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The Wood River Mountains (pictured) within Wood Tikchik State Park, Alaska are the western-most topographic expression of the Denali fault before it becomes submerged beneath Bristol Bay. In this region of southwestern Alaska, the Denali fault strikes ~200, nearly 130 degrees different from its orientation in the Canadian Cordillera. This change in fault strike through southern Alaska is a signature of the Alaskan Orocline. Photo Credit: Trevor Waldien.

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Hertha Aryton in her home laboratory with a wave tank. Published with permission from the Mistress and Fellows, Girton College, Cambridge, UK.

SCIENCE

Oroclinal Bending of Southern Alaska during Final Assembly of the North American Cordillera

Trevor S. Waldien,*,[1] Sean P. Regan,[2,3] and Bernard A. Housen[4]

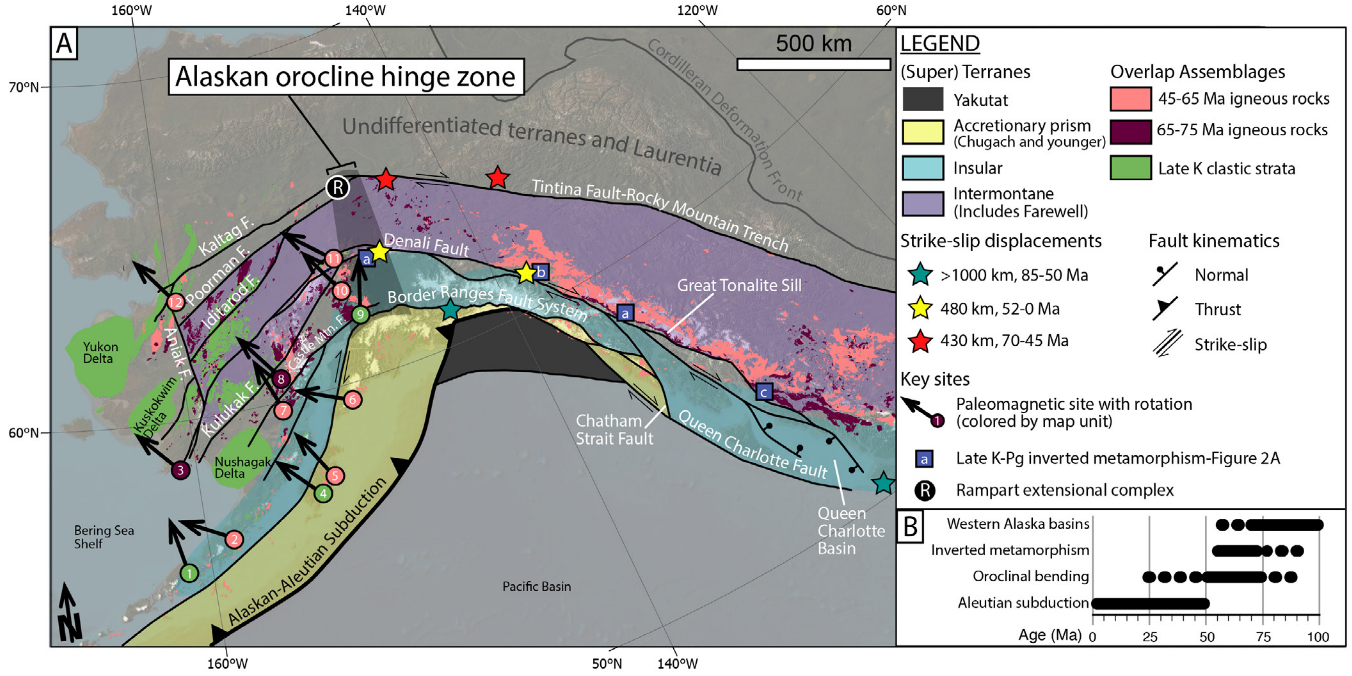

Figure 1. (A) Shaded relief satellite image of the Alaskan-Canadian Cordillera overlain by pertinent superterranes, fault systems, subduction-related igneous belts, and sedimentary strata. Terrane boundaries are modified from Colpron and Nelson (2011), and geologic map units are compiled from Wilson et al. (2015), Cui et al. (2017), and Colpron et al. (2016). See Supplemental Material S5 (text footnote 5) for rotations associated with paleomagnetic sites. Inverted metamorphism sites: a—Regan et al. (2024); b—McKenzie et al. (2024); c—Crawford et al. (1987). F—fault; K—Cretaceous; Pg—Paleogene. (B) Timeline of pertinent tectonic processes operating in the Alaskan-Canadian Cordillera.

ABSTRACT

The Alaskan orocline is a widely recognized example of oroclinal bending that differs from many curved orogens in that it is defined by curved strike-slip faults. Whereas the Alaskan orocline has been tied to counterclockwise (CCW) rotation of western Alaska in the Late Cretaceous–Paleogene, improved timing estimates on strike-slip translation and terrane accretion in the Alaskan-Canadian Cordillera reveal that these processes overlapped in time and may have been kinematically linked. To evaluate this potential link, we analyzed magnetic declination data from paleomagnetic sites in western Alaska and synthesized the interpreted vertical-axis rotations with the Late Cretaceous–Paleogene tectonic evolution of the Alaskan-Canadian Cordillera. The data compilation shows that progressive CCW rotation, distributed strike-slip faulting, and widespread volcanism associated with basin subsidence in western Alaska were synchronous with shortening, high-grade metamorphism, and focused magmatism along the length of the Canadian Cordillera. The Alaskan orocline hinge, defined as the broad region where faults change from NW-striking to SW-striking features, marks the transition between these two distinct geologic domains. The observations motivate a tectonic model for the Alaskan orocline that calls upon lateral extrusion and rotation of western Alaska in response

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to oblique shortening along the Canadian Cordillera in the Late Cretaceous–Paleogene. Lateral extrusion and CCW rotation resulted in plate convergence in the Bering Sea region that initiated the Aleutian subduction zone by ca. 50 Ma. Subsequent strike-slip motion, Aleutian trench retreat, and accretion of the Yakutat terrane likely tightened the orocline during the Cenozoic.

INTRODUCTION

Orogenic curvature is a fundamental feature of mountain belts worldwide that is linked to subduction dynamics (Capitanio et al., 2011), topographic development (Benowitz et al., 2022), and earthquake behavior (Morales et al., 2015). Such curvature has been envisioned to form as either a primary feature of the orogenic belt or by subsequent buckling of an earlier-formed margin after a change in plate-boundary conditions (Johnston et al., 2013). Whereas longitudinal shortening is often invoked to explain secondary buckling of an orogen, primary orogenic curvature can develop progressively in response to along-strike changes in relative plate velocities, mechanical properties of the orogen, or preexisting architecture of the crust (Weil et al., 2010). Distinguishing these end-member mechanisms requires regionally extensive mapping, structural analysis, geochronology, and robust paleomagnetic data to evaluate whether curvature developed synchronously with accretionary processes or was superimposed on the orogen.

Southern Alaska preserves a widely cited example of orogenic curvature, referred to as the Alaskan orocline, which is expressed as an ~100° azimuthal change along strike-slip fault systems and geologic belts through southern Alaska (Fig. 1). The salient model describing oroclinal bending of southern Alaska calls upon a combination of dextral strike-slip faulting throughout the cordillera (Redfield et al., 2007), opening of the North Atlantic (Coe et al., 1989), and resulting convergence between the Alaskan-Canadian Cordillera and Siberia, all superimposed on an older accretionary margin. These processes together are envisioned to have generated longitudinal shortening between the cordillera and Siberia that buckled the northern cordillera (Alaska) during the Late Cretaceous to Paleogene. Buckling is interpreted to have caused counterclockwise (CCW) rotation of southwestern Alaska (Coe et al., 1989) and initiation of the Aleutian subduction zone (Scholl, 2007), resulting in the observed curvature of the southern Alaska margin (Fig. 1). Critical assumptions in this model are: (1) All cordilleran terranes had accreted to the Laurentian margin at the time of oroclinal bending and behaved as passive markers during bending (Coe et al., 1989); and (2) dextral strike-slip motion on the Tintina, Denali, and Border Ranges fault systems overlapped in time, which accommodated escape of cordilleran terranes toward the Bering Sea and differential motion between rotating blocks in western Alaska (Coe et al., 1989; Redfield et al., 2007).

Recent work bracketing the timing of interterrane shortening in the Alaskan-Canadian Cordillera, however, reveals that terrane suturing and oroclinal bending overlapped in time (cf. Coe et al., 1989; Regan et al., 2024). The improved timing constraints outlining the accretionary history in the cordillera imply that oroclinal bending may have taken place by block rotation and translation in response to oblique collisional processes (e.g., Johnston, 2008). Here, we briefly overview the recent advancements in the timing of terrane accretion and strike-slip faulting in the Alaskan-Canadian Cordillera and summarize relevant geochronologic, geochemical, and paleomagnetic declination data from central British Columbia through the Bering Sea shelf. We use the data to propose a revised tectonic origin for the Alaskan orocline.

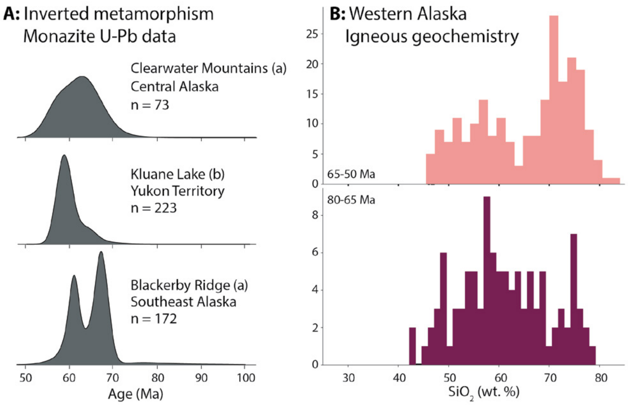

Figure 2. (A) Kernel density estimates of in situ monazite U-Pb ages from inverted metamorphic belts along the Canadian Cordillera (data from Regan et al., 2024; McKenzie et al., 2024). (B) Histogram of Late Cretaceous (bottom) and Paleogene (top) igneous rock SiO_2 concentrations from western Alaska.

TERRANE ASSEMBLY AND MAGMATISM

The Alaskan orocline is expressed as curvature along major dextral strike-slip faults that span the cordillera from British Columbia to the Bering Sea. These structures in most places bound major terranes and thus delineate the lithospheric architecture of the northern part of the North American Cordillera (Fig. 1; Estève et al., 2020). The most pertinent features to development of the Alaskan orocline are the terranes presently outboard (south and west) of the Tintina-Kaltag fault system (Fig. 1). These terranes, including the Insular superterrane, Intermontane superterrane, and Farewell terrane, are curved subparallel to the bounding strike-slip faults and track CCW rotation of western Alaska during development of the Alaskan orocline (Coe et al., 1985, 1989). Although the timing and latitude of suturing of the Intermontane superterrane to the Laurentian margin are disputed, it is widely accepted that the Intermontane superterrane served as the backstop to which the Insular superterrane accreted (cf. Johnston, 2008; Nelson and Colpron, 2007). As such, the Late Cretaceous–Cenozoic latitudinal displacement of the Intermontane superterrane required by paleomagnetic inclination data (Johnston, 2008) would have also transported the Insular superterrane and the Alaskan orocline.

The timing of ocean basin closure and associated metamorphism bracket assembly of the cordilleran terranes to the Mesozoic, either by sequential accretion of terranes to the North American continent (Nelson and Colpron, 2007), or by assembly of a ribbon continent in the marine

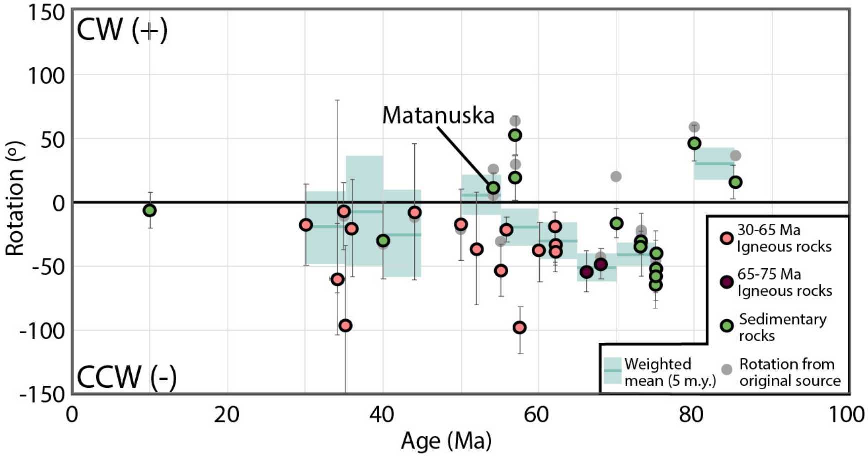

Figure 3. Paleomagnetic vertical-axis rotation data vs. age. Recalculated data points are colored according to map units in Figure 1 and binned into 5 m.y. weighted means with $1\sigma\sigma$uncertainties (blue bars). CW—clockwise; CCW—counterclockwise.

realm prior to final accretion to North America in the Late Cretaceous–Paleogene (Johnston, 2008). Along the Canadian Cordillera, east of the Alaskan orocline hinge, aggregation of the Insular and Intermontane superterranes is recorded by diachronous closure of an intervening marine basin system from the Early Cretaceous to Late Cretaceous, culminating in amphibolite-facies metamorphism of Jurassic–Cretaceous marine strata at various times along the margin (Crawford et al., 1987; Waldien et al., 2021). Syncollisional prograde metamorphism of sedimentary protoliths in the Insular-Intermontane suture developed an inverted metamorphic field gradient that is preserved in isolated exposures from south-central Alaska to at least as far south as central British Columbia (Figs. 1 and 2A; Crawford et al., 1987; Regan et al., 2024). Thrust-sense shear fabrics within the northern exposures (Yukon and Alaska) of the inverted metamorphic belt yield in situ U-Pb monazite ages ranging from ca. 72 to 56 Ma, which are interpreted to record the final phase of syncollisional shortening between the Insular and Intermontane superterranes (Fig. 2A; McKenzie et al., 2024; Regan et al., 2024). In southwestern Alaska, accretion of the Insular superterrane is interpreted from Cretaceous sedimentary basins that record progressive shortening between the Insular superterrane and inboard terranes (Trop and Ridgway, 2007; Hults et al., 2013; Box et al., 2019). The presence of localized depocenters between strike-slip fault systems in western Alaska demonstrates that the basins formed synchronously with motion on the strike-slip faults (Miller et al., 2002), including deep sedimentary basins beneath the active Yukon, Kuskokwim, and Nushagak River deltas (cf. Berg et al., 2020; Fig. 1). Folds within the Late Cretaceous marine strata record shortening and basin inversion related to docking of the Insular superterrane against the Farewell terrane prior to emplacement of crosscutting ca. 75–65 Ma igneous rocks (Miller et al., 2002).

The Alaskan-Canadian Cordillera records nearly continuous arc magmatism from the mid-Cretaceous to the Eocene (Gehrels et al., 2009), which also provides a record of changing tectonic boundary conditions related to terrane amalgamation. Along coastal British Columbia through Yukon, mid-to-Late Cretaceous plutonic belts strike parallel to the orogen and decrease in age from west to east (Gehrels et al., 2009). The ca. 70 Ma plutonic belt is preserved in a narrow zone of highly strained tabular plutons at the structural top of the inverted metamorphic belt and is continuous for >1000 km along strike (Great Tonalite Sill of Ingram and Hutton, 1994; Fig. 1). Late Cretaceous–Paleogene igneous rocks west of the orocline hinge consist of regionally distributed (~500 km width; Fig. 1) exposures of shallowly exhumed volcano-plutonic complexes hosted within low-grade metamorphic or sedimentary rocks (Moll-Stalcup, 1994). The Late Cretaceous igneous rocks from western Alaska display calc-alkalic compositions that have a broad range of SiO_2 concentrations (Moll-Stalcup, 1994; Fig. 2B; see Table S1 in the Supplemental Material[5]). Igneous rocks younger than 65–60 Ma display bimodal SiO_2 concentrations, indicative of dual melt sources, a hallmark of extensional tectonic settings (Fig. 2B; Table S2).

STRIKE-SLIP FAULT DISPLACEMENTS

Throughout the Alaskan-Canadian Cordillera, Late Cretaceous–Cenozoic dextral strike-slip faults accommodated northward displacement of cordilleran terranes toward the Bering Sea (Redfield et al., 2007). East of the orocline hinge, displacement primarily took place along three major fault systems: the Tintina fault (~430 km of slip, ca. 68–45 Ma; Gabrielse et al., 2006), Denali fault (~480 km of slip, ca. 52–0 Ma; Waldien et al., 2021); and the Border Ranges fault (>1000 km of slip, ca. 85–50 Ma; Pavlis and Roeske, 2007). West of the orocline hinge, >400 km of cumulative strike-slip motion was distributed between at least eight subparallel faults, several of which are interpreted to have accommodated dextral slip beginning ca. 100–85 Ma (Fig. 1; Miller et al., 2002). Slip on the entire network of faults records the margin-parallel component of oblique convergence between North America and the Pacific basin in response to multiple tectonic drivers across space and time (Miller et al., 2002; Redfield et al., 2007).

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[5] Supplemental Material. Tables S1–S5. Compiled geochemical and paleomagnetic data. Please visit https://doi.org/10.1130/GSAT.S.30376552 to access the supplemental material; contact editing@geosociety.org with any questions.

VERTICAL-AXIS ROTATION OF WESTERN ALASKA

Oroclinal bending of southern Alaska is expressed as the curvature of regional geologic belts and recorded by vertical-axis rotations interpreted from paleomagnetic declination data (e.g., Coe et al., 1985, 1989). To better understand tectonic causes leading to vertical-axis rotations in western Alaska, we compiled the published paleomagnetic data, excluding data with poor paleohorizontal control, and used the mathematical framework of Demarest (1983) to recalculate vertical-axis rotation values relative to current Late Cretaceous and Paleogene reference poles for North America (Table S3).

The resulting 31 paleomagnetic sites yielded updated vertical-axis rotation values that are less dispersed than those in the original sources, and most sites record CCW rotation (Fig. 3; Table S4). Dispersion persisting in the data can be partly attributed to the proximity of paleomagnetic sites to dextral strike-slip faults, resulting in clockwise (CW) rotation of fault blocks concurrent with CCW rotation of western Alaska. A clear example of this competition between rotation mechanisms is expressed in the Matanuska Valley, which is located between the dextral Border Ranges and Castle Mountain fault systems and records 11° ± 9° of net CW rotation despite being located within the orocline hinge (#9 on Fig. 1; "Matanuska" on Fig. 3).

The data fall on an array wherein older rocks record higher average magnitudes of net CCW rotation than younger rocks (Fig. 3). Due to limited paleomagnetic data on rocks between ca. 150 and 75 Ma in western Alaska, the onset of vertical-axis rotation is not well recorded in the data. However, we interpret the trend of mean vertical-axis rotations to record progressive net CCW rotation of western Alaska from at least 75 to 55 Ma. Sites in rocks younger than ca. 55 Ma are affected by large uncertainties, which are generally attributed to low sample density, but may also record modest net CCW rotation (Thrupp and Coe, 1986).

ALONG-STRIKE TRANSITION IN GEOLOGIC CHARACTER

The data summarized above demonstrate fundamental differences in the geology of the Alaskan-Canadian Cordillera through the Alaskan orocline. East of the orocline hinge, the Late Cretaceous–Paleogene geologic evolution of the Canadian Cordillera involved high-grade metamorphism and regional shortening along the Insular-Intermontane suture, highly localized arc magmatism, and translation along three dominant strike-slip faults. West of the orocline hinge, the Late Cretaceous–Paleogene geologic evolution of western Alaska involved Late Cretaceous sedimentary basin formation, widespread arc volcanism that transitioned to bimodal volcanism at ca. 65 Ma, dextral translation along several strike-slip faults, and progressive CCW rotation of the entire region. Because the hinge of the Alaskan orocline separates these two regions with distinct Late Cretaceous–Paleogene geologic histories, we propose that they were shaped by a common tectonic process that included oroclinal bending of Alaska.

Below, we present a tectonic model that accounts for the along-strike transition in the Late Cretaceous–Paleogene geologic character of the Alaskan-Canadian Cordillera and oroclinal bending of Alaska. Critical geologic observations honored by the model include the following:

(1) CCW vertical-axis rotation and basin formation in western Alaska were coeval with inverted metamorphism and regional shortening along the Canadian Cordillera.

(2) Dextral strike-slip faults in western Alaska began accumulating slip as early as 100 Ma, whereas dextral slip localized onto the eastern Tintina, Denali, and Border Ranges faults after 85 Ma.

(3) Displacement on the Tintina fault (ca. 68–45 Ma) largely preceded displacement on the Denali fault (ca. 52–0 Ma).

LATERAL ESCAPE AND DEVELOPMENT OF THE ALASKAN OROCLINE

Late Cretaceous–Cenozoic strike-slip motion in the Alaskan-Canadian Cordillera has been envisioned as a form of tectonic escape wherein lithosphere was translated from the Canadian Cordillera to the Bering Sea (Redfield et al., 2007). Although this model provides an elegant link between cordilleran strike-slip faulting and onset of the Aleutian subduction zone (e.g., Scholl, 2007), the now-recognized differences in timing of slip among the cordilleran strike-slip faults and ca. 72–56 Ma shortening and associated inverted metamorphism along the Insular-Intermontane suture (Regan et al., 2024) require modification of the model. We propose a revised escape tectonics model that calls upon Late Cretaceous–Paleogene shortening along the Insular-Intermontane suture as a mechanism to extrude western Alaska, initiate Aleutian subduction, and establish the curvature of the southern Alaskan margin.

We illustrate our tectonic model as a set of schematic palinspastic map restorations (Fig. 4). The restorations incorporate vertical-axis rotation of western Alaska, geologic estimates of strike-slip displacement, and associated dissection of igneous belts and sedimentary basins. Importantly, the restorations account only for displacement on mapped major faults and thus provide a minimum estimate of latitudinal terrane displacement compared to paleomagnetic data and other provenance indicators (e.g., Davidson and Garver, 2017; Tikoff et al., 2023). We contend that our model is compatible with data requiring larger latitudinal translation and that incorporating those data would change only the paleolatitude of the processes illustrated herein.

70–55 Ma

In the latest Cretaceous–Paleocene, geology-based strike-slip fault restorations place the Insular superterrane at least 800 km south of its present location. The marine basin system between the Insular and Intermontane superterranes had completely closed by ca. 85 Ma (Waldien et al., 2021), and rocks within the suture experienced amphibolite-facies metamorphic conditions (Crawford et

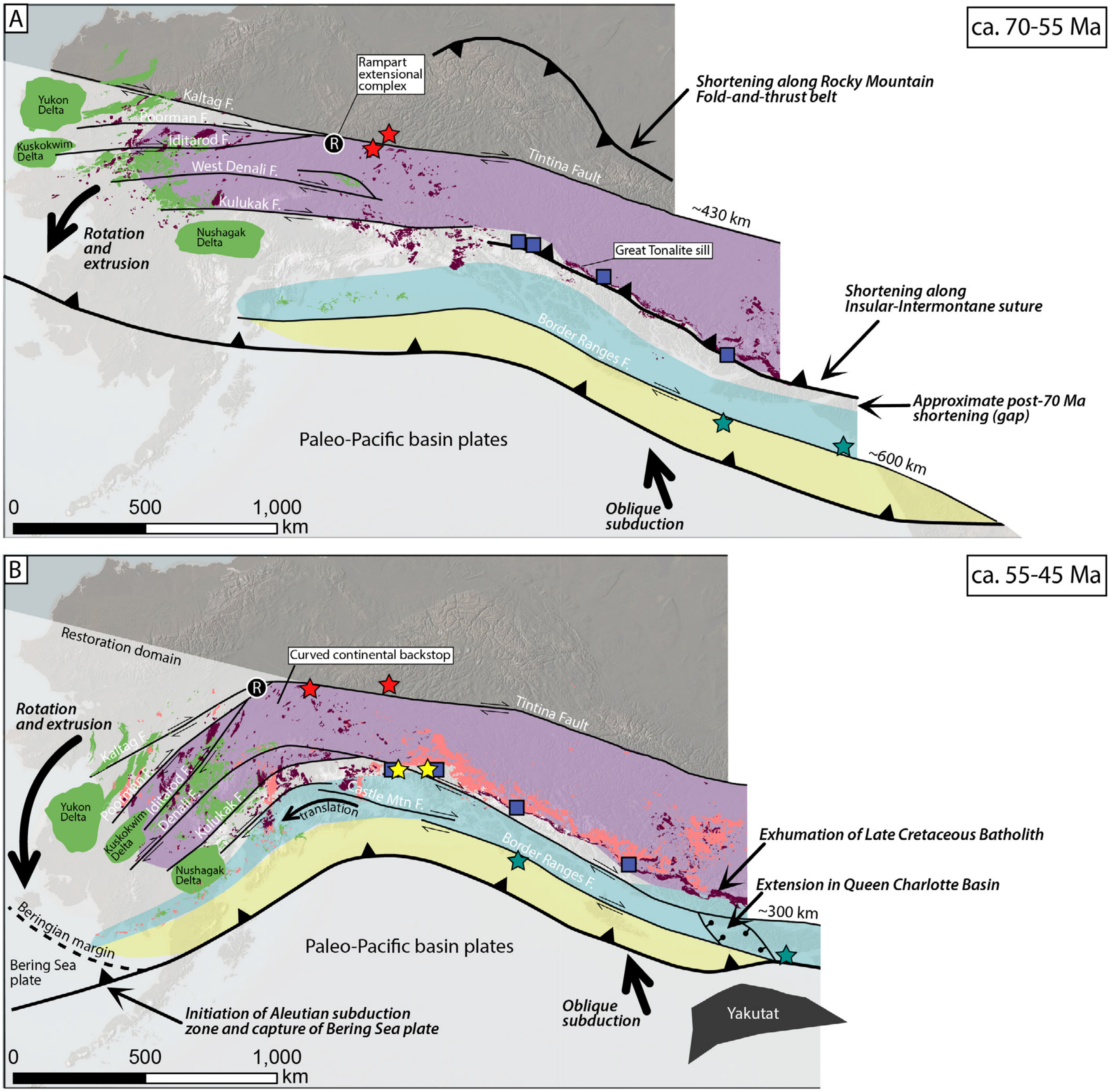

Figure 4. Schematic tectonic restorations illustrating development of the Alaskan orocline. All faults (F) present in each time interval were active during that time interval. See Figure 1 for map unit colors, symbols, and the 0 Ma time interval. Strike-slip displacements represent minimum separation estimates derived from mapped strike-slip faults only.

al., 1987; McKenzie et al., 2024; Regan et al., 2024). Dextral displacement accumulated on the Tintina and Border Ranges fault systems in response to oblique subduction across the cordillera (Pavlis and Roeske, 2007; Johnston, 2008). This region of partitioned oblique convergence and associated metamorphism transitioned northwestward into a zone of distributed strike-slip faulting, localized sedimentary basins, and widespread volcanism in present-day western Alaska. Near the transition between these domains, localized extensional exhumation of high-pressure metamorphic rocks within the Intermontane superterrane south of the Tintina fault (Rampart extensional complex; Fig. 4A) records bending of the lithosphere within the hinge zone of the Alaskan orocline (Till et al., 2007). This extension is kinematically compatible with CCW vertical-axis rotation of western Alaska and associated bending of all faults and geologic belts south of the Rampart extensional complex.

We interpret Late Cretaceous dextral strike-slip faulting in western Alaska to record lateral extrusion of that region during oblique closure of the marine basin system between the Insular and Intermontane superterranes. Synchronous lateral extrusion and CCW vertical-axis rotation of western Alaska initiated in response to a gradient in the magnitude of shortening along strike of the Insular-Intermontane suture during the Late Cretaceous, which lasted into the Paleogene.

55–45 Ma

In the early Eocene, geology-based strike-slip fault restorations place the Insular superterrane at least 400 km south of its present location. Localized slip on the Tintina and Border Ranges fault systems had waned, and translation was transferred primarily to the Denali fault and within the accretionary complex terranes. Along the Canadian Cordillera, dextral slip on the Denali fault system synchronous with initiation of the Queen Charlotte transform fault resulted in dissection of the Insular superterrane by extension in the Queen Charlotte Basin, eventually leading to localization of the Queen Charlotte fault (Rusmore et al., 2010). The multistranded strike-slip fault system and regions of extension along the Canadian Cordillera facilitated exhumation of the Late Cretaceous batholith and associated metamorphic rocks (Hollister and Andronicos, 2006). In western Alaska, dextral slip took place on multiple fault strands, including the Denali fault (Miller et al., 2002). Lateral extrusion and CCW rotation of western Alaska caused convergence between the Beringian margin and oceanic plates to the south, which established the Aleutian subduction zone and captured a fragment of seafloor (Bering Sea plate) by ca. 50 Ma (Scholl, 2007).

We interpret the waning Tintina fault slip and rotation of western Alaska by ca. 45 Ma to have established the curvature of the Intermontane superterrane at that time. The thick lithospheric mantle of the continental terranes inboard of the Denali fault (Estève et al., 2020), cessation of extension in the Rampart extensional complex (Till et al., 2007), and thermochronologic data from the orocline hinge adjacent to the north side of the Denali fault (Benowitz et al., 2022) imply that the continental terranes north of the Denali fault served as a curved backstop that was established by ca. 45 Ma. The curvature of this backstop and transfer of strike-slip motion to the Denali fault at ca. 50 Ma suggest that lithosphere outboard of the Denali fault has been translated through the orocline hinge since the early Eocene (e.g., Glen, 2004). Subsequent tightening of the Alaskan orocline may have been facilitated by such translation through the orocline hinge and Miocene subduction of the buoyant Yakutat oceanic plateau terrane with the southern Alaska margin (Redfield et al., 2007).

SYNTHESIS AND CONCLUSIONS

The data summarized herein demonstrate that CCW rotation and lateral extrusion of southwestern Alaska can be kinematically and temporally linked to shortening along the Insular-Intermontane suture zone. These processes were also contemporaneous with other major changes in the Alaskan-Canadian Cordillera, including shortening along the length of the Rocky Mountain fold-and-thrust belt (Johnston, 2008), a switch from transpression to transtension along the Canadian Cordillera (Hollister and Andronicos, 2006), an abrupt shift in the locus and tempo of arc magmatism (Gehrels et al., 2009), and accretion of voluminous clastic material in the Chugach accretionary prism (e.g., Davidson and Garver, 2017). We interpret the sum of these processes to record final assembly of the cordilleran terranes to the North American continent, followed by a shift in the plate-boundary forces and relative plate motion related to onset of the Aleutian subduction zone along the curved southern Alaskan margin (e.g., Scholl, 2007).

Vertical-axis rotation and lateral tectonic escape along strike-slip faults are widely observed processes in continental collision zones and have been shown to be kinematically linked to subduction dynamics in nearby trenches (e.g., Tapponnier et al., 1982; Reilinger et al., 2006). Here, we have extended the application of this tectonic model to the Alaskan-Canadian Cordillera to explain synchronous CCW vertical-axis rotation of western Alaska, shortening along the length of the Canadian Cordillera, dextral strike-slip faulting in both regions, and initiation of the Aleutian subduction zone. Considering the present data informing the geologic evolution of the Alaskan-Canadian Cordillera, we propose that the Alaskan orocline developed progressively over the Late Cretaceous and Paleogene as southwestern Alaska was extruded and rotated away from oblique terrane collisions in the Canadian Cordillera.

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Huge Thanks to Connects Student Volunteers!

Here's a shout-out of gratitude to all the student volunteers who helped make GSA Connects 2025 in San Antonio an incredible success! Your hard work throughout the conference allowed attendees to enjoy a smooth, informative, and fun conference. GSA could not have hosted Connects without you! Thank you!

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A Color Code to Raise Public Awareness of Lithium Resources

Antonin Richard*[,1] and Alexandre Chagnes[1]

INTRODUCTION

The global development of electric vehicles powered by lithium-ion batteries will put considerable pressure on raw material resources for decades to come (Maisel et al., 2023). However, the environmental impact of metal extraction seems to contradict the goal of the ecological transition, despite being considered one of its pillars (Sonter et al., 2023). In this context, it is crucial to raise public awareness and facilitate communication among stakeholders in the public debate (Brett et al., 2025). Color codes are already being used to refer to different water and hydrogen resources, as well as carbon sinks (Rost et al., 2008; Macreadie et al., 2021; Incer-Valverde et al., 2023). These color codes have various applications within the scientific community and serve as a practical tool for categorizing, communicating, and disseminating knowledge to the public. Here, we propose a simple color code for the main types of lithium resources to that end.

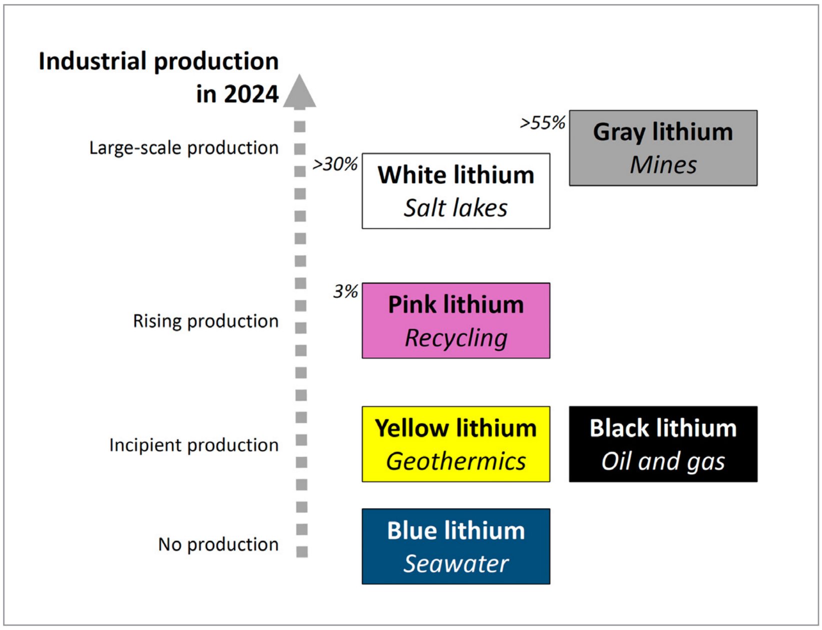

Figure 1. Proposed color code and associated nontechnical keywords (in italics) for the main types of lithium resources ranked by volume of industrial production in 2024 (arbitrary scale). Numbers in italics indicate the contribution to global production (after USGS, 2024; IEA, 2024).

PRESENTATION AND USE OF THE COLOR CODE

The proposed color code is presented in a simple chart (Fig. 1) showing the main types of color-coded lithium resources ranked by volume of industrial production in 2024 and represented by colored boxes. The colored boxes indicate the lithium resources (e.g., white lithium), and nontechnical keywords describe their origin (e.g., salt lakes). As far as possible, the colors reflect the environment in which the resources are found. Combined with keywords, the colors serve as a simple mnemonic device that helps to capture the main characteristics and highlights the diversity of lithium resources. We also provide an overview of their geographic distribution in the form of a world map showing the location of emblematic lithium production sites and advanced projects, color-coded according to the proposed scheme (Fig. 2). The following paragraphs provide more details on the color-coded lithium resources and available estimates of their associated carbon and water use intensity. Using this color code, stakeholders in the public debate (citizens, scientists, companies, the media, policymakers, nongovernmental organizations, etc.) can share a simple common lexicon and basic knowledge without having to master all the technical vocabulary for discussing the issues of lithium extraction.

WHITE LITHIUM—SALT LAKES

White lithium is dissolved in the water beneath salt lakes, also referred to as “salars,” at concentrations of up to several thousand milligrams per liter. The term “white” refers to the color of the salt lake landscapes. However, white lithium is predominantly produced in three major areas: Argentina-Chile, China, and Nevada (Fig. 2). Processes that do not require lithium to be concentrated by solar evaporation over large surfaces will become widespread (e.g., “direct lithium extraction” [DLE]; Vera et al., 2023). However, extracting white lithium puts critical pressure on land use and water resources for populations living around salars, which are located in very arid climates. The production of one ton of lithium carbonate equivalent using the solar evaporation

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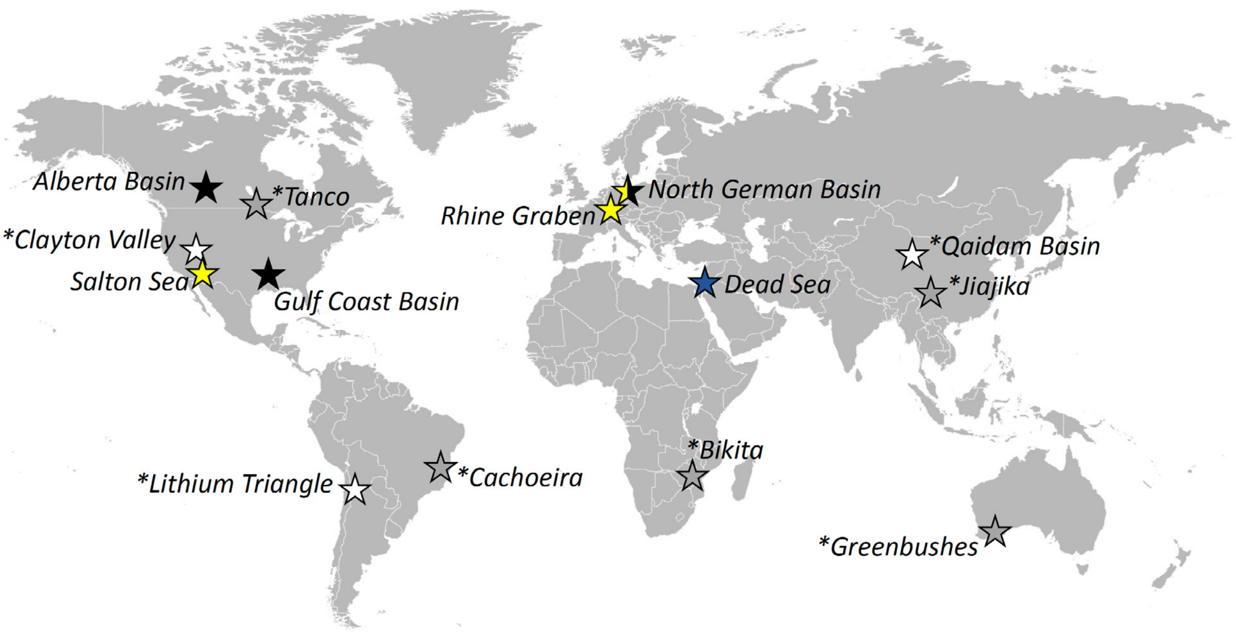

Figure 2. World map showing the locations of emblematic lithium production sites* and advanced projects (except for the Dead Sea), with color code for the main types of lithium resources as indicated in Figure 1. More complete information on lithium resources with or without active exploration/production projects and their precise locations are available from USGS (2024), Munk et al. (2025), Benson et al. (2025), and Brett et al. (2025). For pink lithium, see CAS (2025), showing the locations of lithium-ion battery recycling plants. Background political world map after Wikipedia Commons (2025).

process results in the emission of 3–4 tons of CO_2 equivalent and consumes 25–56 m^3 of freshwater (Kelly et al., 2021; Mas-Fons et al., 2024), not including the water evaporated during solar evaporation (100–300 m^3; Mousavinezhad et al., 2024). DLE requires industrial operations for extraction, purification, and conversion that emit the equivalent of 20 tons of CO_2 and consume 20–150 m^3 of water to produce one ton of lithium carbonate equivalent. However, freshwater can be recovered through the processing of Li-rich brines (Baspineiro et al., 2020; Mousavinezhad et al., 2024).

GRAY LITHIUM—MINES

This is lithium that is extracted from rocks in conventional open-pit or underground mines. By extension, gray lithium can also refer to lithium extracted from mining and processing residues. “Gray” refers to the light color of most lithium-enriched ores, such as pegmatites, granites, clays, and zeolites, which typically contain 0.6%–1.1% lithium. Unlike white lithium, gray lithium resources are found in varying amounts on all continents. However, current production is limited to pegmatite fields in a few countries, mainly Australia (Fig. 2). The quantities of water and energy required to extract gray lithium from pegmatites can be substantial due to mining, milling, and refining operations. It is estimated that producing one ton of lithium carbonate emits the equivalent of 15–22 tons of CO_2 and consumes 77 m^3 of water (Kelly et al., 2021; Mas-Fons et al., 2024). Furthermore, preserving water resources, landscapes, and ecosystems and managing mining waste are additional challenges to the social acceptance and further development of gray lithium.

PINK LITHIUM—RECYCLING

Pink lithium is obtained through recycling, primarily from lithium-ion batteries used in electric vehicles. Despite the boom in construction of recycling plants, the production of pink lithium is currently limited by technical challenges and the supply of battery waste (Neumann et al., 2022; IEA, 2024). Various studies suggest that pink lithium could supply 10%–60% of the raw material needed for lithium-ion batteries by 2035–2040 (Maisel et al., 2023; Zhou et al., 2024). While recycling preserves part of the resource, it is also an energy-intensive process that requires many chemicals. However, it is currently difficult to estimate the CO_2 emissions, energy consumption, and water consumption per ton of lithium carbonate produced by lithium-ion battery recycling processes that will be industrialized in the coming years due to the emergence of many different methods (Chagnes and Forsberg, 2023).

BLACK LITHIUM—OIL AND GAS

This is lithium dissolved at concentrations of up to a few hundred milligrams per liter in deep, nonpotable waters that occur naturally in hydrocarbon reservoirs. “Black” refers to the color traditionally associated with oil. Therefore, black lithium could be extracted from these groundwaters by DLE, with or without the co-extraction of hydrocarbons. Recent studies have revealed black lithium resources comparable in size to white and gray lithium resources (Dugamin et al., 2021; Knapik et al., 2023). Black lithium production could benefit from the infrastructure and investment capacity of oil and gas companies. It could also be coproduced with low-enthalpy geothermal energy, like yellow lithium (see below), or recovered during carbon capture, utilization, and storage operations in saline aquifers. Similarly, "black" lithium could refer to lithium extracted from coal fly ash (Qin et al., 2015). Several black lithium projects are currently in the advanced stages of development worldwide, particularly in Alberta (Canada), Arkansas (United States), and Germany (Fig. 2).

YELLOW LITHIUM—GEOTHERMICS

Yellow lithium is dissolved in warm water used for geothermal energy at concentrations of up to a few hundred milligrams per liter. The term "yellow" refers to the landscape of the world-renowned Yellowstone geothermal area in Wyoming. Substantial and well-distributed potential resources exist around the world (Toba et al., 2021; Gourcerol et al., 2024). Although several projects are well advanced in France, Germany, and California (Fig. 2), production of yellow lithium has not yet reached the large-scale industrial stage. Combining low-carbon geothermal energy with DLE may be attractive from environmental and economic perspectives (Weinand et al., 2023). However, controlling induced seismicity and ensuring the quality of groundwater during geothermal operations will be key factors in the social acceptance of yellow lithium.

BLUE LITHIUM—SEAWATER

Blue lithium refers to lithium dissolved in seawater and ocean water, which has an average concentration of 0.1–0.2 mg per liter. Blue lithium represents a huge lithium resource of ~230 billion tons (Yang et al., 2018). However, due to the presence of interfering ions (e.g., magnesium), extraction of blue lithium at such low concentrations is technically and economically challenging. Blue lithium may also be recovered from the Dead Sea (Fig. 2), where the lithium concentration reaches 30–40 mg per liter, as well as from seawater desalination waste brines (Alsabbagh et al., 2021; Zhang et al., 2021). Currently, there is no operational plan for the industrial extraction of blue lithium.

CONCLUDING REMARKS

Because resource inventories, technologies, and regulations are evolving rapidly, the background information and proposed color code provided here will need to be updated regularly, like the "colors" of hydrogen (Incer-Valverde et al., 2023). Since any industrial extraction or recycling of natural resources has a direct environmental impact, albeit to varying degrees, we recommend avoiding the potentially misleading term "green lithium." While a color code could facilitate communication and awareness in public debates, it is crucial to consider the pros and cons of each mining or recycling project on a case-by-case basis.

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Reflections on Water

Tracing My Path to Becoming an Internationally Engaged Hydrogeologist

Fryar monitoring water quality of a public water-supply well, West Bengal (India), May 2004.

When I decided to become a hydrogeologist, I didn't foresee climbing into a tree house in a Buddhist monastery in Thailand to ask the abbot for permission to sample a well. I grew up in the southern U.S. and didn't travel outside the country until 1986, when I spent a day in Mexico during my MS program at Texas A&M. That fall, I moved to Canada to begin my PhD studies at the University of Alberta; after 5-plus years, I returned to Texas with my Canadian wife. Apart from occasional family trips back to Canada, I never needed a passport. So how did I wind up as the GSA J.B. Thompson Distinguished International Lecturer for 2024–2025?

The world began to open to me in 2001, the year I received tenure at the University of Kentucky (UKY). I was contacted by Abhijit Mukherjee, a prospective graduate student from Kolkata (India), who was interested in the emerging problem of arsenic in groundwater in the Ganges basin. Several months later, Lahcen Benaabidate, a Moroccan professor who had read one of my papers on groundwater recharge in the Texas High Plains, reached out to me about working in the Middle Atlas region. I recruited Abhijit as an advisee and began collaborating long-distance with Lahcen. In summer 2003, at age 39, I took my first trip overseas, during which I traveled to Fez (Morocco) to meet Lahcen and his family. During summer 2004, I spent more than a month in India with Abhijit, including three weeks sampling public water-supply wells in West Bengal state. Those two trips sparked my passion for addressing water issues in developing countries, especially in North Africa and Asia.

Over the past two decades, my international research has evolved. I spent the 2014 spring semester as a Fulbright Scholar based in Fez and the 2023 spring semester as a Fulbright-Kalam Climate Fellow at North-Eastern Hill University in Shillong, India. In both projects, I studied how mountain springs respond to rainfall over various time scales as a function of geology, climate, and land use. With colleagues from Virginia Tech and Khon Kaen University (Thailand), as well as their students, I examined controls on arsenic and other solutes in alluvial aquifers along the Mekong River in northeast Thailand. Two of my advisees and I worked with researchers from the Chinese Academy of Sciences on a study of groundwater recharge and chemistry in a karst basin in Guizhou province, China. I'm currently collaborating with faculty at the American University of Central Asia and Kyrgyz State University on a similar study of springs in the Fergana Valley of southwest Kyrgyzstan.

Beyond research, I've become motivated to engage in exchanges and training. I've hosted Lahcen, two other Moroccan professors, and a professor from Niger as Fulbright Scholars. Through the U.S. State Department's BOOST (Building Opportunities Out of Science and Technology) initiative, with colleagues from UKY, the University of Georgia, and Western Michigan University, I promoted skills development for graduate students in water-related subjects at universities in Morocco, Egypt, Türkiye, and Indonesia. Activities included online modules on GIS, remote sensing, and technical communication; field exercises; a workshop in the U.S.; and student presentations at the 2012 GSA Annual Meeting and 2013 AGU Fall Meeting. During 2017–2018, UKY colleagues and I developed a hybrid

Fryar demonstrating alkalinity titration to Turkish graduate students, Keramet (Türkiye), May 2013. Photo Credit: Carmen Agouridis.

online/field program on water resources for high school students in Kentucky and eastern India, which included visits by Indian students and teachers to the USA and vice versa. During summers 2022–2024, colleagues from the BOOST initiative and I took cohorts of U.S. undergraduate and graduate students to Morocco for 4-to-5–week studies of water resources and management.

Being a Thompson Lecturer has given me an exceptional opportunity to renew contacts and forge new connections abroad. I traveled to India for three weeks this past March, visiting eight universities in the northeast, northwest, southeast, and east of the country. These included return trips to Shillong and to Indian Institute of Technology Kharagpur, where Abhijit is now a professor; I met some of his current and former students and, in several instances, their students. In May, I spent three weeks in northwest, central, and northeast Türkiye, visiting six universities and reconnecting with several of our BOOST participants, who are now faculty members. In June, I went to Kyrgyzstan for 18 days, organizing lectures at three universities in the capital (Bishkek) and the largest city in the south (Osh), and around 11 days of field work in the Fergana Valley. Throughout my tour, besides talking about springs, and visiting them and other geologic features (sinkholes, caves, waterfalls, lakes), I explored local historic and cultural sites, including Roman ruins, Byzantine churches, Ottoman mosques, Hindu temples, and an abandoned Soviet hydropower plant.

I've learned that international work is grounded in relationships; success depends on maintaining respect, curiosity, patience, and a sense of humor.

I think this work is more important than ever as international relations are in flux, government support for science is in question, and university enrollments in geoscience programs have been declining in multiple countries. This year, parts of India are again dealing with devastating floods, while Türkiye has received just over 30% of its usual precipitation. Water-related problems are often transnational; the solutions must be also. I applaud GSA's commitment to international engagement and advancing the geosciences for societal benefit, and I appreciate being able to contribute.

Fryar at outlet of Mawmluh Cave, Meghalaya (India), February 2023.

Alan Fryar is Professor of Earth and Environmental Sciences at the University of Kentucky. Besides water resources in developing countries, his interests include karst hydrology; groundwater/stream interactions; chemical evolution during groundwater recharge and flow; and natural attenuation of contaminants. He is a GSA Fellow and former Hydrogeology Division chair (2013–14). For more information about the Thompson International Distinguished Lecture Series, including posts from the 2024–25 tour, see https://www.geosociety.org/GSA/About/GSA_International/GSA/International/Lecture_Tour/Home.aspx.

Hertha Ayrton
Serendipitous Sedimentologist

Danita Brandt[*,1]

HERTHA WHO?

Long celebrated among electrical engineers for her contributions to electric-arc lighting, Hertha Marks Ayrton (1854–1923) is not widely recognized among geoscientists despite her pioneering work on the formation of sand ripples. Interestingly, a Google Doodle (Nichols, 2016) highlighted her work on ripple formation rather than her more widely known work in electrical engineering and sparked (pun intended) this Rock Stars profile. The story of how Mrs. Ayrton came to study ripples is a reminder of how chance and circumstance, impelled by curiosity and creativity, can shape scientific discovery. Her persistence in the face of societal strictures on women's place in science and society resonates even today.

MENTORS AND MATH

Born to Alice Theresa Moss, a seamstress from Portsea, Hampshire, England, and Levi Marks, a Jewish refugee from Tsarist Poland, Phoebe Sarah Marks (Hertha's birth name, and "Sarah" to her family) faced what might easily have been debilitating hardship from her earliest years. Sarah's father, a jeweler and watchmaker died when she was seven, leaving seven children—with the eighth on the way—and a family in debt. Sarah's mother might have kept her eldest daughter home to help care for her siblings, but, in stark contrast to prevailing Victorian views, Alice Marks held that "women have the harder battle to fight in the world," and because of this, needed a "better education than men" (Mason, 1991, p. 201). Thus, she sent her nine-year-old daughter to live with her wealthier sisters in London (Mason, 1991).

Staying with her aunts afforded Sarah opportunities that would have been out of her reach in Portsea. She learned French, Latin, Greek, and Hebrew, studied music and art, and discovered an innate talent for mathematics. Visitors to the London house included the author George Eliot and educator Madame Barbara Bodichon, a cofounder of Girton, the first girls' college at Cambridge University. Both women recognized Sarah's intellectual potential and made Sarah's enrollment at Girton financially possible. It was during this time of self-actualization that, at a friend's suggestion, Sarah assumed the name Hertha, the Teutonic goddess of Earth. As befit her adopted name, Hertha was not the demure Victorian woman of stereotype but an outspoken, creative, free-thinker who was not afraid to challenge limits imposed by prevailing societal sentiments about suitable pursuits for women.

Figure 1. Hertha Aryton in her home laboratory with a wave tank. Published with permission from the Mistress and Fellows, Girton College, Cambridge, UK.

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While at Girton, Hertha demonstrated a proclivity for tinkering, which culminated in 26 patents over her lifetime. Hertha found an outlet for her love of math by forming a mathematics club and submitting problems and solutions to a mathematics journal.

After earning a certificate in mathematics at Cambridge (women were not allowed to receive degrees from Cambridge until 1923), Hertha taught mathematics in London while at the same time attending a night course at a nearby college, pursuing an interest in electricity. A year later she and the physics instructor, a young widower, William (Will) Ayrton, married. Will Ayrton was a pioneer in electrical engineering as well as a pioneer in progressive attitudes about equal opportunities for women. By all accounts, the Ayrtons had an equal partnership in their shared research interests in electrical engineering and shared attitudes about the role of women in science and society. Both recognized the tendency for women's contributions in male-female partnerships to be overlooked. Will Ayrton was explicit in emphasizing his spouse's independence and originality as a researcher (Tattersall and McMurran, 1995).

As was the fashion in scientific presentations of the day, Hertha's talks were accompanied by demonstrations, first, of the workings of the electric arc and, later, using wave tanks to demonstrate the development of ripples. Although the popular media regarded her gender as much a novelty as her demonstrations, Hertha's scientific colleagues accorded her the courtesy of regarding her as a peer, responsible for addressing questions about her methods and assumptions. Growing up with six brothers may have inured her to the "masculine criticism" she faced and which she handled with aplomb (Sharp, 1926).

SEDIMENTOLOGY AND SUFFRAGE

Hertha was well-established in the electrical engineering community by the time she turned her attention to ripple marks. In the autumn of 1901, the Ayrtons relocated to the seaside to facilitate Will's convalescence from chronic fatigue and insomnia. Away from her home laboratory, yet perpetually intellectually restless, Hertha sought an outlet for her creative research energies and found it in observations of sand ripples during walks along the shore.

A number of mathematicians and scientists, including Cambridge professor George Darwin (one of Charles' sons), had investigated ripple formation and the relationship between sand ripples, the waves that form them, and the substrate on which they form; still, these phenomena were not well understood. After a summer of sketching ripples in the field and attempting to reproduce them in the bathtub (relocated to the sitting room of their rented lodging for the purpose), Hertha returned to their London home and began a series of experiments, constructing wave tanks of different sizes, equipping the largest with rollers and an electric motor to rock the tank, and creating ripples on a sand substrate (Fig. 1). A key to her success in understanding ripple formation was making visible the vortices in the water. Hertha found black ink (used by George Darwin) unsatisfactory and experimented with various substances, initially settling on moistened black pepper and, later, aluminum powder. Hertha showed that the origin of symmetrical wave ripples was not dependent on irregularities in the substrate and frictional forces between sand grains and the substrate, as previously thought, but was a predictable outcome of the action of vortices within the wave.

Hertha's ability to make the invisible visible, through ingenious public demonstrations, earned the respect of even her skeptics (Sharp, 1926). Hertha made history with the results of this work, when, in 1904, she became the first woman to read her own paper, "Origin and Growth of Ripple-mark," in front of the Royal Society.

While chipping away at the barriers to women's membership and participation in a stodgy scientific society through her scientific work, Hertha worked to dismantle other barriers to women in Victorian British society. Hertha and her daughter Barbara participated in demonstrations calling for women's right to vote. Some of the demonstrations turned confrontational and at one of these Barbara was among the activists sent to prison. Of this incident, Hertha wrote to a friend, "Barbie is in Holloway [prison]...I am very proud of her" (Mason, 1991, p. 211).

PATRIARCHY AND PERSISTENCE

Throughout her life, Hertha confronted personal and professional obstacles that might have overwhelmed a less resilient person. Her ability to prevail was facilitated through a combination of inheritance (her mother's fortitude and her father's mechanical skills), circumstance (those wealthy aunts and benefactors), and serendipity (Will Ayrton happened to be teaching that night course), but the factor that perhaps best explains the mark she made on science and society is "persistence."

Hertha nearly breached the ramparts of the Royal Society (founded in 1662), becoming, in 1902, the first woman nominated for membership. She was rejected on a Victorian-era technicality—as a married woman, she had no legal personhood separate from her husband, and the Society ruled that it could only admit "persons." It would be four decades before a second woman was nominated and accepted for membership. However, in 1906, Hertha became the first woman awarded the Royal Society's Hughes medal, the highest honor bestowed by the society, for original discovery in the physical sciences, recognizing her work on both the electric arc and sand ripples. It would be 102 years before the next woman received this award.

Today, a new generation has access to multiple sources of her life story, including a book of notable women scientists for young readers (Ignotofsky, 2016) and a play by American playwright Lauren Gunderson (2019) that centered on the friendship between Hertha and Marie Curie.

Electrical engineer Rollo Appleyard's letter to Hertha after she was awarded the Hughes medal reflected the shifting attitudes about women in science at the beginning of the twentieth century: "Your good work has literally left 'footprints in the sands of time' and it will give many men, and what is of more importance, many women, courage to take heart again, to improve general knowledge and their own lives by looking into what is" (Sharp, 1926, p. 186). Just don't call her a "woman scientist." In a 1919 interview, Hertha said, "Personally I do not agree with sex being brought into science at all. The idea of 'women and science' is entirely irrelevant. Either a woman is a good scientist, or she is not; in any case she should be given opportunities, and her work should be studied from the scientific, not the sex, point of view" (Sharp, 1926, p. 182).

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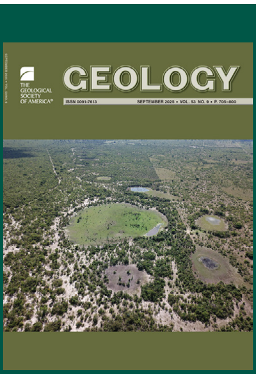

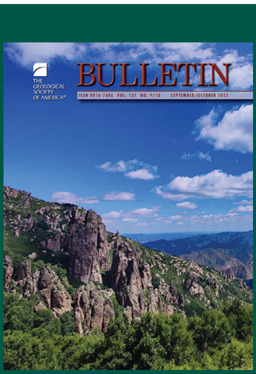

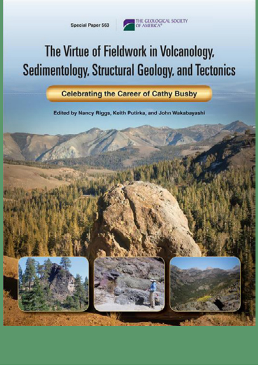

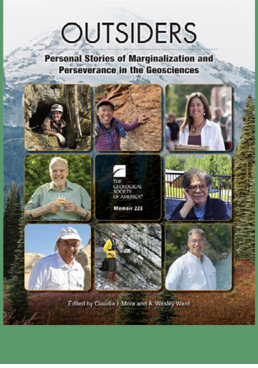

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Sign in to your GSA member profile and select the Divisions that align with your interests.

Did You Know?

Students can join unlimited Divisions for free!

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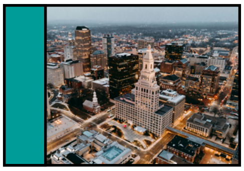
Contribute to the Conversation—Submit Your Abstract for a Section Meeting

Abstract submissions are now open for GSA 2026 Section Meetings! Start planning now to share your research and ideas with a global community of geoscientists.

Early registration and travel grants open 1 December 2025

GSA Triple Joint Southeastern / North-Central / South-Central Section Meeting
Memphis, Tennessee, USA
8–11 March 2026
https://www.geosociety.org/se-mtg



GSA Northeastern Section Meeting
Hartford, Connecticut, USA
21–24 March 2026
https://www.geosociety.org/ne-mtg

GSA Cordilleran Section Meeting
Loreto, Baja California Sur, Mexico
21–24 April 2026
https://www.geosociety.org/cd-mtg

GSA Rocky Mountain Section Meeting
Albuquerque, New Mexico, USA
17–20 May 2026
https://www.geosociety.org/rm-mtg

The Geological Society of America
CONNECTS
11-14 October **2026** Denver, Colorado, USA

Stay tuned for more details and deadlines!

Shape GSA Connects 2026—Submit Your Proposal Now

Do you have a session idea, field trip, or short course you'd like to see at GSA Connects 2026 in Denver, Colorado, USA? Here's your chance to help shape the meeting program!

Proposal submissions are now open, and we invite all members of the geoscience community to contribute ideas that highlight emerging research, cross-disciplinary collaboration, and impactful field experiences.

Whether you're a seasoned organizer or a first-time contributor, your proposal plays a key role in creating a dynamic and inclusive meeting.

Earn Continuing Education Units at Section Meetings

Section Meetings offer an excellent opportunity to earn CEUs toward your continuing education requirements for your employer, K–12 school, or professional registration. The CEU certificate may be downloaded from the meeting website after the meeting.

https://www.geosociety.org/GSA/GSA/edu-career/ceu.aspx

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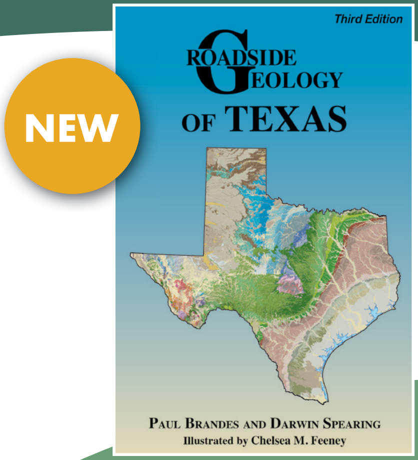

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