur isotopic compositions are generally reported relative to Vienna Canyon Diablo Troilite (VCDT) as $\delta^{34}\text{S}$ values. Measurements of $\delta^{33}\text{S}$ and $\delta^{36}\text{S}$, together with $\Delta^{33}\text{S}$ and $\Delta^{36}\text{S}$ where reported, provide additional constraints on mass-dependent and mass-independent sulfur cycling (Farquhar et al., 2000; Johnston, 2011; Tostevin et al., 2014; Ono, 2017). These records are now used to evaluate seawater sulfate evolution, microbial sulfate reduction, oceanic anoxia, pyrite burial, atmospheric photochemistry, and Earth-system feedbacks through geological time. Representative applications include inference of an anoxic Archean atmosphere from mass-independent sulfur isotope fractionation (Pavlov and Kasting, 2002), documentation of Proterozoic seawater sulfate scarcity (Fakhraee et al., 2019), reconstruction of Ediacaran ocean oxidation (Fike et al., 2006), recognition of Early Triassic seawater sulfate drawdown (Song et al., 2014), and reconstruction of biogeochemical sulfur cycling during Cretaceous oceanic anoxic events (Gomes et al., 2016).

Interpreting such records requires more than the isotopic value itself. Oxidized sulfur archives such as carbonate-associated sulfate (CAS), barite, evaporite sulfate, and porewater sulfate differ in how they incorporate seawater sulfate and in their susceptibility to diagenesis (Present et al., 2020). Pyrite and other reduced sulfur phases record sedimentary sulfide formation rather than seawater sulfate directly, and their $\delta^{34}\text{S}$ values can vary with sedimentation rate, reactive iron availability, organic matter supply, basin restriction, methane cycling, lithology, and local redox structure (Lang et al., 2020; Pasquier et al., 2021; Bryant et al., 2023; Halevy et al., 2023; Spruzen et al., 2024). A phase label, sample context, age model, locality, and source trace are therefore not auxiliary information; they are part of the interpretation.

Several resources already support parts of this work. The Global Sedimentary Sulfur Isotope Database (GSSID) compiles published multiple-sulfur isotopic analyses from sulfur-bearing sediments



(Caruso et al., 2017). Uveges et al. (2023) assembled a minor sulfur isotopic database that is especially useful for comparing $\Delta^{33}\text{S}$ -bearing records during the Great Oxidation Event, with standardized age, stratigraphic, lithological, mineralogical, sulfur-phase, and source fields. Present et al. (2020) combined 6,710 Phanerozoic sulfate-proxy measurements from marine barite, evaporites, and CAS to estimate seawater sulfate $\delta^{34}\text{S}$. Spruzen et al. (2024) released a Cenozoic pyrite sulfur isotopic compilation with methane, lithology, depth, and sedimentation-rate metadata. Broader products such as DM-SED and DSMS-NI show the value of curated deep-time geochemical databases for marine sediments and nitrogen isotopes (Lai et al., 2025; Du et al., 2026), and recent sulfur-cycle syntheses provide interpretive frameworks and compiled materials for Earth-history questions (Fakhraee et al., 2025b). These resources are important, but each was designed around a particular archive, interval, isotopic system, or data purpose. DSSI therefore does not replace them; it reorganizes source-traceable sedimentary sulfur isotopic records into a common structure in which each record remains linked to its sulfur phase and source context, allowing users to filter records by age, locality, sulfur carrier, lithology, depositional setting, and auxiliary geochemistry during Earth history.

The missing integration limits the questions that can be asked quantitatively. Testing whether sulfur isotopic variability reflects global reservoir change or local depositional filtering requires records that can be grouped by phase and then re-filtered by age, locality, lithology, water depth, redox setting, alteration, and source provenance. Evaluating paired sulfate-pyrite behavior, sulfur isotopic mass-independent fractionation, Phanerozoic seawater sulfate trends, Cenozoic pyrite biases, pyrite-burial feedbacks during oceanic anoxia, or sampling density through time requires comparable fields rather than isolated supplementary tables. The FAIR principles formalize the need for findable, accessible, interoperable, and reusable data, but for sulfur isotopes the scientific requirement is more specific: each value must remain linked to phase and geological context (Wilkinson et al., 2016). A database is therefore not only a storage product; it is the infrastructure needed to separate global sulfur-cycle signals from archive-specific and site-specific effects while keeping individual measurements traceable to their sources. This requirement is especially clear for questions about pyrite burial and anoxia-climate feedbacks, where isotopic values have to be evaluated together with sulfur carrier, depositional environment, age, and complementary geochemical constraints (Fakhraee et al., 2025a).



85 Here, we present the global Deep-time Sediment Sulfur Isotopes database (DSSI), a compilation
86 of sedimentary sulfur isotopic records in which each measurement remains linked to its sulfur phase and
87 associated geological context, spanning 4,061–0 Ma. The v1.0 release contains 78,070 rows organized
88 in 136 fields. It links isotopic measurements to phase, age, locality, DOI, lithology, depositional setting,
89 and auxiliary geochemistry where available. DSSI is an integration and standardization layer rather than
90 a replacement for archive-specific compilations or expert evaluation of individual records. Its field
91 structure allows users to construct transparent, question-specific subsets defined by sulfur phase, age,
92 and geological context for synthesis and spatial-temporal screening.

93 **2 Compilation Methods**

94 **2.1 Data compilation and standardization**

95 The compilation began with peer-reviewed articles, source supplements, public repository
96 records, and selected published compilations that contain marine sedimentary sulfur isotopic
97 measurements. Large source products used during integration include GSSID, the [Present et al. \(2020\)](#)
98 Phanerozoic sulfate compilation, the [Uveges et al. \(2023\)](#) minor sulfur isotopic database, the [Spruzen et](#)
99 [al. \(2024\)](#) Cenozoic pyrite compilation, the sulfur-cycle synthesis of [Fakhraee et al. \(2025b\)](#), and DM-
100 SED ([Lai et al., 2025; Table 1](#)). These datasets were not simply appended: records were traced back to
101 publication-level provenance where possible, and overlapping entries were matched using DOI, author-
102 year information, sample identifiers, age, locality, sulfur carrier, and isotopic values.



103 **Table 1. Overview of selected published sulfur isotopic databases and compilations considered during DSSI**
 104 **construction.**

Data source	Scope of source resource	Key metadata	Spatial range	Temporal range
Caruso et al. (2017), GSSID	Published multiple-sulfur-isotopic records; no single source-wide row count reported in the article.	Age; locality; sulfur phase; $\delta^{34}\text{S}$, $\Delta^{33}\text{S}$, and $\Delta^{36}\text{S}$; source information.	Global	3,750–479 Ma
Present et al. (2020), Phanerozoic sulfate compilation	6,710 sulfate-proxy measurements.	Age; site/source; sulfate archive; CAS, barite, or evaporite phase; $\delta^{34}\text{S}$.	Global	Phanerozoic
Uveges et al. (2023), minor sulfur isotopic database	10,765 $\Delta^{33}\text{S}$ records.	Age maximum, mean, and minimum; craton; stratigraphic unit; lithology; mineralogy; sulfur phase; $\delta^{34}\text{S}$, $\Delta^{33}\text{S}$, and $\Delta^{36}\text{S}$; source DOI.	Global	4,061–0 Ma
Spruzen et al. (2024), Cenozoic pyrite compilation	Cenozoic pyrite compilation; no single database-wide row count stated in the article.	Age; location; water depth; methane; lithology; TOC; analytical method; pyrite $\delta^{34}\text{S}$.	Global	165–0 Ma
Fakhraee et al. (2025b), sulfur-cycle synthesis	Review and synthesis; not used as an independent DSSI row-count statistic.	Sulfur phase; source context; Earth-history interval and event context.	Global	3,528–0 Ma
Lai et al. (2025), DM-SED	63,627 entries and 2,522,255 element-level data points.	Fine age; modern coordinate; paleocoordinate; site; formation; depositional environment; lithology; metamorphic grade.	Global	2,850–93.6 Ma

105 Note. Published/source counts are reported only where they are stated directly by the original resource.
 106 Table 1 describes the scope and metadata structure of source products; it does not partition DSSI v1.0
 107 rows by import package because the released table records source provenance at the DOI level rather
 108 than through source-package labels.



109 Data extraction combined information from main-text tables, supplementary spreadsheets,
110 external repository links, and source attachments. Because the source literature spans several decades
111 and uses inconsistent table headers, each entry was reorganized into a common released-field model that
112 preserves DOI-level provenance, spatial and stratigraphic context, sulfur phase, numerical age, and the
113 geological information needed to interpret isotopic values. Curation evidence and other internal
114 workflow material are not part of the released datasheet.

115 Standardization separated isotopic measurements from their geological and analytical context
116 without erasing source-level detail. Sulfur isotopic ratios are stored in unified numerical fields and
117 linked to the sulfur category, component, and carrier hierarchy. Concentration and elemental data were
118 harmonized to common units where possible, while source-supported lithological, stratigraphic, method,
119 and carrier descriptions were retained as reusable metadata. In this study, sulfur phase denotes the
120 sulfur-bearing fraction or material represented by an isotopic measurement. The classification
121 distinguishes broad sulfur categories, specific components such as pyrite, CAS, and sulfate, and the
122 source-reported sulfur carrier. This structure allows users to identify the archive represented by each
123 isotopic value before combining or comparing records.

124 Age information was compiled using a three-level hierarchy. First, we retained numerical ages
125 explicitly reported for individual samples or sample rows in original articles, supplementary datasets, or
126 official repositories. Second, when source materials provided a dated age-depth (or age-height)
127 framework but did not list an age for every sampled horizon, we retained the published model or
128 calculated a linear interpolation between bracketing, height/depth-tied age anchors within the same
129 continuous core or measured section. Interpolation was applied only when the coordinate direction,
130 anchor positions and ages, and stratigraphic continuity were documented; no values were interpolated
131 across reported hiatuses, faults, duplicated intervals, or unbounded formation-level age ranges. Third,
132 where no numerical age or defensible age-depth model was available but the record could be assigned
133 to a named stage, we assigned the midpoint of the lower and upper stage boundaries in GTS2023, based
134 on the International Chronostratigraphic Chart v2023/09 (International Commission on Stratigraphy,
135 2023). Broader stratigraphic labels that could not be resolved to a stage were retained as metadata rather
136 than converted to a numerical age.



137

138 **Table 2. Isotopic fields, reference scales, and descriptions in DSSI v1.0.**

Symbol and field	Reference scale	Description
$\delta^{34}\text{S}$ (d34s_permil)	VCDT	Conventional sulfur isotopic composition of the component recorded in the same row.
$\delta^{33}\text{S}$ (d33s_permil)	VCDT	Minor sulfur isotopic composition where reported by the source.
$\delta^{36}\text{S}$ (d36s_permil)	VCDT	Minor sulfur isotopic composition where reported by the source.
$\Delta^{33}\text{S}$ (delta33s_permil)	Source-defined; VCDT-referenced	Multiple-sulfur-isotopic parameter retained as reported or derived by the source workflow.
$\Delta^{36}\text{S}$ (delta36s_permil)	Source-defined; VCDT-referenced	Multiple-sulfur-isotopic parameter retained as reported or derived by the source workflow.
$\delta^{18}\text{O}$ of sulfate or CAS (d18o_permil)	VSMOW	Oxygen isotopic composition of the sulfate or CAS component where available.
$\Delta^{17}\text{O}$ of sulfate or CAS (delta17o_permil)	Source-defined	Triple-oxygen-isotopic parameter associated with sulfate or CAS where available.
$\delta^{18}\text{O}_{\text{carb}}$ (d18o_carbonate_permil)	VPDB	Carbonate oxygen isotopic composition retained as auxiliary context.
$\delta^{13}\text{C}_{\text{org}}$ and $\delta^{13}\text{C}_{\text{carb}}$ (d13c_org_permil; d13c_carbonate_permil)	VPDB	Organic-carbon and carbonate-carbon isotope compositions retained as auxiliary context.

139

140 Modern latitude and longitude were compiled from original sample tables, drilling-site metadata,
 141 article maps, repository records, administrative locality information, and source-level descriptions. They
 142 are stored in decimal degrees and should be interpreted together with locality descriptors because older
 143 publications commonly report section- or area-level positions rather than exact sample points.

144 For records with sufficient modern-coordinate and age information, paleogeographic positions
 145 were reconstructed by combining modern latitude-longitude and numerical age with finite rotations
 146 from the PALEOMAP Plate Model m15g60_v2d3 and ContOceAnPolyv10u_v2d3 plate polygons
 147 (Scotese, 2016). The resulting palaeolatitude and palaeolongitude values form a derived spatial layer
 148 and are retained only for successful reconstructions.



149 2.2 Data selection and quality control

150 DSSI analyses use field-specific subsets. Time-series analyses require numerical ages, modern
151 spatial summaries require valid modern coordinates, and paleogeographic products require successful
152 reconstructions. Auxiliary geochemical measurements are retained for evaluating depositional setting,
153 alteration, redox context, and diagenetic overprinting, but they do not substitute for missing sulfur
154 isotope, age, or coordinate information.

155 Duplicate control and phase assignment were based on source context rather than isotopic values
156 alone. During curation, potential overlaps were screened with DOI, author-year information, section,
157 age, locality, sample material, sulfur carrier, and isotope-value combinations. Sulfur carrier assignments
158 were based on the analytical target, sample material, extraction method, source table header, and curated
159 carrier information. Records with unresolved context were not reassigned to pyrite, CAS, sulfate, or
160 another specific component unless the source supported that decision.

161 Metamorphism, hydrothermal alteration, and other post-depositional overprints were handled as
162 metadata rather than as automatic exclusion criteria. This choice preserves records that may be useful
163 for regional synthesis, source review, or targeted filtering, while allowing users to remove altered or
164 metamorphosed samples for applications that require a stricter primary-signal subset.

165 The phase framework keeps oxidized sulfur archives, reduced sulfur products, organic sulfur,
166 and bulk measurements analytically distinct. The broad `sulfur_category` field contains pyrite, sulfate,
167 CAS, and other groups. The more specific `sulfur_component` field distinguishes pyrite, CAS, sulfate,
168 barite, anhydrite, gypsum, chromium-reducible sulfur (CRS), acid-volatile sulfide (AVS), H₂S, organic
169 sulfur, bulk sulfur, and related components, while `sulfur_carrier` retains finer mineralogical or
170 extraction-state information. Multiple sulfur isotopic parameters are stored as isotope-system fields
171 rather than as carrier categories. This structure lets users filter by phase, identify paired sulfate-pyrite
172 records, and compare multiple sulfur isotopic measurements without collapsing distinct sulfur pools.

173 2.3 Record architecture and inclusion logic

174 DSSI is organized as a row-wise integration table. A row is a source-level observation structure
175 rather than a guarantee of one physically unique specimen: a source may report separate rows for



different sulfur fractions from the same material, and a single row can retain several isotopic or associated geochemical values. This design preserves the form in which observations can be connected to their stratigraphic, spatial, and analytical context. It also means that row counts should be interpreted as counts of retained observations, not automatically as counts of independent samples, localities, or publications.

Of the 78,070 released rows, 64,990 contain at least one numeric sulfur isotopic value in `d34s_permil`, `d33s_permil`, `d36s_permil`, `delta33s_permil`, or `delta36s_permil`. The remaining 13,080 rows retain associated geochemical, stratigraphic, or contextual information but do not themselves contain a numeric sulfur isotopic value. Such rows are useful when a source reports supporting measurements alongside an isotopic table, but they must not be included in isotopic distributions, temporal trends, or spatial summaries. A basic isotope-analysis subset should therefore require at least one numeric sulfur isotopic field before applying any additional filters.

The appropriate unit of analysis depends on the question. A row-level analysis is suitable for documenting measurement coverage or exploring the distribution of reported values. Comparisons among regions, intervals, or depositional settings should additionally consider repeated observations from the same DOI, section, or locality. Users can aggregate deliberately at the level of a DOI, a section, a locality, an age bin, or a defined phase-component combination, but the aggregation rule should be stated because it can alter the apparent weight of intensively sampled studies.

2.4 Using the standardized sulfur-phase index

The sulfur-phase fields serve different purposes and should not be used interchangeably. `material` describes the sample material or extraction material reported by the source. It can be broad, composite, or host-rock based; for example, a bulk-rock or sediment material can yield a pyrite, CAS, sulfate, or reduced-sulfur measurement. `sulfur_carrier` retains the more detailed sulfur-bearing mineral, chemical pool, or extraction state. `sulfur_component` is the controlled analytical grouping intended for most cross-study comparisons. It resolves the distinction among pyrite, CAS, sulfate, barite, anhydrite, gypsum, CRS, AVS, H₂S, organic sulfur, bulk sulfur, and related components.



For broad exploratory summaries, `sulfur_category` provides the pyrite, sulfate, CAS, and other groupings. For interpretation, `sulfur_component` should normally be the first phase filter because it retains distinctions that can be obscured at category level. `sulfur_carrier` can then refine a subset when extraction state or mineralogy is important, whereas `material` helps evaluate whether the analyzed sulfur pool is compatible with the host material and source description. This hierarchy allows a user to start with an inclusive phase group and then narrow the selection without creating separate, phase-specific isotopic columns.

The index does not make all carriers scientifically interchangeable. In particular, CRS is retained as its own component because the analytical fraction and source interpretation may differ from directly identified pyrite, even where a study uses CRS as a pyrite proxy. Likewise, CAS, barite, evaporitic sulfate minerals, and porewater sulfate can all be classified as sulfate-related but should be separated when their preservation pathways or environmental interpretations differ. The field structure makes those decisions explicit rather than embedding them in a pre-combined global curve.

3 Data summary

3.1 Location fields

Each row is linked to source provenance through `doi`, `author`, and `year`. The `section` field records the outcrop section, drill core, station, locality, or sample-group name reported by the source. Modern geographic coordinates are stored in `latitude` and `longitude` in decimal degrees. `location_primary` records the country, broad region, or ocean basin, whereas `location_secondary` records a province, basin, platform, drilling region, or equivalent second-level locality. Together, these fields preserve a machine-readable spatial reference and human-readable locality context without treating a source sample label as a globally unique identifier.

The `palaeolatitude` and `palaeolongitude` fields provide the derived spatial layer for records that can be placed in the selected paleogeographic model. Modern coordinates remain the primary spatial reference; the reconstruction procedure is described in Section 2.1.



227 3.2 Age fields

228 Each entry can include numerical and stratigraphic age information. The released fields include
 229 age_ma, period, series, stage, formation, member, height_m, and sedimentation_rate_m_per_ma.
 230 age_ma records the selected age in Ma used for database-level plotting and temporal filtering. Following
 231 the hierarchy in Sect. 2.1, it may represent a numerical age explicitly reported by the source, an age
 232 from a documented age-depth or age-height model, or a GTS2023 stage-midpoint value. It should
 233 therefore not be interpreted uniformly as a direct geochronological determination. The period, series,
 234 stage, formation, and member fields preserve source-level chronostratigraphic assignments where
 235 available, so users can work with continuous time, named geological intervals, or section-level position
 236 according to the analytical question.

237 For interpolated records, height_m preserves the source-reported stratigraphic height or core-
 238 depth coordinate and is used only together with a documented source model and bracketing age anchors;
 239 its reported coordinate convention is retained. The v1.0 release contains valid numerical ages for 75,216
 240 rows, spanning 4,061–0 Ma. Stage-midpoint values provide a consistent temporal representation for
 241 records with stage-level geological context, but they are not individual sample dates and do not replace
 242 a source age model. Records without an explicit numerical age, a defensible age-depth model, or a
 243 resolvable stage retain their stratigraphic metadata but are excluded from age-dependent summaries.
 244 This design supports both broad Earth-history synthesis and interval-scale studies that require period,
 245 series, stage, formation, member, or section-position information.

246 3.3 Data fields

247 DSSI stores sulfur isotopic values in common isotopic fields rather than phase-specific isotopic
 248 columns. The d34s_permil field contains 61,524 numeric $\delta^{34}\text{S}$ values. The principal components
 249 represented in that field are pyrite ($n = 33,138$), CAS ($n = 9,444$), sulfate ($n = 5,827$), barite ($n = 1,978$),
 250 CRS ($n = 2,287$), reduced sulfur not otherwise specified ($n = 2,171$), bulk sulfur ($n = 1,666$), and
 251 organic sulfur ($n = 1,542$), with additional anhydrite, gypsum, AVS, H_2S , elemental sulfur, and total
 252 reduced sulfur records. The released fields contain 1,387 numeric $\delta^{33}\text{S}$ values, 215 $\delta^{36}\text{S}$ values, 16,080
 253 $\Delta^{33}\text{S}$ values, and 6,859 $\Delta^{36}\text{S}$ values. In total, 64,990 rows contain at least one numeric sulfur isotopic



254 value. Individual field counts are not additive because a row can contain more than one isotopic
 255 parameter. Table 3 summarizes the released field groups.

256 Analytical metadata, sample material, sulfur carrier, and depositional context remain linked to
 257 the isotopic values in each source entry. Where a source reports several associated isotopic or
 258 geochemical measurements together, they can be retained in the same row. The sulfur phase
 259 classification then allows users to create narrower analytical subsets without discarding the associated
 260 geological context. Figure 1 summarizes the relationship among the principal DSSI field domains.

261

262 **Table 3. Public DSSI v1.0 field groups and descriptions. The released datasheet contains 136 fields; field names and**
 263 **group-level descriptions are provided in the released workbook and in this table.**

Public field group	Description
DOI-level provenance	doi, author, and year identify the source publication or repository. DOI is the primary source identifier in the released table.
Location and spatial reference	section, location_primary, location_secondary, latitude, and longitude retain source locality information. palaeolatitude and palaeolongitude are model-derived coordinates.
Age and stratigraphy	age_ma is the selected Ma value: an explicitly reported source age, an age from a documented age-depth/height model, or a GTS2023 stage midpoint. period, series, stage, formation, and member retain source stratigraphic context.
Section position and accumulation	height_m preserves the reported section-height or core-depth coordinate. It supports linear interpolation only where a continuous section/core and bracketing, coordinate-tied age anchors are documented; sedimentation_rate_m_per_ma is retained where available.
Sample material and lithology	material, lithology, lithology_type, and metamorphic_grade preserve material and alteration context.
Depositional context	depositional_setting and water_depth_m provide environmental information where reported or standardized.
Analytical method	method retains source-supported analytical or extraction method codes and combinations.
Sulfur phase index	sulfur_category provides the broad pyrite, sulfate, CAS, or other grouping. sulfur_component identifies the standardized phase, and sulfur_carrier retains



Public field group	Description
	finer mineralogical or extraction-state information.
Sulfur isotopic fields	d34s_permil, d33s_permil, d36s_permil, delta33s_permil, and delta36s_permil store sulfur isotopic measurements and multiple-sulfur-isotopic parameters.
Oxygen and carbon isotopic context	d18o_permil, delta17o_permil, d18o_carbonate_permil, d13c_org_permil, and d13c_carbonate_permil retain associated isotope information.
Sulfur abundance and pyrite composition	CAS sulfur, total organic and inorganic sulfur, total sulfur, and pyrite abundance/composition fields retain concentration and mineral-context information where available.
Carbon, major-element, trace-element, and pyrite-trace chemistry	Carbon abundance fields, major oxides/elements, trace elements, and pyrite-hosted elemental concentrations provide optional geochemical context for targeted filtering and interpretation.

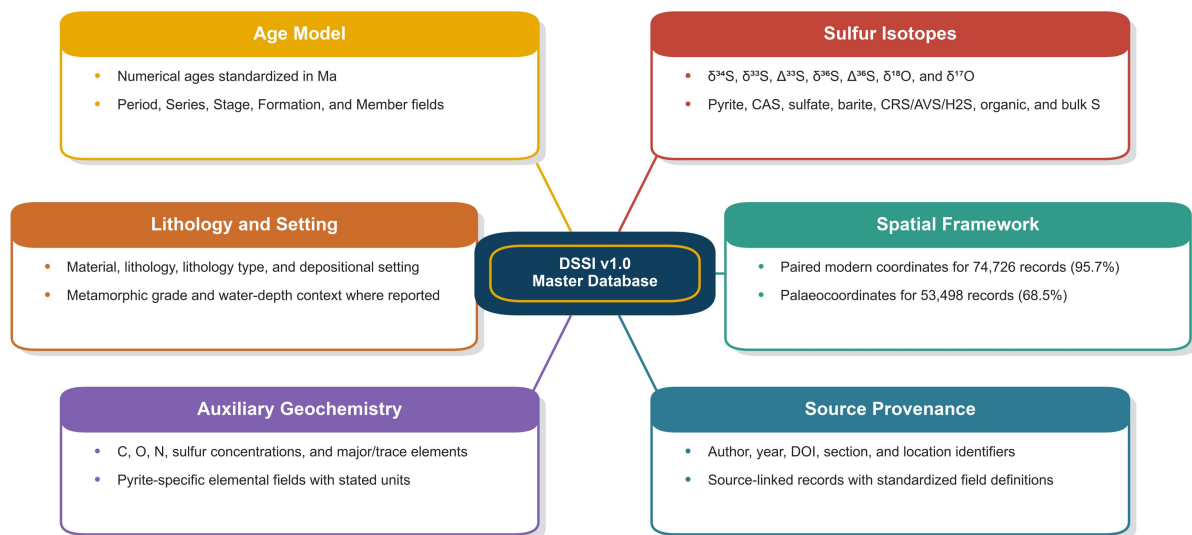


Figure 1. Conceptual overview of the DSSI v1.0 data architecture. The released table links age and stratigraphy, sulfur isotopic and phase information, lithological and depositional context, modern and reconstructed spatial information, auxiliary geochemistry, and DOI-level provenance. The diagram summarizes field domains rather than implying that every row contains every field.



3.4 Petrological characteristic fields

Petrological and environmental fields provide context for sulfur isotopic interpretation. lithology retains source lithological descriptions, whereas lithology_type provides a broader standardized grouping. material, metamorphic_grade, depositional_setting, and water_depth_m preserve source-supported information on sample material, alteration, and environmental setting. Together with the phase index described above, these fields support targeted filtering while retaining records from altered, metamorphosed, or environmentally specific settings for transparent reuse.

3.5 Source provenance and database composition

Sulfur isotopic data are tied to peer-reviewed literature, DOI-traceable repositories, and published compilations, including global sulfur-isotope and deep-time sediment database products (Caruso et al., 2017; Present et al., 2020; Lai et al., 2025; Du et al., 2026). DSSI v1.0 contains DOI values in 77,422 rows, representing 793 unique normalized DOI strings. DOI-level provenance allows publication-level filtering and supports duplicate screening together with author-year, locality, age, phase, and isotopic information. Figure 2 summarizes the growth of the source literature and data volume, and Figure 3 summarizes database composition and metadata coverage.

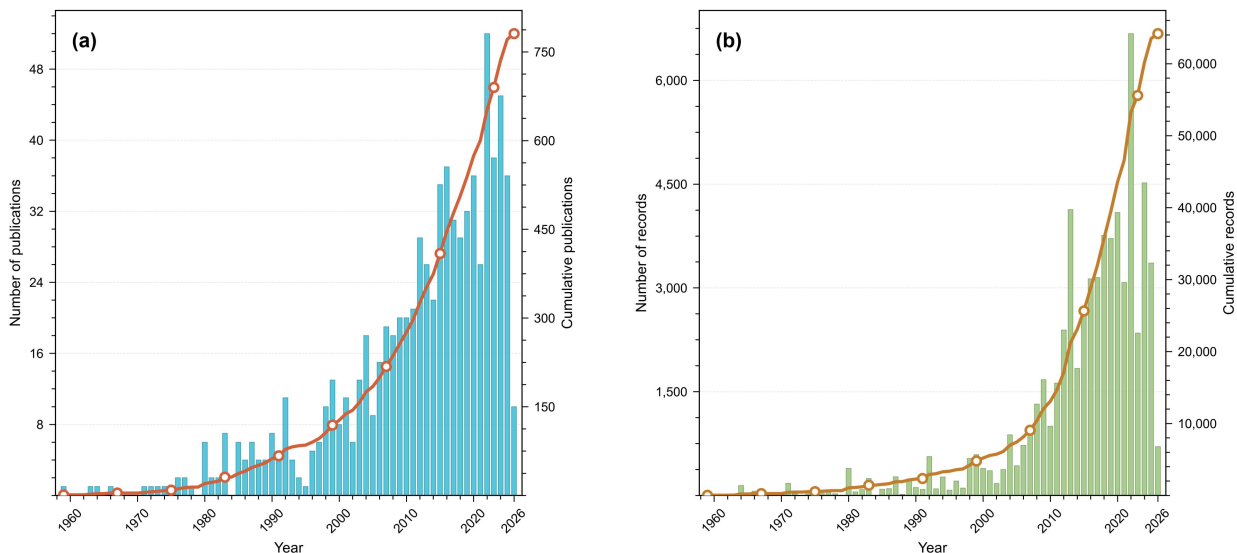




Figure 2. Annual publication and data-point statistics for DSSI v1.0. (a) Number of source publications with a valid publication year, with the cumulative total shown as a line. (b) Number of sulfur-isotope-bearing rows with a valid publication year, with the cumulative total shown as a line.

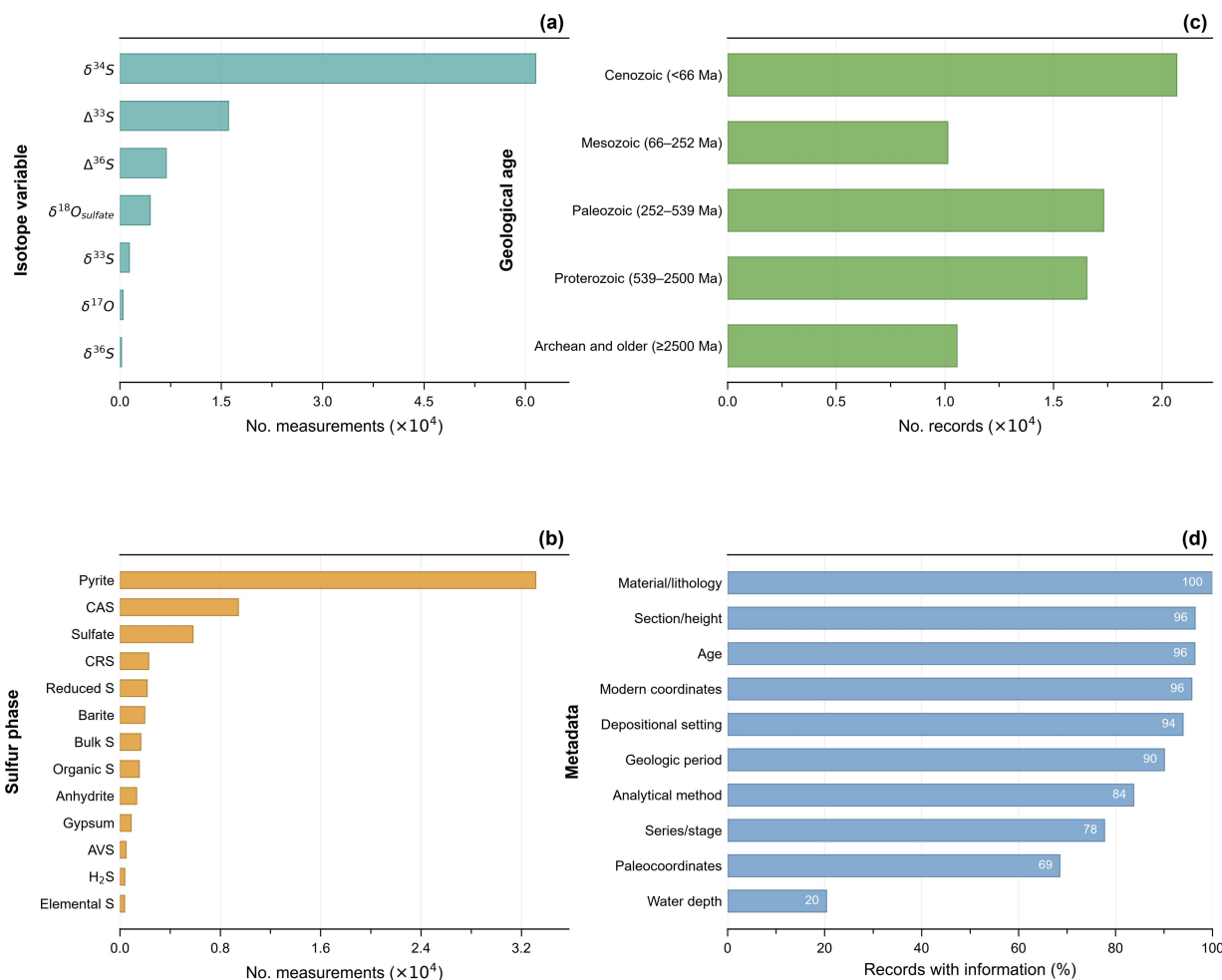


Figure 3. Database composition and metadata coverage in DSSI v1.0. Panels show (a) the number of values by isotopic system, (b) the component-level distribution of $\delta^{34}\text{S}$ values, (c) data distribution by broad geological age intervals, and (d) coverage of selected metadata fields. Counts and percentages are reported by the respective panel axes.

4 Technical validation

Technical validation addresses the data properties required for analysis: DOI-level traceability, interpretable sulfur-phase assignment, numerical age, valid modern geographic position, and successful paleogeographic reconstruction. Each summary therefore uses only the rows that satisfy its relevant



298 field requirements. Figures 4–6 illustrate phase-separated $\delta^{34}\text{S}$ distributions, multiple-sulfur-isotope
299 coverage through time, and isotope-field coverage for major age bins.

300 4.1 Geographic coordinate structure

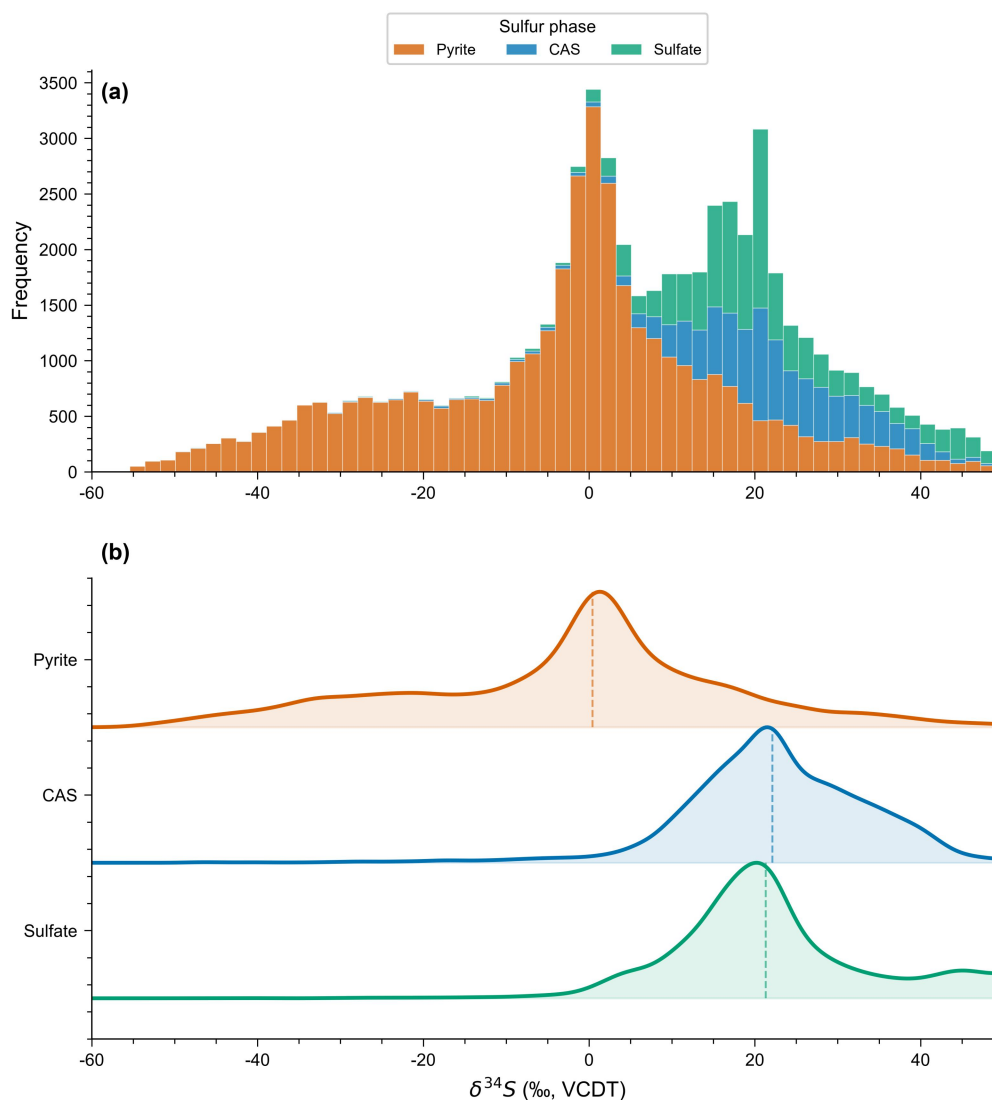
301 Latitude and longitude values used in spatial summaries fall within valid geographic ranges of
302 -90 to 90 and -180 to 180 , respectively. Coordinate assignments integrate country names, ocean basins,
303 public administrative boundaries, drilling-site information, and source-level locality descriptions. The
304 v1.0 release contains 74,726 rows with valid modern coordinate pairs and 53,498 rows with valid
305 reconstructed paleocoordinate pairs. Locality descriptors are retained because some older records
306 necessarily represent locality- or section-level positions rather than exact sample points.

307 4.2 Paleocoordinate validation

308 Paleocoordinates are model-dependent. Paleogeographic maps therefore use only rows with
309 successful reconstructions, whereas rows without the required inputs remain available through their
310 modern locality and DOI metadata. This distinction matters because seawater sulfate $\delta^{34}\text{S}$, pyrite $\delta^{34}\text{S}$,
311 and sulfur isotope mass-independent fractionation signals vary with paleogeographic setting, basin
312 restriction, redox structure, and depositional environment (Lang et al., 2020; Pasquier et al., 2021;
313 Richardson et al., 2019; Spruzen et al., 2024).

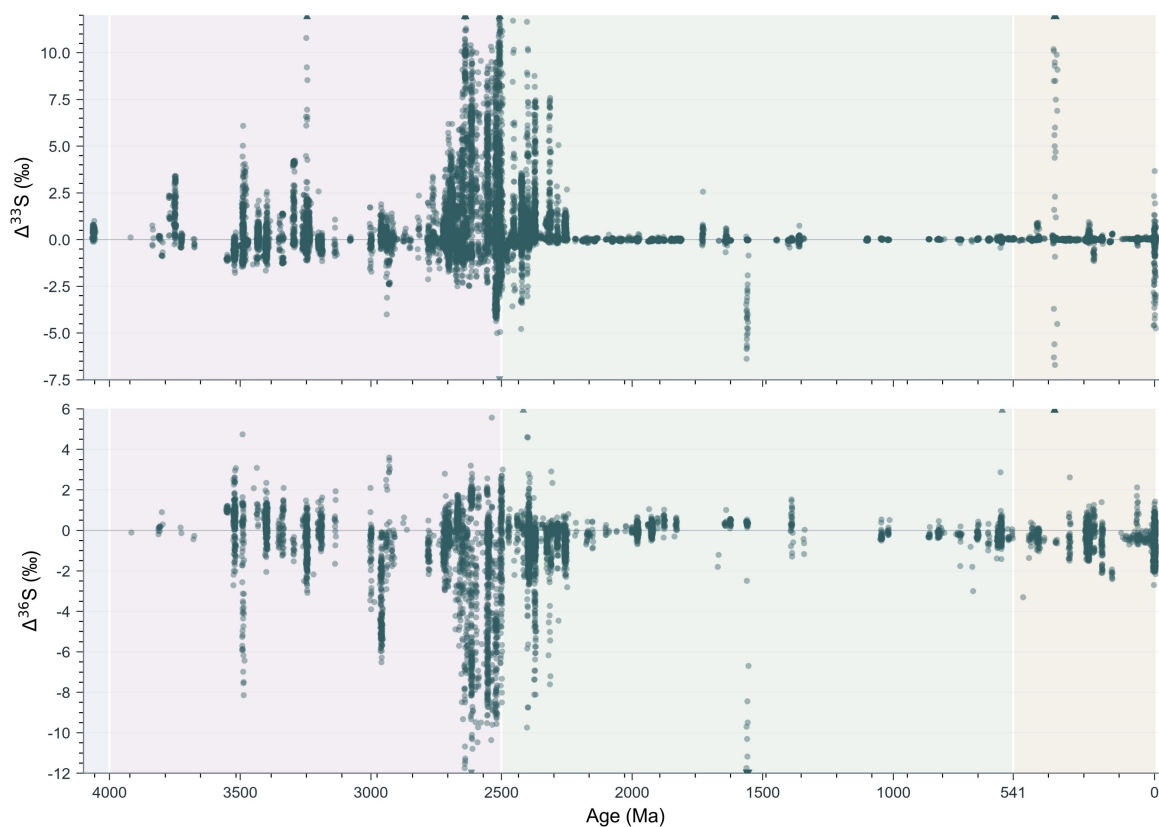
314 4.3 Sulfur isotope distribution

315 Phase-separated isotope distributions provide both a scientific overview and a quality check.
316 Sulfate minerals, barite, CAS, pyrite, organic sulfur, and bulk sulfur do not represent a single statistical
317 population; they respond differently to seawater sulfate composition, extraction protocol, microbial
318 sulfate reduction, diagenesis, sulfate availability, and local redox structure (Present et al., 2020;
319 Edwards et al., 2019; Bryant et al., 2023; Halevy et al., 2023; Spruzen et al., 2024). Figure 4
320 summarizes conventional $\delta^{34}\text{S}$ distributions, Figure 5 shows multiple-sulfur-isotopic data through time,
321 and Figure 6 compares isotope-field coverage. Outlying values should be evaluated against DOI, phase,
322 lithology, analytical method, and age metadata before they are treated as global sulfur-cycle signals.



323

324 **Figure 4. Distribution of $\delta^{34}\text{S}$ values for pyrite, CAS, and sulfate records. (a) Stacked histograms show the observed**
 325 **distributions. (b) Offset smoothed density curves show the same phase groups, with dashed vertical lines marking**
 326 **their central values. The panels illustrate why these archives should not be treated as one sulfur isotope population.**



327

328 **Figure 5. Multiple sulfur isotopic records through time. The upper and lower panels plot $\Delta^{33}\text{S}$ and $\Delta^{36}\text{S}$, respectively,**
 329 **against numerical age for rows with valid ages. Shaded bands identify broad geological intervals and reveal the**
 330 **concentration of these records in Archean and Paleoproterozoic studies.**

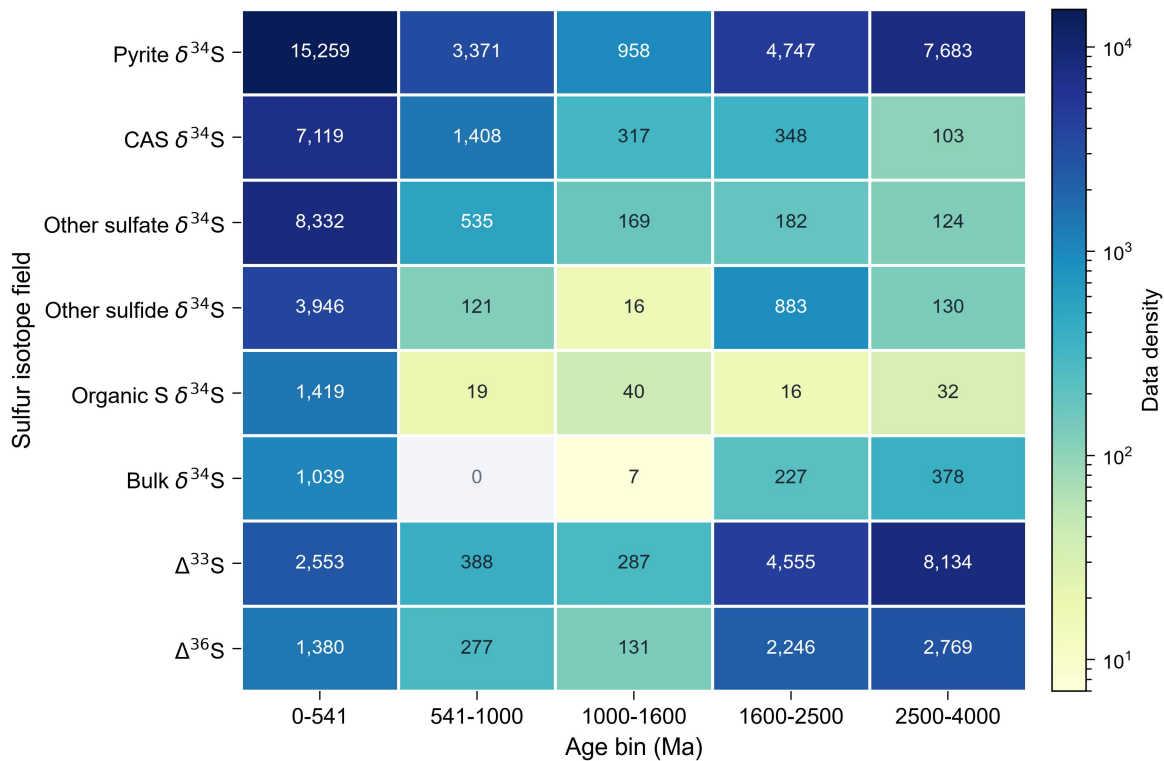


Figure 6. Coverage of principal sulfur isotopic records for five age bins. Cell labels show row counts for pyrite, CAS, other sulfate, other sulfide, organic sulfur, and bulk-sulfur $\delta^{34}\text{S}$, together with $\Delta^{33}\text{S}$ and $\Delta^{36}\text{S}$. Color intensity is logarithmically scaled by record abundance.

4.4 Source integration

Source integration assigns primary provenance at the DOI level while preserving the geological fields required to identify potential repeats. This approach reduces double counting when measurements have been re-hosted in repositories or incorporated into later compilations, and it retains enough context to audit how each value entered DSSI.

4.5 Age model calibration

Geological age information is represented by numerical age together with period, series, stage, formation, member, relative section position, and sedimentation rate where available. The age_ma field provides a practical common age for plotting, filtering, and binning records. For temporal summaries and geological time-scale displays, records were assigned to GTS2023 time-scale cells on the basis of



age_ma. The accompanying stratigraphic fields retain source-level information for users who need to apply alternative age models or work at section scale.

4.6 Source provenance and duplicate control

The released provenance fields are DOI, author, and publication year. They support publication-level filtering and provide a stable route to the full source citation. For future updates, DOI should be combined with section, age, locality, material, phase, and isotopic values when screening candidate duplicate records.

4.7 Metadata completeness and analytical domains

Metadata coverage defines the analytical domains that DSSI can support directly. Valid numerical ages are available for 75,216 rows, valid modern coordinate pairs for 74,726 rows, and valid reconstructed paleocoordinate pairs for 53,498 rows. These values describe availability of the fields needed for specific analyses rather than a universal quality score. A record without a paleocoordinate, for example, can still be suitable for isotopic, stratigraphic, source-level, or modern-geographic analysis; it is simply outside the supported domain of paleogeographic mapping.

Similarly, the presence of a numerical age supports plotting and binning but does not remove uncertainty in the underlying source age model. Fine-scale event studies should retain the accompanying formation, member, stage, section-position, and source context rather than relying on age_ma alone. Coordinate fields should be handled in the same way: decimal-degree validity establishes a usable spatial reference, but it does not imply sample-scale precision when the original source reports a regional or section-level locality. These distinctions are important when converting coverage data into quantitative comparisons.

Field completeness is therefore best treated as a transparent selection criterion. A reproducible analysis can state, for example, that it used rows with numeric $\delta^{34}\text{S}$, a specified sulfur component, an age within a defined interval, and valid modern coordinates. The same workflow can then be repeated with or without depositional-setting, lithology, water-depth, or metamorphic-grade filters to assess the dependence of an interpretation on available contextual metadata.



5 Data records and coverage

The following coverage summaries describe the temporal and spatial structure of sulfur-isotope-bearing rows in DSSI v1.0. Each analysis applies the age or coordinate requirement appropriate to its purpose and retains phase classification so that seawater-sulfate archives and sedimentary sulfide products are not combined by default.

These summaries are coverage diagnostics rather than settled interpretations of the global sulfur cycle. Data density reflects preservation, research intensity, source availability, and the distribution of sulfur-bearing materials; phase and source filters remain necessary for quantitative synthesis.

5.1 Temporal density and distribution of sulfur isotopic records

Sulfur isotopic records in DSSI span the Archean to the Recent, but analytical coverage is uneven through time. Precambrian intervals contain many pyrite and multiple-sulfur-isotopic records, especially in Archean and Paleoproterozoic studies, where mass-independent sulfur isotopic signals are a major interpretive target (Farquhar et al., 2000; Johnston, 2011; Scott et al., 2014; Ono, 2017). Phanerozoic intervals contain a broader mixture of sulfate and sulfide archives. Figure 7 summarizes this temporal coverage after binning records according to GTS2023 interval boundaries and shows where whole-database comparisons are well supported and where interval-specific analyses need phase and source filters.

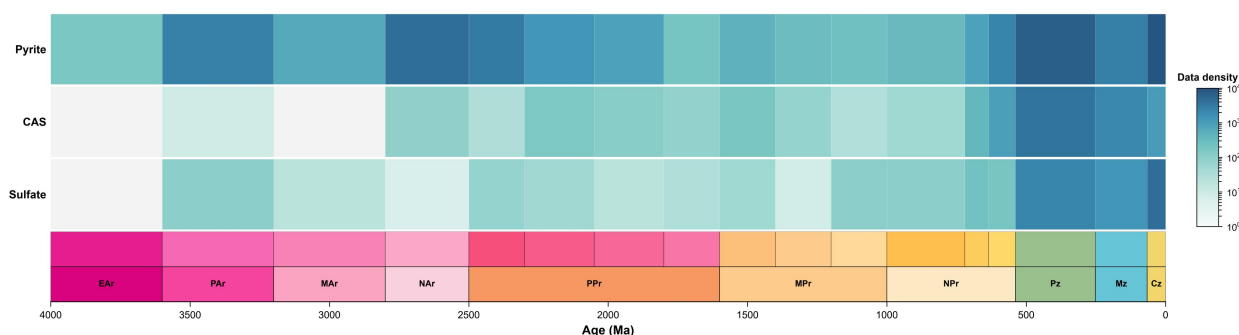


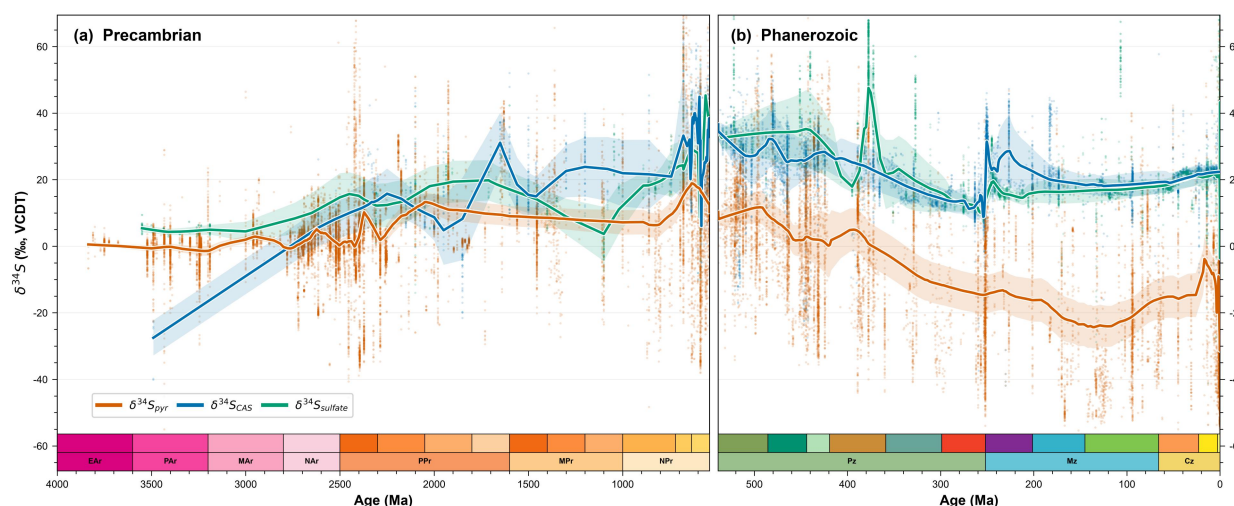
Figure 7. Temporal coverage of pyrite, CAS, and sulfate $\delta^{34}\text{S}$ records binned using GTS2023 time-scale interval boundaries (International Commission on Stratigraphy, 2023). Cell color represents record density and the lower strip provides geological time-scale context. The figure is a coverage diagnostic rather than a global sulfur isotopic curve.



394

395 The representation of sulfur components changes strongly through time. Figure 8 compares
 396 pyrite, CAS, and sulfate-related components, which provide the largest $\delta^{34}\text{S}$ subsets in DSSI. CRS,
 397 reduced sulfur not otherwise specified, bulk sulfur, organic sulfur, and less common components extend
 398 coverage into additional depositional and analytical settings, while multiple-sulfur-isotopic
 399 measurements remain concentrated in studies of mass-independent fractionation or multi-isotope sulfur
 400 cycling (Paytan et al., 1998; Sim et al., 2015). Component-specific totals are reported in Section 3.3.

401



402

403 **Figure 8. Phase-specific $\delta^{34}\text{S}$ records through time for pyrite, CAS, and sulfate. Precambrian and Phanerozoic**
 404 **records are shown separately; points are individual rows and lines with envelopes summarize the plotted phase-**
 405 **specific trends. The contrasting trajectories emphasize the need for component-based queries before records are**
 406 **combined.**

407

408 Temporal density reflects both geological preservation and the history of sampling and analysis.
 409 Quantitative interpretation should therefore report the sulfur component, age interval, source filters, and
 410 number of rows supporting each selected subset.

411 5.2 Spatial density and characteristics of sulfur isotopic records

412 The spatial distribution of sulfur isotopic records is uneven in both modern and reconstructed
 413 paleogeographic reference frames. DSSI includes continental shelves, restricted basins, carbonate



platforms, slope and deep-marine successions, evaporitic basins, and ocean drilling sites, but dense clusters occur mainly in regions with well-exposed sedimentary successions and long histories of geochemical study. Figure 9 summarizes modern sampling locations, and Figure 10 shows era-scale density patterns. These maps are best used to diagnose coverage and define spatial subsets before geographic structure is interpreted as an environmental signal.

In modern geographic space, records are concentrated in well-studied cratonic basins, continental margins, and classic stratigraphic sections, including North America, South China, Europe, Australia, and parts of South Africa. These clusters provide strong regional coverage, but they also document sampling and publication bias. Basin- or continent-scale comparisons should therefore report the number of sources, localities, and phase-specific records used in each spatial subset, especially where depositional environment or local basin conditions are part of the interpretation (Lang et al., 2020; Pasquier et al., 2021; Richardson et al., 2019; Spruzen et al., 2024).

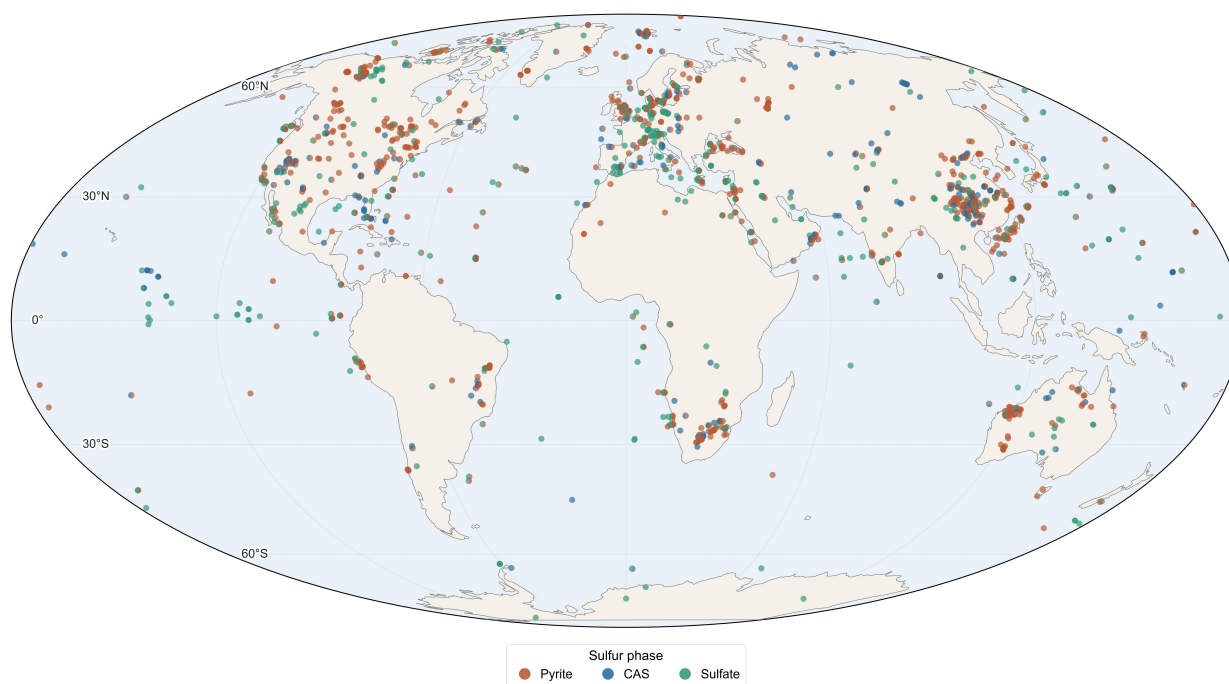
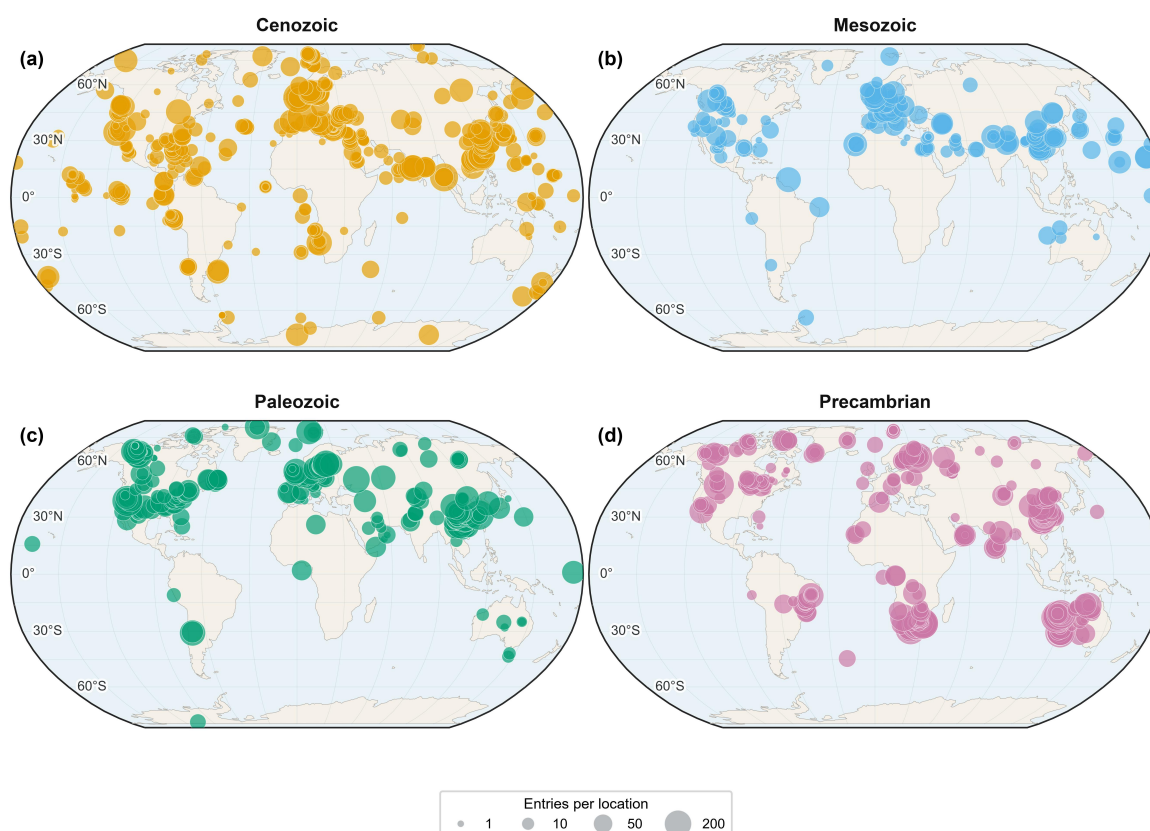


Figure 9. Modern geographic distribution of DSSI $\delta^{34}\text{S}$ sampling locations on a Mollweide projection. Points are colored as pyrite, CAS, or sulfate according to the plotted sulfur component and include rows with valid modern coordinates.

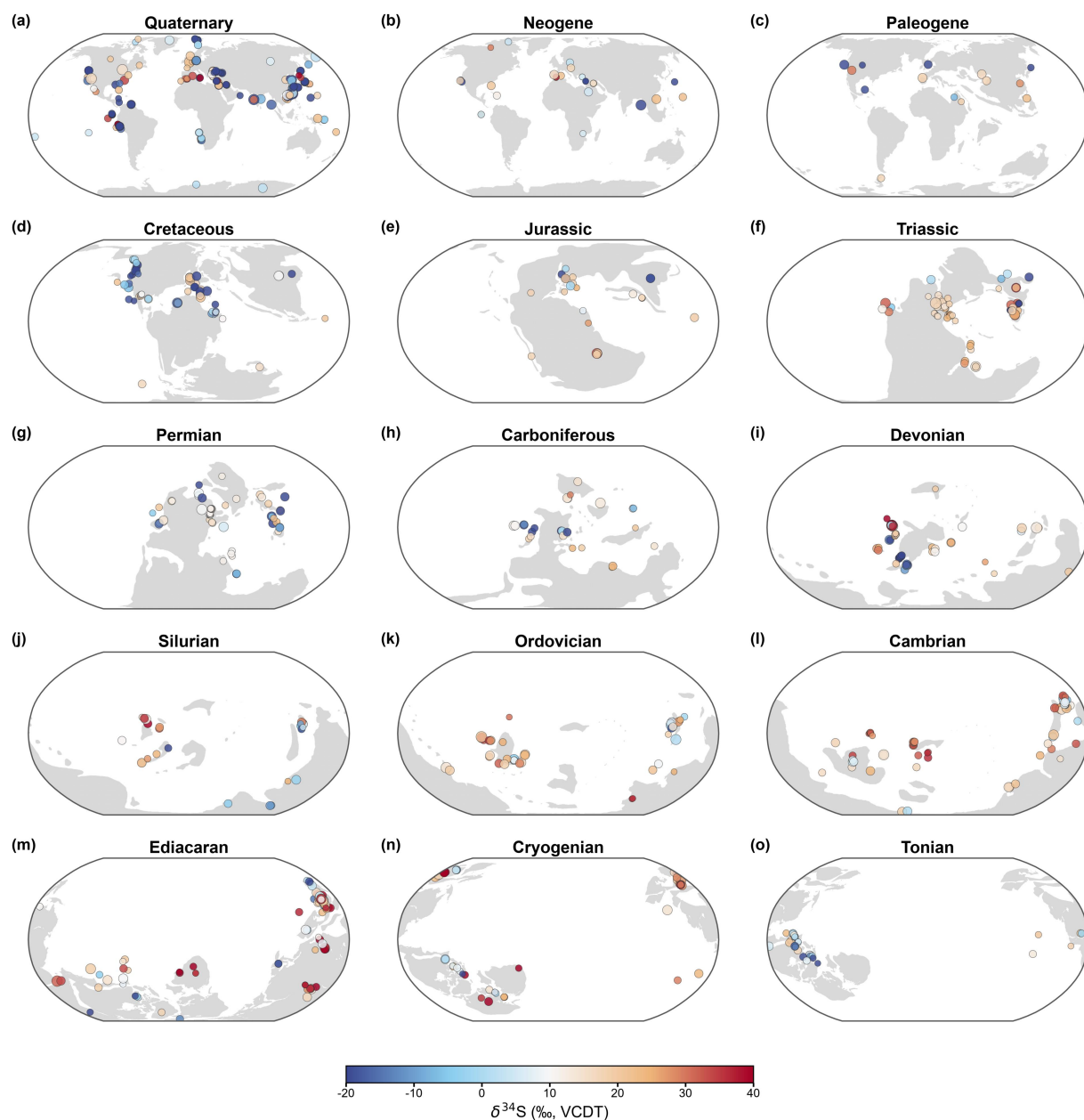


430

431 **Figure 10. Modern geographic sampling density by geological era. Panels show Cenozoic, Mesozoic, Paleozoic, and**
 432 **Precambrian records. Bubble size scales with the number of DSSI entries aggregated at each plotted location.**

433

434 Paleogeographic coverage is summarized in Figure 11. The plotted locality groups show where
 435 reconstructed positions can support broad spatial screening from the Ediacaran through the Phanerozoic.
 436 These maps are locality-level summaries rather than row-level analyses: repeated measurements from
 437 the same source locality are aggregated for display, and quantitative tests should return to the row-level
 438 database or to explicitly defined source-locality summaries. This distinction is important for separating
 439 broad paleogeographic structure from basin-scale controls on sulfur isotopic records (Paiste et al., 2020;
 440 Paiste et al., 2022).



441

442 **Figure 11. Paleogeographic distribution of primary $\delta^{34}\text{S}$ records from the Ediacaran to the Quaternary. Panels use**
 443 **reconstructed palaeolongitude and palaeolatitude coordinates derived with the PALEOMAP Plate Model**
 444 **m15g60_v2d3 (Scotese, 2016). Points are grouped by DOI, locality, and period; color represents the median $\delta^{34}\text{S}$ value**
 445 **in each group and marker size scales with the number of source rows.**



446 5.3 Recommended query workflows and reuse

447 DSSI is designed to support explicit query workflows rather than one default sulfur isotopic
 448 synthesis. For a seawater-sulfate question, a user can begin with rows that contain numeric $\delta^{34}\text{S}$ and
 449 select CAS, sulfate, barite, anhydrite, gypsum, or another stated sulfate-related component. The
 450 component, carrier, lithology, depositional setting, and age fields can then be used to construct a target
 451 archive and to distinguish carbonate-associated or mineral sulfate from other sulfate pools. Pyrite and
 452 other reduced-sulfur components should not be combined with this subset unless the analysis is
 453 specifically designed to compare oxidized and reduced pools (Present et al., 2020).

454 For sedimentary pyrite studies, the starting subset should identify pyrite and, where justified,
 455 CRS or another explicitly defined reduced-sulfur component. The carrier and material fields allow
 456 researchers to distinguish direct mineral identification, operationally extracted fractions, and broader
 457 reduced-sulfur pools. Lithology, depositional setting, water depth, sedimentation rate, metamorphic
 458 grade, and age can then be used to examine whether a pattern persists after local environmental context
 459 is considered. This is important because pyrite $\delta^{34}\text{S}$ can reflect local sedimentary and diagenetic controls
 460 as well as larger sulfur-reservoir change (Lang et al., 2020; Pasquier et al., 2021; Halevy et al., 2023;
 461 Spruzen et al., 2024).

462 Multiple-sulfur-isotope applications should distinguish the conventional $\delta^{33}\text{S}$ and $\delta^{36}\text{S}$ fields
 463 from the $\Delta^{33}\text{S}$ and $\Delta^{36}\text{S}$ fields. A query addressing mass-independent fractionation should select the
 464 reported multiple-isotope parameter required by the chosen convention, retain the sulfur component,
 465 and document the age and source filters. $\delta^{33}\text{S}$ or $\delta^{36}\text{S}$ should not be substituted automatically for $\Delta^{33}\text{S}$ or
 466 $\Delta^{36}\text{S}$, because they represent different quantities and may be reported under different analytical and
 467 calculation conventions (Farquhar et al., 2000; Johnston, 2011; Tostevin et al., 2014).

468 Spatial workflows should begin with a choice of reference frame. Modern-map analyses require
 469 valid latitude and longitude values and should report whether repeated rows were aggregated by
 470 section, locality, or DOI. Paleogeographic workflows additionally require valid palaeolatitude,
 471 palaeolongitude, and numerical age values. In both cases, spatial patterns should be tested within a
 472 defined sulfur component and age window before they are interpreted as global environmental structure.



473 6 Limitations and recommended use

474 DSSI is a curated query system rather than a single global sulfur isotopic curve. Users should
475 define the sulfur component, age interval, spatial frame, and DOI/source filters that match the question
476 being tested. Whole-database summaries are useful for assessing coverage, whereas subsets explicitly
477 defined by sulfur phase are required for interpretations of seawater sulfate evolution, sedimentary pyrite
478 formation, sulfur isotopic mass-independent fractionation, and pyrite-burial feedbacks during anoxic
479 events ([Present et al., 2020](#); [Spruzen et al., 2024](#); [Fakhraee et al., 2025a](#)).

480 Modern coordinate precision varies because older sources may report section-, basin-, or region-
481 level localities rather than exact sample positions. Rows without valid reconstructed paleocoordinates
482 remain available for modern spatial analysis but should not enter paleomap-based summaries without
483 additional review. Likewise, `age_ma` is intended for plotting and binning; source stratigraphic fields
484 should be retained when revising age models or working at section scale, especially for event-scale
485 correlations ([Gumsley et al., 2017](#); [Warke et al., 2020](#)).

486 Duplicate records and contextual uncertainty require explicit attention in quantitative work. DOI
487 should be considered with author-year, section, age, sulfur component, and isotopic values when
488 evaluating repeated measurements. Metamorphic overprinting, source-described alteration, uncertain
489 carrier information, or unusual isotopic values are not automatic grounds for exclusion, but they should
490 be screened for the intended application. This is particularly important for reduced-sulfur records
491 because sedimentation, bioturbation, methane cycling, and depositional environment can shape
492 preserved pyrite $\delta^{34}\text{S}$ values ([van de Velde and Meysman, 2016](#); [Houghton et al., 2022](#); [Riemer et al.,](#)
493 [2023](#); [Spruzen et al., 2024](#)).

494 Provenance and missing-data limitations require additional care. DOI is the primary provenance
495 identifier in the released v1.0 table. It is available for 77,422 rows; the remaining 648 rows lack a DOI
496 and can only be narrowed through the retained author-year, section, locality, stratigraphic, and
497 geochemical information. These legacy or DOI-unavailable records should be identified explicitly in
498 publication-level or source-level summaries. A future release would benefit from a separate persistent
499 legacy-source identifier or a standardized citation table for such records, without reintroducing multiple
500 inconsistent reference strings into the main analytical table.



501 Some records have missing values for various reasons. They can reflect information not reported
502 by the original source, a field that is not applicable to a given archive, or a value that could not be
503 standardized without adding unsupported interpretation. Users should not treat absence of a contextual
504 field as evidence for a geological state. Instead, they should report the filtering rule, the number of
505 records retained, and the resulting loss of coverage when applying any completeness requirement. This
506 practice makes it possible to distinguish a scientific pattern from the structure of the underlying
507 literature.

508 **Code and data availability**

509 The Deep-time Sediment Sulfur Isotopes (DSSI) Database v1.0, comprising an Excel workbook
510 containing the Database and References worksheets and a README file, is available from Zenodo
511 under the Creative Commons Attribution 4.0 International License (CC BY 4.0) (Guo et al., 2026):
512 <https://doi.org/10.5281/zenodo.21675881>. The code used for figure generation and paleogeographic
513 coordinate reconstruction is available from Zenodo under the MIT License (Guo, 2026):
514 <https://doi.org/10.5281/zenodo.21666567>.

515 **Author contributions**

516 Wenyi Guo, Huyue Song, and Yong Du designed the study and secured funding. Thomas J.
517 Algeo, Jing Li, Hui Zhang, Junjie Xue, Jianwei Peng, Xiangpeng Ke, Haijun Song, Daoliang Chu, and
518 Li Tian conducted data acquisition, curation, and validation. Wenyi Guo prepared the manuscript with
519 contributions from all co-authors. All authors reviewed and approved the final manuscript.

520 **Competing interests**

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



522 Acknowledgments

523 We thank the authors of the original studies and the curators of public data repositories whose
524 published data and metadata contributed to the DSSI compilation. During the preparation of this
525 manuscript, the authors used OpenAI Codex (GPT-5) to assist with English-language grammar and with
526 the technical preparation of figures. The tool was not used to make autonomous scientific decisions. All
527 data-processing choices, figure content, analyses, interpretations, and final manuscript text were
528 reviewed, verified, and approved by the authors, who take full responsibility for the work.

529

530 Financial support

531 This work has been funded by the State Key R&D Project of China (grant nos.
532 2024YFF0810300, 2023YFF0804000), the National Natural Science Foundation of China (grant nos.
533 U25A20779, 42172032, 42325202, 42402316), the China Postdoctoral Science Foundation (grant no.
534 2025T180107).

535 References

- 536 Bryant, R. N., Halevy, I., Fike, D. A., and Pasquier, V.: Deconvolving microbial and environmental
537 controls on marine sedimentary pyrite sulfur isotope ratios, *Science*, 382, 912–915,
538 <https://doi.org/10.1126/science.adi3417>, 2023.
- 539 Canfield, D. E.: The evolution of the Earth surface sulfur reservoir, *Am. J. Sci.*, 304, 839–861,
540 <https://doi.org/10.2475/ajs.304.10.839>, 2004.
- 541 Caruso, S., Selvaraja, V., Fiorentini, M. L., and LaFlamme, C.: The Global Sedimentary Sulfur Isotope
542 Database, University of Western Australia Research Repository, [https://doi.org/10.26182/12r5-](https://doi.org/10.26182/12r5-6z79)
543 [6z79](https://doi.org/10.26182/12r5-6z79), 2017.
- 544 Du, Y., Song, H., Algeo, T. J., Zhang, H., Peng, J., Wu, Y., Lai, J., Shu, X., Song, H., Wei, L., Zhang, J.,
545 Stüeken, E. E., Grasby, S. E., Dal Corso, J., Liu, X., Chu, D., Tian, L., Liang, Q., Li, X., Yao, H.,
546 and Song, H.: The global Deep-time Sediment Nitrogen Isotopes in Marine Systems (DSMS-NI)
547 database, *Earth Syst. Sci. Data*, 18, 675–690, <https://doi.org/10.5194/essd-18-675-2026>, 2026.
- 548 Edwards, C. T., Fike, D. A., and Saltzman, M. R.: Testing carbonate-associated sulfate (CAS)
549 extraction methods for sulfur isotope stratigraphy: a case study of a Lower–Middle Ordovician



- 550 carbonate succession, Shingle Pass, Nevada, USA, *Chem. Geol.*, 529, 119297,
551 <https://doi.org/10.1016/j.chemgeo.2019.119297>, 2019.
- 552 Fakhraee, M., Hancisse, O., Canfield, D. E., Crowe, S. A., and Katsev, S.: Proterozoic seawater sulfate
553 scarcity and the evolution of ocean–atmosphere chemistry, *Nat. Geosci.*, 12, 375–380,
554 <https://doi.org/10.1038/s41561-019-0349-9>, 2019.
- 555 Fakhraee, M., Bauer, K. W., Planavsky, N. J., Reinhard, C. T., and Crowe, S. A.: Climate stabilization
556 by alkalinity production from pyrite burial during oceanic anoxia, *Nat. Geosci.*, 18, 495–502,
557 <https://doi.org/10.1038/s41561-025-01698-0>, 2025a.
- 558 Fakhraee, M., Crockford, P. W., Bauer, K. W., Pasquier, V., Sugiyama, I., Katsev, S., Raven, M. R.,
559 Gomes, M., Philippot, P., Crowe, S. A., Tarhan, L. G., Lyons, T. W., and Planavsky, N.: The
560 history of Earth’s sulfur cycle, *Nat. Rev. Earth Environ.*, 6, 106–125,
561 <https://doi.org/10.1038/s43017-024-00615-0>, 2025b.
- 562 Farquhar, J., Bao, H., and Thieme, M.: Atmospheric influence of Earth’s earliest sulfur cycle, *Science*,
563 289, 756–758, <https://doi.org/10.1126/science.289.5480.756>, 2000.
- 564 Fike, D. A., Grotzinger, J. P., Pratt, L. M., and Summons, R. E.: Oxidation of the Ediacaran ocean,
565 *Nature*, 444, 744–747, <https://doi.org/10.1038/nature05343>, 2006.
- 566 Fike, D. A., Bradley, A. S., and Rose, C. V.: Rethinking the ancient sulfur cycle, *Annu. Rev. Earth
567 Planet. Sci.*, 43, 593–622, <https://doi.org/10.1146/annurev-earth-060614-105302>, 2015.
- 568 Gomes, M. L., Hurtgen, M. T., and Sageman, B. B.: Biogeochemical sulfur cycling during Cretaceous
569 oceanic anoxic events: a comparison of OAE1a and OAE2, *Paleoceanography*, 31, 233–251,
570 <https://doi.org/10.1002/2015PA002880>, 2016.
- 571 Gumsley, A. P., Bekker, A., Bleeker, W., Chamberlain, K. R., Ramezani, J., and Söderlund, U.: Timing
572 and tempo of the Great Oxidation Event, *Proc. Natl Acad. Sci. USA*, 114, 1811–1816,
573 <https://doi.org/10.1073/pnas.1610032114>, 2017.
- 574 Guo, W.: DSSI Reproducibility Package: Figure Generation and Paleogeographic Coordinate
575 Reconstruction, Zenodo [code], version 1.0.0, <https://doi.org/10.5281/zenodo.21666567>, 2026.
- 576 Guo, W., Song, H., Du, Y., Algeo, T. J., Li, J., Zhang, H., Xue, J., Peng, J., Ke, X., Song, H., Chu, D.,
577 and Tian, L.: Deep-time Sediment Sulfur Isotopes (DSSI): a database of sedimentary sulfur isotopic
578 records through Earth history, Zenodo [dataset], version 1.0,
579 <https://doi.org/10.5281/zenodo.21675881>, 2026.
- 580 Halevy, I., Pasquier, V., Bryant, R. N., Fike, D. A., and Turchyn, A. V.: Sedimentary parameters control
581 the sulfur isotope composition of marine pyrite, *Science*, 382, 946–951,
582 <https://doi.org/10.1126/science.adh4083>, 2023.
- 583 Houghton, J., Scarponi, D., Capraro, L., and Fike, D. A.: Impact of sedimentation, climate and sea level
584 on marine sedimentary pyrite sulfur isotopes: insights from the Valle di Manche section (Lower-
585 Middle Pleistocene, southern Italy), *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, 585, 110730,
586 <https://doi.org/10.1016/j.palaeo.2022.110730>, 2022.
- 587 International Commission on Stratigraphy: International Chronostratigraphic Chart, v2023/09,
588 <https://stratigraphy.org/chart>, 2023.



- 589 Johnston, D. T.: Multiple sulfur isotopes and the evolution of Earth's surface sulfur cycle, *Earth Sci.*
 590 *Rev.*, 106, 161–183, <https://doi.org/10.1016/j.earscirev.2011.02.003>, 2011.
- 591 Jørgensen, B. B., Findlay, A. J., and Pellerin, A.: The biogeochemical sulfur cycle of marine sediments,
 592 *Front. Microbiol.*, 10, 849, <https://doi.org/10.3389/fmicb.2019.00849>, 2019.
- 593 Lai, J., Song, H., Chu, D., Dal Corso, J., Sperling, E. A., Wu, Y., Liu, X., Wei, L., Li, M., Song, H., Du,
 594 Y., Jia, E., Feng, Y., Song, H., Yu, W., Liang, Q., Li, X., and Yao, H.: Deep-Time Marine
 595 Sedimentary Element Database, *Earth Syst. Sci. Data*, 17, 1613–1626, [https://doi.org/10.5194/essd-](https://doi.org/10.5194/essd-17-1613-2025)
 596 17-1613-2025, 2025.
- 597 Lang, X., Tang, W., Ma, H., and Shen, B.: Local environmental variation obscures the interpretation of
 598 pyrite sulfur isotope records, *Earth Planet. Sci. Lett.*, 533, 116056,
 599 <https://doi.org/10.1016/j.epsl.2020.116056>, 2020.
- 600 Ono, S.: Photochemistry of sulfur dioxide and the origin of mass-independent isotope fractionation in
 601 earth's atmosphere, *Annu. Rev. Earth Planet. Sci.*, 45, 301–329, [https://doi.org/10.1146/annurev-](https://doi.org/10.1146/annurev-earth-082517-010302)
 602 earth-082517-010302, 2017.
- 603 Paiste, K., Fike, D. A., Kirsimäe, K., Jones, C., and Lepland, A.: Testing the global significance of the
 604 sulfur isotope record of the ca. 2.0 Ga Zaonega formation: a micro-scale S isotope investigation,
 605 *Geochim. Cosmochim. Acta*, 331, 86–104, <https://doi.org/10.1016/j.gca.2022.05.019>, 2022.
- 606 Paiste, K., Mänd, K., Kreitsmann, T., Lepland, A., and Martin, A. P.: Identifying global vs. basinal
 607 controls on Paleoproterozoic organic carbon and sulfur isotope records, *Earth Sci. Rev.*, 207,
 608 103230, <https://doi.org/10.1016/j.earscirev.2020.103230>, 2020.
- 609 Pasquier, V., Bryant, R. N., Fike, D. A., and Halevy, I.: Strong local, not global, controls on marine
 610 pyrite sulfur isotopes, *Sci. Adv.*, 7, eabb7403, <https://doi.org/10.1126/sciadv.abb7403>, 2021.
- 611 Pavlov, A. A. and Kasting, J. F.: Mass-independent fractionation of sulfur isotopes in Archean
 612 sediments: strong evidence for an anoxic Archean atmosphere, *Astrobiology*, 2, 27–41,
 613 <https://doi.org/10.1089/153110702753508950>, 2002.
- 614 Paytan, A. and McLaughlin, K.: The oceanic sulfur cycle, *Chem. Rev.*, 107, 580–627,
 615 <https://doi.org/10.1021/cr050350m>, 2004.
- 616 Paytan, A., Kastner, M., Campbell, D., and Thieme, M. H.: Sulfur isotopic composition of Cenozoic
 617 seawater sulfate, *Science*, 282, 1459–1462, <https://doi.org/10.1126/science.282.5392.1459>, 1998.
- 618 Present, T. M., Adkins, J. F., and Fischer, W. W.: Variability in sulfur isotope records of Phanerozoic
 619 seawater sulfate, *Geophys. Res. Lett.*, 47, e2020GL088766, <https://doi.org/10.1029/2020GL088766>,
 620 2020.
- 621 Richardson, J. A., Kiipli, T., Kallaste, T., and Loydell, D. K.: Silurian records of carbon and sulfur
 622 cycling from Estonia: the importance of depositional environment on isotopic trends, *Earth Planet.*
 623 *Sci. Lett.*, 512, 71–82, <https://doi.org/10.1016/j.epsl.2019.02.020>, 2019.
- 624 Riemer, S., Turchyn, A. V., Pellerin, A., and Antler, G.: Digging deeper: bioturbation increases the
 625 preserved sulfur isotope fractionation, *Front. Mar. Sci.*, 9, 1039193,
 626 <https://doi.org/10.3389/fmars.2022.1039193>, 2023.



- 627 Scotese, C. R.: PALEOMAP Plate Model m15g60_v2d3 for use with ContOceAnPolyv10u_v2d3,
 628 PALEOMAP Project, 2016.
- 629 Scott, C., Wing, B. A., Bekker, A., Planavsky, N. J., and Lyons, T. W.: Pyrite multiple-sulfur isotope
 630 evidence for rapid expansion and contraction of the early Paleoproterozoic seawater sulfate
 631 reservoir, *Earth Planet. Sci. Lett.*, 389, 95–104, <https://doi.org/10.1016/j.epsl.2014.01.009>, 2014.
- 632 Sim, M. S., Ono, S., and Hurtgen, M. T.: Sulfur isotope evidence for low and fluctuating sulfate levels
 633 in the Late Devonian ocean and the potential link with the mass extinction event, *Earth Planet. Sci.*
 634 *Lett.*, 419, 52–62, <https://doi.org/10.1016/j.epsl.2015.03.004>, 2015.
- 635 Song, H., Tong, J., Chen, Z., and Bottrell, S. H.: Early Triassic seawater sulfate drawdown, *Geochim.*
 636 *Cosmochim. Acta*, 128, 95–113, <https://doi.org/10.1016/j.gca.2013.12.011>, 2014.
- 637 Spruzen, C., Bradbury, H. J., Kast, E. R., and Turchyn, A. V.: The sulfur isotopic composition of
 638 Cenozoic pyrite is affected by methane content and depositional environment, *Earth Planet. Sci.*
 639 *Lett.*, 648, 119097, <https://doi.org/10.1016/j.epsl.2024.119097>, 2024.
- 640 Tostevin, R., Farquhar, J., Mills, B. J. W., and Poulton, S. W.: Multiple sulfur isotope constraints on the
 641 modern sulfur cycle, *Earth Planet. Sci. Lett.*, 396, 14–21, <https://doi.org/10.1016/j.epsl.2014.04.019>,
 642 2014.
- 643 Uveges, B. T., Izon, G., Ono, S., Beukes, N. J., and Summons, R. E.: Reconciling discrepant minor
 644 sulfur isotope records of the Great Oxidation Event, *Nat. Commun.*, 14, 279,
 645 <https://doi.org/10.1038/s41467-023-35820-w>, 2023.
- 646 van de Velde, S. and Meysman, F. J. R.: The influence of bioturbation on iron and sulphur cycling in
 647 marine sediments: a model analysis, *Aquat. Geochem.*, 22, 469–504,
 648 <https://doi.org/10.1007/s10498-016-9291-9>, 2016.
- 649 Warke, M. R., Le Heron, D. P., Prave, A. R., and Condon, D. J.: The Great Oxidation Event preceded a
 650 Paleoproterozoic ‘Snowball Earth’, *Proc. Natl Acad. Sci. USA*, 117, 13314–13320,
 651 <https://doi.org/10.1073/pnas.2003010117>, 2020.
- 652 Wilkinson, M. D., Dumontier, M., Aalbersberg, I. J., Appleton, G., Axton, M., Baak, A., Blomberg, N.,
 653 Boiten, J.-W., da Silva Santos, L. B., Bourne, P. E., Bouwman, J., Brookes, A. J., Clark, T., Crosas,
 654 M., Dillo, I., Dumon, O., Edmunds, S., Evelo, C. T., Finkers, R., Gonzalez-Beltran, A., Gray, A. J.
 655 G., Groth, P., Goble, C., Grethe, J. S., Heringa, J., ’t Hoen, P. A. C., Hooft, R., Kuhn, T., Kok, R.,
 656 Kok, J., Lusher, S. J., Martone, M. E., Mons, A., Packer, A. L., Persson, B., Rocca-Serra, P., Roos,
 657 M., van Schaik, R., Sansone, S.-A., Schultes, E., Sengstag, T., Slater, T., Strawn, G., Swertz, M. A.,
 658 Thompson, M., van der Lei, J., van Mulligen, E., Velterop, J., Waagmeester, A., Wittenburg, P.,
 659 Wolstencroft, K., Zhao, J., and Mons, B.: The FAIR Guiding Principles for scientific data
 660 management and stewardship, *Sci. Data*, 3, 160018, <https://doi.org/10.1038/sdata.2016.18>, 2016.
- 661