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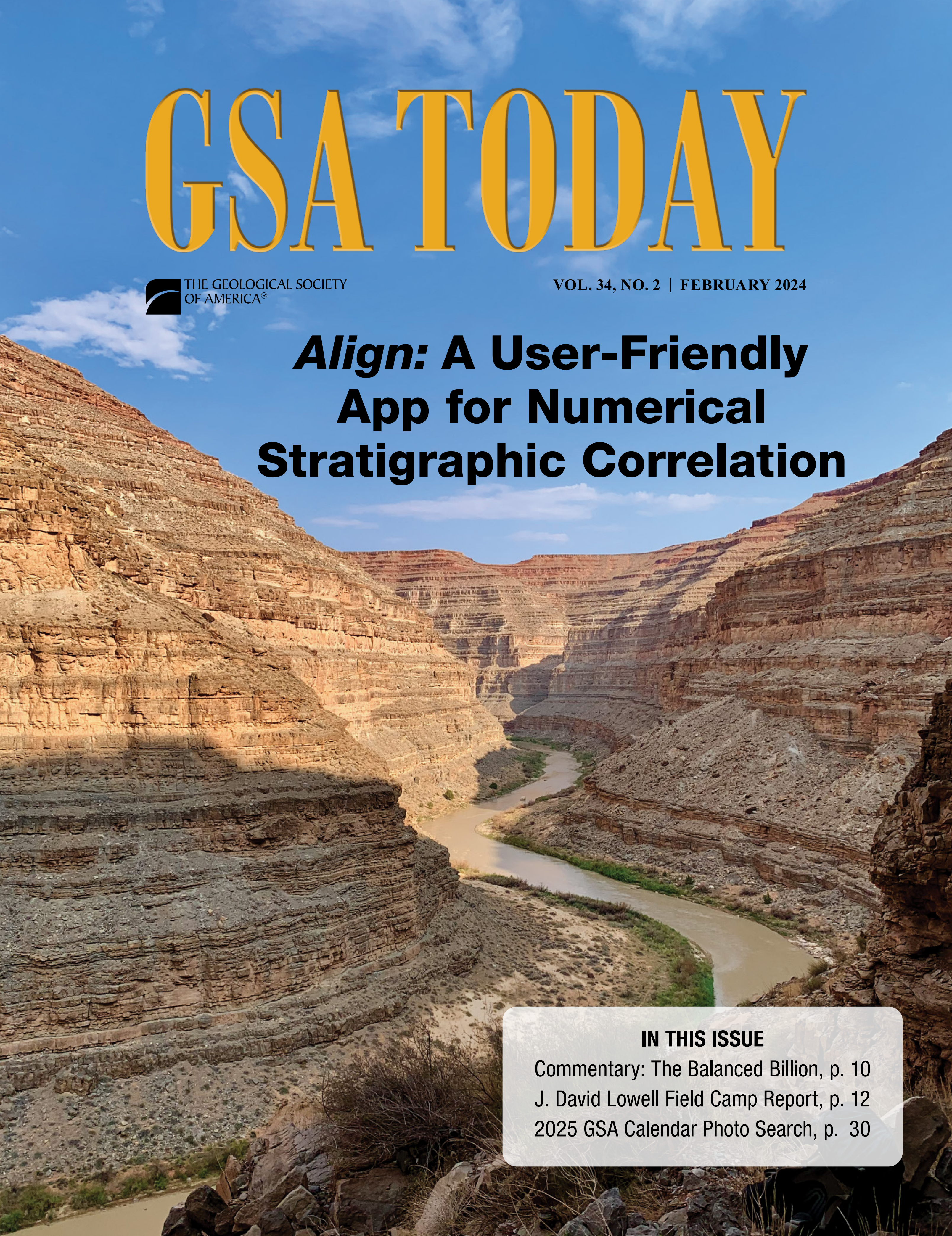
Align: A User-Friendly App for Numerical Stratigraphic Correlation



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Cover: Carboniferous strata of the Paradox and Honaker Trail formations in a canyon carved by the San Juan River. Photo taken west of Goosenecks State Park in Utah, USA, by Cedric Hagen. See related article on pages 4–9.

SCIENCE

GSA NEWS

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Align: A User-Friendly App for Numerical Stratigraphic Correlation

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ABSTRACT

Stratigraphic correlation underpins all understanding of Earth's history, yet few geoscientists have access to, or expertise in, numerical codes that can generate reproducible, optimal (in a least-squares framework) alignments between two stratigraphic time-series data sets. Here we introduce *Align,* a user-friendly computer app that makes accessible a published dynamic time warping (DTW) algorithm that, in a minute or less, catalogs a library of alignments between two time-series data sets by systematically exploring assumptions about the temporal overlap and relative sedimentation rates between the two stratigraphic sections. The *Align* app, written in the free, open-source R programming language, utilizes a graphical user interface (e.g., drop-down menus for data upload and sliding bars for parameter exploration) such that no coding is required. In addition to generating alignment libraries, a user can employ *Align* to visualize, explore, and cull each alignment library according to thresholds on Pearson's correlation coefficient and/or temporal overlap. Here we demonstrate *Align* with time-series records of carbonate stable carbon isotope composition, though *Align* can, in principle, align any two quantitative stratigraphic time-series data sets.

INTRODUCTION

Since William Smith's iconic geological map of England and Wales in 1815 (Sharpe, 2015), stratigraphic correlation has become the integral method to decipher and contextualize Earth's history. Stratigraphic correlation is now facilitated by sophisticated ancillary measurements of sedimentary rocks, including stable isotope composition (e.g., McKinney et al., 1950; Knoll et al., 1986), trace element concentration (e.g., Veizer and Compston, 1974; Elderfield, 1986), and properties such as gamma-ray spectrometry (e.g., Chamberlain, 1984; Cowan and Myers, 1988) and magnetostratigraphy (e.g., Opdyke, 1972; Løvlie, 1989). Computational advances have led to quantitative tools for time-series analysis of these ancillary measurements (e.g., Agterberg and Gradstein, 1988; Tipper, 1988), including software for the correlation of biostratigraphic (e.g., Kemple et al., 1995; Sadler, 2004; Sadler et al., 2009), paleomagnetic (e.g., Clark, 1985; Hagen et al., 2020), lithostratigraphic (e.g., Lewis et al., 2011), cyclostratigraphic (e.g., Meyers, 2014; Li et al., 2019), ice core (e.g., Bay et al., 2010; Hagen and Harper, 2023), and chemostratigraphic data (e.g., Lisiecki and Lisiecki, 2002; Hay et al., 2019). Many of these correlation tools utilize dynamic time warping (DTW), an objective, time normalization algorithm that achieves least-squares alignments between two time-series. These alignments are subject to penalties on the insertion of hiatuses that stretch and squeeze the stratigraphic height/time axis (hence the colloquial term "dynamic time warping"; Sakoe and Chiba, 1978). For two geoscience examples, Lisiecki and Raymo (2005) adopted the Match algorithm of Lisiecki and Lisiecki (2002) to generate the canonical "LR04" stack of 57 Pliocene–Pleistocene benthic oxygen isotope records (although, in this case, manual adjustments were made after applying the algorithm), and the well-resolved Ordovician and Silurian time scales arose from dynamic programming-based constrained optimization (CONOP) for the temporal sequencing (or "slotting") of graptolite first/last appearance datums (Sadler, 2004; Sadler and Cooper, 2008).

Despite the ubiquitous application of chemostratigraphy for stratigraphic correlation across the geological time scale, and this rich archive of algorithms, the stratigraphy community lacks an open-source code for a free programming environment to facilitate quantitative chemostratigraphic alignment that is operable by users without prior coding experience. Here we present *Align* (Fig. 1), a new free and open-source computer app that utilizes the DTW algorithm of Hay et al. (2019). *Align* is available to download from the GitHub data repository[1] and was written in R v.4.2.2 (R Core Team, 2022) using the *Shiny* open-source package (Chang et al., 2017). *Align* utilizes the Hay et al. (2019) DTW algorithm (originally written in MATLAB), rewritten in R to run seamlessly with the app (Hagen, 2023). We chose to make the DTW algorithm of Hay et al. (2019) accessible for three reasons. First, this routine efficiently aligns every individual data point, rather than blocks of data (as the Match algorithm does). Second, the code generates a library of optimal alignments (in a least-squares sense) between two univariate stratigraphic time-series data sets. These alignments are subject to systematic assumptions about the total temporal overlap between the two time-series and the extent to which they can be stretched or squeezed ("time-warped")

[1]The *Align* code archive, which includes detailed documentation and three separate example data sets, is included in the data repository on GitHub: https://github.com/CedricHagen/Align. The R version of the Hay et al. (2019) algorithm is freely available through CRAN: https://cran.r-project.org/package=align.

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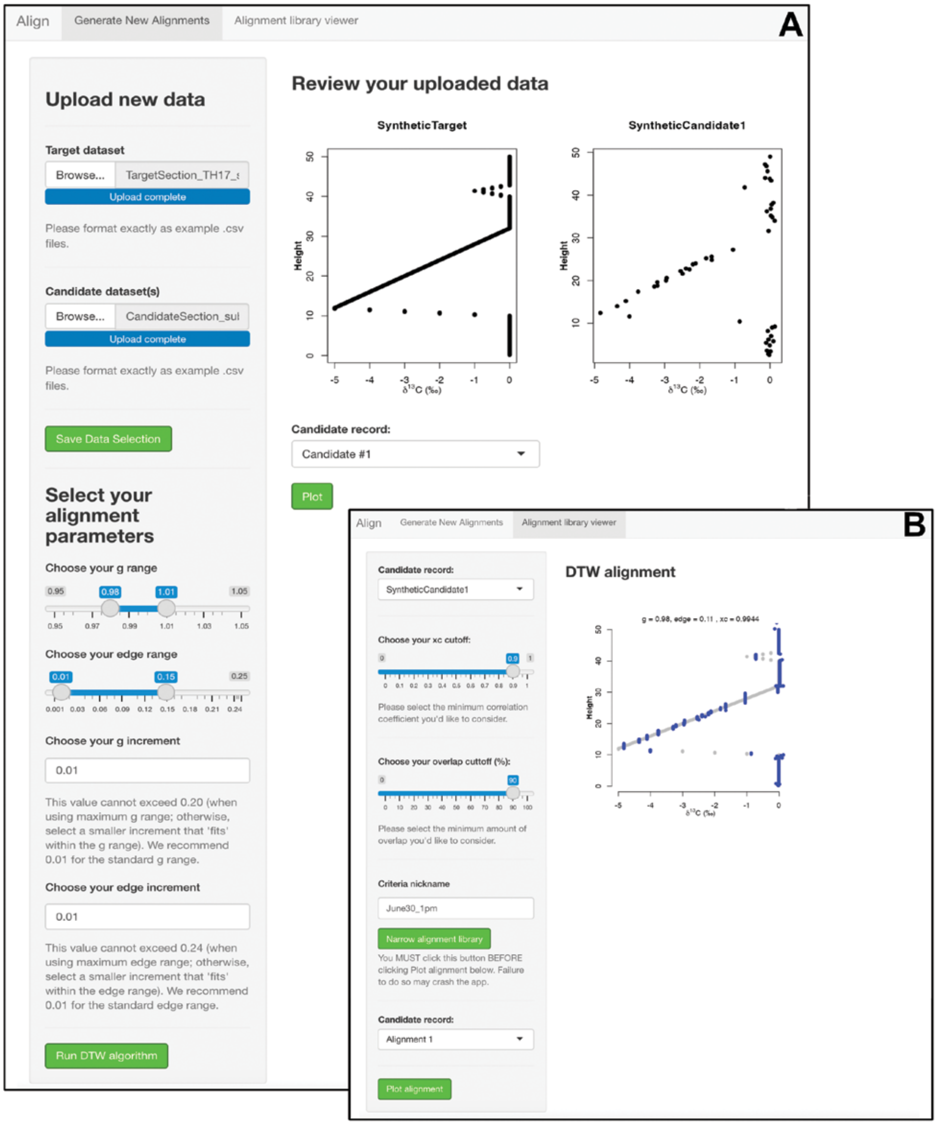

Figure 1. The *Align* app for stratigraphic time-series alignment. (A) A screenshot of the *Align* graphical user interface (tab 1) where menus (on left) prompt the user to upload, plot, and align a target and a candidate time-series data set using the underlying dynamic time-warping (DTW) algorithm. The example target data set "Synthetic TH17" (adopted from Trampush and Hajek, 2017) and candidate data set "Noisy subsample" (see GitHub repository [text footnote 1]) are plotted with a click button (on right) to visually confirm accurate data upload. (B) A screenshot of the *Align* culling interface (tab 2) where sliding scales (on left) allow a user to narrow the resulting alignment libraries by the Pearson correlation coefficient ("xc cutoff") and/or overlap percent cutoffs. The example criteria (xc cutoff = 0.9; overlap cutoff = 90%) narrow the full library of 60 alignments down to nine alignments. The user can use a drop-down menu to plot one of these alignments at a time (on right).

to align with one another (see mathematical description below). This type of analysis is impossible to achieve with the human eye. Third, the code can be applied to any numerical (though not categorical) stratigraphic time-series data set (see GitHub repository for a description of how to upload and review data with *Align*). The *Align* interface utilizes intuitive design features such as drop-down menus, slider control elements, and toggle buttons for the execution of the underlying DTW code without any coding. Here we present a guide for applying the *Align* app to time-uncertain chemostratigraphic correlation by demonstrating the alignment of stable carbon isotope data from carbonate rocks ($\delta^{13}C_{carb}$). We provide a description of the underlying mathematics of DTW.

UPLOADING, VIEWING, STORING, AND CULLING THE LIBRARY OF STRATIGRAPHIC ALIGNMENTS

The *Align* interface allows a user to upload spreadsheets of up to three univariate candidate time-series data sets and a single univariate target time-series data set against which to align the candidate(s) (formatting details are in the *Align* documentation on GitHub). Figure 1 illustrates how the algorithm aligns a synthetic $\delta^{13}C_{carb}$ data set with a –5‰ excursion followed by a –1‰ excursion, both from a background value of 0‰ (Fig. 1A, target; from Trampush and Hajek [2017]), and a synthetic $\delta^{13}C_{carb}$ data set made by randomly subsampling the target (at 20% completeness) and adding noise (Fig. 1A, candidate) to represent a realistic record that a stratigrapher might correlate. A button generates a plot of the uploaded $\delta^{13}C_{carb}$ time-series records to verify accurate data upload and to cache necessary files for the DTW algorithm (Fig. 1A). At this stage, the user slides bars to set the range of *edge* and *g* values (which control the temporal overlap and relative accumulation rate, respectively, as discussed below) that determine the size of the alignment library (# of alignments = # of *edge* values × # of *g* values). After plotting verification, the user clicks the "Run DTW algorithm" button to command the underlying R code to generate the alignment library.

The *Align* app allows the user to vary the *g* and *edge* parameter in any continuous range between 0.95 and 1.05 and 0.01 and 0.25, respectively, with any increment; following Hay et al. (2019), the default *g* value range is set to 0.98–1.01 and the default *edge* value range is set to 0.01–0.15, both in increments of 0.01. As the underlying code runs through the default parameter space, it generates 60 alignments (60 *g*-*edge* pairings for each candidate-target time-series correlation), which are visually presented as x-y scatterplots of $\delta^{13}C_{carb}$-stratigraphic height (Fig. 1B) and corresponding spreadsheets containing the meterage that every candidate time-series $\delta^{13}C_{carb}$ value was aligned to on the target time-series (i.e., the y-axis values for the aligned candidate). A different parameter range and increment will change the number of alignments in the alignment library, and the associated output images/files (see GitHub repository for additional discussion about *g* and *edge* values, as well as hiatal surfaces and data types). Output files are saved to the user's computer in a folder named Output with sub-directories named for the candidate-target alignment pair. Each alignment can be viewed in the underlying Output_Images folder (or plotted in an external application using the .csv files in the underlying Output_Data folder). A subset of output alignments can be viewed in the separate alignment library viewer tab (Fig. 1B).

When a stratigrapher wants to focus on a subset of alignments that adhere to a shared criterion, a separate tab in the *Align* app gives the user the option to manually sort (and narrow) the alignment library according to thresholds for the Pearson's correlation coefficient and the overlap between the aligned time-series (Fig. 1B). Figure 1B shows the *Align* interface for culling an alignment library, here displayed to cull the alignment library to show only those alignments with a Pearson correlation coefficient ≥0.9 ("xc cutoff") and an overlap of the candidate to the target of ≥90% ("overlap cutoff"). When the user clicks the "Narrow Alignment Library" button (Fig. 1B), *Align* saves those alignments that adhere to the cutoff criteria (a "culled library") in a new folder named for the user's inputted name for these culling criteria (e.g., 0.9,90%). For this scenario, the culled alignment library includes nine of the original 60 alignments (the culled alignments can be viewed independently by selecting their name in the drop-down menu; Fig. 1B).

Relative temporal constraints on stratigraphic sections (e.g., biostratigraphy, lithostratigraphic markers, etc.) can be used in conjunction with the time-series data to evaluate an alignment library. For one, the user can restrict the target/candidate time-series to a certain biozone or lithostratigraphic unit (effectively aligning $\delta^{13}C_{carb}$ data presumed to be temporally equivalent). Alternatively, these constraints can be used to evaluate the alignment libraries post analysis.

HOW DYNAMIC TIME WARPING PRODUCES A LIBRARY OF STRATIGRAPHIC ALIGNMENTS

Figure 2 illustrates a simple stratigraphic correlation using DTW with two short, synthetic carbon isotope ($\delta^{13}C_{carb}$) time-series: a seven-sample target sequence composed of a 3.5‰ $\delta^{13}C_{carb}$ excursion over 6 m of stratigraphy (Fig. 2H) and a four-sample candidate sequence with a 4.5‰ excursion over 3 m (Fig. 2H). First, target (Figs. 1A and 2A) and candidate (Figs. 1A and 2B) matrices are constructed whose number of rows ($n = 7$) and columns ($m = 4$) equal the length of the target and candidate $\delta^{13}C_{carb}$ sequences, respectively. The seven $\delta^{13}C_{carb}$ values from the target section fill target matrix column 1 (Fig. 2A, red column) and are replicated m-1 times to fill all remaining columns. The four $\delta^{13}C_{carb}$ values from the candidate section are transposed to fill candidate matrix row 1 and replicated n-1 times to fill the remaining rows (Fig. 2B). The next step is to construct an n-by-m matrix of all of the possible $\delta^{13}C_{carb}$ pairings from the target and candidate sequences. Each matrix element is computed as the difference between an index in the target (tn) and the candidate (cm) sequences: $C(n,m) = (tn - cm$; Fig. 2C) and squared to give a squared-difference matrix (Fig. 2D; Sakoe and Chiba, 1978). Comparison of the 3‰ excursion peak in the target (Fig. 2A, row 4) and candidate sequences (Fig. 2B, column 2) gives a strong constraint because it alone gives a squared difference of 0 (Fig. 2D, cell (4,2)).

An alignment takes the form of a "warping path" that assigns each candidate index m to an index n of the target sequence by minimizing the sum of the squared differences ("cost") across all m (Sakoe and Chiba, 1978). This path is achieved through successive diagonal, horizontal, and vertical steps across the squared-difference matrix, each of which implies a bed-to-bed alignment (Hay et al., 2019). A warping path that begins in the lower-right corner of the squared-difference matrix (Fig. 2D, cell (7,4)) implies that the stratigraphically highest $\delta^{13}C_{carb}$ value from both the target and candidate sections are time equivalent. A warping path that exits the upper-left corner of the squared-difference matrix (Fig. 2D, cell (1,1)) aligns the lowermost values of the two sequences, implying that accumulation began concurrently at both sections. Thus, a warping path that enters and exits both corners of the squared-difference matrix indicates that sediment accumulation at the two sections spans the same interval of geological time. In contrast, when a warping path meets an edge of the squared-difference matrix, this implies that the two sections do not span the same total temporal duration.

Once the warping path enters the matrix, the DTW algorithm objectively finds an optimal pathway in terms of a sequence of diagonal, vertical, and horizontal steps that minimize the associated sum of squared residuals. A diagonal step implies an equivalent rate of *relative* sediment accumulation between the candidate and target time-series. A vertical or horizontal step instead inserts a hiatus in deposition at the candidate or target sections, respectively.

When aligning $\delta^{13}C_{carb}$ sequences, stratigraphers have little or no *a priori* information about the total temporal overlap with the target section, nor the relative rates of sediment accumulation between target and candidate sections. To address these uncertainties, the algorithm explores various optimal warping paths across the squared-difference matrix (e.g., Fig. 2G) conditional on the systematic application of the *edge* and *g* penalty functions (see below) that alter the values of the squared-difference matrix (Fig. 2D) and thereby favor specific stratal pairings.

The *edge* penalty function explores whether the two sequences span the same total interval of time and is so named because the right and bottom squared-difference matrix edges align the stratigraphically highest (youngest) target and candidate $\delta^{13}C_{carb}$ values whereas the left and top edges align the lowest (oldest) $\delta^{13}C_{carb}$ values. The *edge* value is a coefficient that modifies all squared-difference matrix edge cells in clockwise fashion, beginning with the first row and ending with the first column (Fig. 2E; yellow ellipsoids). *Edge* values >1 increase the value of the squared difference for a specific stratal pairing, discouraging their alignment, whereas when $0 < edge < 1$, stratal pairings are encouraged. For example, an (arbitrarily adopted) *edge* value of 0.1 modifies squared-difference matrix element (3,4) = 9 (Fig. 2D) to the lower value of 0.9 (Fig. 2E, cell (3,4)). In this formulation, matrix corners are modified twice (once per edge; see Fig. 2E, cell (1,1)). While Figure 2 illustrates the adoption of a *single* (arbitrary) edge value (edge = 0.1; Fig. 2E), in practice the DTW algorithm systematically varies *edge* values across a user-identified range to discover alternative start/end cells for warping pathways, generating multiple $\delta^{13}C_{carb}$ alignments.

The *g* penalty function is useful for enforcing various levels of similarity of sediment accumulation rate(s) at the two stratigraphic sections throughout their shared deposition history using a range of *g* values. Values of $g > 1$ penalize stretching or squeezing by increasing the augmented cost of all off-diagonal matrix cells, and the opposite is true for $g < 1$; a *g*-value equal to 1 does not augment the cost matrix. For this illustration, we adopt $g = 1$. First, *edge*-modified matrix cell (1,1; Fig. 2E) is replicated to fill the corresponding cell of the cumulative difference matrix (CDM; Fig. 2F). Next, moving right across CDM row 1, every cell value is computed as the sum of values of the corresponding *edge*-modified matrix cell plus all preceding *edge*-modified matrix cells in the row (Fig. 2F;

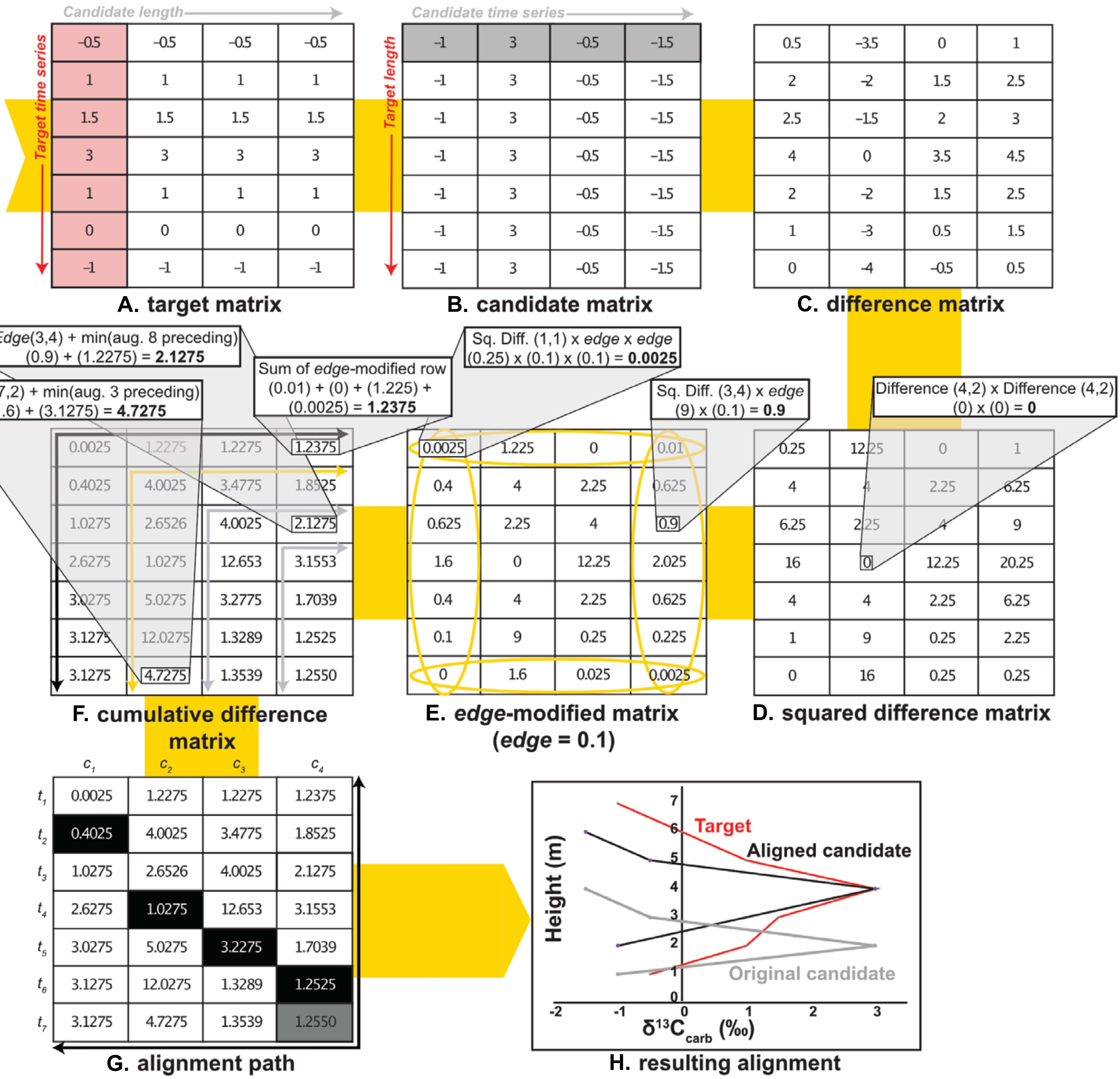

Figure 2. Illustration of the dynamic time warping technique for aligning simple, synthetic $\delta^{13}C_{carb}$ sequences. (A–G) Step-by-step matrix operations to align the two synthetic $\delta^{13}C_{carb}$ sequences (target, original candidate) shown in frame (H). The target and original candidate $\delta^{13}C_{carb}$ sequences populate the columns and rows of the target (A) and candidate (B) matrices, respectively; subtracting the candidate matrix from the target matrix yields the difference matrix (C). Squaring the values in the difference matrix generates the squared-difference matrix (D), a measure of the similarity of all pairs of $\delta^{13}C_{carb}$ from the target and candidate sections. Multiplying the edges of the squared-difference matrix by the adopted value of the *edge* parameter yields the *edge*-modified matrix (E). The cumulative difference matrix (F) incorporates the accumulation of cost arising from the adopted value of the *g* parameter. The alignment path, which reveals the temporally equivalent target and candidate strata/$\delta^{13}C_{carb}$ values, begins in the lower right corner of the cumulative difference matrix and proceeds to the lowest cost cell looking two steps ahead (G). For these synthetic data, the alignment path shifts the aligned candidate section stratigraphically higher on the target sequence relative to the original candidate meterage (H). Abbreviations: Difference = the difference matrix; Sq. Diff. = the squared-difference matrix; min (aug. 8 preceding) = the minimum value of the eight preceding cumulative difference matrix cells; *Edge* = the edge-modified matrix.

horizontal black arrow). For example, CDM (1,4; Fig. 2F) is calculated as the sum of *edge*-modified matrix (1,4), (1,3), (1,2), and (1,1), equal to 0.01, 0, 1.225, and 0.0025, respectively, or 1.2375 (Fig. 2F). This process is repeated vertically for CDM column 1, summing down the column (Fig. 2F; vertical black arrow).

Next, the algorithm calculates the accumulation of cost in each unfilled cell of row 2 and in each unfilled cell of column 2 (Fig. 2F; yellow arrows). These values are computed as the sum of the value in the corresponding *edge*-modified matrix cell (Fig. 2E) and the minimum value of the three preceding *g*-modified cells of the CDM computed as: *g**(*n*, *m*-1), (*n*-1, *m*-1), and *g**(*n*-1, *m*) (Fig. 2F; note that three preceding cells are considered only for cell calculations in row 2 and column 2, whereas cell calculations in all subsequent rows and columns consider eight preceding cells). For example, the algorithm computes CDM cell (7,2) as the sum of *edge*-modified matrix (7,2) = 1.6 (Fig. 2E) and the minimum of the three preceding CDM cells, in this case element (6,1) = 3.1275, yielding 4.7275 (Fig. 2F). Figure 2 adopts $g = 1$ for mathematical ease; had we adopted any $g \neq 1$, this selection would have modified cell (7,1)—calculated as *g**(*n*, *m*-1)—to be a value less than cell (6,1)—unmodified by *g* based on its diagonal position—and thereby changed the final value for CDM cell (7,2). Like the *edge* parameter, the DTW algorithm systematically varies *g* values across a user-defined range to discover alternative warping paths between given start/end cells.

To complete the CDM, the algorithm fills the remaining empty cells in rows 3–7 and columns 3–4 (Fig. 2F; gray arrows). These calculations proceed by summing the corresponding *edge*-modified matrix value and the minimum value of the *eight* preceding CDM cells (looking two steps forward is preferred, considering the eight preceding cells, but this is not possible in row 2 and column 2 due to the dimensions of the matrix and there being no 0th row or column, hence the consideration of only three preceding cells representing one step forward in row 2 and column 2). The CDM cells are modified by *g* as follows: (*n*-1, *m*) and (*n*, *m*-1) are multiplied by *g*; (*n*-1, *m*-2) and (*n*-2, *m*-1) are multiplied by 1.05**g*; (*n*-2, *m*) and (*n*, *m*-2) are multiplied by 1.1**g* (Fig. 2F). Diagonal preceding cells (*n*-1, *m*-1) and (*n*-2, *m*-2) are not modified by *g*. For example, CDM cell (3,4) is computed as *edge*-modified matrix (3,4) = 0.9 (Fig. 2E) plus CDM (1,2) = 1.2275 (because this cell has the minimum value of the eight preceding cells in the CDM: (3,2), (3,3), (2,2), (2,3), (2,4), (1,2), (1,3), and (1,4)), summing to 2.1275 (Fig. 2F).

Every possible pairing of *g* and *edge* values from the input ranges produces a CDM, and the warping path across the CDM begins at the lower-right corner and progressively steps horizontally, diagonally, or vertically (see the illustrative alignment in Fig. 2) to the minimum value of the eight adjacent cells, always looking two steps ahead (Fig. 2G, black cells, with values replicated from Fig. 2F). For each CDM, the corresponding $\delta^{13}C_{carb}$ alignment begins with the stratigraphically lowest cell of the starting edge (the right column or bottom row)—here cell (6,4; Fig. 2G)—and terminates upon meeting an end edge (the left column/top row), here cell (2,1). Note when the algorithm encounters equivalent values, such as cells (6,1) and (7,1), the diagonal is adopted to maximize temporal correspondence by minimizing the insertion of hiatuses. For the adopted *edge* and *g* parameter values, the warping path specifies the *globally* optimal alignment of each $\delta^{13}C_{carb}$ value of the candidate sequence with the target sequence (black cells), with empty rows representing target $\delta^{13}C_{carb}$ values with no time-equivalent at the candidate section (an imposed hiatus). Figure 2H visualizes the target-candidate $\delta^{13}C_{carb}$ alignment arising from the alignment path in Figure 2G (i.e., for *edge* and *g* values of 0.1 and 1, respectively). By repeating this process for a range of *edge* and *g* values, the algorithm systematically generates alignments that encapsulate a spectrum of assumptions about the shared temporal history (via *edge*) and relative rates of sediment accumulation (via *g*) at the target and candidate stratigraphic sections (see Hay et al., 2019). A different pairing of *edge* and *g* values can produce a visually distinct alignment from that shown in Figure 2H (e.g., choosing a *g* value greater than 1, which encourages dissimilar relative sedimentation rates, could increase the overlap of the shoulders of the synthetic excursion). Together, we present the objective alignments arising from all *edge* and *g* pairings as a correlation library for further parsing by statistical analyses and geological insight (see GitHub repository for a brief discussion of computation time and dynamic programming).

SUMMARY

The user-friendly *Align* app makes freely available the proven DTW algorithm for objective, reproducible, and optimal stratigraphic time-series correlation (Hay et al., 2019) to anyone conducting stratigraphic research by eliminating the need for command-line coding. The *Align* app efficiently (~1 minute run time) and systematically generates a library of stratigraphic alignments for the stratigrapher to evaluate, a task otherwise impossible with the human eye. *Align* allows the user to cull an alignment library and saves all outputs in common file formats easily read into figure-design software, making *Align* a powerful new stratigraphy research tool. We welcome collaborations to incorporate additional features into *Align* to grow the capacity of this community tool.

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COMMENTARY

The Balanced Billion

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A mid-Proterozoic stretch of Earth's history (roughly 1.8–0.8 Ga) has been called, non-affectionately, the "boring billion." The moniker was first inspired several decades ago by the apparent absence of any significant carbon isotope anomalies and was linked to the relatively dull interval between Earth's broadly two-step pattern in atmospheric oxygenation (Brasier and Lindsay, 1998; Holland, 2006). Other data sets from Earth's surficial environment during this time have been shown to be equally peculiar, including the disappearance of iron formation, notable absences of any large oxygenation events, phosphorites, or glacial and manganese deposits (Hoffman et al., 2017; Holland, 2006; Planavsky, 2014), and a billion-year lag between the oldest known Paleoproterozoic eukaryote fossils versus pronounced mid-Neoproterozoic eukaryotic diversity and ecological importance (Knoll and Nowak, 2017).

Oddities of this billion years (Fig. 1) come not only from records of surface evolution and palaeoenvironment but also from the solid Earth, including metamorphic style (a paucity of high-pressure conditions; Brown and Johnson, 2019) and either absences (ophiolites) or abundances (anorthosites) of specific igneous rock suites (Roberts et al., 2022). Recently, the mid-Proterozoic anomaly has even been suggested to be expressed as deep as mantle convection and as far flung as the Earth–Moon system, with the billion years suggested to respectively represent the transition from bottom-up to top-down mantle convection (Mitchell et al., 2022) and a remarkable flat-lining of Earth's rotational history at a constant ~19 h per day (Mitchell and Kirscher, 2023). Anomalies can be recognized as deep as Earth's core, because measured palaeomagnetic inclinations (which convert to palaeolatitude assuming a geomagnetic field model) deviate significantly from the expectation of a geocentric axial dipole (Veikkolainen and Pesonen, 2021).

In direct contrast to an eon of ennui, Earth's mid-Proterozoic tectonic record is anything but stagnant. The Grenvillian super-orogen is globally widespread (Condie, 2021) and anomalously deeply eroded (Liu et al., 2017). Regardless of whether individual components of that orogenic system involve collisions between continents during Rodinia assembly (Fig. 2) or are produced by long-lived tectonic accretion (e.g., Slagstad et al., 2018), the attractive temporal correlations between silicate rock weathering and paleoclimate variability in Phanerozoic time (Macdonald et al., 2019) might predict profound atmospheric CO_2 drawdown and glaciation during the Grenvillian interval at ca. 1000 Ma, as well as changes to atmospheric oxygen from pyrite weathering and burial. Instead, climatic stability through the Meso-Neoproterozoic transition highlights the important geochemical flux balances and restorative feedbacks that must have existed around the rock cycle encompassing magmatism, weathering, sedimentation, and metamorphism. Profound and rapid changes in Rodinia's paleolatitude (Evans, 2021) could contribute to repetitive episodic activation of such feedbacks.

In light of (1) the original evidence coming from a relatively stable carbon cycle, (2) the souring over

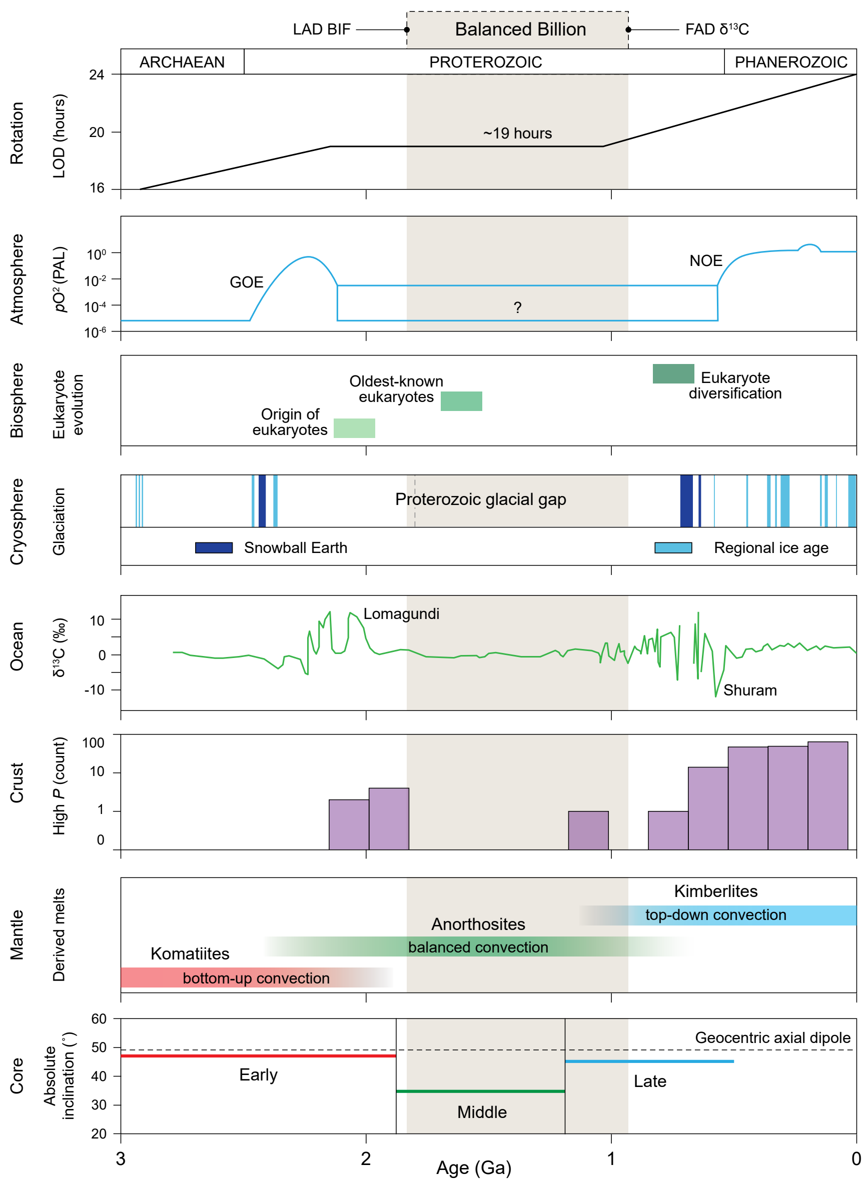

Figure 1. Proxy records from Earth's layers exhibit important idiosyncrasies during mid-Proterozoic time. LAD BIF = last appearance datum banded iron formation; FAD δ13C = first appearance datum of significant carbon isotope excursions; LOD = length of day; GOE = Great Oxidation Event; NOE = Neoproterozoic Oxidation Event. These are proposed lower/upper chronostratigraphic boundaries of the Balanced Billion. See text for data sources.

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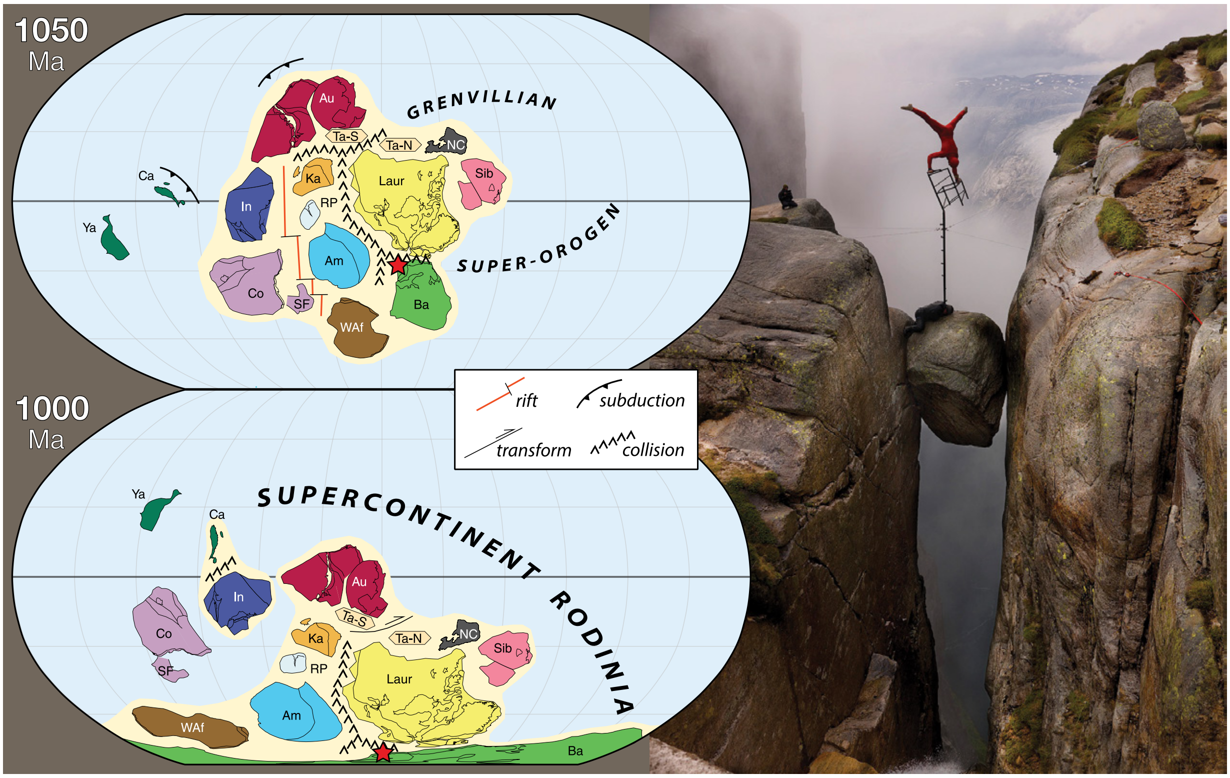

Figure 2. Left: Late Mesoproterozoic Grenvillian super-orogen, which consolidated the Rodinia supercontinent, represents a key component of the Earth-system balancing act required to maintain environmental stability at ca. 1000 Ma. Cratonic reconstructions from Evans (2021); Am = Amazonia, Au = Australia including Antarctic Mawsonland, Ba = Baltica, Ca = Cathaysia, Co = Congo, In = India, Ka = Kalahari, Laur = Laurentia, NC = North China, RP = Rio Plata, SF = São Francisco, Sib = Siberia, Ta-N = Tarim-North, Ta-S = Tarim-South, WAf = West African craton, Ya = Yangtze. Right: Kjeragbolten rock from the Sirdal Magmatic Complex in the Sveconorwegian orogen (Slagstad et al., 2018), denoted by a star in each reconstruction, epitomizes this delicate balance. Photo gratefully used with permission from Balance Eskil Rønningsbakken / Sindre Lundvold (https://www.kompanibliss.no/eskilbalance).

time of the unflattering term "boring billion," and (3) more recent additional clues coming from the deep Earth, we suggest a rebranding of the 1.8–0.8 Ga interval to the "Balanced Billion." The first benefit of this change is that it circumvents the subjectivity of what is "boring" as well as the strawman argument used repeatedly in the literature and news media when a new discovery overturns the concept of dullness. The second, more important benefit of this renaming is that it may inspire better recognition and quantification of mid-Proterozoic Earth system feedbacks—not only in the balanced paleoenvironment, but also in balanced mantle convection and a constant daylength due to balanced solar and lunar tidal torques. Whether these variegated processes are directly related is a frontier for understanding the interconnectedness of the deep-time Earth system and may lead to a better understanding of the long-delayed fuse in the rise of animals. Finally, as modern climate change trends toward increasing extremes (hotter/colder and drier/wetter), unlocking the secrets to the Balanced Billion may help society devise geoengineering solutions that mimic a time when Earth was more measured in its global change.

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J. David Lowell Field Camp Scholarship Award Bolsters Student's Confidence

Alexandria at Oklahoma State University's Les Huston Geology Field Camp.

As I embarked for field camp, I had no idea how the experience would affect me. I had been planning for months in anticipation of, essentially, the unknown. I knew the change in altitude would be a challenge to contend with, but that was not the only issue causing me apprehension. I left my little boy with family members, knowing that it would be five weeks before I could see him again.

As a single mother, the expense of field camp was a major issue that I had to factor into my education, whether I wanted to or not. After attending the GSA South-Central Section Meeting in March, I discovered that I could apply for a field camp scholarship from GSA. When I was awarded the scholarship, I felt a rush of honor and relief, as this meant that most of the cost of field camp would be taken care of. As an unknown bonus, I was also awarded a brand-new engraved Brunton Standard Transit.

"I feel confident knowing that the skills I gained at field camp will continue to serve me as I continue to grow as a geologist."

When I arrived at Oklahoma State University's Les Huston Geology Field Camp outside of Cañon City, Colorado, I knew that I was equipped to tackle whatever field camp could throw at me. Five weeks of taking strikes and dips, mapping, hiking, and scrambling up steep slopes challenged me, but knowing that I had the support of my professors back home, my little boy, and now GSA, allowed me to embrace my capability in the field.

Field work is so important for geologists, and now I know that I am fully prepared to face the next step as a geologist. I think that field camp put me into the least ideal situations that I could face as a working geologist: immense heat, lightning storms on the side of a mountain, and pouring rain that further destabilized already-unstable slopes. I feel confident knowing that the skills I gained at field camp will continue to serve me as I continue to grow as a geologist.

Since field camp, I have graduated with a Bachelor of Science degree in geology from Arkansas Tech University and I have earned the title of Geologist-In-Training from the Association of State Boards of Geology. My exceptional professors at ATU and my rigorously rewarding experience at OSU's field camp have given me the confidence to continue my education at the Boone Pickens School of Geology at Oklahoma State University for my Master of Science degree in geology. I am so grateful for GSA and its support of students that want to attend field camp. It is an honor to be recognized for my efforts and have my education bolstered by this uplifting scientific Society.

Alexandria Bradley
2023 J. David Lowell Field Camp Scholar
Arkansas Tech University, Class of 2023

Insung Jeon/Moment via Getty Images

The 37th International Geological Conference (IGC) Mentoring and Travel Grant Program

BEXCO, Busan, South Korea | 25–31 Aug. 2024

GSA, the GSA Foundation, and the U.S. National Committee for Geological Sciences (of the National Academy of Sciences) are accepting applications for their Mentoring and Travel Grant Program to the 37th International Geological Conference (IGC) in Busan, South Korea.

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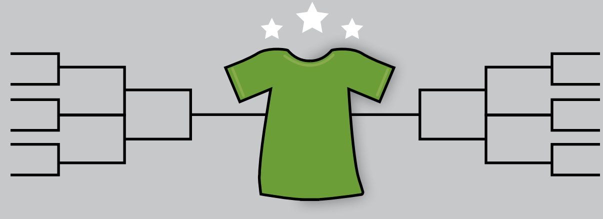

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Penrose CONFERENCE

The Role of Outburst Floods in Earth and Planetary Evolution

5–9 June 2023 | Camp Delany, Coulee City, Washington, USA

CONVENERS

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ATTENDEES

Pablo Iribarren Anacona, Victor Baker, Juan Ballesteros, Emily Bamber, Eric Barefoot, Gerardo Benito, Nathaniel Bergman, Sebastien Bertrand, Bruce Bjornstad, Annie Borch, Abby Burlingame, Jonathan Burton, Sami Cargill, Paul Carling, Kalpana Chaudhari, John Clague, Neil Coleman, Alan Condron, Kristin Cook, Brenda Covington, Jonas Donnenfield, Adam Emmer, Steve Evans, Caleb Fassett, Małgorzata Frydrych, Daniel Garcia-Castellanos, David George, Alan Gillespie, Timothy Goudge, Gordon Grant, Ralph Haugerud, Juergen Herget, Amanda Hoke, Kyle House, Kate Huntington, Tómas Jóhannesson, Jeff Kargel, Kyoko Kataoka, Oliver Korup, Isaac Larsen, Justin Lawrence, Karin Lehnigk, Jerome Lesemann, Joe Levy, Tao Liu, Lucy Luevano, Natalie Lützow, Dorothy Merritts, Aaron Micallef, Brendan Miller, Susannah Morey, Srinanda Nath, Jim O'Connor, Summer Praetorius, David Puhl, Justin Radford, Martin Roy, Kelly Russell, Rannveig Skoglund, Vijayan Sivaprahasam, Larry Smith, Alex Sodeman, Mike Tilston, Georg Veh, Richard Waitt, Mo Walczak, Huiying Wang, Ping Wang, Sasha Warren, Greta Wells, Matt Westoby, Ian Yuh, Anita Zambrowska

FIELD TRIP LEADERS

Victor Baker, University of Arizona; Isaac Larsen, University of Massachusetts–Amherst; Karin Lehnigk, Georgia Institute of Technology; Jerome Lesemann, Vancouver Island University; Jim O'Connor, U.S. Geological Survey; Richard Waitt, U.S. Geological Survey

OVERVIEW

Outburst floods—those floods caused by the breaching of natural or constructed dams— play a significant role in shaping landscapes, impacting societies, and influencing Earth's systems. The year 2023 marks the centennial anniversary of J Harlen Bretz's first publication on the "Spokane floods" in the "Channeled Scabland," which appeared in the Sept. 1923 issue of *GSA Bulletin* (v. 34, p. 573–608). This paper and several more in the next few years kickstarted research on outburst flood science and set off a decades-long debate about the role of catastrophic floods in landscape evolution. Since then, the field has expanded from its origins in eastern Washington to sites across the globe and on other planets, covering myriad aspects of outburst flood processes and effects.

The Penrose Conference aimed to mark the centennial by examining the past century of outburst flood science and looking ahead to the next 100 years of research. Camp Delany—situated in the Dry Falls cataract plunge pool in the Channeled Scabland—served as an inspiring backdrop for these discussions and an ideal point of departure for field trips. Conference sessions were organized around four themes: (1) the Channeled Scabland and Bretz's "Spokane floods," now known as the Missoula floods from their source in Pleistocene glacial Lake Missoula; (2) outburst floods as a universal process, grouped by geographic region: North and South America; Eurasia; and Mars and other planets; (3) mechanics of outburst flood processes; and (4) broader implications of outburst floods, including modern hazards, landscape evolution, and Earth system impacts. The week produced inspiring discussions on the history

Figure 1. Dry Falls cataract complex and Camp Delany, Washington. Photograph by Bruce Bjornstad.

Figure 2. Group photo of conference attendees. Drone image by Bruce Bjornstad.

of outburst flood science, presented state-of-the-art developments in the field, and identified research gaps and future directions. Of equal importance, it fostered collaborations among the international outburst flood community and facilitated knowledge exchange with residents of this incredible landscape, including members of the Confederated Tribes of the Colville Reservation, the National Park Service, and Washington State Parks.

CONFERENCE DETAILS

The conference took place at Camp Delany, a rustic retreat center within Sun Lakes–Dry Falls Washington State Park near Coulee City, Washington. Camp Delany lies within the plunge pool of the Grand Coulee cataract complex, which was carved by the Missoula floods and provided a stunning setting for discussing outburst flood science (Fig. 1). Numerous attendees commented on the drama of presenting talks and eating meals in the shadow of canyon walls sculpted by outburst floods. The camp offered tent and cabin accommodations, a large meeting room, kitchen facilities, and indoor and outdoor dining areas (and an abundant mosquito population).

The conference included 70 participants (Fig. 2) from institutions in 16 countries on four continents (Fig. 3), as well as three members of the Confederated Tribes of the Colville Reservation. Of the participants, 31% identified as female, 17% as graduate students, and 21% as early career researchers (<10 years post–PhD completion). The conference emphasized student and early career researcher participation by giving extended oral presentation time to students and early career attendees, reserving time for "students first" questions following talks, and organizing a mentoring program by pairing students and early career scientists with more senior scientists to encourage one-on-one conversations on research and professional development.

Discussion took place through a variety of presentation formats:

- Oral presentations (42 talks)
- Poster sessions (24 posters), introduced by lightning talks
- One plenary talk on the history of outburst flood science
- One panel discussion on "Traditional Ecologic Knowledge and Understanding of Outburst Floods" involving seven conference participants: representatives from the Confederated Tribes of the Colville Reservation, National Park Service rangers, and scientists from five countries who discussed Indigenous perspectives on flood landscapes across the world
- Two field trips: a full-day trip to inspect iconic outburst flood landforms in the northwest Channeled Scabland and a half-day trip focused on flood erosion and deposition in Grand Coulee
- Breakout sessions organized by emergent, overarching themes of the week with the goal of charting "the next 100 years of outburst flood science"
- Recreational activities including trivia night, hikes and swims in the surrounding Sun Lakes–Dry Falls State Park, international volleyball, musical jam sessions around the campfire, and a guided tour of the Dry Falls Visitor Center by a Washington State Parks interpretative ranger
- The OutBees: a final-night talent show featuring music, poems, skits, and a competition to correctly pronounce "jökulhlaup" (appropriately judged by an Icelandic participant), as well as presentation awards for categories such as "Best Picture," "Best Mystery Flood," and "Best Original Screenplay"

Generous sponsorship from the Geological Society of America and the National Science Foundation enabled the conveners to cover full registration fees and partial travel support for all students and early career participants.

EMERGENT THEMES

Several key themes emerged during the week. First, despite the great diversity of outburst flood science—spanning geographic regions, planets, methods, and time periods—many researchers grapple with the same underlying questions. What is the role of outburst floods in landscape evolution, and how do landscapes recover post-flood? How scalable is a single flood event to different landscapes, time periods, or triggering mechanisms? How can we most effectively integrate numerical models and field studies? What new methods or approaches are needed to address remaining knowledge gaps?

The two field trips illustrated many of these themes. Though focused on the Missoula floods in the Channeled Scabland, field trip stops provoked discussions on other flood landscapes across the solar system, as well as paleoflood reconstruction challenges, flood erosional mechanics, sediment transport, and tracing floodwater sources. The trips also offered opportunities for informal

Figure 3. Map of conference attendee institutions (regionally grouped). Basemap credit: United Nations Geospatial Contributor: UNGIS, UNGSC, Field Missions.

conversations among participants—networking is often more impactful when done while digging through paleolake sediment sequences or examining flood-deposited boulders.

Another key theme was the importance of tackling research questions with an interdisciplinary, multi-method approach. Presentations described linking onshore and offshore records to reconstruct flood impacts on ocean circulation and climate; combining different geochronological techniques to date paleofloods; and linking remote sensing, field observations, and modeling results. They also demonstrated the lessons that can be learned from other study sites—for example, recognizing similar depositional sequences from floods on different continents; comparing erosional features on Earth and Mars; or adapting early warning systems to different flood basins.

Finally, hearing perspectives from Colville Reservation tribal members both in the meeting room and at field trip stops provided powerful insight on the role these landscapes play outside the sphere of the geosciences alone—as ancestral lands, cultural sites, and (as illustrated by the National Park Service and Washington State Park participants) recreational and educational places. Situating outburst flood science within these contexts was a unique and powerful aspect of this conference that many attendees appreciated. It also demonstrated the value and responsibility of exchanging knowledge between different groups.

OUTBURST FLOOD MEETING OUTCOMES

A classic outcome of such meetings is discussion and consideration of future research challenges and directions. This was the case here, when, on the final afternoon, participants met in breakout groups to discuss emergent themes with the aim of charting a course for the next 100 years of outburst flood research. We identified the following action points:

- Increase interdisciplinary communication and collaboration among geoscientists, engineers, oceanographers, etc., via working groups, conferences, and special journal issues.
- Study outburst floods with a systems approach—for example, considering the sediment impact from source to sink, not just deposits within a single valley.
- Link different flood records—for example, terrestrial and marine records, different geochronological data sets, etc.
- Balance and incorporate multiple methods—field observations, remote sensing, numerical models, and physical experimentation studies.
- Develop a database of flood events on Earth and other planets.
- "Share your science"—the importance of communicating research to society for both outreach and policy reasons (e.g., flood disaster mitigation strategies).
- Create a listserv for the outburst flood community, as well as a subgroup for students and early career scientists.

Another outcome, possibly more gratifying to the convenors (who may not fully witness the next 100 years of outburst flood research), has been the continued engagement among outburst flood researchers, especially early career scientists. Some of this was manifest formally in an American Geophysical Union session in December 2023, but much of it has been accomplished informally through proposal sharing, social media groups, and new and renewed collaborations.

Overall, this Penrose Conference affirmed that the future is bright for the next century of outburst flood science. The field continues to expand in new geographic, thematic, and methodological directions, and it involves an increasingly diverse group of scientists from across the globe who strive for effective collaboration and communication. Despite a century of study, the Channeled Scabland—like other outburst flood landscapes—still holds fascinating unanswered questions for all who explore it. We are excited to see what questions and answers the coming decades will bring.

ACKNOWLEDGMENTS

Lindsey Henslee at GSA provided outstanding logistical support at every step of conference planning. Ian Yuh at the U.S. Geological Survey was also invaluable for planning and on-site organization. We would like to thank Denis Felton of Washington State Parks for facilitating our stay at Camp Delany. La Javelina provided a catering service that received rave reviews from conference attendees. The conference experience was also greatly enhanced by participation from members of the Confederated Tribes of the Colville Reservation, who shared perspectives on the role of this incredible landscape in their cultural traditions. We also thank rangers from the National Park Service Ice Age Floods National Geologic Trail for sharing information and Washington State Parks Interpretative Ranger David McWalter for guiding a tour of the Dry Falls Visitor Center. Finally, a huge thank you to those attendees who volunteered to help around the camp, and especially those who volunteered to drive shuttles between Seattle and Camp Delany and on field trips—spending a day behind the wheel of a 15-passenger van is no small task!

SECOND ANNOUNCEMENT AND FINAL CALL FOR PAPERS

Joint Meeting: Cordilleran and Rocky Mountain Sections

120th Annual Meeting of the Cordilleran Section, GSA
74th Annual Meeting of the Rocky Mountain Section, GSA

Spokane, Washington, USA
15–17 May 2024

www.geosociety.org/cd-mtg

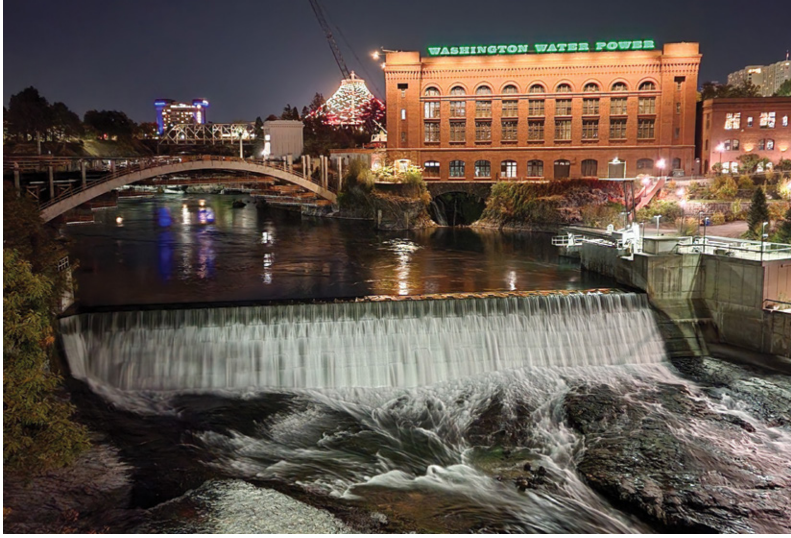

Photo credit: Chad Pritchard.

Sharing at the Falls

LOCATION

Get ready for an unforgettable experience at "Sharing at the Falls," the GSA 2024 Joint Cordilleran and Rocky Mountain Section Meeting in Spokane, Washington, USA. Nestled west of the world-renowned Silver Valley, Spokane serves as a crossroads of geological history, with an incredible location at the intersection of Pleistocene megafloods, Miocene Columbia River basalt, the breakup of supercontinent Nuna, and the majestic Rocky Mountains, all intricately carved by the picturesque Spokane River. These features and more will be on display during a built-in field trip to the Spokane River and Falls at the meeting. Our meeting venue, the Davenport Grand Hotel, is perfectly situated along the enchanting Riverfront Park with a wealth of local restaurants, pubs, and coffee shops located nearby. The hotel is also conveniently close to hiking, climbing, and water sports, giving you ample opportunity to make the most of your time in this geological wonderland.

CALL FOR PAPERS

Abstracts deadline: 6 February 2024, 11:59 p.m. PST
Submit online at **www.geosociety.org/cd-mtg**
Abstracts submission fee: GSA members: professionals US$30, students US$18; non-members: professionals US$60, students US$36. If you cannot submit an abstract online, please contact Heather Clark, hclark@geosociety.org.

REGISTRATION

Registration opens February 2024
Early registration deadline: 8 April 2024
Cancellation deadline: 15 April 2024

All fees are listed in US$. For further information, or if you need special accommodations, please contact one of the general co-chairs: Chad Pritchard, cpritchard@ewu.edu; Peter Larson, plarson@wsu.edu; Tom Williams, tomw@uidaho.edu; or Jerry Fairley, jfairley@uidaho.edu.

Member Type	Early		Standard	
	Full Mtg.	One Day	Full Mtg.	One Day
Professional Member	US$295	US$220	US$350	US$250
Professional Member 70+ & 30-year member	US$245	US$145	US$270	US$175
Professional Nonmember	US$375	US$295	US$405	US$320
Early Career Professional Member	US$220	US$145	US$250	US$175
Student Member	US$95	US$50	US$125	US$110
Student Nonmember	US$170	US$130	US$185	US$145
K-12 Professional	US$145	US$105	US$160	US$120
Guest or Spouse	US$145	US$145	US$155	US$155
Field Trip/Short Course Only	US$70	US$70	US$95	US$95

TECHNICAL PROGRAM

Theme Sessions

T1. **Recent Advances in Mineral Resources Research and Exploration.** Niki Wintzer, U.S. Geological Survey, nwintzer@usgs.gov; Allen Andersen, U.S. Geological Survey, akandersen@usgs.gov.

A session devoted to mineral exploration and ore deposit research within the western United States. Presentations involving a variety of methods—such as geophysical surveys, geologic and mineral potential/prospectivity mapping, and geochemistry/geochronology—are invited. Active research on critical mineral resources will be emphasized.

T2. **Magmatic Rare Earth Element Ore Deposits and Minerals for the Future.** Kathryn Watts, U.S. Geological Survey, kwatts@usgs.gov; Erin Benson, U.S. Geological Survey, ekbenson@usgs.gov.

Rare earth elements (REEs) are critical mineral commodities in high demand as the global economy transitions from fossil fuels to renewable energy sources. REEs also serve as essential industrial applications. We welcome research contributions on magmatic REE deposits, including geological, structural, experimental, and geometallurgical aspects of their genesis and extraction.

T3. **Mineral Deposits of the Western United States: A View from the States and Industry.** Virginia S. Gillerman, Idaho Geological Survey, vgillerm@uidaho.edu; Haley Rambur, Perpetua Resources, Haley.Rambur@Perpetua.us.

Presentations and posters related to any aspect of mineral deposits and related issues are welcome. Papers are especially encouraged from industry, state surveys and agencies, and students. All commodities are fair game. New research and findings encouraged.

T4. **Undergraduate and Graduate Geoscience Student Lightning Talk Showcase (Posters).** James MacDonald, Florida Gulf Coast University, jmacdona@fgcu.edu; Peter Davis, Pacific Lutheran University, davispb@plu.edu; Chris Mattinson, Central Washington University, mattinson@geology.cwu.edu.

This lightning talk session invites undergraduate and graduate students to present their research findings as a short, one-slide talk followed by a poster session later in the meeting. This will allow students to gain experience giving a talk at a scientific meeting in a reduced-pressure setting.

T5. **The Boring Billion Was Not So Boring! Mesoproterozoic Tectonics, Sedimentation, and Geochronology of Northwest Laurentia.** Robert C. Thomas, University of Montana Western, rob.thomas@umwestern.edu; Paul Link, Idaho State University, paullink@isu.edu.

The Boring Billion (1850 to 850 Ma) was not so boring! Northwest Laurentia was tectonically active during the Mesoproterozoic, as shown by sedimentologic and geochronologic studies about the Belt Supergroup and overlying strata. The session is dedicated to Don Winston, whose passion for the Belt was essential to this understanding.

T6. **Advancements in Geologic Carbon Sequestration in Basalt.** Lee Florea, Washington Geological Survey, lee.florea@dnr.wa.gov; William Gallin, Washington Geological Survey, william.gallin@dnr.wa.gov; Todd Schaef, Pacific Northwest National Lab, todd.schaef@pnnl.gov.

Large basalt provinces in the Pacific Northwest, such as the Columbia Basin and the Snake River Plain, host enormous potential to permanently mineralize and store carbon. We invite ongoing research on reactive transport, reservoir properties, mapping and modeling of targets and seals, and plans for future implementation.

T7. **Faults, Fractures, and Fluids: Structural Control of Fluid Flow, Fault Zones, and Hydrothermal Processes.** Ben Melosh, U.S. Geological Survey, bmelosh@usgs.gov; Owen Callahan, En Echelon Geoconsulting, ocallahan@eegeos.com; Max Wilmarth, Baseload Power U.S., max.wilmarth@baseloadpower.us; Stanley Mordensky, U.S. Geological Survey, smordensky@usgs.gov.

We welcome recent studies on the structural control of fluid flow, geothermal resources, and the influence of hydrothermal processes on fault strength evolution. This multidisciplinary session encompasses field geology, microstructure, rock mechanics, geophysics, numerical simulations, and neotectonics, with implications for resource development, fault zone mechanics, and structural evolution.

T8. **Geochemistry, Hydrology, and Microbiology in Yellowstone and Other Western North American Hydrothermal Systems.** Peter B. Larson, Washington State University, plarson@wsu.edu; Ken W. Sims, University of Wyoming, kims7@uwyo.edu; Everett Shock, Arizona State University, eshock@asu.edu; Jerry Fairley, University of Idaho, jfairley@uidaho.edu.

Hydrothermal systems are products of heat and mass transfer from the mantle and crust to Earth's surface. Yellowstone forms a natural laboratory for their examination. We invite contributions from Yellowstone and other western North American hydrothermal areas to discuss their chemical, hydrologic, biologic, and physical aspects.

T9. **Geothermal Resources of the Pacific Northwest and Intermountain West.** Lee Florea, Washington Geological Survey, lee.florea@dnr.wa.gov; Aaron Rothfolk, Washington Geological Survey, aaron.rothfolk@dnr.wa.gov.

Since the 1960s, geothermal energy has been developed across the western U.S. Recently, this green energy resource has expanded beyond conventional hydrothermal settings. We invite talks discussing the spectrum of evolving geothermal resources and technologies: enhanced geothermal systems, heating and cooling, thermal energy storage, direct use, and REE extraction.

T10. **Paleontology in the West: Fossils, Localities, Research, and Education in the Rocky Mountain and Cordilleran Regions.** Lindsay MacKenzie, Eastern Washington University, lmackenzie1@ewu.edu; John Orcutt, Gonzaga University, orcutt@gonzaga.edu.

Western North America has one of the world's richest fossil records, encompassing everything from Precambrian microbes to Pleistocene megafauna. We welcome submissions focused on fossils and localities from the western U.S., Canada, and Mexico, their paleoecological and geological context, and their use in education and outreach.

T11. **Baja BC: What Is New, What Do Fossils Tell Us?** Peter Ward, University of Washington, argo@uw.edu.

The Baja BC Hypothesis rages on. Yet little from the fossil record has been put forward for many years. In this session, let us see what fossils, new paleomagnetism, and new zircon work can say.

T12. **Northwest Cordillera Eocene Tectonics, Volcanism, and Climate: Bridging the Borders.** Nancy Van Wagoner, Thompson Rivers University, nvanwagoner@tru.ca.

Complexities of Early Eocene tectonics are recorded in the rocks of the NW Cordillera. This session aims to bring geoscientists together from across geographical borders to share ideas regarding the geology, geochronology, and geophysics of the NW Cordillera at that time, with implications for tectonic models and global climate.

T13. **New Developments in the Magmatic Drivers of Cascades Volcanism.** Nathan Andersen, U.S. Geological Survey Cascade Volcano Observatory, nandersen@usgs.gov; Dawn C.S. Ruth, U.S. Geological Survey California Volcano Observatory, druth@usgs.gov; Dawnika L. Blatter, U.S. Geological Survey California Volcano Observatory, dblatter@usgs.gov; Emily R. Johnson, U.S. Geological Survey Cascade Volcano Observatory, erjohnson@usgs.gov.

The Cascades are marked by substantial diversity in the composition, eruptive style, and distribution of volcanic centers. We seek contributions that utilize petrologic and/or geochemical approaches to derive insights into magma genesis, evolution, and storage; the distribution and character of vents; or processes that catalyze eruptions in the Cascades.

T14. **Continental Mafic Volcanism: Honoring the Career of Vic Camp.** Arron Steiner, Washington State University, arron@wsu.edu; John Wolff, Washington State University, jawolff@wsu.edu; Emily Cahoon, Oregon State University, emily.cahoon@oregonstate.edu.

Vic Camp has made career-long contributions to understanding Cenozoic mafic volcanism in the inland northwestern U.S. and elsewhere. We encourage contributions on continental mafic magmatism, especially focused on the Columbia River basalts and broader Yellowstone Hotspot province as well as other large igneous provinces and intraplate volcanism.

T15. **Distributed Volcanic Fields in Western North America.** Kellie Wall, U.S. Geological Survey, kwall@usgs.gov; Nancy Riggs, Northern Arizona University, nancy.riggs@nau.edu; Emily Johnson, U.S. Geological Survey, erjohnson@usgs.gov; Mark Stelten, U.S. Geological Survey, mstelten@usgs.gov.

Distributed volcanic fields (DVFs) abound in Cascadia and western North America. DVFs may produce a variety of volcanic features, compositions, and eruption styles, including monogenetic scoria cones and polygenetic volcanoes. We invite contributions that apply field observations, geochemistry, geochronology, and/or geophysics to investigate the processes and hazards of DVFs.

T17. **The Highest and the Deepest: The U.S. Frontier of Cave and Karst Research.** Lee Florea, Washington Geological Survey, lee.florea@dnr.wa.gov; Georgia Schneider, University of Denver, georgia.schneider@du.edu.

The western U.S. hosts caves of epigene, hypogene, volcanic, and glacial origin. The wide range of karst environments in temperate rainforests, deserts, and alpine landscapes produces an unrivaled diversity of karst. We invite presentations highlighting the origin, evolution, and modern-day processes associated with these important resources often on federal lands.

T18. **Using Geologic and Geophysical Data to Unravel Neotectonics and Long-Term Deformation across Cascadia.** Lydia Staisch, U.S. Geological Survey, lstaisch@usgs.gov; Scott Bennett, U.S. Geological Survey, sekbennett@usgs.gov; Ray Wells, U.S. Geological Survey, rwells@usgs.gov; Richard Blakely, U.S. Geological Survey, blakely@usgs.gov.

This session explores the dynamic tectonic architecture of Cascadia, which has been constructed through geodynamic mechanisms including hotspot, flood basalt, and arc volcanism, crustal accretion, subduction, regional rotation, and extension. We solicit abstracts focusing on geologic and geophysical approaches toward understanding long-term tectonic evolution, neotectonics, and earthquake hazards.

T19. **Structure and Tectonics of the North American Cordillera and Rocky Mountains.** David Pearson, Idaho State University, peardavi@isu.edu; Ryan Anderson, Idaho State University, ryananderson@isu.edu.

This session will explore the structural development and tectonics of the Cordillera and Rocky Mountains. We encourage submissions at all scales, as well as process-based studies, including work investigating its pre-orogenic framework, evolution as a convergent orogenic system, modification into a transform margin, and subsequent phases of extension.

T20. **Neotectonics across the Intermountain West from New Data to Classic Concepts.** Cal Ruleman, U.S. Geological Survey, cruleman@usgs.gov; David Lageson, Montana State University, lageson@montana.edu; Michael Stickney, Montana Bureau of Mines and Geology, mstickney@mtech.edu.

We invite new data and revisit foundational neotectonic and geomorphic concepts defining the tectonic development of intermountain west landscapes. We welcome papers on structures, rates, kinematics, and geomorphology contributing to our regional understanding of Quaternary tectonism across western North America. We challenge submittals to place local work into regional relationships.

T21. **Implications of Lithosphere-Crust Interactions within the Northern Cordillera.** Marlon Jean, Colorado Mesa University, mjean@coloradomesa.edu; Erin Todd, U.S. Geological Survey, etodd@usgs.gov.

The northern segment of the North American Cordillera is in part the product of interactions between oceanic lithosphere and western North America. Our session welcomes investigations that explore geochemical interactions between contrasting lithosphere types, their underlying mantle, and the diversity of igneous and metamorphic rocks resulting from those interactions.

T22. **Management of Hydrologic and Geologic Resources.** Attila Folnagy, Montana Department of Natural Resources and Conservation, afolnagy@mt.gov.

Effective planning and management of natural resources is critical for their conservation, development, utilization, and sustainability. This session will focus on projects with a broad applicability in managing natural resources. Management projects of interest include water quantity and quality, aquifer storage and recovery, carbon sequestration, exploration, characterization, restoration, and remediation.

T23. **The Transport and Fate of Contaminants in Aquatic Systems.** Priya M. Ganguli, CSU Northridge, priya.ganguli@csun.edu; Scott C. Hauswirth, CSU Northridge, scott.hauswirth@csun.edu; Erin N. Bray, CSU San Francisco, ebray@sfsu.edu.

We welcome presentations that explore physical, chemical, and biological processes that influence the mobility, form, and/or toxicity of contaminants, including sediment. Aquatic systems of interest include, but are not limited to, surface water and groundwater in coastal marine, riparian, lacustrine, and wetland environments. Student presentations are encouraged.

T24. **What Lies Beneath: The Basement Geology of Western North America.** Rich Gaschnig, University of Massachusetts Lowell, richard_gaschnig@uml.edu; Tsai-Wen Chen, Washington State University, tsai-wen.chen@wsu.edu.

The age and extent of the Precambrian crystalline basement throughout western North America remain of fundamental interest to the geologic community. This session seeks contributions on the basement geology of western North America. Topics include age and origin of terranes, assembly into cratons, and implications for supercontinent configuration.

T25. **Exceptional Floods in the Cordillera.** James O'Connor, U.S. Geological Survey, Portland, oconnor@usgs.gov; Richard Waitt, U.S. Geological Survey, Vancouver, waitt@usgs.gov.

Exceptional floods in the Cordillera range from the huge late-Pleistocene megafloods to more recent natural dam failures, volcanic lahars, tsunamis, and meteorological floods. These floods have produced a lasting legacy of landforms, oceanic deposits, ecosystems, and cultural consequences. We invite contributions addressing all aspects of large floods.

T26. **Landscape Evolution and Geomorphology of the Greater Pacific Northwest and Northern Rockies.** Jessica Stanley, University of Idaho, jessicastanley@uidaho.edu; Joel Pederson, Utah State University, joel.pederson@usu.edu; Sean LaHusen, U.S. Geological Survey, slahusen@usgs.gov; Carlos Montejo, University of Idaho, mont7968@vandals.uidaho.edu.

The Pacific Northwest and northern Rockies are shaped by a myriad of processes from the mantle to Earth's surface, including complex tectonism, hotspot and subduction-related volcanism, glacial and fluvial erosion, landslides, and a changing climate. We invite a wide range of contributions focused on landscape change in the region.

T27. **Undergraduate Research Posters (Posters).** Jeff Marshall, Cal Poly Pomona, marshall@cpp.edu.

This poster session will highlight geoscience research conducted by undergraduate students. Abstracts must be written by students, but may include non-student co-authors (faculty mentors or collaborators). The students must present the poster. Topics may include undergraduate research in any geoscience discipline or related field of study.

T28. **Mapping the West (Posters).** Kelsay Stanton, Washington Geological Survey, kelsay.stanton@dnr.wa.gov.

This poster session will focus on maps produced in the geosciences: geologic, geophysical, hydrologic, hazards, the list goes on! Both professional and student submissions are welcome.

FIELD TRIPS

Field trip registration opens in February. Please visit https://www.geosociety.org/ GSA/Events/Section_Meetings/GSA/Sections/cd/2024mtg/fieldtrips.aspx for dates and cost. For additional information, please contact the field trip co-chairs: Mark McFaddan, mlmcfaddan@gmail.com, and Chad Pritchard, cpritchard@ewu.edu.

Elbow Tectonics: Smashing, Translating, and Rotating Outboard Terranes of the Syringa Embayment of the Laurentian Accretionary Margin of Western Idaho. Russell V. Di Fiori, Idaho Geological Survey, russelld@uidaho.edu; Keegan L. Schmidt, Lewis-Clark State College, klschmidt@lcsc.edu; Cody Steven, University of Idaho, csteven@uidaho.edu; Basil Tikoff, University of Wisconsin, basil@geology.wisc.edu; Ellen Nelson, University of Wisconsin, emnelson8@geology.wisc.edu.

This trip will showcase an array of impressive structures and oceanic/continental rock assemblages in the N–S-to-E–W elbow in the arc-continent boundary of western Idaho. Includes transects across the N–S boundary along the Salmon and South Fork Clearwater Rivers and along the E–W boundary on the main Clearwater River.

Sunset at Columbia River Gorge, Oregon, USA. Photo credit: 4nadia / iStock / Getty Images Plus via Getty Images.

Arc Versus River: The Geology of the Columbia River Gorge. Jim O'Connor, U.S. Geological Survey, oconnor@usgs.gov; Ray Wells, U.S. Geological Survey, rwells@usgs.gov; Scott Bennett, U.S. Geological Survey, sekbennett@usgs.gov; Charles Cannon, U.S. Geological Survey, ccannon@usgs.gov; Lydia Staisch, U.S. Geological Survey, lstaisch@usgs.gov.

The Columbia River Gorge is a deep chasm cutting through the Cascade Range. The unique setting of a continental-scale river crossing an active and deforming volcanic arc has created a dynamic landscape where lava flows, landslides, and tectonic and magmatic deformation compete against fluvial processes to shape the river corridor.

Geologic Cross Section of the Mesoproterozoic Belt Basin from Glacier National Park, Montana, to Sand Point, Idaho. Jim Sears, Emeritus Professor, University of Montana, james.sears@umt.edu; Stuart Parker, Montana Bureau Mines and Geology, sparker1@mtech.edu.

The field trip will focus on the stratigraphy and paleotectonic evolution of the Mesoproterozoic Belt Basin on an E–W transect from the shallow-water facies of the east margin of the basin in Glacier National Park through its deep-water interior near Sand Point. The transect crosses the northern Rocky Mountains, with beautiful scenery and excellent exposures of the Belt Supergroup.

Uncovering a Miocene Forest in Ancient Lake Clarkia. Lindsay MacKenzie, Eastern Washington University, lmackenzie1@ewu.edu; Renee Love, University of Idaho, rlove@uidaho.edu; Ian Spendlove, University of Idaho, spen2878@vandals.uidaho.edu.

Discover the ancient flora and fauna preserved in ancient Lake Clarkia during the mid-Miocene Climatic Optimum. Modern and historical paleobiological sites of the Clarkia Fossil Beds Lagerstatte in northern Idaho will be investigated. Current and future research of the sites will be discussed and fossil collection will be permitted.

Depositional Contacts of Loess-CRB as Analogs for Lunar Regolith, Martian Dust, and the Matrix of Impact Ejecta Breccia Lobes. Shawn Wright, Planetary Science Institute, swright@psi.edu; Dr. Mark Sweeney, University of South Dakota, Mark.Sweeney@usd.edu.

Several outcrops in the Spokane region will be investigated. The guidebook and discussion will focus on the composition of the loess from multiple sources, including CRB, along with the amorphous content and composition of Martian dust (remotely), Martian soil (Curiosity Rover), and basaltic impact ejecta (Lonar Crater and theoretical from basalt source).

Geologic and Anthropologic History of Riverfront Park, Spokane, Washington. Chad Pritchard, Eastern Washington University, cpritchard@ewu.edu.

This field trip to Riverfront Park, Spokane, Washington, showcases the impacts from historic Silver Valley mining practices, incisions into the Miocene Columbia River basalt, cataclysmic Pleistocene megafloods, the Spokane fault (which was recently described based on 15 mm of offset from satellite images), hydroelectric generation, stormwater solutions, and additional fascinating history.

Basement, Belt, and Batholith: Bedrock Geology of the Idaho Panhandle. Richard Gaschnig, University of Massachusetts Lowell, richard_gaschnig@uml.edu; Andy Buddington, Spokane Community College, Andy.Buddington@scc.spokane.edu; Reed Lewis, Idaho Geological Survey, University of Idaho, reedl@uidaho.edu.

This trip will showcase the geology of the Idaho Panhandle with a focus on Archean and Proterozoic basement gneisses, the Mesoproterozoic Belt Supergroup, and the Cretaceous Kaniksu batholith.

Stratigraphy, Eruption, and Evolution of the Columbia River Basalt Group. Vic Camp, San Diego State University, vcamp@sdsu.edu; John Wolff, Washington State University, jawolff@wsu.edu; Arron Steiner, Washington State University, arron@wsu.edu; Evan Soderberg, Washington State University, evan.soderberg@wsu.edu; Rachelle Hart, Washington State University, rachelle.hart@wsu.edu.

The Columbia River Basalt Group is world famous as the best studied continental flood basalt province on Earth. This two-and-a-half-day field trip to the eastern Columbia Plateau will focus on the basalt flow sequence, dikes, vents, evolution of the basaltic magmas, and their relation to the larger Yellowstone Hotspot Province. The locations to be visited are in and adjacent to the canyon country of southeast Washington, western Idaho, and northeast Oregon, and feature feeder dikes, near-vent associations, and thick plateau basalt lava sequences. The formations to be examined include the Imnaha, Grande Ronde, and Wanapum Basalts. The stops are mostly roadside and involve walking a short distance (no strenuous physical activity). Accommodation is double-occupancy hotel rooms (single rooms available at extra cost). The trip will depart from and return to Spokane.

Unscrambling the Proterozoic Supercontinent Record of Northeastern Washington State. Daniel T. Brennan, Montana Bureau of Mines and Geology, dbrennan@mtech.edu; Stephen E. Box, United States Geological Survey, sbox@usgs.gov; Athena Eyster, Tufts University, Athena.Eyster@tufts.edu.

Northeastern Washington State contains a unique Proterozoic record that spans two Supercontinents, and is perhaps the most complete stratigraphic record of the "Boring Billion" in the western US. This field trip includes 11 planned stops over a single day and will cover the geology of the Belt Supergroup, Deer Trail Group, Buffalo Hump Formation, and Windermere Supergroup in the region just north of Spokane. Topics will span from historic regional economic geology to original mapping and more recent isotopic provenance data, with discussion of their local to global implications. This field trip will start and end at the Spokane convention center, and will consist of mostly roadside stops with minimal hiking.

A Tour of the Fabulous Coeur d'Alene Mining District, Shoshone County, Idaho. Earl Bennett, University of Idaho, bennett@uidaho.edu; Steve Petroni, HECLA (retired), petronisteve@gmail.com.

The Coeur d'Alene Mining District in northern Idaho is one of the largest silver-producing districts in the world. From the beginning of lode mining in 1884, the district's mines have produced over 1.25 billion ounces of silver, 8.5 million tons of lead, 3.4 million tons of zinc, and byproduct antimony, cadmium, copper, and gold. The total historic value of this production is over $7.4 billion. This one-day bus tour will discuss the regional geology and history of Silver Valley, Idaho.

Cataclysmic, Ice Age Megafloods through the Cheney-Palouse Scabland Tract. Bruce Bjornstad, bjorn99352@yahoo.com; Eugene Kiver, Eastern Washington University, froghollow@sisna.com.

It's been a hundred years since J Harlen Bretz first presented his outrageous hypothesis for ice age megafloods within the Channeled Scablands of eastern Washington. This two-day field excursion will examine the evidence for multiple megafloods within the Cheney-Palouse Scabland Tract, including some going back to the early Pleistocene.

Biostratigraphy of Cambrian Metaline Limestone Exposed in the Lafarge Quarry. Glen Schofield, FCGLEN01@msn.com.

Explore the Cambrian fossils and tectonic deformation of the Metaline Limestone at the LaFarge quarry in Metaline Falls, NE Washington. Trilobites and other Cambrian fossils reported in 2011 from these quarries refined the age to Early Middle Cambrian and identified new variations of trilobites. Sheared trilobites, deformed pyrite, and calcite-filled fractures also display amazing NW-to-SE compression from the Severe Orogeny and likely deformation associated with the Newport fault. Come and collect fossils and strain structures with us and enjoy the view.

SHORT COURSES

Preparing Your Students for the Jobs They Want. Anne Egger, NAGT and Central Washington University, Anne.Egger@cwu.edu; Karen Viskupic, Boise State University, karenviskupic@boisestate.edu.

In this short course, we will help you make more explicit connections between the skills you are building in your undergraduate geoscience programs and the skills that geoscience employers seek. You will explore what we know about what employers want and strategies to integrate workforce skills into your courses and programs.

Getting the Most Out of Your TA Experience. Anne Egger, NAGT and Central Washington University, Anne.Egger@cwu.edu; Karen Viskupic, Boise State University, karenviskupic@boisestate.edu.

In this short course, we will help graduate students build their skills as teaching assistants (TAs) and articulate those skills for future careers. Participants will develop skills in facilitating learning activities, explore strategies for fostering inclusive learning environments, and recognize and communicate the skills they develop as a TA.

Teaching Quantitative Reasoning Using Data: Project EDDIE. Carmen Nezat, Eastern Washington University, cnezat@ewu.edu.

This short course will focus on teaching scientific concepts using data exploration and open inquiry. Participants will build expertise in teaching quantitative reasoning using Environmental Data-Driven Inquiry and Exploration (EDDIE) modules that include topics from multiple environmental disciplines with a flexible structure to fit all teaching situations. Visit https://serc.carleton.edu/eddie/index.html for more information on Project EDDIE.

ACCOMMODATIONS

Hotel registration deadline: 23 April

A block of rooms has been reserved at the Davenport Grand Hotel, 333 W Spokane Falls Blvd., Spokane, Washington 99201, USA, which is the meeting location. The meeting rate is US$149 per night plus tax. You can book directly via this reservation link: www.marriott.com/events/start.mi?id=1693242805154&key=GRP

OPPORTUNITIES FOR STUDENTS AND EARLY CAREER PROFESSIONALS

Career Mentoring Luncheons

Ask your career-related questions and learn about nonacademic pathways in the geosciences while networking with professionals at the Roy J. Shlemon and John Mann mentor luncheons. GSA student members are welcome to attend.

Career Workshop Series

This three-part series will feature career development planning, an exploration of geoscience job sectors, and information on best practices for crafting a résumé and cover letter. Nontechnical skills and workforce statistics will be reviewed. The series will be led by workshop presenters and geoscientists. No registration is required, and everyone is welcome.

Learn more at **www.geosociety.org/mentors/.** Questions? Contact Jennifer Nocerino at jnocerino@geosociety.org.

STUDENT VOLUNTEERS

Take advantage of work opportunities to earn free meeting registration. Students interested in helping with the various aspects of the meeting should contact Nigel Davies, Eastern Washington University, ndavies2@ewu.edu.

PROFESSIONALS

If you would like to share your interest, enthusiasm, and experience in applied geology, consider being a GSA mentor. Being a mentor is a rewarding experience. To learn more about serving as a mentor at this meeting, contact Jennifer Nocerino at jnocerino@geosociety.org.

CONTINUING EDUCATION CREDITS

The GSA 2024 Joint Cordilleran and Rocky Mountain Section Meeting also offers an excellent opportunity to earn continuing education units (CEUs) toward your continuing education requirements for your employer, K–12 school, or professional registration. Please check the meeting website after the meeting to download your CEU certificate.

LOCAL COMMITTEE

General Co-Chairs: Chad Pritchard, cpritchard@ewu.edu; Peter Larson, plarson@wsu.edu; Tom Williams, tomw@uidaho.edu; Jerry Fairley, jfairley@uidaho.edu
Technical Program Chair: Kelsay Stanton, kelsaystanton@gmail.com
Field Trip Co-Chairs: Mark McFaddan, mlmcfaddan@gmail.com; Chad Pritchard, cpritchard@ewu.edu
Exhibits/Sponsorships Chair: Christopher Dail, chris.dail@perpetua.us
Student Volunteer /Activities Chair: Nigel Davies, ndavies2@ewu.edu

Northeastern Section Meeting

Manchester, New Hampshire
17–19 March

www.geosociety.org/ne-mtg

Left: Beach near Portsmouth, New Hampshire.

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Joint Cordilleran/ Rocky Mountain Section Meeting

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15–17 May

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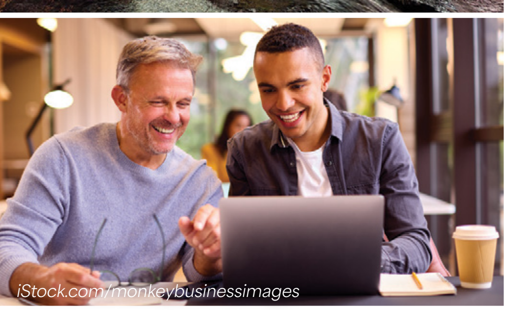
Below: Spokane Falls. Photo credit: Chad Pritchard.

Southeastern Section Meeting

Asheville, North Carolina
15–16 April

www.geosociety.org/se-mtg

Above: Blue Ridge Mountains. Photo credit: Ashley Lynn.

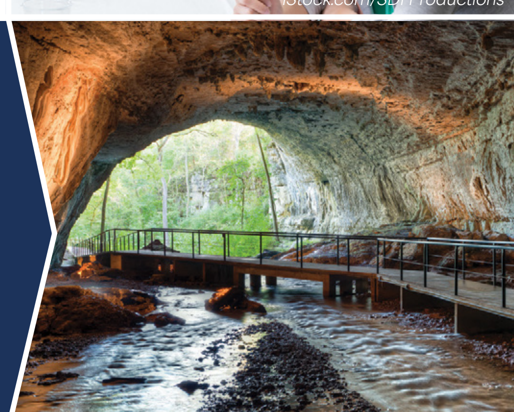


Joint North-Central/ South-Central Section Meeting

Springfield, Missouri
21–23 April

www.geosociety.org/nc-mtg

Right: Smallin Civil War Cave. Photo credit: Springfield CVB.



2023 Outstanding Earth Science Teacher Awards

The National Association of Geoscience Teachers (NAGT) has announced the 2023 Outstanding Earth Science Teacher (OEST) Award winners. This annual award recognizes excellence in earth science teaching at the pre-college level. GSA awards the section recipients US$700 in travel money to attend a GSA meeting and complimentary GSA membership for three years. State winners receive a one-year complimentary GSA membership.

SECTION WINNERS

Central Section: Kate Krischke-Grobart, *Waukegan High School, Illinois*
Eastern Section: David R. Amidon, *LaFayette Junior-Senior High School, New York*
New England: Sarah Ford Faulkner, *East Granby Middle/High School, Connecticut*
Southeastern Section: Tammie Hodnett Marlow, *Cleveland Central Middle School, Missouri*
Pacific Northwest: Hillary Brown, *Ida B. Wells-Barnett High School, Oregon*

STATE WINNERS

Alabama: Scott Coonfare
Florida: Katherine Stoltz
Georgia: Nicole Marte
Indiana: Jon Schrange
Iowa: Mallory Wills-Howe
Louisiana: Lacey Hoosier
Michigan: Andy Epton
Minnesota: Melissa (Missie) Olson
Mississippi: Tammie Hodnett Marlow
New Hampshire: Michele Cusack
New York: Joseph C. Perry
North Carolina: Charlene Horton
South Carolina: Amy Umberger
Tennessee: Gregory Smith

Read more about the section and state winners:
https://nagt.org/nagt/awards/oest/2023_oest.html

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UNTAPPED POTENTIAL

Is Geology Accreditation Needed? It Is Already Here!

Laurie C. Anderson,* *Dept. of Geology and Geological Engineering, South Dakota School of Mines and Technology, Rapid City, South Dakota 57701, USA;* ***John S. Gierke,*** *Dept. of Geological and Mining Engineering and Sciences, Michigan Technological University, Houghton, Michigan 49931, USA;* ***Jeffrey B. Connelly,*** *Dept. of Earth Sciences, University of Arkansas Little Rock, Little Rock, Arkansas 72204, USA*

INTRODUCTION

In the 2000s, geoscience program accreditation was a regular topic in journal articles, opinion pieces, meeting sessions, and committee reports (e.g., Corbett and Corbett, 2001; GSA Ad Hoc Committee on Accreditation, 2008). Geoscience accreditation discussions subsequently subsided for apparent lack of proactive, interactive interest and with no consensus achieved (GSA Ad Hoc Committee on Accreditation, 2008; Bralower et al., 2008). Simultaneously, an increasing emphasis on continuous improvement in higher education has led to regular, formal assessment of student outcome achievement, efforts to align program outcomes to workforce needs, and expansion of competency-based learning. As a result, calls have been made for professional societies to develop certification, accreditation, or badging programs (Wikle, 2018; Mosher and Keane, 2021; Klyce and Ryker, 2022).

Two recent publications (Mosher and Keane, 2021; Klyce and Ryker, 2022) indicate that geoscience lacks an accrediting body, but accreditation of geoscience programs is already in place via ABET. The Applied and Natural Science Accreditation Commission (ANSAC) of ABET has adopted program criteria for "Geology, Geological Science and Similarly Named Programs." The first geology program was ANSAC-ABET accredited in 2017, and as of 2023, five geology programs (three international, two U.S.) have accreditation. These institutions are the University of Arkansas at Little Rock, South Dakota School of Mines and Technology, Universidad Industrial de Santander, United Arab Emirates University, and the University of Jordan.

We are three active geology program evaluators (PEVs) for ANSAC who have served in administrative roles in departments hosting geology programs. We wish to raise awareness of the ANSAC accreditation process, accreditation costs and benefits, and the need for additional geoscientists to become PEVs. All PEVs serve as ABET volunteers on behalf of their member societies for the program discipline(s) that they review.

ACCREDITATION PROCESS

ABET is a nonprofit organization of volunteers belonging to professional STEM member societies. General accreditation criteria evolve over time through the collective efforts of these volunteers. Program criteria, PEV training, and PEV assignments are administered by the member society (or societies) overseeing a discipline. The Society for Mining, Metallurgy, and Exploration (SME-AIME) is currently the lead society for geology programs, as well as mining engineering and geological engineering programs, and is a cooperating society for environmental and metallurgical engineering programs.

Each science and engineering discipline is represented on the relevant ABET commission (ANSAC for science; Engineering Accreditation Commission for engineering disciplines) by one or more commissioners from member societies. Each discipline has a pool of PEVs who conduct evaluations. Geology has one commissioner from SME-AIME on the ANSAC Commission, and, currently, many geological engineering PEVs also are serving as geology PEVs until a cadre of more geoscience-centric volunteers can be recruited.

ABET does not mandate a rigid curriculum of required courses. Instead, "[t]he program's faculty must assure that the curriculum devotes adequate attention and time to each component, consistent with the objectives of the program and institution, while preparing students for life-long learning" (ABET, 2023). The accreditation process uses an outcomes-based approach focused on what students learn and experience, and ABET provides a framework for a program to

1. articulate goals for professional attainment of recent graduates (program educational objectives [PEOs]);
2. define and consult constituencies for developing and revising PEOs;
3. establish additional student (learning) outcomes (SOs) beyond those in the general criteria, if desired (see Table S1 in the Supplemental Material[1] for full list of SOs);
4. assess acquired student knowledge and skills for each SO (see Table S1 for an example of performance indicators used in one geology program); and
5. use multiple data sources for improvement of courses, curricula, and/or programs.

Curriculum requirements for baccalaureate programs accredited under ANSAC are

1. a combination of college-level mathematics and sciences (some with laboratory

[1]Supplemental Material. Table S1: 2023–2024 ANSAC Student Outcomes (SOs); Table S2: ANSAC's geology program criteria, ASBOG Fundamentals of Geology (FG) exam topics, and California's educational requirements for professional geologist licensure eligibility. Please visit https://doi.org/10.1130/GSAT.S.24446617 to view the supplemental material, and contact editing@geosociety.org with any questions.

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and/or experimental experience) appropriate to the discipline;
2. advanced technical and/or science topics appropriate to the program;
3. a general education component that complements the technical and scientific content of the curriculum and is consistent with the program and institution objectives; and
4. capstone comprehensive projects or experiences based on the cumulative knowledge and skills acquired in earlier course work (ABET, 2023).

The six ANSAC SOs require assessment and focus on multiple skills, including application of mathematics and science knowledge to solve topics relevant to the discipline, effective communication, ethics, and teamwork (see Table S1). A program may develop additional SOs, and if it does, those outcomes must also be assessed.

Geology program criteria (see Table S2) are not a list of required courses, and course credits assigned to each topic are not prescribed. Instead, a program's curriculum must be consistent with its PEOs. Program criteria assessment is not required, although a program must demonstrate where topics are covered and how criteria are met.

COSTS AND BENEFITS

ABET accreditation is not feasible for all programs, especially if most of the content outlined in general and program criteria is not already part of the curriculum or the institution lacks other ABET-accredited programs. There are institutional (monetary and reporting) and program (assessment and reporting) investments. Geology program accreditation is more practicable on a campus with other ABET-accredited programs, as the workload documenting institutional-level resources and support can be shared, and expertise from across campus can be leveraged.

There are advantages for programs pursuing ABET accreditation. Regional accreditation organizations (e.g., Higher Learning Commission) require rigorous assessment of, and continuous improvement based on, student outcomes for all institutional programs. For public institutions, state governing boards or departments of higher education often mandate that degree programs undergo periodic program review, which may include self-studies with program assessment and paid external evaluators visiting campus. ABET accreditation can meet these requirements.

While ABET accreditation is not mandatory for the geology programs we represent, our programs are subject to student-learning assessment as part of university accreditation. When faced with the option to seek ABET accreditation or participate in another round of review to satisfy state and regional accreditation requirements, the choice was self-evident: Our programs could be ABET accredited with little additional work, we would receive quality feedback from trained PEVs, and we could bypass future in-house assessment exercises. Thus, rather than simply complying with a mandate, our programs receive an internationally respected accreditation and associated public recognition.

Accreditation may also help retain and secure resources. For instance, field methods are an explicit part of ANSAC's geology program criteria (see Table S2), which could help justify continuation of field courses or camps. Although both costly and labor intensive, and therefore a potential target of cost-cutting measures, these opportunities remain common in geoscience programs (Klyce and Ryker, 2022) and are required for professional licensure in some states (e.g., California; California Code of Regulations, 2023; see Table S2).

Accreditation also benefits graduates. The common perception that most professional geologists have master's degrees is not the case (Shafer and Viskupic, 2022). For professionals with bachelor's degrees, certification as professional geologists (through state licensure) and/or as certified professional geologists (through the American Institute of Professional Geologists) is often important for career advancement. Because geology program criteria are closely aligned with topics in the National Association of State Boards of Geology (ASBOG) Fundamentals of Geology exam (see Table S2), students are well prepared for professional practice. In fact, California recognizes graduation from an ANSAC-accredited geology or related program as meeting educational requirements for professional geologist licensure eligibility (California Code of Regulations, 2023).

NEED FOR GEOLOGY PEVS

ABET accreditation relies on PEVs from industry, agencies, and academia. Our SME-AIME colleagues in both engineering and geology were strong supporters as geology accreditation took shape. Current evaluators, however, do not represent the full spectrum of geoscience expertise. Becoming a geology PEV requires membership in SME-AIME and a PEV application to ABET (<30 min). Training involves ~20 hours of online work, a 1.5-day simulated campus visit at ABET (ABET supports this travel), a half-day training session led by the SME-AIME Volunteer Selection Committee (ABET does not support this travel), and participation as an observer during an ANSAC team visit (ABET supports this). Biennial refresher training is also required. Serving as a PEV, therefore, is a significant service commitment, but we feel that these efforts are important to our programs, our students, and the future of geoscience education.

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Manuscript accepted 26 October 2023

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