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1 **The Sedimentary Geochemistry and Paleoenvironments Project Phase 2 Data Release: An**  
2 **open data resource for the study of Earth's environmental history**

3  
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## 223 **Abstract**

224 Geochemical data from sedimentary rocks are the primary source of information regarding Earth's  
225 surface evolution through time, including its air and water envelopes and interactions with life and  
226 deep Earth processes. The Sedimentary Geochemistry and Paleoenvironments Project (SGP) is a  
227 scientific consortium centered around open data and community-driven development of  
228 cyberinfrastructure tools and resources for sedimentary geochemistry and Earth history. Here we  
229 describe the SGP Phase 2 data release, which focused on incorporating Paleoproterozoic and

230 Mesoproterozoic (2500 – 1000 million years ago) data and better accommodating carbonate data.  
231 This data release was built through the involvement of >200 researchers worldwide in academia,  
232 government, and industry, and provides the largest available public data resource for our user  
233 community in the academic fields of geochemistry, sedimentology, tectonics, paleontology, Earth  
234 history, and paleoclimate, as well as the petroleum and minerals industries. The dataset now  
235 encompasses 126,006 samples and 4,132,371 geochemical analyses. In addition to direct entry by  
236 SGP Team Members, we have ingested and incorporated datasets from the Geoscience Australia  
237 OZCHEM database, the Alberta Geological Survey, and the Deep-Time Marine Sedimentary  
238 Element Database (DM-SED) compilation. This paper details sampling in the Phase 2 dataset with  
239 respect to age, geography, lithology, and other geological characteristics, documents access via our  
240 search website and API, discusses possible issues and/or biases in the dataset that could impact  
241 analyses, describes plans for governance and stewardship of data from Indigenous lands, and  
242 serves as the citable reference paper for the data release.  
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## 245 **1. Introduction**

246 How has Earth’s surface, including its atmosphere, oceans, and depositional systems  
247 changed over time? How have these changes affected life on Earth? Were these environmental  
248 changes driven by tectonic changes and solid Earth processes, or driven by life itself? Answers to  
249 these first-order questions about Earth and its history are found in the geochemistry of Earth’s  
250 sedimentary rocks. For decades, geologists, geochemists, paleontologists, and sedimentologists  
251 have generated relevant data. As results accumulated, researchers increasingly gravitated towards  
252 larger data compilations and global syntheses, a prerequisite for studies across long timescales  
253 (Alcott et al., 2025). Compilation efforts initially took the form of flat-file (e.g., Excel) data tables.  
254 In 2016, the Sedimentary Geochemistry and Paleoenvironments Project (SGP), an open research  
255 consortium styled after efforts in the biomedical community, spurred the development of a  
256 sedimentary geochemical database, now accessible via a search website and Application  
257 Programming Interface (API). More details on the history of SGP and the philosophy and  
258 reasoning behind its inception can be found in Farrell et al. (2021). Our Phase 1 project (Farrell et  
259 al., 2021) primarily focused on Neoproterozoic–Paleozoic (1000-250 million years ago, Ma) shale  
260 records, and has been fundamental to diverse studies of environmental change, weathering history,  
261 carbon and nutrient cycling, fossil preservation, paleoclimate, and ore and petroleum deposits (for  
262 a non-exhaustive list, refer to Bian et al., 2025; Bishop and Robbins, 2024; Bubphamanee et al.,  
263 2025; Canfield et al., 2025; Cui et al., 2023; Emmings et al., 2022; Ernst et al., 2023; Hantsoo et  
264 al., 2024; Kimmig and Pratt, 2022; Lipp et al., 2021; Mehra et al., 2021; Murray and Jagoutz,  
265 2024; Olson et al., 2025; Roest-Ellis et al., 2023; Stockey et al., 2024; Tang et al., 2024; Venugopal  
266 et al., 2025, 2023; Walton and Shorttle, 2024; Wang et al., 2023; Wei et al., 2024; Ye et al., 2024;  
267 Zhang et al., 2022; Zhao et al., 2024). This paper describes our Phase 2 data release, which  
268 involved data ingestion, cleaning, and database updates carried out between late 2020 and early  
269 2025.

270 Following the model established by biomedical research consortia, we publicly release data  
271 in scheduled ‘data freezes.’ First, we build a proprietary data product with novel scientific value.  
272 This step allows our scientific Working Groups to focus solely on analysis, leading to high-impact  
273 scientific studies that would otherwise not be possible. After a set period of proprietary access, the  
274 data are publicly released via our search website and API. Concurrently, we publish a group paper  
275 as a citable reference describing the data product (e.g., this paper). This approach is similar to the

276 long-successful embargo period for International Ocean Drilling Program/International Ocean  
277 Discovery Program (IODP) (ocean drilling) data and samples, which gives participating scientists  
278 time to publish their manuscripts while also establishing a repository for future research. This  
279 database and its access points are designed in accordance with and align to FAIR principles  
280 (Findability, Accessibility, Interoperability, Reusability) for scientific data management and  
281 reusability (Wilkinson et al., 2016).

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283

## 284 **2. Database**

285 SGP uses a PostgreSQL relational database that remains relatively unchanged from the  
286 Phase 1 database described in Farrell et al. (2021; additional changes described below). It is based  
287 around a modified version of the British Geological Survey Geochemistry database. SGP is  
288 a sample-centric database — rock samples are the core entity at the center of the schema, with all  
289 other data types linked to them. Samples are linked to sample-level data (e.g., lithology, age) as  
290 well as to sites (e.g., drillcore or stratigraphic section) that record higher-level geographic features.  
291 Geochemical methodologies are tracked using three controlled vocabularies for a) preparation  
292 method (how the sample was ground to a powder; e.g., in a tungsten carbide vessel), b)  
293 experimental method (processing steps; e.g., a weak nitric acid digestion), and c) analytical method  
294 (how the measurement was made; e.g., ICP-MS). Details on measurement accuracy, precision,  
295 reference materials, and upper/lower measurement limits are recorded as reported in ingested data  
296 tables. Tables for geological, geographical, and sample details are based on collection management  
297 databases such as Specify6 and Arctos, as well as the Observations Data Model 2 (an information  
298 model for Earth observations). However, additional tables and modifications have been introduced  
299 to address the specific geological and geographical context data required for the SGP project (and  
300 sedimentary geochemistry more broadly). Our full schema is described in  
301 [https://ufarrell.github.io/sgp\\_phase2/](https://ufarrell.github.io/sgp_phase2/). While the database is tailored to the specific research needs  
302 of the sedimentary geochemistry community, in keeping with FAIR principles (Wilkinson et al.,  
303 2016) it is also designed with larger communities in mind. We have used common vocabularies  
304 and standard community-approved terms wherever possible, and the database structure shares  
305 features (and identifiers) with existing databases such as EarthChem, Macrostrat, and the  
306 Paleobiology Database (PBDB). This facilitates the transfer of data to, or interaction with, other  
307 public community databases.

308 Recently we have implemented a direct database-level integration with Macrostrat (Peters  
309 et al., 2018), a geoinformatics project that compiles data on geological maps, stratigraphic  
310 columns, and age models—the geological framework for our geochemical data. Specifically, we  
311 have 1) harmonized and aligned definitions for rock attributes, 2) linked SGP samples to  
312 Macrostrat units and columns, and are 3) building new web interfaces for stratigraphic column  
313 visualization and entry, and 4) engaging the SGP community in capturing column data that  
314 contextualize geochemical data. Our samples will ultimately be linked to Macrostrat’s continuous-  
315 time and automatically revised age model (in addition to our declarative age model) and details on  
316 depositional environment, lithology, and paleogeography—a critical step for maintaining the  
317 future utility of sedimentary geochemical data archived in SGP. This also represents steps towards  
318 the establishment of unified chronostratigraphic frameworks for geochemical and paleontological  
319 data that have been identified as a key goal by the deep-time research community (Alcott et al.,  
320 2025).

321

322 *2.1 Carbonate and metal isotope data*

323 In Phase 2, modifications were made to the database to support correct storage of carbonate  
324 geochemical data. Because carbonate data are more commonly from a specific allochem (for  
325 instance a brachiopod fossil) or a specific matrix (for instance micrite versus cement) compared to  
326 shale geochemical data (which are generally from a “bulk” analysis) we have introduced “sample  
327 type” as a sample-level feature. We have also incorporated ‘parent/child’ relationships for sub-  
328 samples (e.g., analyzing multiple different brachiopod fossils within a carbonate hand sample).  
329 Although most analyses in the database remain “bulk,” this allows for future flexibility in  
330 incorporating essentially any type of sub-sample analysis (e.g., LA-ICP-MS data). Following  
331 community input from carbonate workers, we have also incorporated a more detailed break-down  
332 of depositional environments (“depositional environment detail”), allowing for discrimination  
333 between multiple inner shelf environments such as peritidal, carbonate shoal, reef, etc., in addition  
334 to the coarser “depositional environment bin” of fluvial/lacustrine/inner shelf/outer shelf/basinal.

335 Adding carbonate data has also required a re-structuring of analyte naming conventions.  
336 Correct interpretation of sedimentary geochemical data requires knowing what mineral or phase  
337 was analyzed: for instance, if a  $\delta^{13}\text{C}$  analysis is from organic carbon or carbonate, or if a  $\delta^{238}\text{U}$   
338 analysis is from carbonate or shale. In these examples, the two paired phases have substantial  
339 isotopic differences related to carbon isotope fractionation during photosynthesis (Park and  
340 Epstein, 1960) and nuclear volume effect changes during uranium reduction and incorporation into  
341 a shale (Andersen et al., 2017), respectively. These are apples-and-oranges measurements that  
342 cannot be mixed in a data table. Naming analytes according to phase existed to an extent in SGP  
343 Phase 1, for instance recording  $\delta^{13}\text{C}$ -organic versus  $\delta^{13}\text{C}$ -carbonate, or  $\delta^{34}\text{S}$ -pyrite versus  $\delta^{34}\text{S}$ -  
344 gypsum, rather than the isotopic measurement itself (i.e., simply  $\delta^{13}\text{C}$  or  $\delta^{34}\text{S}$ ). In Phase 2 we have  
345 more broadly applied this logic to elemental and metal isotopic data, using a tripartite system to  
346 track analyses targeting specific phases:

347  
348 **Auth:** authigenic, from a weak/dilute acid leach on shales, targeting metals associated with organic  
349 matter or pyrite. This usually involves a single-acid leach; note that the strength and type of the  
350 acid can vary.

351  
352 **Carb:** carbonate, from a weak/dilute acid leach on carbonates, targeting metals in the carbonate  
353 crystal lattice. This usually involves a single-acid leach; note that the strength and type of the acid  
354 can vary. Analyses may include relatively strong acids (e.g., a 6N HCl digest) that may leach  
355 elements from clay or detrital minerals compared to a weaker leach, but that are philosophically  
356 targeting the carbonate fraction.

357  
358 **Total:** Elemental abundance or metal isotopes in all phases including detrital, resulting from total  
359 digestion of the rock. Note that aqua regia digests are considered total, although such analyses  
360 underestimate the total as they do not digest silicate and oxide minerals.

361  
362 This tripartite division, and exactly what digestion types are included in each category, will remain  
363 static in the Phase 2 website but this is an area where we aim to continue improving and evolving  
364 in consultation with the community. Aqua regia (concentrated nitric + hydrochloric acid) digests  
365 are a good example; these are run by many commercial geochemical labs (e.g., Actlabs, Bureau  
366 Veritas) and since many of the chalcophile elements like Mo or Ni in shale are hosted by organic  
367 matter or pyrite that are dissolved by aqua regia, it is a ‘nearly total’ extraction for these elements.

368 But it is not as ‘total’ as a four-acid digestion involving hydrofluoric acid, or a fusion methodology,  
369 and could equally be considered authigenic (or even be poorly quantitative, depending on the  
370 element and host phase(s) (refer to Xu et al., 2012)). This tripartite division also diverges from  
371 other databases such as EarthChem, which simply reports the analyte irrespective of phase or  
372 extraction type. We believe that such data tabulations (for instance a table of  $\delta^{13}\text{C}$  data without  
373 discrimination whether it comes from organic matter or carbonate) have low utility for sedimentary  
374 geochemistry and Earth history studies. While capturing information on phase is critical, this does  
375 introduce problems in future data harmonization efforts that are an important goal of the  
376 geoinformatics community (Chamberlain et al., 2021; note however that our more granular analyte  
377 names can easily be collapsed—for instance  $\delta^{13}\text{C}$ -organic or  $\delta^{13}\text{C}$ -carbonate to simply  $\delta^{13}\text{C}$ —  
378 whereas the reverse is not true).

379  
380 In the current website, “total” element abundances are exposed under the Show → Elements tab  
381 (or filtered in the Analyte Filters → Elements tab in a Detailed Search). “Carbonate” elemental  
382 abundances (along with common carbonate geochemical proxies for diagenesis such as Mn/Sr) are  
383 exposed in the Show → Carbonate Proxies tab. All metal isotopes, including auth, carb, and total,  
384 are exposed in the Show → Metal Isotopes tab. We have relatively few “authigenic” elemental  
385 abundances (primarily thallium and vanadium) and these are exposed with identifying subscripts  
386 under the Show → Elements tab. More details on data presentation and access are included below.

387  
388

### 389 **3. Data Collection and Phase 2 Updates**

390 Data collection, collation, and entry into the SGP database occurs through SGP  
391 Collaborative Team direct entry and by ingestion of larger published data products. These “data  
392 sources” can be selected/filtered through the API or in the first tab under Sample Filters on the  
393 Detailed Search or Analysis search pages. In SGP direct entry, Collaborative Team Members fill  
394 in standardized context sheets with relevant geological meta-data, which are then directly entered  
395 into the database. More information on direct entry is available in Farrell et al. (2021) and the SGP  
396 wiki. This process continued during Phase 2, and some data entered during Phase 1 were updated  
397 based on newly published geological information or geologic/informatic errors identified by  
398 database users (specifically, the geological context data of thousands of samples were enhanced).  
399 SGP direct entry now comprises 48,154 samples.

400 In Phase 1 we ingested data from the United States Geological Survey (USGS) Critical  
401 Metals in Black Shales project (Granitto et al., 2017) (USGS-CMIBS) and the USGS National  
402 Geochemical Database: Rock (USGS-NGDB).

403 In Phase 2 we ingested data from three new data sources: the Geoscience Australia  
404 OZCHEM database, the Alberta Geological Survey, and the Deep-Time Marine Sedimentary  
405 Element Database, or DM-SED (Lai et al., 2025). We also excluded a number of samples  
406 (primarily from USGS-NGDB and USGS-CMIBS) in our efforts to better incorporate Indigenous  
407 data stewardship principles (refer to “Indigenous Data Governance” below). Some Phase 2  
408 samples do not have associated data, and therefore total sample counts are slightly higher than the  
409 sum of samples by data source (samples are linked to data source through batches of data).  
410 Extended details on sample counts, data ingestion, and illustrations of sampling by age, geography,  
411 and lithology for each data source can be found on the SGP wiki  
412 ([https://github.com/ufarrell/sgp\\_phase2/wiki](https://github.com/ufarrell/sgp_phase2/wiki)).

413

414 *3.1 USGS-NGDB and CMIBS updates*

415 During Phase 2 we updated all interpreted ages for these projects that were solely derived  
416 from the Macrostrat age model with the newest available ages. We also replaced some samples  
417 with a more precisely coded version from the original authors as part of SGP Collaborative Team  
418 direct entry. Reference works were added and linked to CMIBS samples, based on the CMIBS  
419 “publ\_id.” We also note a growing recognition that the CMIBS project may include some  
420 mineralized samples and that the NGDB database includes a large proportion of terrestrial samples.  
421 Internet searches of Phase 1 NGDB and CMIBS formation names that had three or more samples  
422 suggested that 129 formations (29%) were terrestrial, 264 formations were marine (59%), and 52  
423 formations (12%) were mixed terrestrial/marine (Canfield et al., 2025). The majority of terrestrial  
424 and mixed formations (86%) were from NGDB, largely due to a robust historical USGS sampling  
425 program of western U.S. sandstones. Because NGDB samples are not coded with respect to  
426 depositional environment (“environmental bin”) and terrestrial samples cannot easily be excluded,  
427 caution is warranted when considering whether to include these data in studies aiming to  
428 reconstruct marine geochemical trends. The environmental interpretations of Canfield et al.  
429 (2025), based on Google searches of formation names in NGDB and CMIBS, are now available  
430 under “environmental notes” and could be used for manual sampling culling. With respect to  
431 CMIBS, although the papers included during Phase 1 were initially screened to exclude clearly  
432 mineralized samples/ore systems, the focus of that literature compilation was identifying  
433 anomalous enrichments in critical metals. These studies commonly analyzed samples ‘distal’ to  
434 ore systems or from complex volcanic-sedimentary terranes. Such geological settings may have  
435 experienced some mineralization, and these samples would not have been removed by our initial  
436 manuscript-level screening. Note that both USGS projects remain uncoded for “sample type”  
437 because such details are not available, even though both are largely comprised of data from “bulk”  
438 samples. Publicly available USGS-NGDB and USGS-CMIBS data sources now contribute 42,585  
439 and 12,276 samples, respectively.

440

441 *3.2 Geoscience Australia OZCHEM*

442 Inorganic geochemistry data were added from the Geoscience Australia OZCHEM National Whole  
443 Rock Geochemistry Dataset, accessed through the Exploration for the Future Portal  
444 (<https://portal.ga.gov.au/persona/efrf>) in 2021. 5,813 samples from 3,317 sites broadly distributed  
445 across Australia were entered, with 262,417 analytical results. Samples were screened to remove  
446 igneous and metamorphic/altered samples based primarily on lithology, lithology  
447 descriptions/qualifiers, and stratigraphic unit names. The samples included are predominantly fine-  
448 grained (~30%) and coarser-grained (~39%) siliciclastics. Carbonates comprise about 16% of the  
449 samples. Most samples are Proterozoic–Paleozoic in age. Interpreted ages were entered primarily  
450 based on the Australian Stratigraphic Units Database (ASUD). A large number of samples (38%)  
451 do not have interpreted ages, and manual or third-party age coding in SGP Phase 3 would increase  
452 the amount of data available for Earth history studies. The data consist primarily of whole-rock  
453 major, minor, and trace elements measured by ICP-MS, XRF, and AAS. As with the USGS-CMIBS  
454 samples, given the working relationship between Geoscience Australia and the active mineral  
455 exploration industry in Australia, there is a likelihood that some samples have experienced a degree  
456 of mineralization.

457

458 *3.3 Alberta Geological Survey*

459 Six open-access datasets were added from the Alberta Geological Survey in 2022, chosen based  
460 on their alignment with SGP goals, including inorganic and organic geochemistry and  
461 mineralogical data. Most of the data came with detailed methodological information, in some cases  
462 including the labs where analyses were made and the experimental methods (e.g., acid digestion  
463 procedures). 4,192 samples were entered, with 332,226 analytical results, from 550 sites in Alberta,  
464 Canada. The samples are mostly fine-grained siliciclastic rocks (72%) with some sandstones (6%)  
465 and carbonates (13%). The samples are mostly Paleozoic and Mesozoic in age. Sampling is biased  
466 towards organic-rich fine-grained units (i.e., potential source rocks) that may generate petroleum.  
467

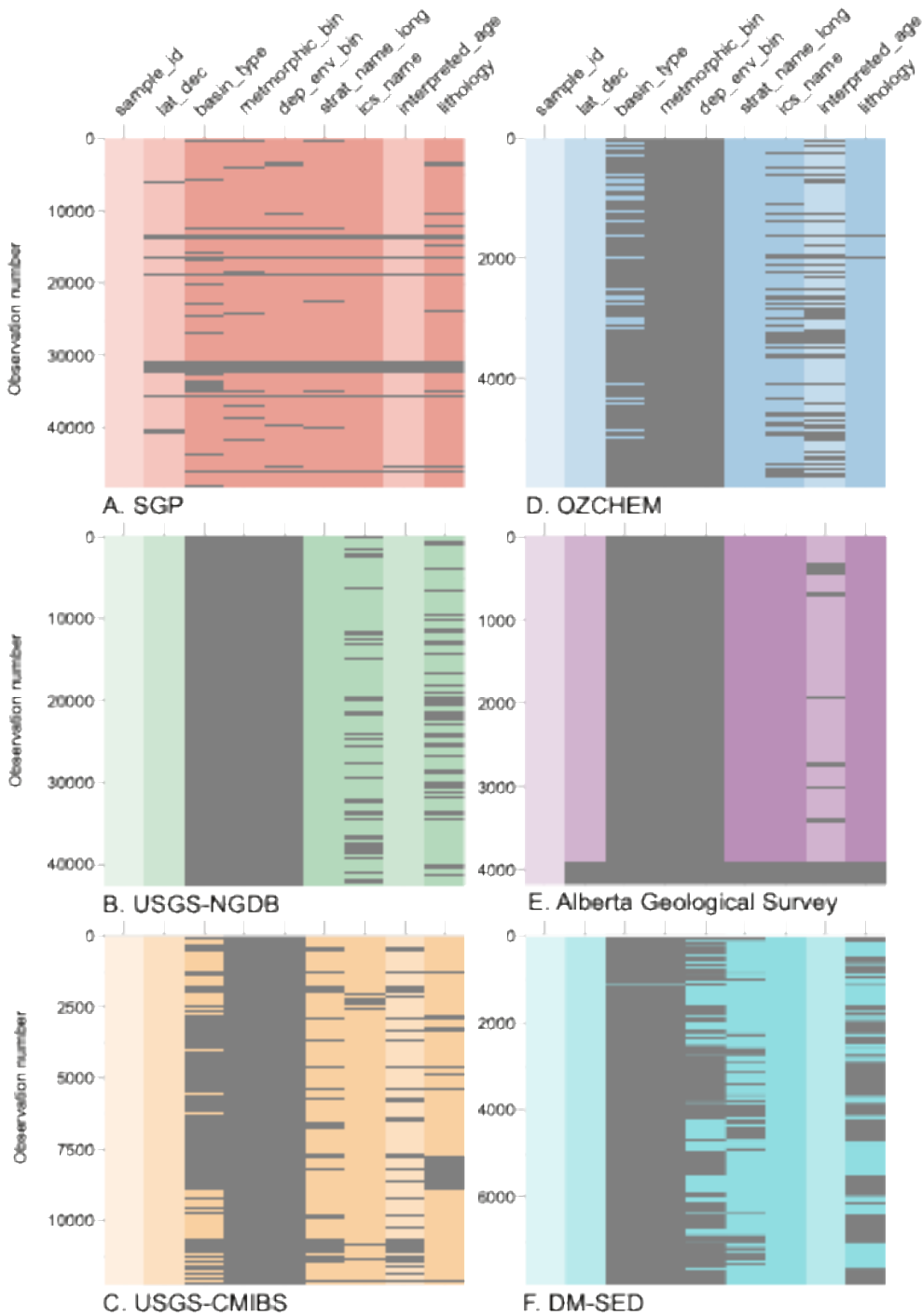
### 468 *3.4 DM-SED*

469 The Deep-Time Marine Sedimentary Element Database (DM-SED) is a compilation study  
470 published in 2025 (Lai et al., 2025), with a similar focus to SGP. The project built on SGP Phase  
471 1, with new data added from studies from a broad range of ages (Proterozoic and Phanerozoic),  
472 with global coverage and from studies dating back to the 1960s. Samples in DM-SED were divided  
473 into two projects: “New Compilation” and “SGP.” The “New Compilation” data were assembled  
474 by a team of researchers who collated data, extracted geological meta-data (including digitizing  
475 stratigraphic heights from older publications or tracking down latitude/longitude information from  
476 other studies) and developed sample-level age models. This diligent compilation work is  
477 nonetheless commonly less precise for meta-data like sample lithology than when coded directly  
478 by the original authors. Specifically in the case of DM-SED, samples are assigned a broad  
479 “LithType” category of “siliciclastic” or “carbonate”, with additional detail provided in the  
480 “LithName” field. However, for more than half of the ingested samples (56%), no “LithName” is  
481 available, and the lithology is therefore recorded only at the higher level. We used the DM-SED  
482 0.0.01.csv download (V3). New compilation data that overlapped with SGP direct entry were first  
483 removed. We also excluded data from studies younger than 2017 or from Ocean Drilling  
484 Project/Deep Sea Drilling Project (ODP/DSDP) studies. We focused on older papers because 1)  
485 we hope to engage authors of more recently published studies in directly coding their data into the  
486 SGP database and becoming involved in the project, and 2) geochemical data and geological meta-  
487 data from older papers is less commonly digitized and harder to extract, and our intention is not to  
488 duplicate the efforts of the DM-SED project. We did not incorporate ODP/DSDP data because  
489 ongoing efforts to digitize all such data (for instance, Sessa et al., 2023) should allow for future  
490 bulk ingestion with consistent age models. In total, data ingestion from DM-SED incorporated  
491 8,029 samples with 212,506 analytical results from 456 sites across the globe; samples have been  
492 associated with their source publications (123 publications total). Note the DM-SED dataset only  
493 incorporated a subset of published geochemical analytes (generally elemental abundances and light  
494 stable isotopes; refer to details in Lai et al. (2025)). Thus some samples/papers may be included in  
495 the SGP reference list and searchable as “projects” but some data, for instance metal isotopes or  
496 iron or phosphorus speciation data, are not present.  
497

### 498 *3.5 Consideration of data sources*

499 All data in the SGP database have passed a minimum bar that we consider appropriate for studying  
500 Earth’s sedimentary carapace and its history. Nonetheless, all data sources have biases; for instance  
501 the direct entry from predominantly academic studies tend to be biased towards stratigraphic or  
502 biological events in the Phanerozoic, whereas the geological surveys are commonly tilted towards  
503 targets of economic interest (such as petroleum for the Alberta Geological Survey or ore deposits  
504 for OZCHEM). Careful consideration of data provenance, together with the use of available

505 geological context and geochemical methodology data to filter samples or correct for sampling  
506 biases (Figure 1), will help improve the accuracy of scientific interpretations based on data from  
507 SGP. Note that samples can be included/excluded at the “Data Source” level in Detailed Search →  
508 Sample Filters → Data Source/Project on the search website. Ultimately, we believe that the best  
509 approach will be similar to those adopted by paleontological studies (Dunhill et al., 2012; Kidwell,  
510 2005; Peters, 2005; Peters and Foote, 2001; Raja et al., 2022; Smith and Benson, 2013): all datasets  
511 are biased by geographical, sociological, or methodological collection approaches, and our goal is  
512 to figure out when biases do and do not matter, and then to statistically correct for them—as much  
513 as possible—in order to infer how the Earth surface has evolved through time (e.g., Mehra et al.,  
514 2021).



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**Figure 1:** Completeness of geological context data for the six data sources compiled in the SGP Phase 2 data release including SGP (panel A, red, n = 48,154), USGS-NGDB (panel B, green, n = 42,585), USGS-CMIBS (panel C, orange, n = 12,276), OZCHEM (panel D, blue, n = 5,813), Alberta Geological Survey (AGS) (panel E, purple, n = 4,192), and DM-SED (panel F, aqua, n = 8,029) (acronyms in Table 1). From left to right, columns indicate the data field as written in the database, including sample ID, latitude in decimal degrees (lat\_dec; all samples with latitude also

523 have longitude), metamorphic bin, depositional environment bin (dep\_env\_bin), lithostratigraphic  
524 unit (strat\_name\_long; i.e., formation), geologic period according to the International Commission  
525 on Stratigraphy time scale (ics\_age), numerical age in millions of years (interpreted\_age), and  
526 lithology. Each horizontal line (observations) corresponds to one individual sample from that data  
527 source. Colored bars indicate that context data are present; dark grey indicates that data are absent.  
528

529

#### 530 **4. Phase 2 Data Description**

531 The published and public Phase 2 database includes 126,006 samples. Of these, 121,047  
532 samples have geochemical data (some samples are entered into the database but not yet linked to  
533 data), and 120,499 samples have geochemical data (4,132,371 analytical results) available through  
534 the search website (some unusual/less useful analytes have data stored in the database but not  
535 presented on the website). Note that the number of available samples/analyses accessible on the  
536 Phase 2 website will change slightly as data from land under U.S. Tribal jurisdiction becomes  
537 available (additional details below).  
538

539

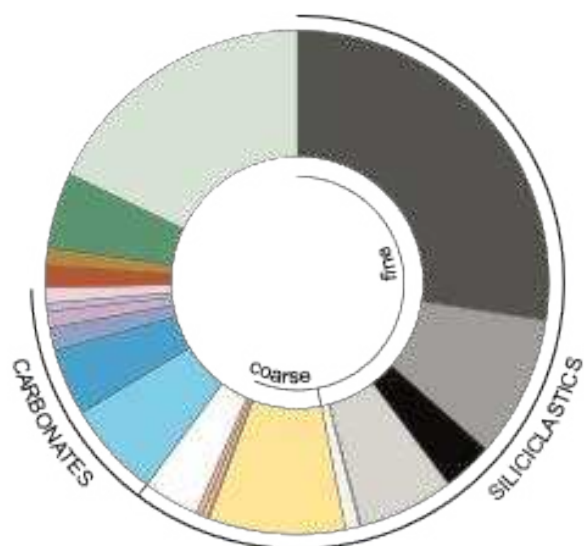
##### 539 *4.1 Site type*

540 49% of samples are from outcrop, 43% are from core, 7% are unknown, and 1% are modern/other.  
541

542

##### 542 *4.2 Lithology*

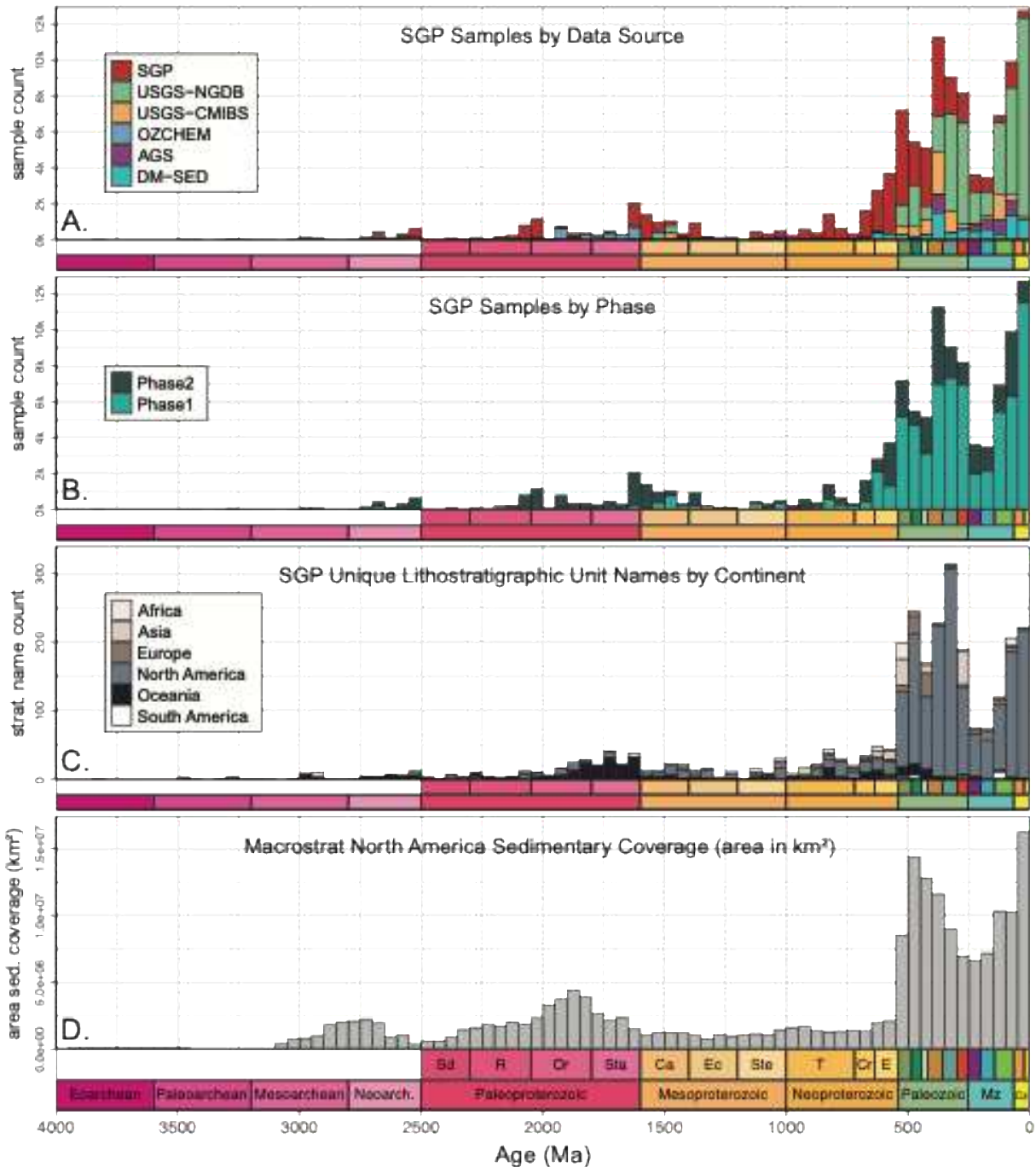
543 As in Phase 1, the majority of samples in the SGP database are fine-grained siliciclastics (lithology  
544 names coded as: argillite, clay, claystone, marl, marlstone, meta-argillite, metapelite, metasiltstone,  
545 mud, mudstone, oil shale, pelite, silt, siltite, siltstone and shale; available as “Shales only” under  
546 the Simple Search website option) (Figure 2; 59% of samples with a lithology code). Coarse-  
547 grained siliciclastics comprise 10.7% for sandstones and 0.8% for conglomerates. Carbonate  
548 lithologies now comprise 19% of coded samples (including: lime mudstone, wackestone,  
549 packstone, grainstone, boundstone, crystalline limestone, dolomudstone, dolowackestone,  
550 dolopackstone, dolograinstone, crystalline dolomite, ooze, carbonate, limestone, dolomite,  
551 dolomicrite, limestone/dolomite; available as “Carbonates only” under the Simple Search website  
552 option). While the overall percentage of carbonate samples has only grown a little since Phase 1  
553 (largely because the Alberta Geological Survey, OZCHEM, and DM-SED data sources brought in  
554 a large number of siliciclastic samples), we have substantially grown the absolute number of coded  
555 carbonate samples from 8,514 to 19,427. Additional lithologies with minor representation in the  
556 database include iron formation (0.29%), chert (1.35%), and phosphorite (1.7%). Additional  
557 details on lithology textures, modifiers, and composition are also available for many samples.



558  
559 **Figure 2:** Distribution of lithologies in the SGP Phase 2 data release.

560  
561 *4.3 Geologic Age*

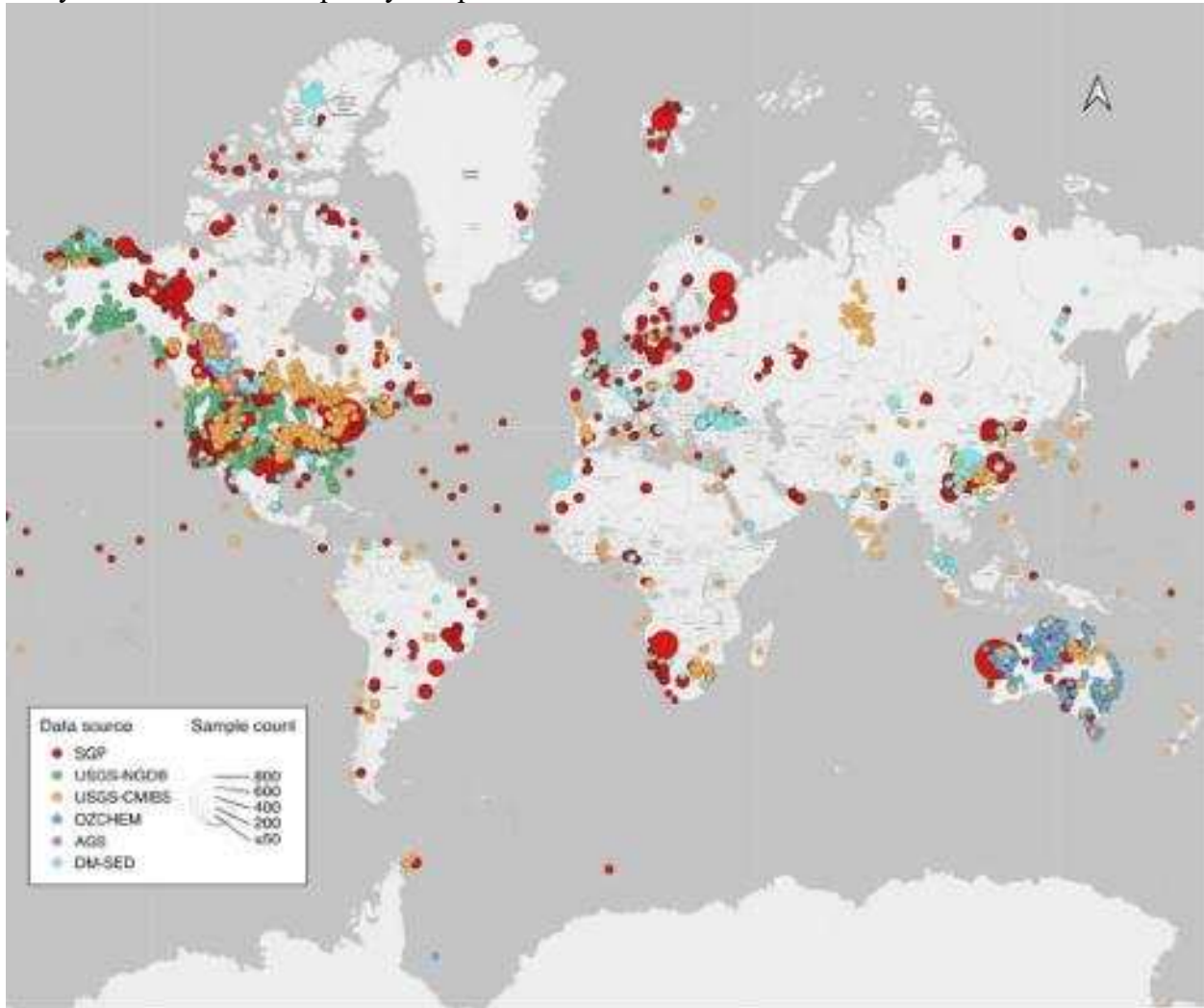
562 Data collection in Phase 1 focused on the Neoproterozoic and Paleozoic, whereas Phase 2  
563 focused on adding data primarily in the Paleoproterozoic, Mesoproterozoic, and lower  
564 Neoproterozoic. We have added substantial data holdings in deeper time, increasing the number of  
565 pre-Neoproterozoic samples from 5,023 to 18,082 (Figure 3). Most of these samples were through  
566 SGP direct entry, with accompanying rich geological context data, but the OZCHEM database also  
567 added a substantial number of Paleoproterozoic samples. We have also generally doubled the  
568 number of samples available in each Neoproterozoic time bin. Note that while the Phanerozoic is  
569 far better sampled than the Proterozoic, this is at least partly a function of the available rock record  
570 (e.g., Husson and Peters, 2017 and Fig. 3D) and in a qualitative sense we believe we have captured  
571 much of the published Proterozoic geochemical samples (at least for fine-grained siliciclastics).  
572 The Phase 2 data release has 2,811 Archean samples, 8,050 Paleoproterozoic samples, 7,221  
573 Mesoproterozoic samples, 14,389 Neoproterozoic samples, 46,488 Paleozoic samples, 23,011  
574 Mesozoic samples, and 17,137 Cenozoic samples.



575  
 576 **Figure 3:** Plots through time of SGP samples, color-coded by data source (A) and phase (B); SGP  
 577 unique lithostratigraphic unit names by continent (C); and, for comparison, area of North American  
 578 sedimentary coverage from Macrostrat (D). Plot D created using the rmacrostrat package from  
 579 Jones et al. (2024). Data are plotted in 50 million year bins. On plots A and B sample counts “k”  
 580 = thousand, such that 2k = 2000 samples. Timescale abbreviations from left to right, top to bottom:  
 581 Sd- Siderian, R- Rhyacian, Or- Orosirian, Sta- Statherian, Ca- Calymmian, Ec- Ectasian, Ste-  
 582 Stenian, T- Tonian, Cr- Cryogenian, E- Ediacaran, Nearch.-Neoarchean, Mz-Mesozoic, Cz-  
 583 Cenozoic. Phanerozoic periods not labelled but follow the standard International Commission on  
 584 Stratigraphy color scheme.

585 *4.4 Geographic sampling*

586 Geographic sampling in the database remains heavily biased towards North America. This  
587 is due to the ingestion of data from the USGS-NGDB and Alberta Geological Survey (both of  
588 which are regionally focused) and the fact that, like in other fields of Earth science (e.g., Raja et  
589 al., 2022) socio-political factors have led to substantial data generation in that region. There is also  
590 the sociological bias that SGP organizers are based in North America and are more familiar with  
591 North American researchers and data. Australia now represents a sampling hotspot due to data  
592 from OZCHEM, USGS-CMIBS, and SGP direct entry. Substantial sampling from China is present  
593 through SGP direct entry and DM-SED (note this is primarily focused on Mesoproterozoic,  
594 Neoproterozoic, and Cambrian data, with relatively little post-Cambrian data). While these regions  
595 (plus northern Europe) represent the most densely sampled geographic regions, global sampling  
596 has expanded substantially over Phase 2. This has been driven, at least in part, by an increased  
597 geographic diversity of SGP Collaborative Team members from Africa, South America, and India.  
598 Despite this growth in global sampling, we recognize that the complete stratigraphic column in  
599 many areas worldwide is poorly sampled in the SGP database.

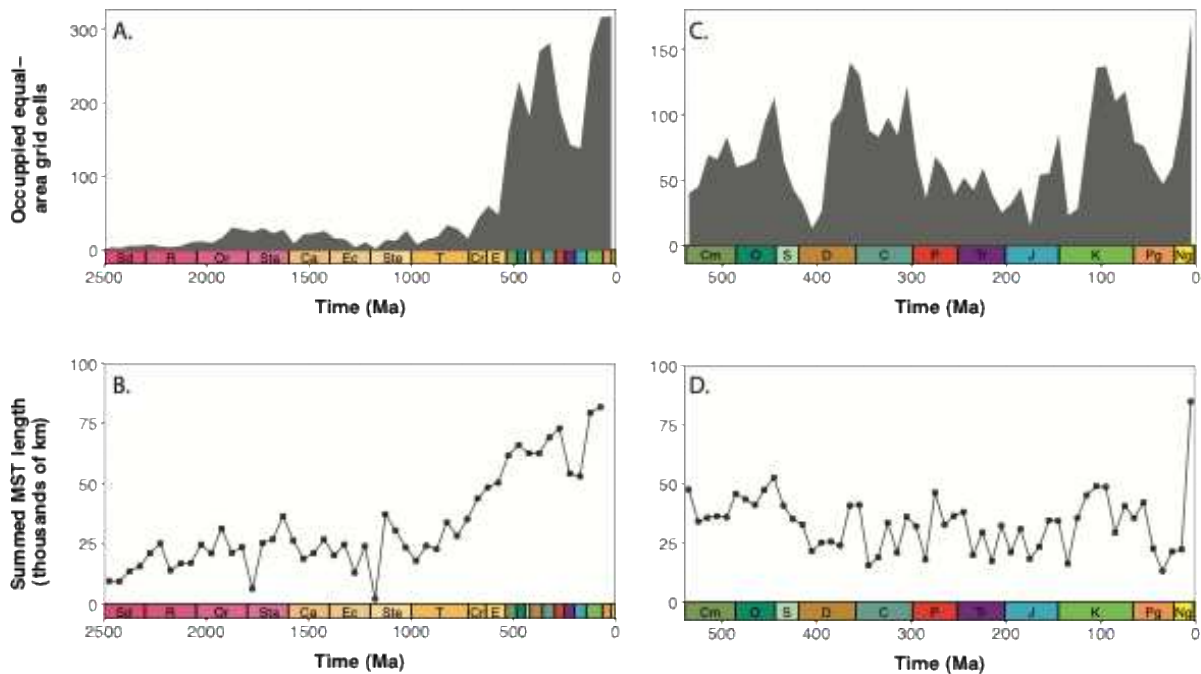


600 **Figure 4:** SGP Phase 2 geographic coverage. Samples are from 19,734 sites in 84  
601 countries/oceans. The size of the dot at each site scales to the number of samples and is color-  
602 coded to data source.  
603

604 4.5 Sampling completeness through time

605 Combining data from Figure 3 (temporal sampling) and Figure 4 (geographic sampling)  
606 allows us to analyze global sampling completeness through time in the SGP database. Following  
607 Jones and Eichenseer (2021), we evaluated two metrics of sampling completeness: the number of  
608 occupied equal-area grid cells (100 kilometer spacings) and the length of the Minimum Spanning  
609 Tree (MST; the convex hull encompassing sampling points) (Figure 5). Over broader timescales  
610 (last 2500 million years) the global sampling pattern primarily reflects macrostratigraphic trends  
611 in the rock record (Husson and Peters, 2017), with substantially greater volumes of Phanerozoic  
612 strata more highly sampled by geologists and geochemists. Nonetheless, the Phase 2 data release  
613 now includes relatively even sampling across the Proterozoic, allowing for increasingly robust  
614 analyses across billion-year timescales. Notable global sampling gaps exist in the Siderian, upper  
615 Rhyacian, and Ectasian–Stenian.

616 Both sampling metrics reflect our focus on the Neoproterozoic–Paleozoic in Phase 1 and  
617 Mesoproterozoic–Paleoproterozoic in Phase 2. Consequently, the best-sampled interval remains  
618 the lower Paleozoic. In Phanerozoic-scale sampling completeness plots, both metrics show a low  
619 around the Silurian–Devonian transition. The number of occupied grid cells then increases  
620 dramatically over the upper Devonian and Carboniferous, but without a substantial rise in MST.  
621 This is due to substantial sampling in North America and Europe with relatively little global  
622 sampling. The Triassic, Jurassic, and Lower Cretaceous are relatively poorly sampled globally for  
623 both metrics. The middle and Upper Cretaceous are better sampled (especially compared to Phase  
624 1) due to increased global data from SGP direct entry and the Alberta Geological Survey data. The  
625 Paleogene represents an additional interval with relatively poor global sampling.



626 **Figure 5:** Plots of geographic sampling in the SGP Phase 2 data release through time for the last  
627 2500 million years in 50 million year bins (A and B) and Phanerozoic in 10 million year bins (C  
628 and D). Number of occupied equal area grid cells (A and C) shows the number of cells sampled  
629 but may be geographically restricted (e.g., North America). The Summed Minimum Spanning Tree  
630 (MST, B and D) is the length of the convex hull encompassing all sampling points. Proterozoic  
631

632 time scale abbreviations as in Fig. 4. For Phanerozoic abbreviations: Cm- Cambrian, O-  
633 Ordovician, S- Silurian, D- Devonian, C- Carboniferous, P- Permian, Tr- Triassic, J- Jurassic, K-  
634 Cretaceous, Pg- Paleogene, Ng- Neogene.

635  
636

## 637 **5. Data Presentation and Access**

638 The SGP search website (<https://sgp-search.io>) is hosted on Amazon Web Services (AWS)  
639 (front-end: React.js, back-end: Node.js). SGP data products (back-end) are exposed to front-end  
640 users via a REST-ful API and using industry-standard JSON format for query and response. Our  
641 website was substantially revised for the Phase 2 data release in direct response to user feedback  
642 at our SGP Collaborative Team meetings. Specifically, we have made basic searches more  
643 straightforward and enhanced custom searches to access full methodological details. There are  
644 now three available search options:

645

### 646 *5.1 Simple Search*

647 This search is designed to provide quick access to data, with pre-set filters on sample and  
648 geological meta-data. Samples are grouped based on lithology (refer to Phase 2 Data Description  
649 above), allowing users to choose between “All Samples,” “Shales only,” or “Carbonates only.”  
650 Users can then narrow their search based on age range or geographic location (the two most  
651 common search criteria) and choose geochemical analytes of interest. The query is returned with  
652 pre-set geological metadata. In this search type the units are standardized, replicate results are  
653 averaged, and oxides are converted to elements.

654

### 655 *5.2 Detailed Search*

656 This option gives users complete control over their search and is more similar to the Phase 1  
657 website interface. Users can filter based on:

- 658 ● 22 parameters related to geological and geographic context
- 659 ● Ranges of values for a given analyte
- 660 ● Specific methodologies (for instance, only including trace metals analyzed by ICP-MS).
- 661 ● Data source or Project (samples grouped together by publication or data ingestion source,  
662 such as SGP direct entry or OZCHEM).

663

664 Users can then select geochemical analytes of interest and chose exactly what geological meta-  
665 data to include in the data export. Note that the “No HHXRF” search type, a variant of the Detailed  
666 Search in Phase 1 with data from handheld XRF excluded, no longer exists as this functionality  
667 can be achieved with the new methodology search features. As with Simple Search, units are  
668 standardized, replicate results are averaged, and oxides are converted to elements.

669

### 670 *5.3 Analyses Search*

671 This option allows users to access individual analytical results exactly as published or provided  
672 (i.e. units are not standardized, replicate results are not averaged, and oxides are not converted to  
673 elements). Analytes and units appear as values in rows, rather than as column headers.

674

675 A major upgrade during Phase 2 is the ability for users to filter and export based on analytical  
676 methods (available in Detailed and Analyses searches; refer to  
677 [https://github.com/ufarrell/sgp\\_phase2/wiki/C.-Analyses](https://github.com/ufarrell/sgp_phase2/wiki/C.-Analyses)) for a summary of Phase 2 data

678 distribution by method). This is critical as specific methodologies can result in false interpretations  
679 of geochemical signals (for instance, grinding vessel contamination (Hickson and Juras, 1986) or  
680 the strength and type of acid in carbonate dissolution (Cao et al., 2020; Clarkson et al., 2020; Liu  
681 et al., 2018; Zhang et al., 2024)). Using standardized vocabularies allows for further filtering,  
682 sorting, or automated data correction in programs such as Python or R, or for weighting and/or  
683 inclusion as a predictor variable in multivariate or machine learning analyses.

684

#### 685 *5.4 Indigenous ancestral lands*

686 Many samples in the SGP database have come from Indigenous ancestral lands around  
687 the world. While the geographic boundaries of ancestral lands are difficult to determine, SGP  
688 has instituted the ability on our website to access information from the Native Land Digital  
689 website (<https://native-land.ca>) as a starting point. While Native Land Digital is considered the  
690 most comprehensive worldwide reference for such information, it is neither complete nor a legal  
691 reference nor recognized for use in government-to-government consultation efforts. As such, this  
692 functionality is provided for the use and education of SGP website users (and is not used in  
693 Section 6 on Indigenous data governance and stewardship). The data can be displayed in the  
694 data table and included in data downloads via Show → Samples Context and clicking the  
695 “traditional territory” button.

696

697 *5.5 Data visualization and export:* After users have completed their search, they have the option  
698 to explore their query results in a data table. This table is sortable based on high/low values for a  
699 column, has expandable menus with methodology details, and has a geological context info button  
700 for each sample. The user can also copy the API call for future re-use or to include in a paper as a  
701 reproducibility step. Data downloads are returned as a .csv file. Finally, the user can explore the  
702 queried data on a new dynamic map feature that is color-coded to the geological timescale. Users  
703 can zoom in to the site level and easily access the geological context of samples from that site.

704

705 Note that since the Simple and Detailed searches average replicate results on the same analyte,  
706 measurements above (the maximum) or below (the minimum) detection limits will be removed, as  
707 they cannot be averaged. This is important for studies of analytes whose abundances are near  
708 detection limits for common geochemical methodologies—in the case of low-abundance elements,  
709 most analyses (i.e., below detection) will be removed, and only anomalously ‘high’ analyses will  
710 be returned. The following analytes have more than 25% of analyses below detection limits: Ta-  
711 carb, Ir, Pd, Sb-carb, Pt, Zr-carb, Os, Au, Re, In, Te, Bi, Ge, Ag, Re-carb, Sn, Cd, Ta, W, As-carb,  
712 Tl, Eu, Ho, Sb, Be, As, Hf, Pr, Hg, Hf-carb, Se, Sm, Li, Se-carb, Nb, Th, Er, B, Tb, U, S-org, Mo,  
713 Tm, S-SO<sub>4</sub>, Dy (listed from highest proportion below detection, Ta-carb at 100%, to Dy at 25.2%;  
714 more details can be found on the SGP wiki ([https://github.com/ufarrell/sgp\\_phase2/wiki/C.-  
715 Analyses#abovebelow-detection](https://github.com/ufarrell/sgp_phase2/wiki/C.-Analyses#abovebelow-detection)). We do not imply that statistical analyses of such analytes is  
716 inappropriate; rather that users should be aware of this specific feature of the Simple and Detailed  
717 data export.

718

## 719 **6. Indigenous Data Governance and Stewardship**

720 SGP acknowledges that many of the lands and waters where we live, where geological  
721 samples are collected, and where geochemical measurements are conducted may be on the present-  
722 day and ancestral lands of Indigenous People. We recognize the continued significance of these

723 lands and waters for Indigenous Peoples since time immemorial and are cognizant of the need for  
724 proper and respectful stewardship of these data.

725 In some cases, geological data have been collected from Indigenous land worldwide  
726 without permission or consultation (Kempf et al., 2023; Monarrez et al., 2022). Due to the long  
727 history of geoscience data collection, large quantities of such data exist in legacy datasets that  
728 persist in repositories. The absence of Indigenous stewardship of geologic data can directly impact  
729 community health (Moore-Nall, 2015), economic stability (Nacho Nyäk Dun elders et al., 2019),  
730 territorial control (Goodman, 2018), and/or continued perpetuation of past injustices (Eichstaedt,  
731 1994). The Global Indigenous Data Alliance (GIDA) established four principles for Indigenous  
732 data governance: Collective benefit, Authority to control, Responsibility, and Ethics (CARE)  
733 (Carroll et al., 2021, 2020). Since the initial establishment of the CARE principles, there has been  
734 increased interest in the proper application of these principles in different branches of science, such  
735 as biology (Jennings et al., 2023), genomics (Carroll et al., 2022), archeology (Gupta et al., 2023),  
736 and Earth Science (Jennings et al., 2025; O'Brien et al., 2024). Applying CARE principles to a  
737 compilation dataset (like SGP) first involves understanding which data are from Indigenous lands,  
738 then contacting the appropriate Indigenous group (O'Brien et al., 2024). As outlined in Hudson et  
739 al. (2023), even if data from Indigenous lands were ingested from a public source where permission  
740 was granted, publication and/or presentation of that data in a new context should have new  
741 approval.

742  
743 Our first efforts here are focused on the United States, where SGP is based, and so we have  
744 given specific attention to lands under the jurisdiction of federally recognized Tribes. Such lands  
745 include reservations and trust lands, as well as Oklahoma Tribal Statistical Areas, some of which  
746 have been or are becoming recognized as reservations in the wake of *McGirt v. Oklahoma* 140 S.  
747 Ct. 2452 (2020) and its progeny. Using public TIGER/Line shape files provided by the U.S. Census  
748 Bureau, we have identified 3,814 samples (2.94% of the 129,820 samples we had originally  
749 compiled), from 743 geographic sites, with 134,165 geochemical analytes, where the recorded  
750 SGP latitude and longitude site-matched with lands under Tribal jurisdiction. These 3,814 samples  
751 were ingested from four distinct publicly available data sources including the USGS-NGDB  
752 database (91%), third-party literature compilations by USGS-CMIBS (6%) and DM-SED (1%),  
753 and SGP direct entry from published literature (2%). Note that many of these same samples/data  
754 are also held by other non-governmental Earth Science repositories such as EarthChem and  
755 Macrostrat. Even though contributions from United States Government agencies, academia, and  
756 industry may have been obtained in accordance with any applicable laws and policies in place at  
757 the time of collection/reception, these data will now be presented in this new context of the SGP  
758 search website and API. Therefore, we have taken the proactive step of removing these data from  
759 the Phase 2 release.

760  
761

## 762 *6.2 Future SGP goals regarding CARE principles*

763 Moving forward, we have integrated a PostGIS-based spatial check into our data ingestion  
764 pipeline to flag new samples that may come from lands under Tribal jurisdiction. Our next step  
765 will be detailed vetting of the samples that site-matched to lands under U.S. Tribal jurisdiction to  
766 determine whether this was the likely point of origin (note that SGP samples have varying degrees  
767 of geographic precision; refer to Farrell et al. (2021)). With our finalized list of samples, we will  
768 notify Tribal Nations of our intent to include data about the samples on the SGP website. If a Tribe

769 wants to restrict (in whole or in part) any data from the SGP website, we will abide by the Tribe's  
770 decision. We will also seek the Tribe's input for future data ingestion and presentation. While the  
771 products of these consultations will be incorporated, we recognize that individual Native Nations'  
772 needs and opinions on data holdings can and will change over time and continued open  
773 communication is necessary for proper stewardship.

774 We are cognizant that the proposed work here represents just one step towards implementation of  
775 CARE principles. Many complex issues remain, including treatment/stewardship of data from  
776 ancestral lands, Indigenous data from outside the United States, and data handling considerations  
777 prior to and during consultation (refer to Carroll et al., 2021; O'Brien et al., 2024). SGP is  
778 committed to developing new modes of collaboration, engagement, and partnership with  
779 Indigenous peoples for the care and stewardship of past and future heritage collections.

780

## 781 **7. Future Goals and Directions**

782 Many of our future goals and directions for SGP Phase 3 flow from Figures 1-5. With  
783 respect to lithologies, we now have a database and methodological structure appropriate for  
784 carbonate data but only a small fraction of the carbonate geochemical data that have been generated  
785 by the geochemical community to date has been entered. Expanding data holdings in carbonate  
786 geochemistry is thus a top goal. From a temporal perspective, the Mesozoic–Cenozoic has limited  
787 geographic sampling compared to the Paleozoic and is dominated by North American samples.  
788 This means that Phanerozoic-scale studies (and geochemical comparisons with the fossil record  
789 across this interval) have higher potential for spatial and temporal sampling imbalances. Building  
790 the Archean through Rhyacian and Ectasian–Stenian records are secondary temporal goals. With  
791 respect to analytical data types, database revisions (Section 2.1) have greatly enhanced our ability  
792 to usefully input and export trace metal isotope data, and these analytes will be a focus in Phase 3.  
793 Including organic geochemical (biomarker) data is an aspirational goal but would require  
794 substantial database updates and extensive community consultation to ensure SGP is appropriately  
795 capturing critical data and methodological details. These lithological, analytical, and temporal  
796 goals will require proactive outreach to new research communities, specifically carbonate  
797 geochemists, organic geochemists, and researchers working in the Archean and Mesozoic–  
798 Cenozoic, as researchers at both ends of the geological timescale commonly specialize temporally  
799 due to the unique features of those records. We will also continue to seek external data sources for  
800 bulk import and integration. In particular, we are interested in engaging and collaborating with  
801 national/regional geological surveys worldwide. In addition to our planned proactive approaches,  
802 we encourage any researchers in these areas to reach out directly and join SGP. This is an open,  
803 community-driven project and we welcome your involvement. Finally, Figure 4 illustrates that we  
804 have considerable work ahead to build a globally comprehensive database. We are planning  
805 regional outreach events over Phase 3 in Africa, Asia, and South America, and again we welcome  
806 and encourage geologists and geochemists in these regions to reach out to us about accessioning  
807 data and joining the SGP community.

808

## 809 **8. Data license and Citation**

810 The SGP Phase 2 data release is available under a Creative Commons BY 4.0 International  
811 license. Users are free to share (copy and redistribute the material in any medium or format for  
812 any purpose) or adapt (remix, transform, and build upon the material for any purpose) the data and  
813 database if attribution and credit is provided. Such attribution and credit to the geoscientists that

814 generated these data and provided relevant geological meta-data is given through citation of this  
815 manuscript.

816

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822 or product names is for descriptive purposes only and does not imply endorsement by the U.S.  
823 Government.

824

825 **Table 1.** Acronyms used in this manuscript.

<b>Acronym</b>	<b>Definition/explanation</b>
OZCHEM	The Geoscience Australia data product. Sedimentary geochemical data from this database were ingested during SGP Phase 2
DM-SED	A third-party compilation of geochemical data (refer to Lai et al., 2025). Older (pre-2017) data from this compilation were ingested during SGP Phase 2
API	Application Programming Interface: a software intermediary that enables two programs to communicate using a set of definitions and protocols. Data in SGP can be accessed directly through our API, or from our search website, which uses an API call to retrieve requested data.
FAIR	Principles for management and stewardship of scientific data: data should be Findable, Accessible, Interoperable, and Reusable (refer to Wilkinson et al., 2016)
ICP-MS	Inductively Coupled Plasma Mass Spectrometry
LA-ICP-MS	Laser Ablation Inductively Coupled Plasma Mass Spectrometry
USGS-CMIBS	The Critical Metals in Black Shale project from the United States Geological Survey (USGS). A third-party compilation of shale geochemical data that was ingested during SGP Phase 1
USGS-NGDB	The USGS National Geochemical Database, storing geochemical data from decades of USGS projects; ingested during SGP Phase 1
XRF	X-ray Fluorescence
AAS	Atomic Absorption Spectroscopy
CARE	Principles for management and stewardship of Indigenous data: data must facilitate Collective benefit for Indigenous groups, Indigenous groups must have Authority to control, there is a Responsibility to nurture respectful relationships, and be collected and managed in an Ethics framework that focuses on Indigenous Peoples' rights and well-being (refer to Carroll et al., 2020).
TIGER/Line	Topologically Integrated Geographic Encoding and Referencing - U.S. Census Bureau format for geospatial data.

826

827

828

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