deeptime: an R package that facilitates highly customizable and reproducible visualizations of data over geological time intervals

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Abstract

Data visualization is a key component of any scientific data analysis workflow and is vital for the summarization and dissemination of complex ideas and results. One common hurdle across the Geosciences and other scientific fields remains the reproducibility of many types of visualizations of data over long time intervals (10^{4+} years). Here I introduce the R package *deeptime*, which provides easy-to-use functions to facilitate fully reproducible visualizations of geological data. The package includes functionality to add various geological timescales to many

different types of plots, use standardized stratigraphical patterns within figures, visualize continuous and discrete temporal data, and more. By leveraging the existing framework of the *ggplot2* R package, *deeptime* allows for these visualizations to be highly customizable. The open-source and constantly evolving package is accompanied by exhaustive documentation about the myriad options available to users and several tutorials demonstrating the available functionality. My hope is that *deeptime* will reduce the amount of time and experience needed to make reproducible and professional data visualizations, giving scientists more time to ensure that these visualizations are more accessible and engaging.

1. INTRODUCTION

The Geosciences have a long history of visualizing data, with the oldest preserved geologic map, the Turin Papyrus, dating back to 1150 BC (Harrell and Brown, 1992). More than 3000 years later, data visualization remains a key component of studying the Earth, from detailed stratigraphic columns to three-dimensional cartography (Zhao et al., 2019; Nesbit et al., 2020; Kraak and Ormeling, 2020). However, despite an increased adherence to open science principles in the Geosciences (e.g., open data, see Vance et al., 2024), much data visualization remains unreproducible (Fekete and Freire, 2020), with many researchers still using proprietary and commercial software to annotate or even entirely generate their figures (e.g., ArcGIS, ENVI, GEO5, LIME, Mathematica, MATLAB, and various Adobe products) (Mader and Schenk, 2017; Ramachandran et al., 2021). These software packages often have graphical user interfaces and dedicated, paid support staff, but their use also incurs a financial burden on researchers and institutions. Further, the implementation of these packages often remains opaque, with no way to confirm the underlying operations or source code. Open-source software packages, on the other hand, have no licensing fees, offer unrestricted use to users, and allow for user customization (Steiniger and Bocher, 2009). Furthermore, despite not having warranties or devoted support staff, developers of open-source software packages are often more accessible and open to adding new features that are requested by users. Finally, open-source software packages often have large communities of users, (e.g., Stack Overflow, https://stackoverflow.com/), who effectively support one another despite no monetary incentives (Mamykina et al., 2011). Fortunately, there are now many grassroots efforts to develop and broaden the availability of open-source software for geostatistics and data visualization (Steiniger and Bocher, 2009; Mader and Schenk, 2017; Brovelli et al., 2017; Jones et al., 2023).

The R open-source programming language, originally developed primarily for statistics, has emerged as one of the most widely used coding languages among Earth scientists, especially for reproducible data visualization (Grunsky, 2002; Pebesma et al., 2012; Mader and Schenk, 2017; R Core Team, 2024). For example, the *geoscale* R package (Bell, 2022) has long been a staple for generating a range of bivariate base R plots with timescales on the x-axis. The *palaeoverse* R package (Jones et al., 2023) greatly expands on this functionality by adding one or more timescales to any axis on existing base R plots. The *strap* R package (Bell and Lloyd, 2015) can be used to visualize phylogenies within a stratigraphic context. Also, the *GEOmap* R package (Lees, 2024) can be used for topographic and geologic mapping. The *stratigrapheR* (Wouters et al., 2021), *SDAR* (Ortiz and Jaramillo, 2018), and *tidypaleo* (Dunnington et al., 2022) R packages can be used to visualize stratigraphic columns and associated data. The *ggtern* R package (Hamilton and Ferry, 2018) is a popular *ggplot2* (Wickham, 2016) extension for the creation of ternary diagrams. Finally, the IsoplotR R package can be used to analyze and visualize radiometric geochronology data (Vermeesch, 2018). However, gaps remain in the breadth and customizability of reproducible Earth science visualizations that can be made in R.

Here I present *deeptime*, an R package that supplements these existing resources by embracing community naming and symbology standards while enhancing the ease, reproducibility, and customizability of Earth science data visualization. The package facilitates streamlined access to geological reference data, such as geological timescales and lithostratigraphic patterns, and includes novel functionality to incorporate these data into a wide range of existing visualizations, particularly those developed with the popular *ggplot2* visualization system (Wickham, 2016). By fully integrating with existing R visualization systems such as *grid* and *ggplot2* (Wickham, 2016; R Core Team, 2024), *deeptime* helps facilitate highly customizable and reproducible publication-quality figures. Herein, I first provide instructions on package installation and implementation details. I then demonstrate typical usage of the package by presenting four worked examples. Finally, I discuss the resources that are available to users of the package and potential future development.

2. INSTALLATION

The *deeptime* package can be installed from CRAN using the `install.packages()` function in R (R Core Team, 2024):

```
install.packages(“deeptime”)
```

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

```
remotes::install_github("willgearty/deeptime")
```

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

```
library(deeptime)
```

3. IMPLEMENTATION

The *deeptime* R package has three broad suites of functions: 1) functions associated with accessing timescales and integrating them with existing visualizations, 2) functions associated with plotting continuous and discrete temporal data, and 3) functions associated with accessing and using standardized lithostratigraphic patterns.

3.1 Accessing and integrating timescales with visualizations

The timescale suite of functions represents the original purpose of the package and allows for users to access and add highly customizable timescales to nearly any type of plot that has been generated using *ggplot2*. A summary of this suite of functions is provided in Table 1. The *deeptime* package includes built-in data that is based on the Geological Time Scale (GTS) by the International Commission of Stratigraphy (ICS) (Cohen et al., 2013). The GTS is broken down by interval type into five different built-in datasets: `eons`, `eras`, `periods`, `epochs`, and `stages`, all of which are loaded into the R environment when the *deeptime* package is loaded. This built-in data is updated regularly, using the Macrostrat (https://macrostrat.org/) Application Programming Interface (API) (Peters et al., 2018), to reflect any changes that the ICS has made to the GTS. The `get_scale_data()` function can be used to retrieve any of these built-in timescales or data about more than 30 other timescales that are available from the Macrostrat API. This includes timescales such as the North American land mammal ages (NALMA); the American Association of Petroleum Geologists' Correlation of Stratigraphic Units of North America (COSUNA); trilobite, ammonite, and foraminiferal zonations; and geomagnetic polarity chrons. While these other timescales are not included as built-in data, they can easily be accessed by name with `get_scale_data()`—with partial name matching to ease lookup—or within any of the other timescale suite of functions by supplying their name to the `dat` argument (see Section 4.1 below). Once accessed, timescales can then be supplied to various other *deeptime* functions or even used with various functions from the *palaeoverse* R package (Jones et al., 2023).

To integrate these timescales with existing *ggplot2* visualizations, *deeptime* currently provides three functions: `coord_geo()`, `coord_geo_radial()`, and `guide_geo()`. The `coord_geo()` function builds upon `coord_cartesian()`, the transformed Cartesian coordinate system from *ggplot2,* to add continuous or discrete timescale(s) to the specified side(s) of a plot (see Section 4.1 below). The most important arguments are the `dat` argument, which specifies which timescale should be added to the plot, and the `pos` argument which specifies to which side the timescale should be added. It should be noted that the `dat` argument here is quite flexible, and the value supplied can be one of the built-in timescales (e.g., "periods", the default), a full or partial name of one of the Macrostrat timescales (e.g., "mammal"), or even a custom data.frame object that represents a user's custom timescale and matches the format of the built-in datasets. Beyond specifying the timescale(s), users are presented with many customization options, many of which have been added based on user requests, including height of the interval boxes, box borders, box fill color, label font, label size, label color, label abbreviation, and more. A second function, `coord_geo_radial()`, is also available to transform the plot into polar coordinates and add annulus-shaped timescale intervals to the background of the plot. This is particularly useful for plotting phylogenies in a "fan" arrangement (see Section 4.2 below). The `guide_geo()` function is also available to add individual timescales as axis guides. In most cases this duplicates the functionality of `coord_geo()`, but it can be combined with `coord_geo_radial()` to present both annulus-shaped background intervals and a horizontal timescale like that from `coord_geo()` (see Section 4.2 below).

Table 1: Summary table of the suite of functions currently available in the *deeptime* R package related to accessing and integrating timescales.

Function	**Description**
get_scale_data()	Retrieve geological timescale data from Macrostrat
coord_geo()	Transformed coordinate system with geological timescale

coord_geo_radial()	Polar coordinate system with geological timescale
guide_geo()	Geological timescale axis guide

3.2 Facilitating the visualization of temporal data

The *deeptime* package also includes a suite of functions designed for helping visualize continuous and/or discrete temporal data which is summarized in Table 2. Two “scale_*” functions are included, `scale_color_geo()` and `scale_fill_geo()`, which can be used to modify the color and fill aesthetics, respectively, of any *ggplot2* geometries based on the colors from a particular timescale. This can make it clearer to the viewer which data correspond to which discrete time interval. Both functions match the names of the included time intervals to the desired timescale to retrieve and assign the correct color values. The `facet_wrap_color()` and `facet_grid_color()` functions can be used to visually split data across discrete time intervals. These functions behave like their *ggplot2* counterparts, `facet_wrap()` and `facet_grid()`, but also color the facet label “strips” based on the colors from the desired timescale (GTS stages by default). To have multiple levels of discrete time shown, *deeptime* also includes `facet_nested_color()` and `facet_nested_wrap_color()`, which are based on the `facet_nested()` and `facet_nested_wrap()` functions, respectively, from the *ggh4x* R package (Brand, 2024). These functions allow for nested facets (e.g., periods nested within eras), all of which may similarly be colored based on the desired timescales. All six of these functions can use any of the built-in timescales or any of the other Macrostrat timescales (provided that the intervals have assigned colors).

Table 2: Summary table of the suite of functions currently available in the *deeptime* R package related to plotting temporal data.

Function	**Description**
scale_color_geo() and scale_fill_geo()	Scales for *ggplot2* that style geometries based on the colors from a particular timescale
facet_wrap_color() and facet_grid_color()	Versions of facet_wrap() and facet_grid() that color the label strips with the colors from a particular timescale
facet_nested_color() and facet_nested_wrap_color()	Versions of facet_nested() and facet_nested_wrap() that color the label strips with the colors from a particular timescale
geom_points_range()	Display data points and their range across each discrete value

Also within this suite of functions is `geom_points_range()`, which was designed to simplify the creation of taxon range plots that are very common in biostratigraphy (e.g., Macellari, 1986; Wignall and Atkinson, 2020) (see Section 4.3 below). This function behaves somewhat similarly to the `geom_pointrange()` and `geom_linerange()` functions from *ggplot2*, except individual points are supplied instead of pre-calculated limits. All the necessary calculations are performed in the background by *deeptime*, then all of the supplied points are plotted as specified along with the range lines. It should be noted that this function works for any set of discrete categories, not just biological taxa, each of which has a range of data points reflecting some continuous variable. As with other "geom"s it fully supports a range of *ggplot2* aesthetics such as color, shape, size, and linewidth. If the supplied aesthetics (e.g., different colors) result in disconnected groups of points for any given category, the range lines will similarly be disconnected.

3.3 Accessing and integrating lithostratigraphic patterns with visualizations

The final suite of functions facilitates access to and the use of a standardized set of patterns for geologic maps and stratigraphic columns and is summarized in Table 3. In 2006, the U.S. Geological Survey (USGS) and the Geologic Data Subcommittee of the Federal Geographic Data Committee (FGDC) established the Digital Cartographic Standard for Geologic Map Symbolization (Federal Geographic Data Committee, 2006). This is the National Standard for the digital cartographic representation of geologic map features, including line symbols, point symbols, colors, and patterns. Within this standard are surficial, sedimentary, igneous, metamorphic, and glacial/periglacial patterns for geologic maps and sedimentary, igneous, metamorphic, and vein-matter lithologic patterns for stratigraphic columns or charts. These standardized patterns are included in *deeptime* as vectorized *grid* "grobs" and each pattern has an assigned pattern number or "code" (e.g., 603 = crossbedded gravel or conglomerate, 702 = quartzite). These individual "grob" objects, representing a single instance of the pattern, can be accessed using the `geo_grob()` function. Alternatively, users can use the `geo_pattern()` function which returns individual "GridPattern" objects, which are repeated instances of the pattern. Once retrieved, these objects can then be plotted wherever the user desires using the low-level `grid.draw()` function from the *grid* package (R Core Team, 2024).

Table 3: Summary table of the suite of functions currently available in the *deeptime* R package related to accessing and plotting geologic and lithostratigraphic patterns.

Function	**Description**
geo_grob() and geo_pattern()	Retrieve Federal Geographic Data Committee patterns as "grob" or "GridPattern" objects

scale_fill_geopattern()	A fill scale for *ggplot2* that fills geometries with geologic and stratigraphic patterns
grid.pattern_geo()	Plot an individual Federal Geographic Data Committee pattern using *grid* (used in

The *deeptime* package also supplies three high-level methods for using these patterns in *ggplot2* visualizations. The most convenient of these methods is the `scale_fill_geopattern()` function, which takes the FGDC pattern codes assigned to *ggplot2* geometries as aesthetic fill values and converts them to geologic and stratigraphic patterns. This method is the easiest to implement in a visualization but also does not allow for any customization beyond the pattern type. If users would like to change the color, scale, and/or transparency of the patterns, they can use the *ggpattern* R package (FC et al., 2024). This package has a variety of geometries that are designed to include pattern fills. By specifying the "geo" `pattern` in any of these geometry functions (e.g., `geom_col_pattern(pattern = “geo”, ...)`), the `pattern_type` aesthetic can then be used to define the assignment of FGDC pattern codes to individual geometries or to a discrete variable within the data (e.g., using `scale_pattern_type_manual()` or `scale_pattern_type_identity()`, see Section 4.4 below). The machinery that makes this happen behind the scenes is the *deeptime* function `grid.pattern_geo()`, which takes an individual FGDC pattern number and plots the pattern within a specified polygon. If desired, this function can be used on its own, although it is much more cumbersome than using the *ggpattern* "geom_*_pattern" functions.

4. APPLICATION

4.1 Multiple timescales on a single plot

This first application example showcases the versatility of the `coord_geo()` function (Figure 1). Here, we will plot some global benthic δ^{18}O data for 0 – 5.3 Ma (Lisiecki and Raymo, 2005) that is included in the *gsloid* R package (Marwick et al., 2022). As in Lisiecki and Raymo (2005), we plot the geomagnetic polarity subchrons along one side of the plot. In the same `coord_geo()` command we can also include a second axis along the other side of the plot, in this case the planktic foraminiferal primary biozones. To facilitate this, we can use a `list()` of side names for the `pos` argument. When doing this, nearly all the other arguments can also be `list()`s, in which case the order of the values corresponds to the same order of the values supplied to `pos`. If these lists are not as long as `pos`, the elements will be recycled as necessary, and if individual values (or vectors) are used for these parameters, they will be applied to all time scales. In this case, both of our desired timescales come from the Macrostrat API as discussed above, so we can access them by name (or partial name). To match common practices with the use of the geomagnetic polarity subchrons (i.e., alternating black and white), we can also manually change the fill and label colors with the `fill` and `lab_color` arguments, respectively. Finally, some of the interval names are long, so we use the "auto" `size` option.

```
# Load packages
library(deeptime)
library(ggplot2)
# Load gsloid for oxygen isotope data
library(gsloid)
# Plot isotope data
ggplot(lisiecki2005) +
  geom_line(aes(x = Time / 1000, y = d18O)) +
```

```
scale_x_reverse("Time (Ma)") +
scale_y_reverse(expression(delta^18*O)) +
# Add timescale
coord_geo(
  pos = list("bottom", "top"),
  dat = list("Planktic foraminiferal Primary Biozones",
             "Subchron"), # partial matching also works
  xlim = c(5.5, 0), ylim = c(6, 2),
  # Use default colors for biozones and
  # custom black/white colors for the subchrons
  fill = list(NULL , c("black", "white")),
  lab_color = list(NULL, c("white", "black")),
  # Use biozone abbreviations, auto-size labels
  size = "auto", abbrv = list(TRUE, FALSE)
) +
# Choose theme and increase font size
theme_classic(base_size = 14)
```

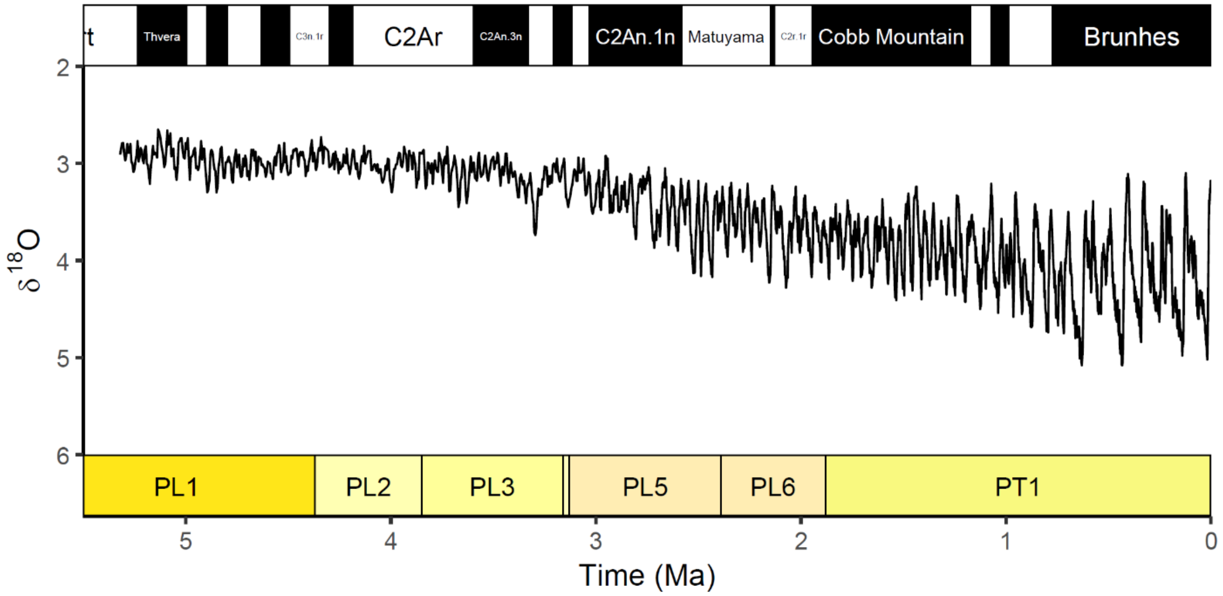

Figure 1: Plot of global benthic $\delta^{18}O$ data for 0 – 5.3 Ma (Lisiecki and Raymo, 2005) with geomagnetic polarity subchrons displayed on the top x-axis and planktic foraminiferal primary biozones plotted on the bottom x-axis.

4.2 Timescales and phylogenies

Another common use case of timescales is for phylogenetics, especially as it is becoming very common to infer large, time-calibrated phylogenies with and without paleontological information (Wright et al., 2022; Portik et al., 2023). The *ggtree* R package (Yu et al., 2017), an extension of the *ggplot2* system that is available on Bioconductor (https://bioconductor.org/), is commonly used to visualize phylogenies within R. The `coord_geo()`, `coord_geo_radial()`, and `guide_geo()` functions are all designed to work in tandem with *ggtree*. Here, we will develop an example that uses both `coord_geo_radial()` and `guide_geo()` to add timescale information to a small phylogeny of mammals (Garland et al., 1992) that is hosted within the *phytools* R package (Revell, 2024) (Figure 2). In this case, `coord_geo_radial()` transforms the entire plot into polar coordinates, creating a "fan" phylogeny. Further, it adds a timescale to the background in a series of colored annulus-shaped intervals. To ensure the background is not too distracting, we use a very light grey scale alternating between light grey and white. However, the plot also needs a way to indicate to viewers what these intervals represent, so we also use `guide_geo()` to add a horizontal scale like one would get from `coord_geo()` on a non-polar plot.

```
# Load packages
library(deeptime)
library(ggplot2)
library(ggtree)
# Load phytools for the example phylogeny
library(phytools)
```

```
data(mammal.tree)
# Plot the phylogeny; revts reverses the time axis
revts(ggtree(mammal.tree)) +
  # Transform to polar coordinates and add background timescale
  # “end” must be less than 1.5 * pi to leave space for guide
  coord_geo_radial(dat = "stages", fill = c("grey95", "white"),
                   end = 1.49 * pi) +
  # Set x-axis ticks and labels; remove negative signs
  scale_x_continuous(breaks = seq(-60, 0, 20),
                     labels = seq(60, 0, -20),
                     expand = expansion(mult = c(0.05, 0))) +
  # Set expansions at each end of the y-axis; remove guide
  scale_y_continuous(guide = NULL,
                     expand = expansion(mult = c(0.02, 0.05))) +
  # Add horizontal timescale to the r-axis using guides
  guides(r = guide_axis_stack(
               guide_geo("epochs", neg = TRUE, size = "auto",
                         rot = -90, height = unit(1, "line")),
               guide_axis(),
               spacing = unit(0, "line"))
             ) +
  # Choose theme and increase font size
  theme_classic(base_size = 14) +
```

```
        # Make the tick labels black
        theme(axis.text.y = element_text(color = "black"))
```

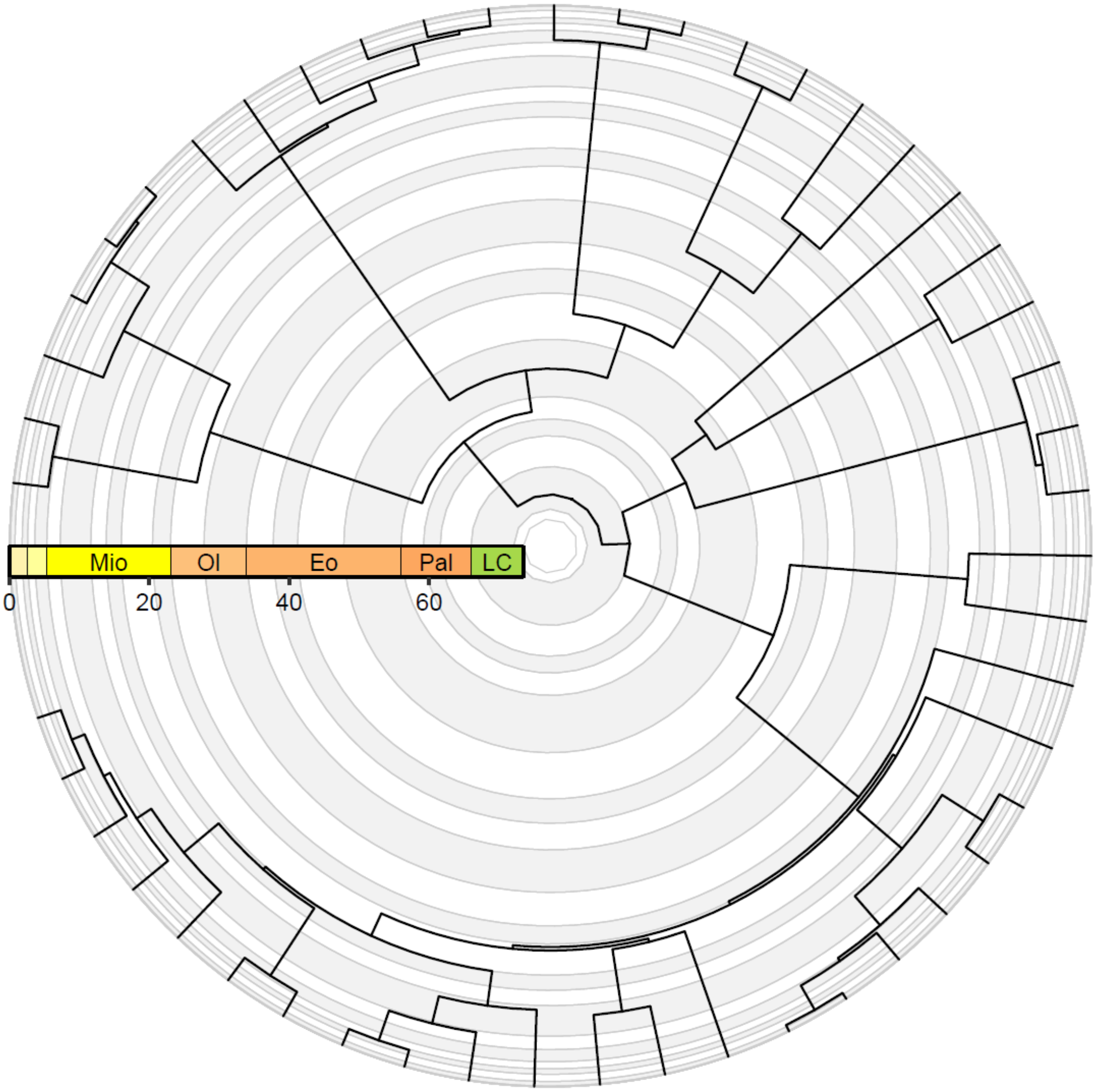

Figure 2: A mammal phylogeny (Garland et al., 1992) plotted using the *ggtree* and *deeptime* packages. The greyscale background indicates geological stages, whereas the colored timescale indicates geological epochs.

4.3 Visualizing taxonomic occurrence data

A common way to visualize fossil occurrence data is with a taxonomic/biostratigraphic range chart (e.g., Macellari, 1986; Wignall and Atkinson, 2020). Here we will demonstrate how to use the `geom_points_range()` function to generate an entire taxonomic range chart for a subset of Permian tetrapod occurrences from a built-in dataset in the *palaeoverse* R package (Jones et al., 2023) (Figure 3). First, we filter this large dataset to a much more manageable set of 300 occurrences for this toy example, prioritizing the most common genera to limit the number of genera we need to handle. We then reorder the genera by their oldest occurrences for a more visually appealing order in the chart. In many cases, we may be more or less certain about the age or affinity of some occurrences compared to others. To mimic this, we then add a new column that is populated with some dummy binary data to represent whether we are certain or not with the occurrences.

```
# Load packages
library(deeptime)
library(ggplot2)
library(dplyr)
# Load palaeoverse for tetrapod occurrence data
library(palaeoverse)
data(tetrapods)
occdf <- tetrapods %>%
  # Filter to genus occurrences
  filter(accepted_rank == "genus") %>%
  select(occurrence_no, accepted_name, max_ma, min_ma) %>%
```

```
  # Reorder by genus commonality
  mutate(accepted_name = reorder(accepted_name, accepted_name,
                                 length)) %>%
  arrange(desc(accepted_name)) %>%
  mutate(age = (max_ma + min_ma) / 2) %>%
  # Get a reasonable subset of occs. of the most common genera
  slice(1:300) %>%
  # Reorder by first occurrence of genera
  mutate(accepted_name = reorder(accepted_name, age, max,
                                 decreasing = TRUE)) %>%
  # Add a dummy certainty column with random binary data
  mutate(certainty = factor(sample(0:1, nrow(occdf),
                                   replace = TRUE)))
```

We then generate the taxonomic range chart with the `geom_points_range()` function and annotate it with timescales for periods and stages. We indicate the uncertain points with open circles and if the uncertain points are outside of the bounds of the certain points for each genus, the function indicates this with a dashed line.

```
ggplot(data = occdf) +
  # Generate the taxon range chart
  geom_points_range(aes(x = age, y = accepted_name,
                        fill = certainty, linetype = certainty),
                    shape = 21) +
  scale_x_reverse() +
```

```
scale_fill_manual(values = c("white", "black")) +
scale_linetype_manual(values = c("dashed", "solid")) +
# Add timescales for periods and stages on the bottom
coord_geo(pos = list("bottom", "bottom"),
          dat = list("stages", "periods"),
          abbrv = list(TRUE, FALSE), expand = TRUE,
          size = "auto") +
labs(x = "Time (Ma)", y = NULL) +
# Choose theme, set font size, and make tick labels black
theme_classic(base_size = 14) +
theme(axis.text = element_text(color = "black"))
```

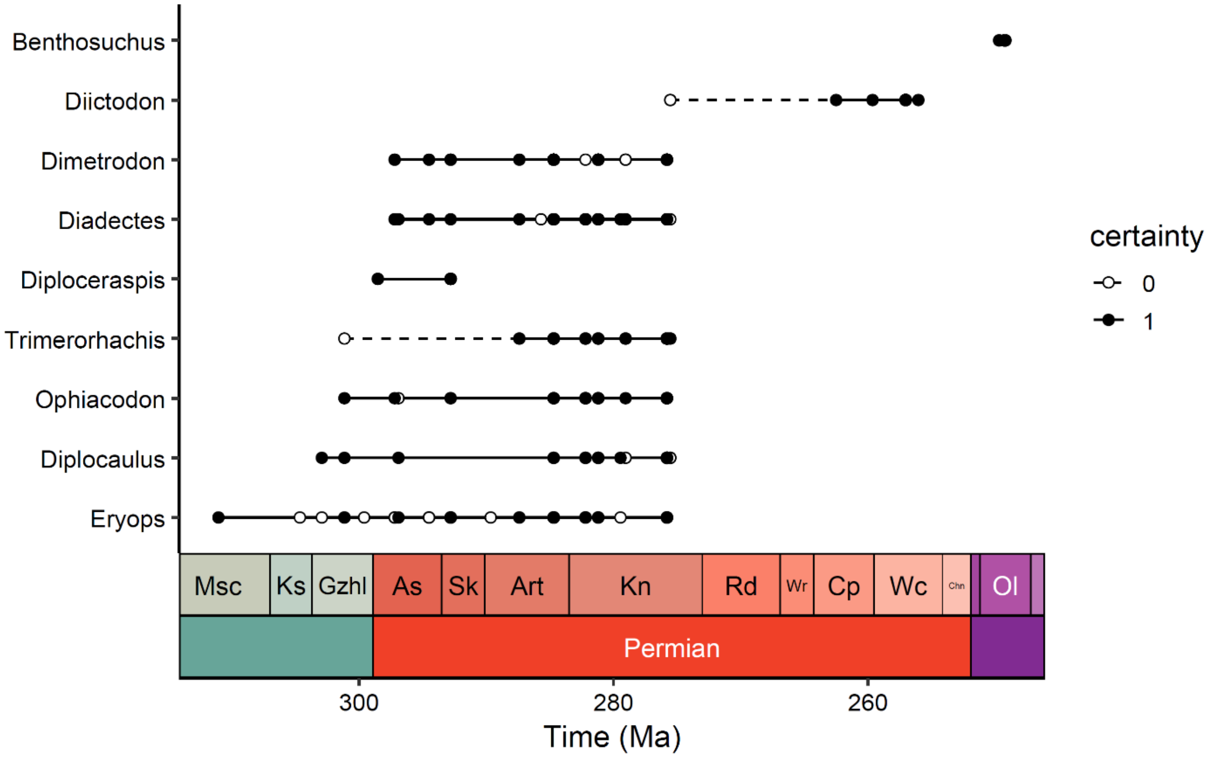

Figure 3: Early tetrapod occurrence data (Jones et al., 2023) plotted as a taxonomic/biostratigraphic range plot using the `geom_points_range()` function.

4.4 Stratigraphic column with patterns

The *rmacrostrat* R package (Jones et al., 2024) allows users to access the Macrostrat API (Peters et al., 2018), which includes various geological data (e.g., lithostratigraphic units) and definitions/metadata associated with those data. The package includes several vignettes that walk through how to retrieve and visualize various types of data from the database. Here, we will exemplify how *deeptime* can be used with such data by plotting a stratigraphic column, including patterned fills for the lithologies, for the San Juan Basin, a large structural depression which spans parts of New Mexico, Colorado, Utah, and Arizona (Figure 4). The details about downloading this data are thoroughly presented in an *rmacrostrat* vignette (https://rmacrostrat.palaeoverse.org/articles/stratigraphic-column.html). For the purposes of this example, we will skip ahead and download the unit-level stratigraphic data for this basin during the Cretaceous. We will also download a list of lithology definitions from the Macrostrat API, which includes the lithology names (which match the unit data) and the associated FGDC pattern codes.

```
# Load libraries
library(deeptime)
library(ggplot2)
library(ggpattern)
library(ggrepel)
library(rmacrostrat)
```

```
# Get lithology definitions
liths <- def_lithologies()
# Using the column ID, retrieve the units in the San Juan Basin
san_juan_units <- get_units(column_id = 489,
                            interval_name = "Cretaceous")
```

Many of these units have multiple lithologies (packaged together as a data.frame), so we pick just the most abundant one for each unit. Once there is a single lithology for each unit, we then can assign a pattern code to each unit using the “fill” column from the Macrostrat lithologies.

```
# Get the primary lithology for each unit
san_juan_units$lith_prim <- sapply(san_juan_units$lith,
                                   function(df) {
                                     df$name[which.max(df$prop)]
                                   })
# Assign pattern code
san_juan_units$pattern <-
  factor(liths$fill[match(san_juan_units$lith_prim, liths$name)])
```

Now that we have the unit data and the pattern codes, we can go ahead and plot the section using the *ggpattern* (FC et al., 2024) and *ggrepel* packages (Slowikowski, 2024).

```
# 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 with pattern fills
ggplot(san_juan_units, aes(ymin = b_age, ymax = t_age,
                           xmin = x_min, xmax = x_max)) +
  # Plot units, patterned by lithology
  geom_rect_pattern(aes(pattern_type = pattern), pattern = "geo",
                    pattern_color = "black",
                    pattern_fill = "white",
                    fill = "white", pattern_scale = 4) +
  # Use identity of pattern_type aesthetic to set pattern type
  # Also, substitute lithology names for codes in the legend
  scale_pattern_type_identity(name = NULL, guide = "legend",
                              breaks = factor(liths$fill),
                              labels = liths$name) +
  # Add text labels
  geom_text_repel(aes(x = x_max, y = m_age,
                      label = strat_name_long),
                  size = 3.5, hjust = 0, force = 2,
                  min.segment.length = 0, direction = "y",
                  nudge_x = rep_len(x = c(2, 3),
```

```
                                  length.out = 17)) +
# Add geological time scale
coord_geo(pos = "left", dat = list("stages"), rot = 90) +
# Reverse direction of y-axis
scale_y_reverse(limits = c(145, 66), n.breaks = 10,
                name = "Time (Ma)") +
# Remove x-axis guide and title
scale_x_continuous(NULL, guide = NULL) +
# Choose theme and font size
theme_classic(base_size = 14) +
# Make tick labels black and increase legend key size
theme(axis.text.y = element_text(color = "black"),
      legend.key.size = unit(1.2, 'cm'))
```

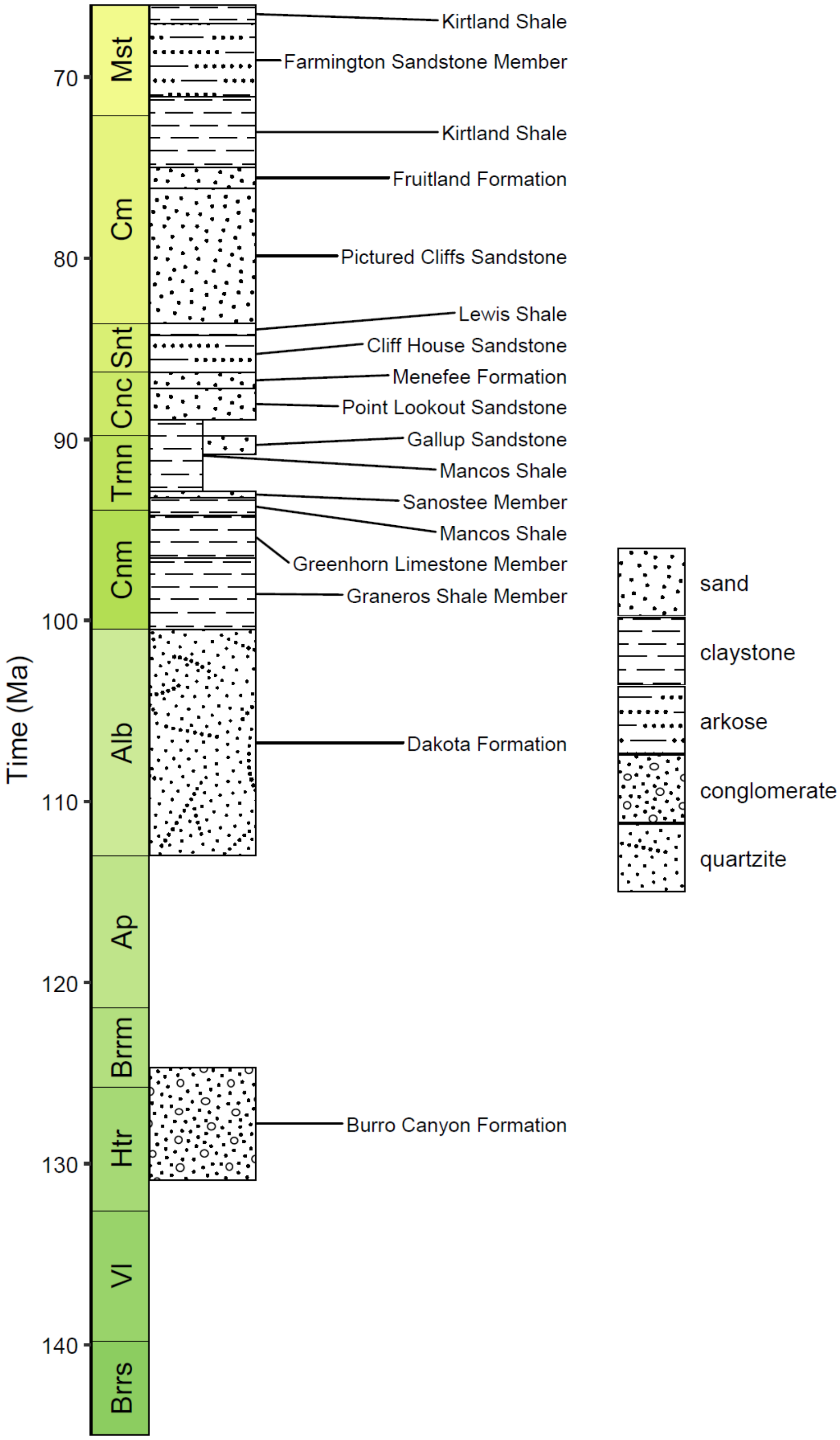

Figure 4: A stratigraphic column of Cretaceous lithostratigraphic units from the San Juan Basin, USA. The pattern fills indicate the primary lithologies of the units as reported by the Macrostrat API (Peters et al., 2018) via the *rmacrostrat* R package (Jones et al., 2024).

5. RESOURCES AND FUTURE DEVELOPMENT

The above examples are merely a subset of the functional possibilities of the *deeptime* R package. Complete documentation for all functions is bundled with the package and is also available on the package website (https://williamgearty.com/deeptime). I have also developed several vignettes/tutorials that provide walkthroughs on how to develop complex visualizations using many of the functions within the package. These vignettes are also bundled with the package and available on the package website (https://williamgearty.com/deeptime/articles/). Users are strongly encouraged to file issues, bugs, and feature requests via GitHub (https://github.com/willgearty/deeptime/issues), and contributions from users and other developers are strongly encouraged.

Given the developmental inertia within the R community, the future of visualization in the Geosciences is bright. However, gaps in the visualization toolbox remain, and I plan to continue to add features to *deeptime* into the foreseeable future to help fill these gaps. Future planned features for the *deeptime* package include additional customization options, built-in themes for commonly used theme settings, further integration with other packages such as *palaeoverse* and *rmacrostrat* (Jones et al., 2023, 2024). Further, I plan to ensure that the package maintains clean interoperability with other packages, especially those in the Palaeoverse ecosystem (Jones et al., 2023). Finally, the *ggplot2* package often has rapid and dramatic development cycles, and I plan to ensure that *deeptime* continues to work smoothly with *ggplot2*.

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CODE AVAILABILITY

Name of the code/library: *deeptime*

Contact: willgearty@gmail.com, 001-781-414-6059

Hardware requirements: Hardware requirements: PC with at least 2 GB of RAM, supporting Unix, MacOS or Windows operating systems.

License type: GPL-3.0

Program language: R

Software required: R, version 3.4

Program size: 2,899 KB

All source code for the *deeptime* package is available on GitHub (https://github.com/willgearty/deeptime/) and archived on Zenodo (https://zenodo.org/badge/latestdoi/152502088). The package is also available on CRAN. See https://cran.r-project.org/package=deeptime.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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