rmacrostrat: An R package for accessing and retrieving data from the Macrostrat geological database

Lewis A. Jones[1], Christopher D. Dean[2], William Gearty[3], and Bethany J. Allen[4,5]

[1]Centro de Investigación Mariña, Departamento de Ecoloxía e Bioloxía Animal, Universidade de Vigo, Vigo, Spain

[2]Department of Earth Sciences, University College London, London, UK

[3]Division of Paleontology, American Museum of Natural History, New York, New York, USA

[4]Department of Biosystems Science and Engineering, ETH Zurich, Klingelbergstrasse 48, 4056 Basel, Switzerland

[5]Computational Evolution Group, Swiss Institute of Bioinformatics, Quartier Sorge, Bâtiment Amphipôle, 1015 Lausanne, Switzerland

Corresponding author: LewisA.Jones@outlook.com

This manuscript is a pre-print and has not been peer-reviewed. The manuscript is currently being submitted to *Geosphere*. Subsequent versions of this manuscript might vary in content. If accepted, the final version of this manuscript will be available via the 'Peer-reviewed publication DOI' link on this page. Please feel free to contact the corresponding author(s) with any queries. We welcome any feedback!

ABSTRACT

The geological record is a vast archive of information that provides the only empirical data about the evolution of the Earth. In recent years, concentrated efforts have been made to compile macrostratigraphic data into the online centralized database Macrostrat (https://macrostrat.org). Macrostrat is a global stratigraphic database containing information regarding surface and subsurface rock units and their respective ages, lithologies, geographic extents, and various other associated metadata. However, these data are currently only accessible through the Macrostrat application programming interface (API), which is a barrier

to potential users that are less familiar with such services. This data accessibility hurdle currently prevents full capitalization of the value offered by Macrostrat, particularly its potential to improve understanding of the geological and biological evolution of the Earth. Here, we introduce *rmacrostrat*, an R package which interfaces with the Macrostrat database, to access and retrieve a variety of geological, paleontological, and economic data directly into the R programming environment. In this article, we provide details about how the package can be installed, its implementation, and potential use cases. For the latter, we showcase how *rmacrostrat* can be used to visualize regional stratigraphic columns, produce regional geologic outcrop maps, and estimate the proportion of North American carbonate and siliciclastic sediments through time. We hope that this package will make geological data more readily accessible, and in turn will facilitate new research utilizing Earth System data.

INTRODUCTION

Earth's geologic record provides a unique spatiotemporal archive of the evolutionary history of the planet (Ernst and Youbi, 2017; Tetley et al., 2019; Cao et al., 2019; Scotese et al., 2021). Historically, to understand macro-scale Earth System trends through geological time, researchers were required to synthesize local or regional quantitative studies, predominantly from data gathered in the form of regional geological maps, sections, and individual sedimentary logs or boreholes (e.g., Ronov et al., 1980; Seslavinskiy, 1991; Bosscher and Schlager, 1993; Miall, 2022). However, the introduction of large online open-access databases, in which a variety of complementary datasets are already digitized and synthesized, has facilitated the development of macroscale analyses through both time and space. One such database is Macrostrat (http://macrostrat.org/), a relational geospatial database that aims to aggregate and synthesize field-derived geological data from geological maps and regional geological columns into a dataset that describes the spatial distribution of geological units within the Earth's upper crust (Peters et al., 2018). Macrostrat contains information regarding individual rock "units", linked by unique identification numbers to associated lithological, environmental, paleontological, and economic attributes, alongside information regarding their respective chronostratigraphic context. These units are organized spatially into "columns", representing a cross-section of the upper crust within particular geological basins, and temporally by Macrostrat's internal chronostratigraphic age model (Figure 1). Sequentially deposited units bounded by unconformities form geological "sections", which also have their own unique identification numbers. Additionally, Macrostrat units are linked by unique identification numbers to geological mapping data amalgamated from a variety of sources, as well as data from other large geoscience databases such as the Paleobiology Database (PBDB; http://paleobiodb.org/) (Peters and McClennen, 2016; Uhen et al., 2023) and Mindat (http://mindat.org/).

Since its initial compilation in 2005 from the American Association of Petroleum Geologists Correlation of Stratigraphic Units of North America (COSUNA) charts (Peters, 2006), Macrostrat has grown into a comprehensive and well-established database containing over 35,000 units and 1,500 geologic columns, all of which are publicly accessible. Macrostrat aims to provide such data on a global scale, and while the abundance and resolution of available data is currently geographically variable, improving spatial coverage is one of the major aims of the project moving forwards (Quinn et al., 2024). Data hosted by Macrostrat have been used for a wide variety of applications in scientific research, as well as science communication and education. The broad temporal and spatial scale of data hosted by Macrostrat has facilitated a diverse array of research related to Earth Systems through time, including in the fields of sedimentology (Peters and Husson, 2017), stratigraphy (Tasistro-Hart and Macdonald, 2023), igneous petrology (Peters et al., 2021), geochemistry (Husson and Coogan, 2023), and paleobiology (Peters and Heim, 2010, 2011a, 2011b; Heim and Peters, 2011; Rook et al., 2013; Nelsen et al., 2016; Peters et al., 2017; Balseiro and Powell, 2019, 2023; Ye and Peters, 2023). Macrostrat has also collaborated with the extending Ocean Drilling Pursuits project (eODP; https://eodp.github.io/) to integrate existing drill core data from sources such as the International Ocean Drilling Program (IODP) into the database (Sessa et al., 2023). Geologic map data held within Macrostrat is also displayed by a variety of software and mobile applications that aim to enable usage of geologic materials by the wider scientific community, the general public, and university education and teaching platforms (Cohen et al., 2018). Macrostrat is also currently developing plans to expand and integrate community-led validation of sections, ingestion of stratigraphic column data, and development of new software to facilitate data collaboration (Quinn et al., 2024). As such, Macrostrat is a vital resource for Earth scientists investigating a variety of issues related to both the geological history of our planet and the impacts of geological processes today.

Despite the apparent opportunities offered by Macrostrat, its hosted data can currently only be accessed via the database's Application Programming Interface (API). Although a powerful resource, this single data access avenue means that familiarity with both the structure of the database and how to interact with APIs is necessary in order to use the database. Those able to overcome this data accessibility hurdle are still required to develop their own custom protocols to integrate Macrostrat data into coding-based scientific workflows; this can inherently lead to researchers 'reinventing the wheel', and producing code that is case-specific and difficult to repurpose, inhibiting the reproducibility of research conducted using Macrostrat data. Such processes are often carried out in the programming language R, which the Earth Science community has broadly adopted to access, prepare, analyze, and plot data (e.g. Bell and Lloyd, 2015; Varela et al., 2015; Ortiz and Jaramillo, 2018; Barido-Sottani et al., 2019; Kocsis et al., 2019; Jones et al., 2023; Gearty, 2024). In particular, several R packages have been developed to interface with databases relevant to the geosciences through API services, supporting the generation of readable, reusable, and reproducible workflows (Varela et al., 2015; Gearty and Jones, 2023; Vidaña and Goring, 2023). However, until now, no such package has been available for interacting with the Macrostrat database.

Here, we present *rmacrostrat*, a dedicated R package for interfacing with the geological database Macrostrat. The package provides streamlined functionality for querying the database via its API service and retrieving various geological data (e.g., lithostratigraphic units) and definitions/metadata associated with the hosted data (e.g., lithological terms). First, we provide instructions for installing the package and details on its implementation. We then demonstrate the functionality available in *rmacrostrat* and provide typical usage examples. Finally, we provide details about the resources we have made available to support *rmacrostrat* users. By providing a programmatic solution to accessing the data hosted by Macrostrat, we endeavor to facilitate new research across the Earth Sciences that is conducted in a streamlined, readable, reusable, and reproducible manner.

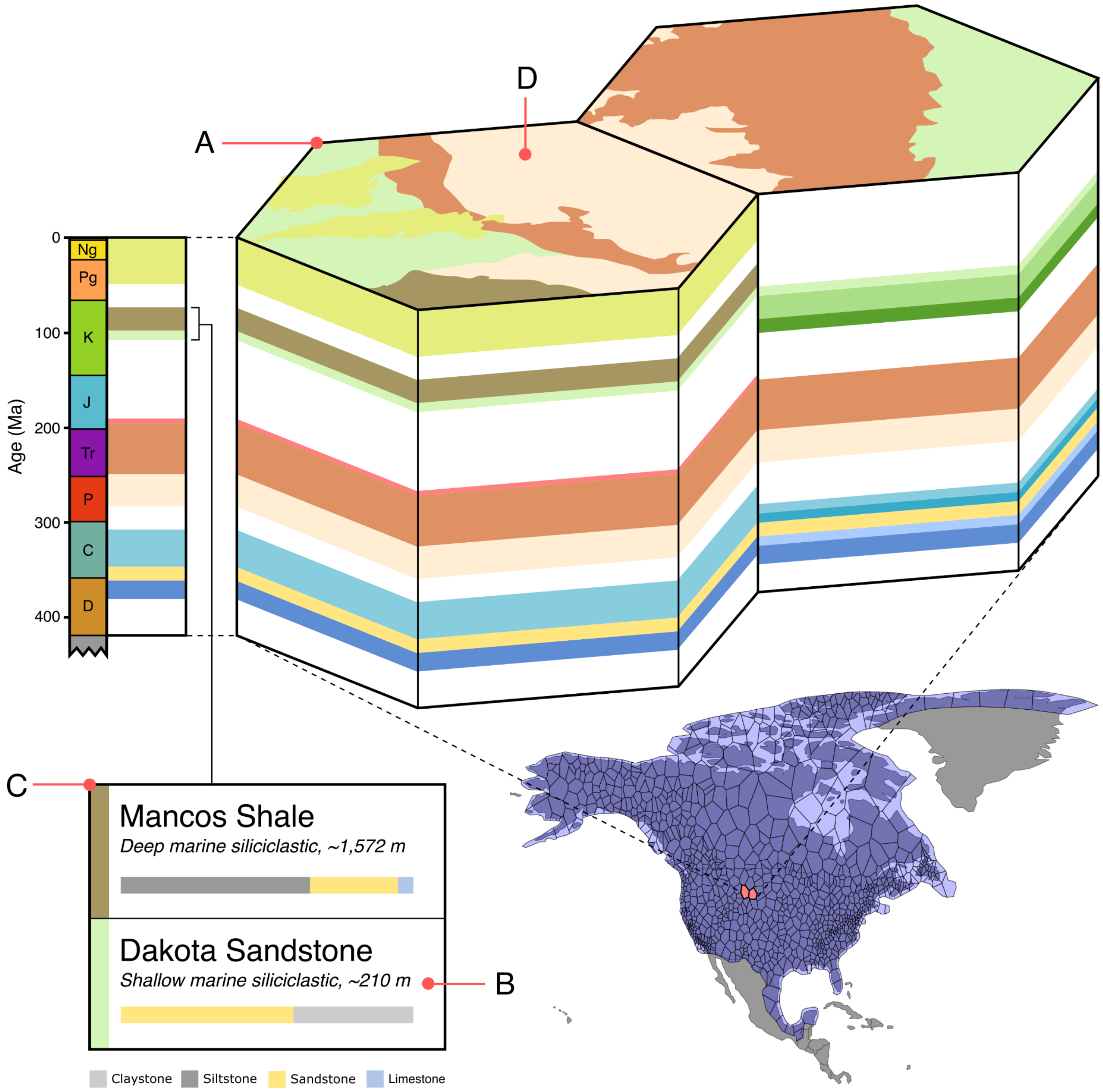

Figure 1: Schematic showing the relationships between geological and stratigraphic data stored in Macrostrat. Data are arranged spatially as ‘columns’ (A), which contain chronostratigraphic columns of distinct stratigraphic ‘units’ (B), distinguished by a variety of attributes (e.g. lithology, environment etc.) and organized temporally by Macrostrat’s time–age model. Packages of continuously deposited units bounded by unconformities can be subset into ‘sections’ (C). Macrostrat units can also be linked to Macrostrat’s geological map outcrop (D), amalgamated from a variety of sources. Note that columns are idealized over the region, and do not intersect accurately with surficial geological maps.

INSTALLATION

The *rmacrostrat* package can be installed from CRAN (**PENDING ACCEPTANCE**) using the install.packages() function in R (R Core Team, 2023):

```
install.packages("rmacrostrat")
```

If preferred, the development version of *rmacrostrat* can be installed from GitHub via the remotes R package (Csárdi et al., 2023):

```
remotes::install_github("palaeoverse/rmacrostrat")
```

Following installation, *rmacrostrat* can be loaded via the library() function in R:

```
library("rmacrostrat")
```

Dependencies

The current version of *rmacrostrat* (ver. 0.0.1) depends on R (>= 4.0) (R Core Team, 2023), and imports functions from curl (Ooms, 2024), geojsonsf (Cooley, 2022), httr (Wickham, 2023), jsonlite (Ooms, 2014), and sf (Pebesma and Bivand, 2023). The package was developed with the support of the R packages devtools (Wickham et al., 2024b), testthat (Wickham, 2011) and roxygen2 (Wickham et al., 2024a).

IMPLEMENTATION

Functions are broadly grouped into two categories in *rmacrostrat*: (1) def_* and (2) get_*. The def_* suite of functions provides access to the definitions (or metadata) associated with data stored in Macrostrat, such as lithologies (def_lithologies()), measurements (def_measurements()), or Macrostrat columns (def_columns()). A summary of this suite of functions is provided in Table 1. The get_* suite of functions are for retrieving data from Macrostrat, such as Macrostrat columns (get_columns()), Macrostrat units (get_units()), and geological map outcrop objects (get_map_outcrop()). Detailed descriptions of these functions are provided in Table 2.

Table 1: Summary table of the definition suite of functions (def_*) currently available in the *rmacrostrat* R package.

Function	**Description**
catalog()	Wrapper function to retrieve all definitions within a given definition set (e.g., lithologies)
def_columns()	Retrieve definitions for Macrostrat columns
def_drilling_sites()	Retrieve metadata for variables associated with extending Ocean Drilling Pursuits (eODP)
def_econs()	Retrieve definitions for economic resources (e.g., coal)
def_environments()	Retrieve definitions for environments (e.g., dune)
def_grain_sizes()	Retrieve definitions for grain sizes (e.g., cobble)
def_intervals()	Retrieve definitions for time intervals (e.g., Cenozoic)
def_lithologies()	Retrieve definitions for lithologies (e.g., sandstone)
def_lithology_att()	Retrieve definitions for lithology attributes (e.g., tabular)
def_measurements()	Retrieve definitions of different measurements (e.g., porosity)
def_minerals()	Retrieve definitions of different minerals (e.g., Agate)
def_plates()	Retrieve definitions of tectonic plates (e.g., Eurasia)
def_projects()	Retrieve definitions of Macrostrat projects (e.g., eODP)
def_references()	Retrieve definitions for published references
def_sources()	Retrieve definitions for geological maps (e.g., USGS)
def_strat_names()	Retrieve definitions for stratigraphic names (e.g., Hell Creek)
def_strat_name_concepts()	Retrieve definitions for stratigraphic name concepts (e.g., Dakota)
def_structures()	Retrieve definitions for geological structures (e.g., antiform)
def_timescales()	Retrieve definitions for timescales (e.g., international periods)

Table 2: Summary table of the data retrieval suite of functions (get_*) currently available in the *rmacrostrat* R package.

Function	Description
get_units()	Get data for Macrostrat units
get_sections()	Get data for Macrostrat sections
get_columns()	Get data for Macrostrat columns
get_age_model()	Get information about the age models for Macrostrat columns
get_map_outcrop()	Get spatial polygon data for geologic map outcrop
get_map_points()	Get spatial point data for geologic map measurements (e.g., strike, dip)
get_map_legends()	Get information from geologic map legends, associated with outcrop and points
get_fossils()	Get Paleobiology Database collections data associated with Macrostrat entities
get_eodp()	Get extending Ocean Drilling Pursuits data associated with various drilling programs
get_measurements()	Get measurements relevant to making geological inferences
get_paleogeography()	Get paleogeographic geometries based on the Wright et al. (Wright et al., 2013) Global Plate Model
get_stats()	Get statistics about Macrostrat projects

Definition Functions

Definitions (or metadata) of the various data stored in Macrostrat are retrieved from the Macrostrat API service via the def_* suite of functions (Table 1). The coverage of each of these functions should hopefully be immediately recognizable via their naming convention (e.g., def_lithologies() returns definitions of the lithologies used in Macrostrat). Data returned using the def_* suite of functions contains both categorical (and often hierarchical) information about data attributes of interest (e.g., def_lithologies() will return individual lithologies ["sandstone"], as well as the type ["siliciclastic"] and class ["sedimentary"] of the lithology) as well as unique identification numbers for individual attributes that can be used to query

Macrostrat. Without user-specified arguments, all def_* functions will return a data.frame object containing the entire dataset of definitions associated with that function:

```
# Get all lithologies
def_lithologies()
# Get all minerals
def_minerals()
# Get all time intervals
def_intervals()
```

Alternatively, users can search for definitions of specific entities or groups of entities using the specific arguments for each def_* function. This can generally be achieved using specific unique identification numbers (integers) for those definitions, or via a name (character strings):

```
# Get all marine environments by name
def_environments(environ_class = "marine")
# Get specific environment by ID
def_environments(environ_id = 2)
```

For convenience, we have also provided a wrapper around all def_* functions via the catalog() function. This function returns complete sets of definitions for each def_* function, which takes the suffix of an individual def_* function for its argument:

```
# Get all geological timescales
catalog(type = "timescales")
# Get all geological structures
catalog(type = "structures")
```

We strongly recommend using the def_* suite of functions prior to retrieving data from Macrostrat to better understand both the structure of the database and the utility offered by the functions available in *rmacrostrat*. Due to the wide variety of data available in Macrostrat, individual get_* functions include a large array of potential arguments which can differ substantially between functions (see below). By using the specific def_* functions related to potentially useful search criteria, users can efficiently identify arguments and parameters with which to query the database via the get_* suite of functions. Examples of the utility of the def_* functions are provided in the application section below, as well as in the available vignettes for the package.

Data Retrieval Functions

Data can be retrieved from the Macrostrat database API directly into the R environment using the get_* suite of functions (Table 2). These functions either return data related to specified Macrostrat entities (e.g., Macrostrat columns, units, sections, and age definitions), geologic map elements, or external data related to Macrostrat entities (e.g., PBDB collections, eODP data, paleogeographies), and can be returned either as a standard data.frame or as a spatial simple features (i.e., sf) object. In accordance with the def_* suite of functions, the purpose of individual get_* functions are intended to be easily identifiable from their named suffix (e.g., get_columns() retrieves data for Macrostrat columns).

As opposed to the def_* suite of functions, the get_* suite of functions require at least one supplied argument for a valid database query. Although the array of possible arguments differs substantially between get_* functions, users can generally retrieve data based on several categories. Firstly, users can search by unique identification number, for either the chosen data type to retrieve, or based on another Macrostrat entity.

```r
# Get specific column according to an ID
get_columns(column_id = 45)
# Get units and sections associated with a specific column ID
get_units(column_id = 45)
get_sections(column_id = 45)
# Get map outcrop related to specific unit ID
get_map_outcrop(unit_id = 1610)
```

Attribute information—such as lithostratigraphic name, lithology, environment or economic source—can also be used independently, or in combination in some instances, to retrieve subsets of Macrostrat data. These attributes can be specified either using their unique identification number or by character string. Further information about each attribute to search by can be found in the respective def_* functions (e.g., lithology attribute information can be found in the def_lithologies() function).

```
# Get units inferred to be marine
get_units(environ_class = "marine")
# Get all sandstone units by name or ID
get_units(lithology = "sandstone")
get_units(lithology_id = 10)
```

Data can also be retrieved using temporal limits, either by specifying a specific interval name as a character string (e.g., "Permian"), a unique identification number, a numeric value (e.g., 275 Ma), or from providing constraints based on numerical limits (e.g., 251.9–298.9 Ma). All Macrostrat entities which overlap with the specified parameter(s) in terms of their chronostratigraphic range defined in the Macrostrat age model are returned.

```
# Get units by interval name
get_units(interval_name = "Aptian")
# Get units by interval ID
get_units(interval_id = 43)
# Get units by age
get_units(age = 200)
# Get units by age range
get_units(age_bottom = 250, age_top = 200)
```

Finally, some get_* functions allow the user to query the database using geographic or spatial information. This can either be achieved by specifying coordinates in decimal latitude/longitude degrees, or if continental scale resolution is desired, through the use of Macrostrat projects. Macrostrat data is split into regional projects, such as North America (project_id = 1) and Australia (project_id = 6); setting this argument will return all Macrostrat entities associated with that regional project.

```
# Get sections which appear at a specific longitude & latitude
get_sections(lng = -105.15, lat = 37.89)
# Get map outcrop which appears at a specific longitude & latitude
```

```
get_map_outcrop(lng = -105.15, lat = 37.89)
# Get all Macrostrat unit data for the North American continent
get_units(project_id = 1)
```

As aforementioned, it is recommended that these arguments are used in tandem with the def_* suite of functions to maximize search potential and data retrieval. For instance, a user interested in retrieving units deposited in a specific paleoenvironment may want to use the def_environments() function prior to their search to see the full variety of parameters with which to search by.

APPLICATION

Herein, we provide three example applications of the *rmacrostrat* package. These examples are greatly expanded in step-by-step vignettes provided alongside the package, available online via the associated package website (https://rmacrostrat.palaeoverse.org/articles/) and are also bundled with the package, accessible via:

```
browseVignettes(package = "rmacrostrat")
```

Constructing Stratigraphic Columns

An understanding of stratigraphy—that is, the relationships between adjacent geological units—is fundamental to accurately reading the geological record, enabling researchers to put relative ages to lithological units and making temporal and spatial correlations. Using *rmacrostrat*, the geological data within the Macrostrat database can be easily retrieved and used to generate a stratigraphic column for a specific location and/or time interval. Below we provide an example showing how to retrieve and plot a stratigraphic column for the San Juan Basin, an asymmetric structural basin in northwestern New Mexico and southwestern Colorado (Four Corners region of Southwestern United States), containing sedimentary rocks ranging from Cambrian to Holocene in age (Fassett and Hinds, 1971). For this example, we restrict our column data to the Cretaceous, but this approach could equally be applied to any other basin or temporal interval. As the most broad-scale geological entity available within Macrostrat is a column, def_columns() is first used to identify the column associated with the San Juan Basin. The unique column identification number can then be used to get data for all appropriate units via get_units(). As the example focuses only on the Cretaceous, additional arguments available in get_units() can be used to further filter the queried data. With the returned data—Cretaceous lithostratigraphic units within the San Juan Basin—a stratigraphic column can be generated.

```r
# Load packages
library(rmacrostrat)
library(ggplot2)
library(ggrepel)
library(deeptime)
# Get the column definition of the San Juan Basin
column_def <- def_columns(column_name = "San Juan Basin")
# Using the column ID, retrieve all units of Cretaceous age
san_juan_units <- get_units(column_id = column_def$col_id,
                            interval_name = "Cretaceous")
# Specify x_min and x_max in dataframe
san_juan_units$x_min <- 0
san_juan_units$x_max <- 1
# Tweak values for overlapping units
san_juan_units$x_max[10] <- 0.5
san_juan_units$x_min[11] <- 0.5
# Add midpoint age for plotting
san_juan_units$m_age <- (san_juan_units$b_age +
                         san_juan_units$t_age) / 2
# Plot stratigraphic column
ggplot(san_juan_units, aes(ymin = b_age, ymax = t_age,
                           xmin = x_min, xmax = x_max)) +
  # Plot units, colored by rock type
  geom_rect(fill = san_juan_units$color, color = "black") +
  # Add text labels
  geom_text_repel(aes(x = x_max, y = m_age, label = unit_name),
                  size = 3.5, nudge_x = 1.5) +
  # Reverse direction of y-axis
  scale_y_reverse(limits = c(145, 66), n.breaks = 10,
                  name = "Time (Ma)") +
  # Theming
  theme_classic() +
  theme(legend.position = "none",
        axis.line.x = element_blank(),
        axis.title.x = element_blank(),
        axis.text.x = element_blank(),
        axis.ticks.x = element_blank()) +
  # Add geological time scale
  coord_geo(pos = "left", dat = list("stages"), rot = 90)
```

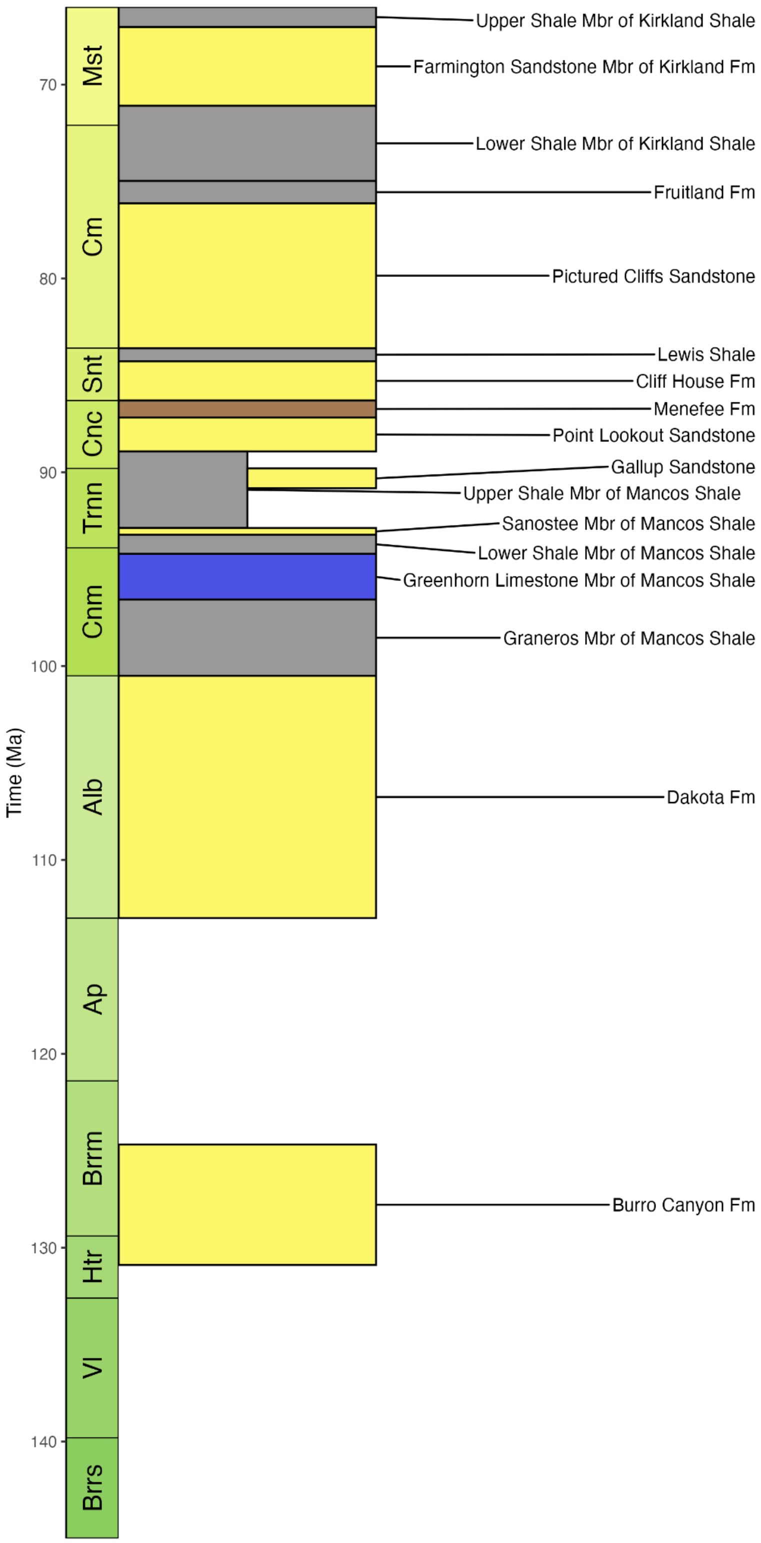

Figure 2: A stratigraphic column of Cretaceous lithostratigraphic units from the San Juan Basin. Lithostratigraphic units were fetched from the Macrostrat database (https://macrostrat.org/) using the *rmacrostrat* package ver. 0.0.1.

Plotting Geologic Outcrop Maps

A commonly required figure across a range of disciplines within the geosciences is a geographic map of the outcrop for a specific geologic formation. These figures can be easily generated using the get_map_outcrop() function of *rmacrostrat*, which retrieves geospatial data associated with lithostratigraphic units. Below we provide an example for constructing a map of outcrop for the Hell Creek Formation, a geologic formation from the latest Cretaceous and early Paleogene of North America, which is found cropping out across Montana, and North and South Dakota, in the United States (Johnson et al., 2002; Fastovsky and Bercovici, 2016). As outcrop spatial data is compiled from various map sources, the definition function def_strat_names() is first used to find the appropriate identification numbers for any stratigraphic names of formations that include the Hell Creek. This information can then be used with the get_map_ouctrop() function to retrieve geospatial data for the formation as a simple features (sf) object. These data can be plotted to produce a geological map (Figure 3).

```
# Load libraries
library(rmacrostrat)
library(rnaturalearth)
library(ggplot2)
library(sf)
# Get data for chosen formation, specifying by stratigraphic rank
hc_def <- def_strat_names(strat_name = "hell creek",
                          rank = "Fm")
# Get spatial outcrop data for the chosen formation based on ID
hc <- get_map_outcrop(strat_name_id = hc_def$strat_name_id,
                      sf = TRUE)
# Load background maps
n_a <- ne_states(country = "united states of america",
                 returnclass = "sf")
ca <- ne_states(country = "canada",
                returnclass = "sf")
# Plot the map
ggplot() +
  geom_sf(data = n_a) +
  geom_sf(data = ca) +
```

```
geom_sf(data = hc,
        fill = '#C7622B',
        lwd = 0) +
coord_sf(xlim = c(-112, -97), ylim = c(44, 50),
         expand = FALSE) +
labs(x = "Longitude (º)", y = "Latitude (º)") +
theme_bw()
```

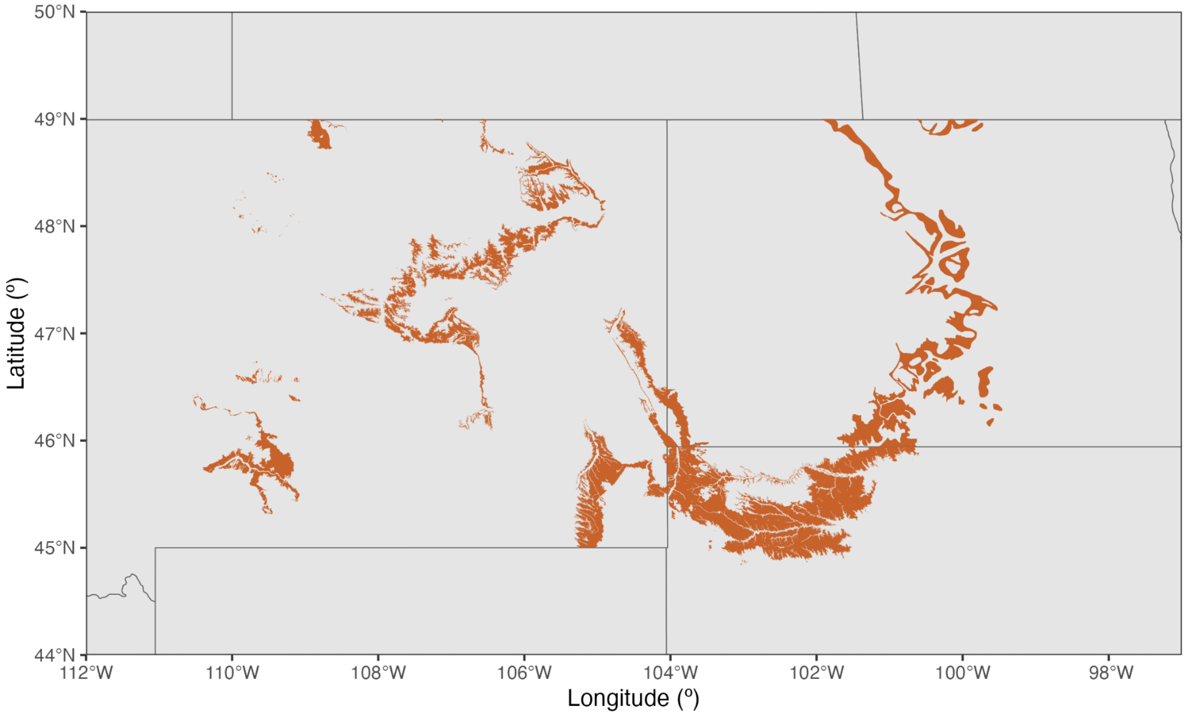

Figure 3: Outcrop of the Hell Creek Formation across Montana, and North and South Dakota. Outcrop data were fetched from the Macrostrat database (https://macrostrat.org/) using the *rmacrostrat* R Package ver. 0.0.1.

Macrostratigraphic Time Series Analyses

Initial publications using data from the Macrostrat database quantified how the number and proportion of Macrostrat entities, as well as different lithostratigraphic unit types associated with different paleoenvironments (e.g., marine, marginal, mixed, terrestrial), varied throughout the Phanerozoic (Peters and Heim, 2010). *rmacrostrat* facilitates access to these types of data, and allows for similar analyses to be conducted. Below we provide an example of such an analysis, in this case estimating the number of siliciclastic versus carbonate lithostratigraphic units in North America throughout the Phanerozoic.

For this example, the relevant lithostratigraphic unit data from Macrostrat is first fetched using the get_units() function from *rmacrostrat*. For this query, several filters are applied to retrieve the appropriate data. First, the environ_type argument is used to filter for carbonate and siliciclastic sediments. Second, the interval_name argument is used to filter to units only from the Phanerozoic. Finally, the project_id argument is used to filter results to units from the North American geological record:

```
# Load library
library(rmacrostrat)
# Get units by environment type, interval, and project ID
carbonate <- get_units(environ_type = "carbonate",
                       interval_name = "Phanerozoic",
                       project_id = 1)
siliciclastic <- get_units(environ_type = "siliciclastic",
                           interval_name = "Phanerozoic",
                           project_id = 1)
# Add column of sediment type
carbonate$sediment_type <- "Carbonate"
siliciclastic$sediment_type <- "Siliciclastic"
# Bind data
units <- rbind.data.frame(carbonate, siliciclastic)
```

With this data, the number of siliciclastic and carbonate lithostratigraphic units for each international geological stage (i.e., time bin) through time can be calculated. Functionality available in the palaeoverse R package can be used to retrieve relevant information about geological stages (Jones et al., 2023):

```
# Load libraries
library(palaeoverse)
# Generate stage-level time bins
bins <- time_bins(scale = "international ages")
# Rename age columns in units to be consistent with our bins
```

```r
colnames(units)[which(colnames(units) == "b_age")] <- "max_ma"
colnames(units)[which(colnames(units) == "t_age")] <- "min_ma"
# Bin data
units <- bin_time(occdf = units, bins = bins,
                  min_ma = "min_ma", max_ma = "max_ma",
                  method = "all")
# Calculate the number of environment classes per bin assignment
counts <- group_apply(occdf = units,
                      group = c("sediment_type",
                                "bin_assignment"),
                      fun = nrow)
# Rename columns to ease reading and merging
colnames(counts) <- c("count", "sediment_type", "bin")
# Merge datasets by bin number
counts <- merge(x = bins, y = counts, by = "bin")
```

Using additional R packages for visualization, such as ggplot2 (Villanueva and Chen, 2019) and deeptime (Gearty, 2024), Phanerozoic stage-level counts of North American lithostratigraphic units can be plotted by sediment type (Figure 4):

```r
# Load libraries
library(ggplot2)
library(deeptime)
# Generate a plot of lithostratigraphic units through time
ggplot(counts, aes(fill = sediment_type, y = count, x = mid_ma)) +
  # Stacked bar chart with width specified by interval duration
  geom_bar(position = "stack", stat = "identity",
           width = counts$duration_myr,
           color = "black", linewidth = 0.1) +
  # Label y-axis
  scale_y_continuous("Number of lithostratigraphic units") +
  # Label x-axis and reverse direction
  scale_x_reverse("Time (Ma)") +
  # Data plotting colors
  scale_fill_manual(values = c("#add8e6", "#C4A484")) +
  # Theming
  theme_bw() +
  theme(legend.title = element_blank(),
        legend.position = c(0.1, 0.9)) +
  # Add geological time scale
  coord_geo()
```

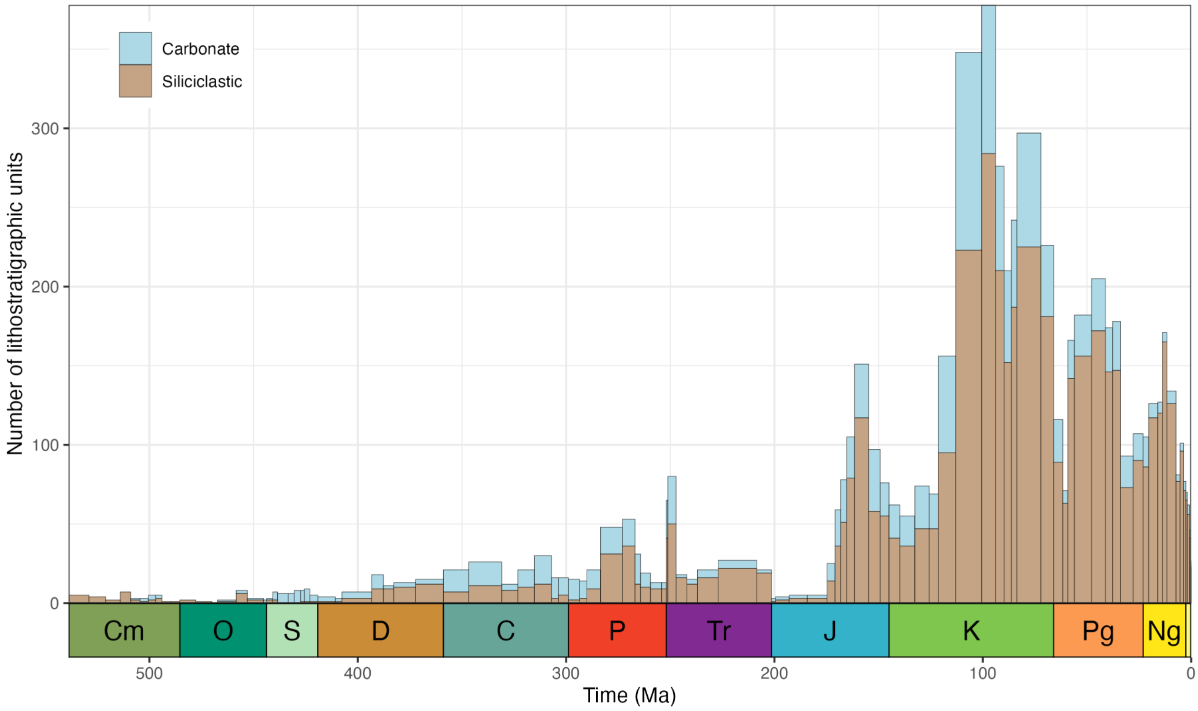

Figure 4: Phanerozoic lithostratigraphic units. The number of Macrostrat lithostratigraphic units throughout the Phanerozoic (541–0 Ma) binned by stratigraphic stage-level bins and grouped by sediment type (carbonate and siliciclastic). Units are counted for all time bins they overlap with. Lithostratigraphic units were fetched from the Macrostrat database (https://macrostrat.org/) using the *rmacrostrat* package ver. 0.0.1.

RESOURCES

We have made several resources available for our users. First, we have built a package website (http://rmacrostrat.palaeoverse.org) that provides information on how to use and contribute to *rmacrostrat*, how to report issues and bugs, and a contributor code of conduct. We have also made available three vignettes/tutorials for the package, which provide user-friendly usage guides (https://rmacrostrat.palaeoverse.org/articles). Through *rmacrostrat*, we hope to further foster collaboration and the sharing of resources within the Earth Science community. With this goal in mind, we warmly welcome the community to join and follow our community spaces, such as our GitHub organization page (https://github.com/palaeoverse) and Google Group (https://groups.google.com/g/palaeoverse), where users can share ideas and resources, advertise opportunities, and network with colleagues.

FUTURE PERSPECTIVES

The development of *rmacrostrat* expands upon the current suite of software toolkits available within the Palaeoverse (https://palaeoverse.org/) 'universe' (Jones, 2022; Gearty and Jones, 2023; Jones et al., 2023). Through *rmacrostrat*, we hope to improve accessibility to the vast geological data available within the Macrostrat database (https://macrostrat.org/) and facilitate new research across the Earth Sciences. The *rmacrostrat* R package offers researchers the opportunity to streamline their research by providing a bridge between Macrostrat and the R environment, as well as supporting the capacity to generate fully-reproducible pipelines. We hope that these benefits will encourage the community to further capitalize on the value offered by Macrostrat, and may ultimately lead to higher data quality through peer review. As we have demonstrated with our example applications, *rmacrostrat* can be used to support the efficient plotting of stratigraphic columns, mapping of geological outcrop, and quantification of temporal dynamics in available lithostratigraphic units. However, we envision that *rmacrostrat* can also be used to support a wide range of additional analyses across the Earth Sciences, such as economic resource exploration, comparisons between deep-time diversity dynamics and environmental change, and hazard mapping.

AUTHOR CONTRIBUTIONS

Lewis A. Jones conceived the project. All authors contributed to developing the project. Lewis A. Jones and William Gearty developed the core functionality of the *rmacrostrat* package. All authors contributed to developing the full functionality and documentation available, as well as testing and reviewing the code. Lewis A. Jones and Christopher D. Dean drafted the manuscript. Lewis A. Jones, Christopher D. Dean, and Bethany J. Allen produced the figures. All authors contributed to the final editing and checking of the manuscript.

ACKNOWLEDGEMENTS

We would like to thank Shanan Peters, Daniel Segessenmen, Daven Quin, Amy Fromandi, Michael McClennen, Andrew Zaffos and all those who develop and maintain the Macrostrat database. We would also like to thank the Swiss National Science Foundation for supplying a Scientific Exchanges grant to B.J.A. which facilitated the construction of this package and associated materials (IZSEZ0_224089). L.A.J. was supported by a Juan de la Cierva-formación 2021 postdoctoral fellowship (FJC2021-046695-I / MCIN / AEI / 10.13039 / 501100011033) from the European Union "NextGenerationEU"/PRTR and a Norman Newell Early Career Grant from the Paleontological Society. W.G. was supported by the Lerner-Gray Postdoctoral Research Fellowship from the Richard Gilder Graduate School at the American Museum of Natural History and a Norman Newell Early Career Grant from the Paleontological Society. C.D.D. was supported by a Royal Society grant (RF_ERE_210013, awarded to Philip D. Mannion). B.J.A was supported by ETH Zurich. This is Macrostrat publication number XXX and PBDB publication number XXX.

REFERENCES

Balseiro, D., and Powell, M.G., 2019, Carbonate collapse and the late Paleozoic ice age marine biodiversity crisis: Geology, v. 48, p. 118–122, doi:10.1130/G46858.1.

Balseiro, D., and Powell, M.G., 2023, Relative oversampling of carbonate rocks in the North American marine fossil record: Paleobiology, p. 1–14, doi:10.1017/pab.2023.16.

Barido-Sottani, J., Pett, W., O'Reilly, J.E., and Warnock, R.C., 2019, FossilSim: an R package for simulating fossil occurrence data under mechanistic models of preservation and recovery: Methods in Ecology and Evolution, v. 10, p. 835–840, doi:10.1111/2041-210X.13170.

Bell, M.A., and Lloyd, G.T., 2015, strap: an R package for plotting phylogenies against stratigraphy and assessing their stratigraphic congruence: Wiley Online Library.

Bosscher, H., and Schlager, W., 1993, Accumulation Rates of Carbonate Platforms: The Journal of Geology, v. 101, p. 345–355, doi:10.1086/648228.

Cao, W., Williams, S., Flament, N., Zahirovic, S., Scotese, C., and Müller, R.D., 2019, Palaeolatitudinal distribution of lithologic indicators of climate in a palaeogeographic framework: Geological Magazine, v. 156, p. 331–354, doi:10.1017/S0016756818000110.

Cohen, P.A., Lockwood, R., and Peters, S., 2018, Integrating Macrostrat and Rockd into undergraduate earth science teaching: Cambridge University Press, https://www.cambridge.org/core/elements/integrating-macrostrat-and-rockd-into-undergraduate-earth-science-teaching/460456BD59734928F9A641C69B09AD28 (accessed May 2024).

Cooley, D., 2022, geojsonsf: GeoJSON to Simple Feature Converter: R package version 2.0.3, doi:10.32614/CRAN.package.geojsonsf.

Ernst, R.E., and Youbi, N., 2017, How Large Igneous Provinces affect global climate, sometimes cause mass extinctions, and represent natural markers in the geological record: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 478, p. 30–52, doi:10.1016/j.palaeo.2017.03.014.

Fassett, J.E., and Hinds, J.S., 1971, Geology and fuel resources of the Fruitland Formation and Kirtland Shale of the San Juan Basin, New Mexico and Colorado: US Geological Survey Professional Paper 676, https://doi.org/10.3133/pp676.

Fastovsky, D.E., and Bercovici, A., 2016, The Hell Creek Formation and its contribution to the Cretaceous–Paleogene extinction: A short primer: Cretaceous Research, v. 57, p. 368–390, doi:10.1016/j.cretres.2015.07.007.

Gearty, W., 2024, Deeptime: Plotting tools for anyone working in deep time: R package version 1.1.1, doi:10.32614/CRAN.package.deeptime.

Gearty, W., and Jones, L.A., 2023, rphylopic: An R package for fetching, transforming, and visualising PhyloPic silhouettes: Methods in Ecology and Evolution, v. 14, p. 2700–2708, doi:10.1111/2041-210X.14221.

Heim, N.A., and Peters, S.E., 2011, Covariation in macrostratigraphic and macroevolutionary patterns in the marine record of North America: GSA Bulletin, v. 123, p. 620–630, doi:10.1130/B30215.1.

Husson, J.M., and Coogan, L.A., 2023, River chemistry reveals a large decrease in dolomite abundance across the Phanerozoic: Geochem. Perspect. Lett., v. 26, p. 1–6, doi:10.7185/geochemlet.2316.

Johnson, K.R., Nichols, D.J., and Hartman, J.H., 2002, Hell Creek formation: A 2001 synthesis: Geological society of America special paper, v. 361, p. 503–510.

Jones, L.A. et al., 2023, palaeoverse: A community-driven R package to support palaeobiological analysis: Methods in Ecology and Evolution, v. 14, p. 2205–2215, doi:10.1111/2041-210X.14099.

Jones, L.A., 2022, sepkoski: Sepkoski's Fossil Marine Animal Genera Compendium: R package version 0.0.1, doi:10.32614/CRAN.package.sepkoski.

Kocsis, Á.T., Reddin, C.J., Alroy, J., and Kiessling, W., 2019, The R package divDyn for quantifying diversity dynamics using fossil sampling data: Methods in Ecology and Evolution, v. 10, p. 735–743, doi:10.1111/2041-210X.13161.

Miall, A.D., 2022, Stratigraphy: The Modern Synthesis, *in* Miall, A.D. ed., Stratigraphy: A

Modern Synthesis, Cham, Springer International Publishing, p. 341–417, doi:10.1007/978-3-030-87536-7_7.

Nelsen, M.P., DiMichele, W.A., Peters, S.E., and Boyce, C.K., 2016, Delayed fungal evolution did not cause the Paleozoic peak in coal production: Proceedings of the National Academy of Sciences, v. 113, p. 2442–2447, doi:10.1073/pnas.1517943113.

Ooms, J., 2024, Curl: A modern and flexible web client for r:

Ooms, J., 2014, The jsonlite Package: A Practical and Consistent Mapping Between JSON Data and R Objects:, http://arxiv.org/abs/1403.2805 (accessed June 2024).

Ortiz, J.R., and Jaramillo, C.A., 2018, SDAR: a toolkit for stratigraphic data analysis in R:

Pebesma, E., and Bivand, R., 2023, Spatial data science: With applications in R: Chapman and Hall/CRC, https://www.taylorfrancis.com/books/mono/10.1201/9780429459016/spatial-data-science-edzer-pebesma-roger-bivand (accessed June 2024).

Peters, S.E., 2006, Macrostratigraphy of North America: The Journal of Geology, v. 114, p. 391–412, doi:10.1086/504176.

Peters, S.E., and Heim, N.A., 2011a, Macrostratigraphy and macroevolution in marine environments: testing the common-cause hypothesis: Geological Society, London, Special Publications, v. 358, p. 95–104, doi:10.1144/SP358.7.

Peters, S.E., and Heim, N.A., 2011b, Stratigraphic distribution of marine fossils in North America: Geology, v. 39, p. 259–262, doi:10.1130/G31442.1.

Peters, S.E., and Heim, N.A., 2010, The geological completeness of paleontological sampling in North America: Paleobiology, v. 36, p. 61–79, doi:10.1666/0094-8373-36.1.61.

Peters, S.E., and Husson, J.M., 2017, Sediment cycling on continental and oceanic crust: Geology, v. 45, p. 323–326, doi:10.1130/G38861.1.

Peters, S.E., Husson, J.M., and Czaplewski, J., 2018, Macrostrat: A Platform for Geological

Data Integration and Deep-Time Earth Crust Research: Geochemistry, Geophysics, Geosystems, v. 19, p. 1393–1409, doi:10.1029/2018GC007467.

Peters, S.E., Husson, J.M., and Wilcots, J., 2017, The rise and fall of stromatolites in shallow marine environments: Geology, v. 45, p. 487–490, doi:10.1130/G38931.1.

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

Peters, S.E., Walton, C.R., Husson, J.M., Quinn, D.P., Shorttle, O., Keller, C.B., and Gaines, R.R., 2021, Igneous rock area and age in continental crust: Geology, v. 49, p. 1235–1239, doi:10.1130/G49037.1.

Quinn, D.P., Idzikowski, C.R., and Peters, S.E., 2024, Building a multi-scale, collaborative, and time-integrated digital crust: The next stage of the Macrostrat data system: Geoscience Data Journal, v. 11, p. 11–26, doi:10.1002/gdj3.189.

R Core Team, 2023, R: A Language and Environment for Statistical Computing:, https://www.R-project.org/.

Ronov, A.B., Khain, V.E., Balukhovsky, A.N., and Seslavinsky, K.B., 1980, Quantitative analysis of Phanerozoic sedimentation: Sedimentary Geology, v. 25, p. 311–325, doi:10.1016/0037-0738(80)90067-6.

Rook, D.L., Heim, N.A., and Marcot, J., 2013, Contrasting patterns and connections of rock and biotic diversity in the marine and non-marine fossil records of North America: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 372, p. 123–129, doi:10.1016/j.palaeo.2012.10.006.

Scotese, C.R., Song, H., Mills, B.J.W., and van der Meer, D.G., 2021, Phanerozoic paleotemperatures: The earth's changing climate during the last 540 million years: Earth-Science Reviews, v. 215, p. 103503, doi:10.1016/j.earscirev.2021.103503.

Seslavinskiy, K.B., 1991, GLOBAL TRANSGRESSIONS AND REGRESSIONS DURING

THE PALEOZOIC: International Geology Review, doi:10.1080/00206819109465676.

Sessa, J.A., Fraass, A.J., LeVay, L.J., Jamson, K.M., and Peters, S.E., 2023, The Extending Ocean Drilling Pursuits (eODP) Project: Synthesizing Scientific Ocean Drilling Data: Geochemistry, Geophysics, Geosystems, v. 24, p. e2022GC010655, doi:10.1029/2022GC010655.

Tasistro-Hart, A.R., and Macdonald, F.A., 2023, Phanerozoic flooding of North America and the Great Unconformity: Proceedings of the National Academy of Sciences, v. 120, p. e2309084120, doi:10.1073/pnas.2309084120.

Tetley, M.G., Williams, S.E., Gurnis, M., Flament, N., and Müller, R.D., 2019, Constraining absolute plate motions since the Triassic: Journal of Geophysical Research: Solid Earth, v. 124, p. 7231–7258, doi:10.1029/2019JB017442.

Uhen, M.D. et al., 2023, Paleobiology Database User Guide Version 1.0: PaleoBios, v. 40, doi:10.5070/P9401160531.

Varela, S., González-Hernández, J., Sgarbi, L.F., Marshall, C., Uhen, M.D., Peters, S., and McClennen, M., 2015, paleobioDB: an R package for downloading, visualizing and processing data from the Paleobiology Database: Ecography, v. 38, p. 419–425, doi:10.1111/ecog.01154.

Vidaña, S.D., and Goring, S.J., 2023, neotoma2: An R package to access data from the NeotomaPaleoecology Database: Journal of Open Source Software, v. 8, p. 5561, doi:10.21105/joss.05561.

Villanueva, R.A.M., and Chen, Z.J., 2019, ggplot2: Elegant Graphics for Data Analysis (2nd ed.): Measurement: Interdisciplinary Research and Perspectives, v. 17, p. 160–167, doi:10.1080/15366367.2019.1565254.

Wickham, H., 2023, httr: Tools for working with URLs and HTTP: R package version 1.4.7,

doi:10.32614/CRAN.package.httr.
Wickham, H., 2011, testthat: Get started with testing.: R J., v. 3, p. 5, doi:10.32614/RJ-2011-002.
Wickham, H., Danenberg, P., Csárdi, G., and Eugster, M., 2024a, roxygen2: In-Line Documentation for R: R package version 7.3.2, doi:https://doi.org/10.32614/CRAN.package.roxygen2.
Wickham, H., Hester, J., Chang, W., and Bryan, J., 2024b, devtools: Tools to Make Developing R Packages Easier: R package version 2.4.5, doi:10.32614/CRAN.package.devtools.
Wright, N., Zahirovic, S., Müller, R.D., and Seton, M., 2013, Towards community-driven paleogeographic reconstructions: integrating open-access paleogeographic and paleobiology data with plate tectonics: Biogeosciences, v. 10, p. 1529–1541, doi:10.5194/bg-10-1529-2013.
Ye, S., and Peters, S.E., 2023, Bedrock geological map predictions for Phanerozoic fossil occurrences: Paleobiology, v. 49, p. 394–413, doi:10.1017/pab.2022.46.