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Continental Magmatism and Uplift as the Primary Driver for First-Order Oceanic $^{87}Sr/^{86}Sr$ Variability with Implications for Global Climate and Atmospheric Oxygenation

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SCIENCE

Cover: Mountain peaks, glaciers, and prayer flags near the Kunzum La Pass, a high mountain pass connecting the Lahaul and Spiti valleys in the Indian Himalaya. Photo by Timothy Paulsen. See related article, p. 4–10.

GSA NEWS

Continental Magmatism and Uplift as the Primary Driver for First-Order Oceanic $^{87}Sr/^{86}Sr$ Variability with Implications for Global Climate and Atmospheric Oxygenation

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ABSTRACT

Oceans cover 70% of Earth's surface, setting it apart from the other terrestrial planets in the solar system, but the mechanisms driving oceanic chemical evolution through time remain an important unresolved problem. Imbalance in the strontium cycle, introduced, for example, by increases in continental weathering associated with mountain building, has been inferred from shifts in marine carbonate $^{87}Sr/^{86}Sr$ ratios. There are, however, uncertainties about the spatial and temporal patterns of crustal evolution in Earth's past, particularly for the period leading up to the Cambrian explosion of life. Here we show that U-Pb age and trace element data from a global compilation of detrital zircons are consistent with marine carbonate $^{87}Sr/^{86}Sr$ ratios, suggesting changes in radiogenic continental input into Earth's oceans over time. Increases in riverine Sr input were related to the break-up and dispersal of continents, with increased weathering and erosion of a higher proportion of radiogenic rocks and high-elevation continental crust. Tectonic processes exert a strong influence on the chemical evolution of the planet's oceans over geologic time scales and may have been a key driver for concomitant increases in atmosphere-ocean oxygenation and global climate cooling.

INTRODUCTION

Planetary differentiation has led to two fundamental types of crust on Earth: (1) continental, which tend to survive over long periods acquiring ancient rock records and evolved compositions; and (2) oceanic, which tend to be juvenile and rapidly recycled by subduction (Campbell and Taylor, 1983). According to standard models, continental crust is primarily formed by fluid flux melting in the mantle wedge above subducting hydrated oceanic plates as they are recycled into the mantle. This is then followed by fractional crystallization of mantle-derived magmas and/or partial melting of preexisting crustal lithologies (Hawkesworth and Kemp, 2006; Moyen et al., 2021). Collectively, these "distillation" processes have led to the development of a more felsic crust with a significant enrichment of incompatible elements, such as rubidium and strontium, with respect to the mantle as Earth has aged (Veizer, 1989; McDermott and Hawkesworth, 1990). However, the questions of how the continental crust has evolved chemically over time and how it has influenced Earth's oceans and atmosphere remain as fundamental unresolved problems.

Earth's present oceans have a uniform Sr isotopic composition ($^{87}Sr/^{86}Sr = 0.7092$) that primarily reflects the balance between radiogenic Sr input from weathering of the continents and unradiogenic Sr input from hydrothermal alteration of oceanic crust (Veizer and Mackenzie, 2014). Although $^{87}Sr/^{86}Sr$ ratios in marine carbonates are better documented for Phanerozoic versus Precambrian marine limestones, oceanic $^{87}Sr/^{86}Sr$ ratios appear to have departed from mantle values as early as ca. 2.8 Ga (Shields and Veizer, 2002) (Fig. 1A). This transition has been interpreted to mark a change from mantle- to river-buffered oceans as the continents rose and hydrothermal circulation of oceanic crust decreased as heat dissipated from Earth with time (Veizer and Mackenzie, 2014). $^{87}Sr/^{86}Sr$ ratios have subsequently risen in association with the differentiation of the crust, with rapid increases during two principal intervals in the Precambrian, namely in the Paleoproterozoic and Neoproterozoic (Shields and Veizer, 2002) (Fig. 1A). Identifying potential drivers for these shifts in marine $^{87}Sr/^{86}Sr$ ratios during the Precambrian is of widespread interest because of possible links to major perturbations in the global carbon cycle and hypothetical connections to changes in tectonism, climate, and atmospheric-oceanic oxygenation (Shields, 2007; Campbell and Allen, 2008; Sobolev and Brown, 2019).

The average Sr isotopic composition of the present oceanic crust is relatively uniform (~0.703), but the Sr isotopic composition of today's continental crust (~0.73 on average) is spatially highly variable (~0.703 to >0.73) due to a heterogeneous rock record that includes juvenile and ancient, evolved crustal components (Veizer and Mackenzie, 2014). The average Sr isotopic composition of today's rivers (~0.711) reflects a balance of the weathering of such sources on a global scale (Veizer and Mackenzie, 2014), but the dynamic nature of the solid Earth has likely led to changes in the proportion of radiogenic rocks being weathered on Earth's surface over time. This notion is supported by recent analyses of a global detrital zircon database, which have led to the conclusion that, at least for the past 1.0 Ga, increases in the $^{87}Sr/^{86}Sr$ ratios recorded in marine limestones generally coincide with decreases in the εHf composition of zircons produced by increased magmatic reworking of preexisting radiogenic crust (Bataille et al., 2017). Decreases in zircon

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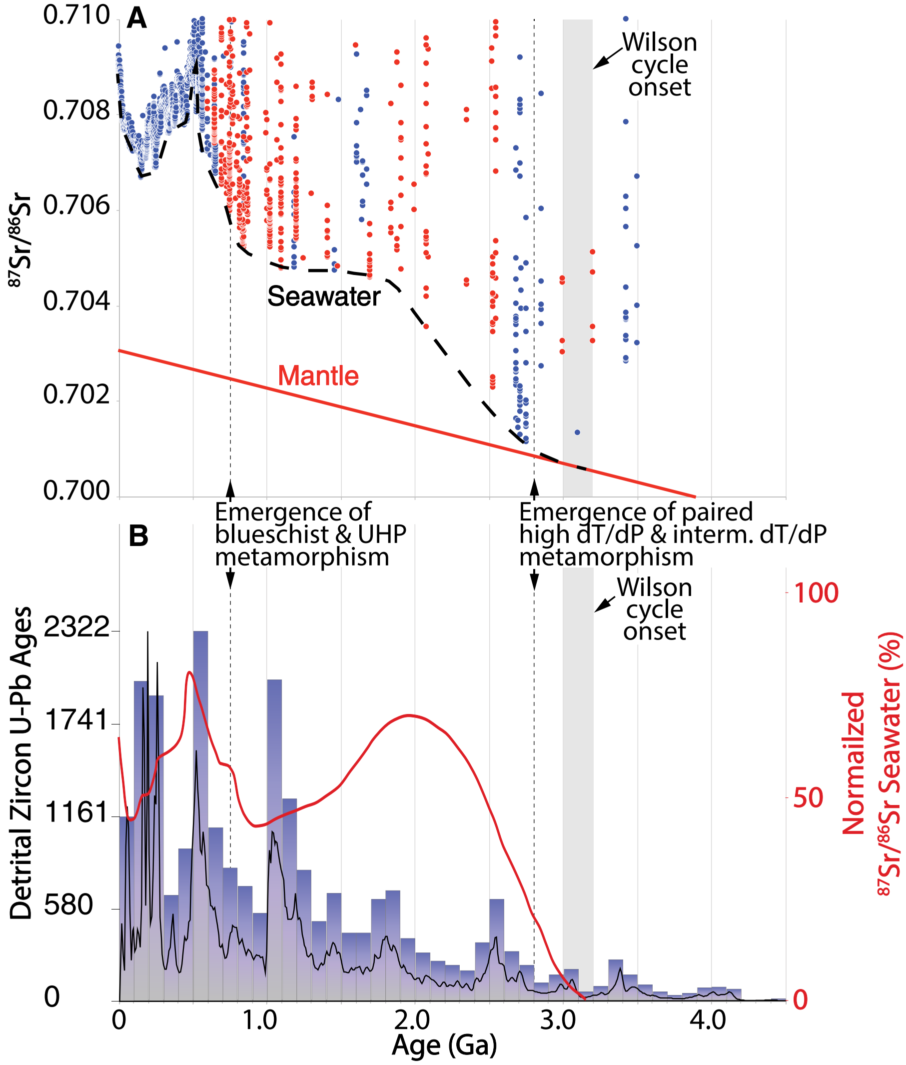

Figure 1. (A) $^{87}Sr/^{86}Sr$ evolution of seawater from marine limestones and fossils with respect to the mantle contribution (Shields and Veizer, 2002). Red data points are poorly constrained in age (greater than ± 50 Ma). (B) Normalized marine $^{87}Sr/^{86}Sr$ evolution from Shields (2007) with respect to kernel density estimate plot and histogram (Vermeesch, 2012) of cumulative U-Pb age data (*n* = 24,190) for the global compilation of detrital zircons analyzed in this study. Emergence of paired high dT/dP-intermediate dT/dP metamorphism and widespread ultrahigh-pressure (UHP) and blueschist metamorphism (cold subduction) from Brown and Johnson (2018), and Wilson cycle onset from Shirey and Richardson (2011).

εHf have been found to correlate with increases in whole-rock $^{87}Sr/^{86}Sr$ ratios (Bataille et al., 2017). Increases in oceanic $^{87}Sr/^{86}Sr$ ratios have, therefore, been linked to the production, and weathering, of extensive felsic igneous rocks along convergent margins involving subduction or collisions (Bataille et al., 2017). A plausible causal link exists because such rocks tend to be eroded rapidly due to their high elevations above sea level in proximity to oceans (Milliman and Syvitski, 1992).

Increases in the $^{87}Sr/^{86}Sr$ ratios recorded in marine limestones have recently been shown to correlate with changes in zircon trace element ratios indicative of increased crustal reworking and thickness recorded in Neoproterozoic to Triassic sandstones from Antarctica (Paulsen et al., 2020). Increases in crustal thickness lead to increases in continental elevation (mountain building), which has in turn been associated with increased Sr runoff into Earth's oceans (Edmond, 1992; Richter et al., 1992; Raymo and Ruddiman, 1992; Shields, 2007). Therefore, the record of increases in crustal assimilation and thickness from Antarctica may point to significant, punctuated releases of Sr from the continental reservoir. This represents a potentially important suite of coupled processes operating outside of the steady-state, and hence warrants investigation on a global scale.

This study integrates detrital zircon U-Pb age and trace element proxies for an exceptionally large global detrital zircon data set (*n* = 24,206) from samples derived from Earth's major continental landmasses to develop a better understanding of the petrotectonic evolution of continental crust through time and its potential link to the $^{87}Sr/^{86}Sr$ evolution of Earth's oceans (see Supplemental Material[1] for data, sources, and methods). The cumulative zircon age distribution binned in 0.1-Gyr age intervals in Figure 1B shows a series of age peaks similar to other global U-Pb detrital zircon age data sets (Campbell and Allen, 2008). The majority of zircons in this data set (Th/U >0.1) are expected to be derived from felsic igneous rocks formed along convergent margins, which represent the primary source for zircons within the geologic record (Lee and Bachmann, 2014).

PATTERNS OF CRUSTAL REWORKING

Thorium is an incompatible element that becomes enriched relative to other elements as continental crust matures (McLennan and Taylor, 1980). Therefore, increases in Th/Yb ratios in zircon should correlate with increases in the production of evolved felsic rocks associated with magmatic recycling of older radiogenic crust (Barth et al., 2013). Monte Carlo bootstrap resampling of the trace element record (to minimize the effect of sampling bias presented by zircon age peaks) shows that increased Th/Yb ratios are generally associated with two principal periods in the Precambrian since 3.0 Ga (Fig. 2A). The results suggest a higher proportion of magmas characterized by increased assimilation of radiogenic crust at 2.5–1.9 Ga and 0.7–0.5 Ga. Igneous zircon Th contents may be influenced by the presence of rare accessory phases (e.g., allanite) that compete to incorporate Th during crystallization (Kirkland et al., 2015). However, this pattern is also recognized on a global scale in the zircon Hf isotope record, the isotopic value of which is primarily controlled by the amount of crustal recycling in magmas. εHf-age values from a separate

[1]Supplemental Material. Table S1 (detrital zircon U-Pb age and trace element ratio global compilation, sample location maps, methods, and data sources). Go to https://doi.org/10.1130/GSAT.S.16942894 to access the supplemental material; contact editing@geosociety.org with any questions.

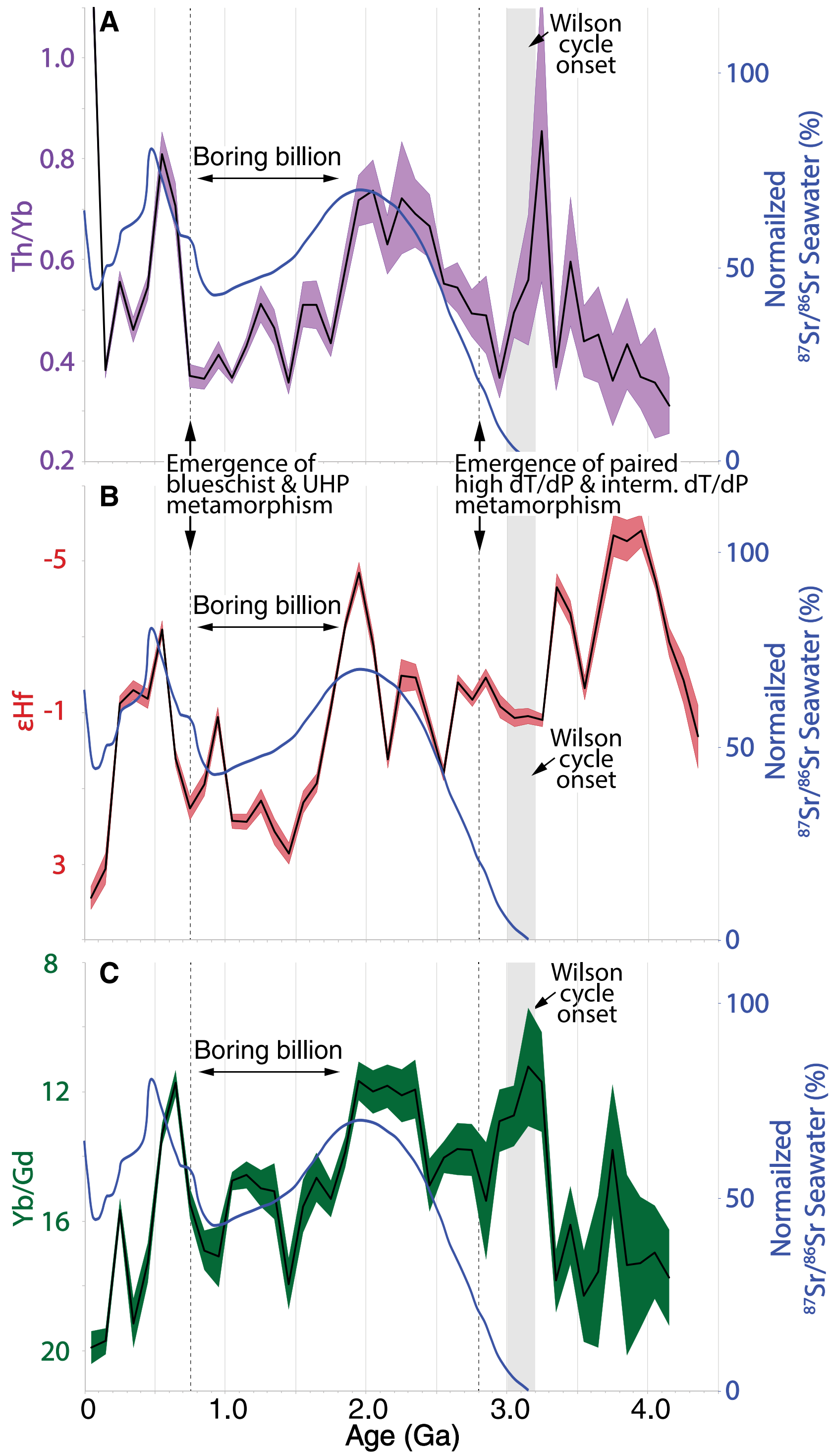

Figure 2. (A) Average Th/Yb (crustal input proxy); (B) εHf (crustal input proxy; note axis reversal); and (C) Yb/Gd (crustal thickness proxy) with their 95% confidence envelopes determined by Monte Carlo bootstrap resampling of zircons in 0.1-Gyr time brackets compared to normalized marine $^{87}Sr/^{86}Sr$ evolution. εHf data from Puetz and Condie (2019). Age of "boring billion" from Holland (2006). UHP—ultrahigh-pressure.

large detrital zircon data set (n = 70,656) show that significant negative deviations of εHf values correlate with these Th/Yb peaks (Fig. 2B). The $^{87}Sr/^{86}Sr$ isotope curve shown in Figures 2A–2B, which is normalized to model $^{87}Sr/^{86}Sr$ ratios of the global river and mantle inputs, shows increases that post-date the peaks in crustal assimilation indicated by zircon Th/Yb and εHf values—a time lag that may in part reflect processes such as weathering and erosion. The zircon trace element data are, therefore, consistent with the hypothesis that increases in the proportion of evolved magmas along convergent margins have had an important influence on radiogenic Sr input into Earth's oceans during these time intervals.

PATTERNS OF CRUSTAL THICKENING

Increases in magmatic reworking of pre-existing radiogenic crust should occur associated with thermal maximums as the crust thickens (DeCelles et al., 2009). Garnet is a mineral found in crustal magmas that is highly sensitive to pressure and incorporates heavy rare earth element (HREE)+Yb relative to other trace elements (Ducea et al., 2015). Therefore, changes in Yb/Gd ratios in zircon, for example, are thought to correlate with changes in the crustal thickness during magmatism (Barth et al., 2013). The trace element record retained within the zircon data shows that the lowest Yb/Gd ratios in the data set (Fig. 2C) correlate well with the Paleoproterozoic and Neoproterozoic Th/Yb and εHf peaks. These crustal thickness patterns are similar to those presented recently based on La/Yb ratios for a global compilation of 5587 detrital zircons (Balica et al., 2020). In particular, both analyses show Paleoproterozoic and Neoproterozoic peaks in crustal thickness that are separated by an intervening interval from ca. 1.8 Ga to 0.8 Ga during a period of environmental stasis known as the "boring billion" (Holland, 2006). The trace element data are therefore consistent with increased assimilation of radiogenic crust during periods of increased crustal thickness along convergent margins. Increases in crustal thickness are in turn associated with mountain building driven by tectonic shortening along Earth's major convergent plate boundaries involving advancing states of subduction and collisions. Thus, the patterns in the zircon trace element data are also consistent with the hypothesis that increases in the proportion of radiogenic rocks (e.g., older basement) uplifted and exposed along convergent margins have had an important influence on radiogenic Sr input into Earth's oceans (Richter et al., 1992).

CRUSTAL THICKNESS AND Sr FLUX

Geologists have long recognized that the widespread generation of continental topographic relief, which increases the overall surface area and potential energy, should correlate with increases in sedimentary flux into Earth's oceans. Analysis of Phanerozoic sedimentary rock records suggests that increasing sedimentary flux correlates with increases in $^{87}Sr/^{86}Sr$ ratios in marine limestones (Hay et al., 2001). Detrital zircon age peaks have been attributed to increases in sedimentary flux associated with widespread continental collisions and convergent margin magmatism (Campbell and Allen, 2008; McKenzie et al., 2016). However, other authors have favored increases in preservation for these age peaks (Hawkesworth et al., 2009), and zircon abundance does not always correlate with increases in $^{87}Sr/^{86}Sr$ ratios in Earth's oceans over time (Fig. 1B).

Increases in sedimentary flux derived from weathering of a greater proportion of elevated continental crust should, however, occur associated with an increase in flysch deposition. Flysch successions include interbedded graywackes and shales rich in quartz and feldspars, which, when water-saturated, are fertile sources for the generation of S-type granites (Collins and Richards, 2008; Zhu et al., 2020). Thus, S-type granite production may serve as a proxy for previous intervals of increased flysch deposition. We identified zircons that are likely to have been derived from S-type granite using the trace element discrimination procedure of Zhu et al. (2020), wherein S-type granites typically have elevated phosphorus concentrations relative to I-type granites because apatite $[Ca_5(PO_4)_3(OH,F,Cl)]$ crystallization is suppressed in the S-type magmas. To test the hypothesis that the peaks in crustal thickness were associated with an increase in S-type granites, we integrated S-type zircons identified within our data set with those found through an examination of zircons from 52 of Earth's major rivers (Zhu et al., 2020). Peaks in S-type zircon percentages overlap or even postdate the latter stage of increases in crustal thickness identified here (Fig. 3A). Thus, increasing radiogenic Sr input into Earth's oceans appears to be related to (1) the weathering of a greater proportion of radiogenic rocks produced and exposed as the crust thickened during the Paleoproterozoic and Neoproterozoic time intervals, and (2) concomitant increases in continental weathering and sedimentary flux into the oceans.

The results reviewed above provide important confirmation that increases in Sr recorded in marine carbonates correlate with first-order changes in convergent margin tectonism over time (Bataille et al.,

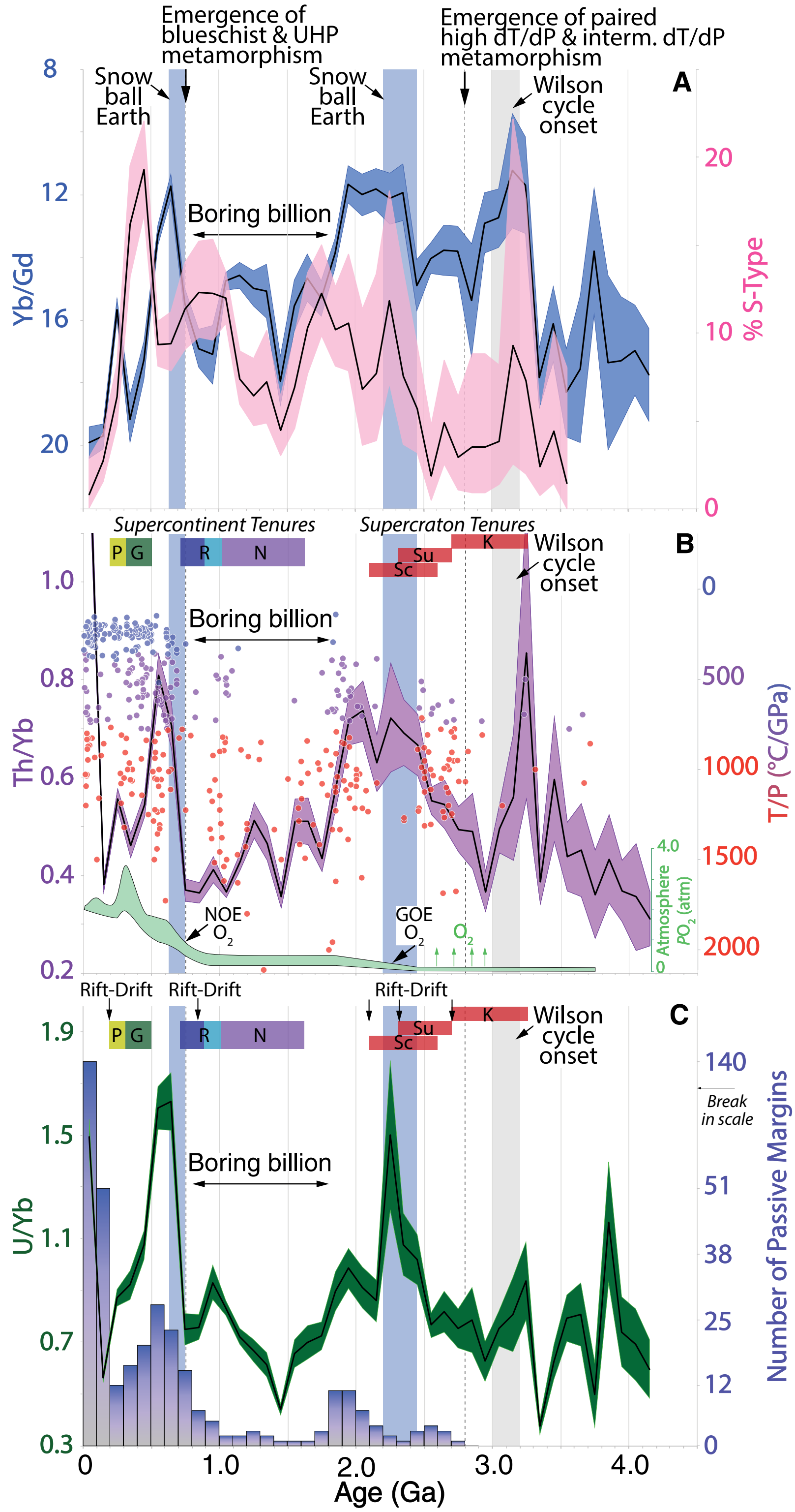

Figure 3. (A) Average Yb/Gd (crustal thickness proxy) compared to the percentage of S-type zircons with its 95% confidence envelope. (B) Th/Yb (crustal input proxy) compared to a global compilation of ages versus temperature/pressure (*T/P*) (°C/GPa) of high dT/dP (granulite–ultrahigh temperature [UHP]) (red); intermediate dT/dP (eclogite–high-pressure granulite) (purple); and low dT/dP (high-pressure–UHP) metamorphism (blue) from Brown and Johnson (2018). (C) U/Yb (crustal input and fluid input proxy) compared to a global compilation of passive margin abundance from Bradley (2008). Tenure of supercontinent/cratons from Bradley (2011), increases in atmospheric oxygen, early "whiffs" of oxygen (green arrows) and intervening boring billion from Holland (2006) and Lyons et al. (2014), and snowball Earth glaciations adapted from Sobolev and Brown (2019). Supercontinent/craton abbreviations: K—Kenor; Su—Superia; Sc—Sclavia; N—Nuna; R—Rodina; G—Gondwana; P—Pangea. NOE—Neoproterozoic oxygenation event; GOE—Great oxygenation event.

2017; Gernon et al., 2021). Increasing $^{87}Sr/^{86}Sr$ ratios in Cenozoic marine limestones have been associated with decreases in unradiogenic Sr flux related to lower seafloor spreading rates (Van Der Meer et al., 2014) and cooler ocean temperatures (Coogan and Dosso, 2015), suggesting that the cause of increased $^{87}Sr/^{86}Sr$ ratios in the oceans may be multifactorial. The ancient ocean crust record is in large part lost due to subduction (Scholl and von Huene, 2009), but our results suggest that increases in $^{87}Sr/^{86}Sr$ ratios in oceans have been strongly influenced by a continental component. If the increases in the proportion of radiogenic sources and sedimentary flux represent a coupled suite of processes as we contend, then they raise the question as to why convergent margin tectonism changed during these time periods. Insight into this issue comes from an examination of modeling and other proxy data sets to which we now turn.

SUPERCONTINENT PATTERNS AND SR FLUX

Modeling studies suggest that supercontinent tenures should be marked by elevated temperatures in the underlying subcontinental mantle with convergent margins in retreating states with arcs on thinner crust in outboard locations with respect to the continents (Lenardic et al., 2011; Lee et al., 2013; Lenardic, 2016). Temporal considerations based on multiple proxy data sets suggest that the lows in crustal recycling and thickness identified in the zircon proxy data overlap with the tenure of supercontinents over Earth's history (Figs. 3A–3B) (Bradley, 2011). For example, the low in crustal recycling and thickness during the boring billion correlates with the tenure of Nuna during a period dominated by high dT/dP metamorphism (Fig. 3B) and higher thermal gradients (Brown and Johnson, 2018). This pattern may reflect supercontinent insulation of the mantle (Brown and Johnson, 2018) associated with the development of hot back-arc environments (Hyndman et al., 2005) and a greater proportion of convergent margins in retreating states with arcs on thinner crust in outboard localities (Roberts, 2013; Paulsen et al., 2020; Tang et al., 2021).

Supercontinent break-up, by contrast, should lead to a release of potential energy stored in the underlying mantle (Lenardic, 2016). Thermal release of the mantle induces changes in the geodynamic state of the leading edge of continents by driving them into advancing compressional states of subduction and collisions involving arcs and continental blocks that favor crustal thickening (Lee et al., 2013). Increases in crustal recycling and thickness identified in the zircon proxy data correlate with an increase in passive margin abundance (Bradley, 2008) (Fig. 3C). These increases around the Proterozoic-Phanerozoic time interval also correlate with a decrease in thermal gradients of high dT/dP metamorphism (Brown and Johnson, 2018). Collectively, these patterns are consistent with supercontinent break-up driving a greater proportion of convergent margins into compressional advancing states and collisions with magmatism in thicker crust. High $^{87}Sr/^{86}Sr$ ratios in oceans during these periods are presumably due to increases in the proportion of exposed radiogenic sources and sedimentary flux from the continents associated with a reorganization of riverine drainage networks.

The correlations between the zircon proxy data and processes involving subduction outlined above warrants an examination of the U/Yb ratio in the zircon data set. The U/Yb ratio in zircon has been used as a proxy for crustal reworking (Verdel et al., 2021) but may also reflect the amount of subducting slab fluid addition in magmas, because U is a fluid-mobile large-ion lithophile element (LILE; K, Sr, Rb, Cs, Ba, Pb, U) extracted from slabs, and is, therefore, enriched relative to HREE such as Yb (Barth et al., 2013). U/Yb increases correlate with the increases in crustal assimilation and thickness we have identified (Fig. 3C), consistent with a higher amount of crustal recycling and flux of subduction fluid along a greater proportion of convergent margins during these periods. We, therefore, conclude that the increases in riverine Sr input into Earth's oceans were related to geodynamic changes in convergent margin networks, which were required to accommodate the birth and maturation of new ocean basins created by supercontinent break-up and dispersal. These episodes were associated with increased weathering and erosion of radiogenic rocks along convergent margins and greater expanses of uplifted, higher-elevation radiogenic crust found along the leading edges of continents. Increases in riverine Sr were likely amplified by the exhumation of continental crust associated with rifting (DeLucia et al., 2018), which is consistent with the general thesis supported here, that increases in riverine Sr are primarily driven by tectonism induced by global changes in plate margin networks. Increasing $^{87}Sr/^{86}Sr$ compositions in Cenozoic marine sediments have also been associated with glaciation (Palmer and Elderfield, 1985). Snowball Earth deglaciation likely contributed to the Paleoproterozoic and Neoproterozoic Sr excursions (Sobolev and Brown, 2019), but the data reviewed here suggest that tectonism played a major role. Collectively, the balance of these processes is likely recorded in today's continental rock record by the great unconformities at the Precambrian-Phanerozoic and Archean-Proterozoic boundaries (Windley, 1984; Peters and Gaines, 2012).

BROADER IMPLICATIONS

Our results suggest that increases in $^{87}Sr/^{86}Sr$ ratios in oceans occur when a greater proportion of continental crust is thick and high, leading to increases in evolved felsic magmatism, radiogenic basement exposure, and riverine sedimentary flux. From a broader perspective, the results raise the important question of whether solid Earth processes play a fundamental role in modulating global climate and atmospheric oxygenation over geologic time scales. If the correlations outlined above are representative of a global tectonic pattern as we contend, then the generation of continental relief highlights the introduction of a significant silicate weathering sink associated with the drawdown of CO_2 and associated transition into periods of global glaciation (Hoffman and Schrag, 2002) (Fig. 3). Uplift associated with convergent margin tectonism may therefore have further enhanced CO_2 drawdown associated with the exhumation and weathering of rocks associated with continental rifting and dispersal (Donnadieu et al., 2004; DeLucia et al., 2018). Continental uplift has also been previously postulated to be linked to steps in oxygenation of Earth's atmosphere during the Paleoproterozoic and Neoproterozoic through enhanced erosion and nutrient supply to the oceans, as well as changes in the proportion of subaerial volcanism (Campbell and Allen, 2008; Gaillard et al., 2011) (Fig. 3B). Oxygenation may have fostered the decrease of CH_4, a potent greenhouse gas (Fakhraee et al., 2019), while uplifts along convergent margins promoted nascent glaciation in cooler, high-elevation habitats, providing further feedback (albedo) for a runaway global glaciation. The ultimate drivers for these important steps in Earth's evolution are controversial and likely involved a complex set of variables and inextricably linked feedbacks. However, in general terms, potential links between the solid Earth and the evolution of its climate, atmosphere, and oceans are highlighted by recent modeling that suggests that global climate may ultimately be modulated by changes in outgassing and weathering sinks associated with mantle thermal states during the assembly and break-up of supercontinents (Jellinek et al., 2020). While the oceans have played a fundamental role in the geochemical evolution of the continents (Campbell and Taylor, 1983), the continents have, in turn, shaped the oceans and perhaps major evolutionary steps in Earth's global climate and the oxygenation of its ocean-atmosphere system.

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Minerals Matter: Science, Technology, and Society

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The expertise of earth scientists is crucial for solving some of today's most pressing challenges, including global warming and the climate crises, natural hazard reduction, water and soil quality, exploration for critical elements for our technological society, and many others.

INTRODUCTION

Minerals, the solid material comprising planet Earth, are within the intellectual realm of earth scientists but are much more fundamental to science, technology, and society. From the beginnings of humankind, Earth's minerals have been essential for technological advances. Prior to written language, paintings made of mineral pigments adorned caves. The advent of human-produced fire owes its source to two minerals: pyrite and flint. Early Homo species were likely the first mineralogists, separating different minerals into useful tools based on their physical properties to identify, in part, those minerals that perfectly fractured when worked. Utilization of different minerals through melting, smelting, or physical manipulation defines the Ages of Man: Stone, Bronze, Iron, and Technology. Minerals are important basic resources that can inform us about how solid materials work on the atomic level and be modified to humanity's benefit. They serve as templates for technologically advanced materials, necessary to fulfill many societal needs.

The attributes of minerals to science, technology, and society are illustrated by a single mineral, elbaite. Elbaite is a species of the tourmaline supergroup that incorporates nearly the entire periodic table in its structure (Fig. 1). For geoscientists, it embeds unparalleled geologic information when properly interpreted; for technology, it was utilized during WWII as a pressure sensor to monitor underwater explosions due to its piezoelectric properties; and for society, it is a mineral that contains lithium, an element critical to powering modern electronic devices.

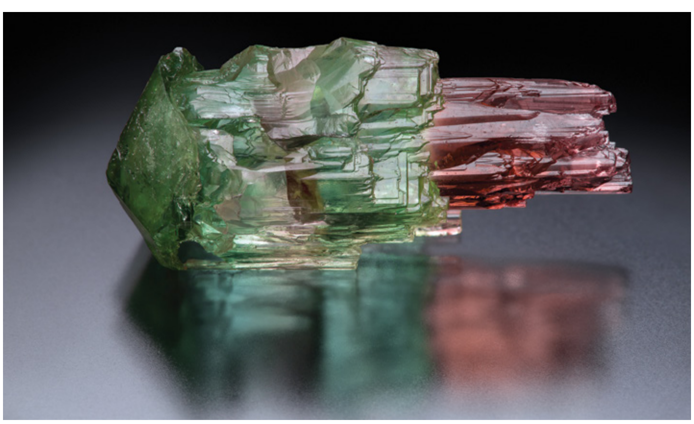

Figure 1. Elbaite crystal, a species of the tourmaline supergroup containing lithium, showing its noncentrosymmetic growth along the long axes (c) which is responsible for its piezoelectric (and pyroelectric) properties, contributing to its utility as a technological material. Color change reflects incorporation of different chemical elements in response to its host environment.

The expansive subject of minerals is familiar to Geological Society of America (GSA) audiences. Several past presidents have spoken on minerals and related topics, presumably beginning with the second president of GSA, James Dwight Dana, in 1890—perhaps best known for his enduring textbook *The Manual of Mineralogy*, first published in 1848 (J.C. Wiley and Sons), and now in its twenty-third edition (Klein and Dutrow, 2007). Why should we continue to care about mineral sciences in the twenty-first century? Because minerals still matter.

Figure 2. Banded iron formation, a source for iron, a critical component of steel and other manufactured materials. Iron was one of the earliest mined and smelted minerals.

ESSENTIAL BUT UNDERVALUED

Minerals are vastly underappreciated, and the science of mineralogy is disappearing despite their centrality to society and to the earth sciences. Minerals (continue to) power our lives. They are used in nearly every aspect of our lives, yet do we think of minerals when we walk on planet Earth or answer the cell phone or turn on the lights or start the car? The U.S. Geological Survey (USGS) reports that an average automobile "contains more than a ton of iron and steel, 240 lbs of aluminum, 50 lbs of carbon, 42 lbs of copper, 22 lbs of zinc, and 30 other mineral commodities" (USGS, 2021). These materials do not include the cerium used to polish mirrors or the other components in hybrid or electric vehicles. One primary reason for their underappreciation is that, for the most part, we do not use minerals, per se; we utilize their contents—their chemical constituents (Fig. 2). From aluminum to zinc, the elements extracted from minerals form the basis for advanced materials for our ever-improving standard of living.

While mineralogy, or mineral sciences, has been taught largely as an underpinning subject or in support of other earth-science fields (e.g., petrology or geochemistry), its utility to all facets of science, technology, and society elevates this discipline well beyond the geosciences. As industry and governments look to a sustainable

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future and Environmental Social Governance (ESG) guides business decisions, the earth sciences, specifically mineral sciences, are ever more important to provide foundational information.

Yet, the study of minerals has dwindled, gradually disappearing from the earth-science curriculum, particularly in the U.S. (e.g., Nietzel, 2020; Bierman, 2021). Commonly viewed as "too traditional," mineralogy classes have been reduced in many curricula, compressed into another class (e.g., "earth materials"), or abandoned altogether and expunged from the curriculum, with the concomitant loss of critical expertise. No funding agency supports "mineralogical research" per se. One recent editorial described how difficult it is to find properly trained mineralogists in the U.S. (R. Ewing, personal commun., 2021).

This short article provides a case for mineralogical expertise and implores earth scientists to re-engage with this discipline, because its foundational knowledge and skill sets are integral to earth-science solutions required to tackle some of society's most challenging problems. Additionally, embracing mineralogy in all its forms, by supporting mineralogical research and education, provides fundamental information required to help solve many of Earth's most closely guarded secrets. The criticality of mineralogical knowledge is demonstrated by connecting the mineral sciences across scientific disciplines and into the realm of humankind by providing select examples in science, technology, and society.

To geoscientists, the value of minerals to science is broadly recognized. Resulting from complex planetary processes, minerals are extraordinary archives of Earth's mysteries, allowing scientists to decipher ~4.5 billion years of embedded history. For example, the minerals in a pallasite meteorite contain clues to the composition, formation conditions, and evolution of the early Solar System, with implications for core-mantle development of Earth. Glacial ice, a mineral, shapes continents, modulates Earth's surface temperatures, and moderates climate variations; it also traps gas bubbles that sample prehistoric CO_2 and CH_4 levels. Other minerals, such as calcite, can record in their oscillatory zoning patterns the thermal, chemical, and mechanical interactions in complex geosystems. Portions of the biosphere, such as pollen grains, invertebrate exoskeletons, and vertebrate bones and teeth are (bio)minerals. Their former presence, now as fossilized remnants of past life, owe their persistence to mineral replacement (Fig. 3).

Figure 3. Belemnite, replaced by the mineraloid opal, preserves former remnants of life. Early Cretaceous: 135 Ma. From Coober Pedy, South Australia. © Jeff Scovil photo. Rob Seilecki specimen. Used with permission.

While mineralogy is deeply embedded in most aspects of the earth sciences (Fig. 4), mineralogy bridges disciplinary boundaries and connects earth sciences to other science, technology, engineering, and mathematics (STEM) fields. One such example was recently released by the American Chemical Society in their "reaction" series titled "Are we standing on a quadrillion diamonds?" (ACS, 2021). Chemists are capitalizing on the inspiration and engagement of chemical reactions to make (natural) minerals—clearly trying to take the spotlight from the geosciences. Much of materials science and advanced materials research is built on templates from nature (i.e., minerals). This approach has been largely in the domain of chemists and physicists—yet earth scientists have much to contribute. Because of my mineral-science background, I had the pleasure of serving as a Ph.D. committee member in the chemistry department for a candidate studying the crystal structure of MoS_2, which mineral geoscientists know as molybdenite. During the questioning, I asked the candidate if they could identify the shiny, gray, foliated sample of MoS_2 I proffered. He looked at me quizzically and replied that he had no idea that MoS_2 was an actual mineral that occurred naturally on Earth. Clearly, geoscientists with a mineralogical background can inform the STEM community about mutually beneficial subjects. Geoscientists understand complex, heterogeneous, multicomponent, and natural materials over ranges of spatial scales and through time, and are superb analysts, providing natural connections to these disciplines. As such, mineralogy is a translational science, within and outside of the earth sciences.

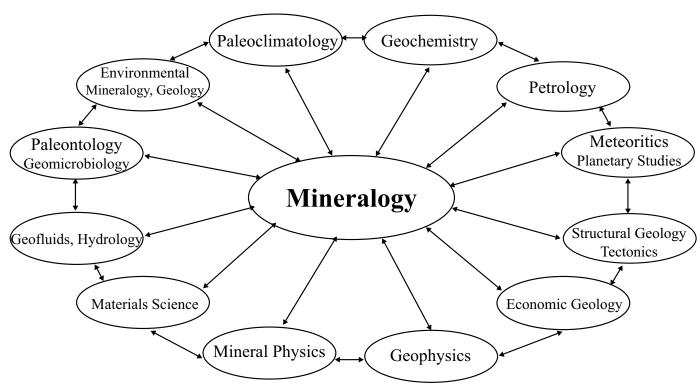

Figure 4. Centrality of mineralogy to earth-science disciplines (modified from Klein and Dutrow, 2007).

MINERALS AND CLIMATE

Although a myriad of examples is available to demonstrate the value of minerals in technology and society, this article focuses on select mineralogical contributions that will serve as integral components to mitigate the climate crises. These examples include (1) mineral trapping as one method for carbon capture and long-term storage; (2) mineral constituents as essential materials for the energy transformation, highlighting renewable energy and electric vehicles; and (3) minerals as templates for advanced functional materials.

Mineral Trapping

As the world struggles with the impact of climate change, carbon capture and long-term storage are required for reducing greenhouse gas emissions into the atmosphere, stabilizing and lowering carbon dioxide levels, and ensuring a more robust sustainable climate path into the future. Sequestering greenhouse gases can, in part, be achieved by chemical reactions with minerals for one effective approach to carbon sequestration, that is, mineral trapping (e.g., Seifritz, 1990; Oelkers et al., 2008). Magnesium-rich minerals (e.g., olivine, serpentine) react with carbon dioxide to form carbonate minerals that sequester the carbon [e.g., *serpentine + carbon dioxide = magnesite + quartz + water;* $Mg_3Si_2O_5(OH)_4 + CO_2 = MgCO_3 + SiO_2 + H_2O$]. Not only is this method geologically rapid—kinetics from both the lab and the field suggest mineral trapping occurs in about two years (Matter et al., 2016)—it results in more permanent storage for carbon than for other geologic mechanisms of trapping (e.g., Oelkers et al., 2008). According to the International Energy Agency (IEA, 2021), there are ~20 commercial carbon-capture, utilization, and storage facilities worldwide, with 30 more planned. Earth scientists with an understanding of mineralogy and mineral-fluid interactions are essential for this 4-billion-dollar industry.

Critical "Minerals"

Across the spectrum of renewable "clean" energy technologies, elements obtained largely through the mining of particular minerals, and less commonly the minerals themselves, are critical for implementation. Topping IEA's list of overall critical elements are copper, nickel, chromium, and zinc, along with rare earth elements (REEs), cobalt and lithium for battery storage, and aluminum for electricity networks (IEA, 2021). While the absolute amount varies depending on the energy system, stated governmental policy goals, future planning scenarios, and technological advancements, the ability to secure mineral commodities is the fulcrum in achieving the energy transition away from fossil fuels. This need is crucial for electric vehicle (EV) and battery technologies. REEs, essential in the manufacture of hybrid and electric cars, high-strength magnets for wind turbines, and solar energy panels, are housed in unusual minerals or adsorbed onto their surfaces. The demand for REEs continues to outstrip supply, a situation likely to continue unabated even as new sources are discovered (e.g., monazite sands; Network NewsWire, 2021). Knowledge of mineralogy and mineral systems is needed to locate new resources as demand increases, and to mine, extract, and manufacture materials and their byproducts in responsible ways to minimize environmental damage and human-health impacts.

The global clean energy transitions will have far-reaching consequences for mineral demand over at least the next 20 years. IEA predicts that by 2040, total mineral demand from clean energy technologies will double in some scenarios and quadruple in others (IEA, 2021). EV and battery storage account for about half of the mineral demand growth, largely for battery materials (lithium, graphite, cobalt, nickel, manganese). To support this increasing technological demand, mineral requirements will grow tenfold to over 30 times over the period to 2040. By weight, graphite, copper, and nickel dominate. The need for lithium has the fastest growth rate, predicted to be more than 40 times current requirements, although new battery technologies may dampen some of this demand (IEA, 2021).

Current battery technology alone will have significant implications for specific elements. A single lithium-ion EV battery pack (CNM532) contains ~8 kg of lithium, 35 kg of nickel, 20 kg of manganese, and 14 kg of cobalt (Castelvecchi, 2021). With the prediction that in ~15 years 50% of the global passenger fleet will be electric (IEA, 2021), hundreds of millions of vehicles will carry batteries that require immense quantities of these of critical materials.

Most lithium derives from minerals, making minerals the lynchpin for progress. Spodumene, $LiAlSi_2O_6$, is the most commonly mined and abundant mineral used for lithium extraction (Table 1, Fig. 5; Bowell et al., 2020). Spodumene contains 3.7 weight percent (wt%) Li per formula unit. Thus, 214 kg of pure spodumene are needed for a single car battery! Recently, spodumene was priced at an all-time high of US$2240/tonne (from western Australia). Worldwide estimates of lithium reserves suggest more than 62 Mt (Bowell et al., 2020). As IEA notes, this massive industrial conversion marks a "shift from a fuel-intensive to a material-intensive energy system" (IEA, 2021). Minerals are the key—they are the reservoirs for our technological future.

Table 1. Major minerals from which lithium is extracted

Minerals*	Li_2O (wt%)	Chemical formula
Spodumene#	6–9	$LiAlSi_2O_6$
Petalite	4.71	$LiAlSi_4O_{10}$
Lepidolite (series polylithionite-trithionite)	4.19	$KLi_2Al(Si_4O_{10})(F,OH)_2$ to $KLi_{1.5}Al_{1.5}(Si_3AlO_{10})(F,OH)_2$
Amblygonite–Montebrasite	7.4	$LiAlPO_4F$ to $LiAlPO_4(OH)$
Eucryptite	9.7	$LiAlSiO_4$
Triphylite	9.47	$LiFe^{2+}PO_4$

*Data from Bowell et al. (2020).
#8 kg Li = 214 kg spodumene.

Figure 5. Spodumene, a primary source of lithium. (A) Specimen 28 × 15.6 × 2.2 cm. Big Kahuna II zone, Oceanview Mine, Pala District, San Diego County, California, USA. Oceanview Mines, LLC, specimen (20120615–01); (B) spodumene in the rock. © Mark Mauthner photos, used with permission.

Minerals as Templates

Minerals can act as functional templates for advanced materials underlying renewable energy systems. "Wide ranges of additional minerals are used and will be used as the energy landscape is transformed to more renewable, cleaner energies" (Saucier, 2021). Geoscientists with an understanding of minerals, their structures, and compositions, are the "backbone" of the energy transition (Saucier, 2021). Earth scientists are familiar with the perovskite group of minerals. The magnesium-silicate perovskite species, bridgmanite ($MgSiO_3$), comprises ~70% of Earth's lower mantle (Tschauner et al., 2014), which is ~38% of Earth's total volume. Volumetrically, it is the most abundant mineral in planet Earth. Its flexible crystal structure allows for a wide range of possible chemical substituents; it can be engineered to incorporate REEs, making this material extremely useful as a functional material. Their ability to be fabricated in thin films makes perovskites ideal for solar photovoltaic cells (Fig. 6). Perovskite photovoltaics are an emerging technology due to their high efficiencies for converting sunlight to energy. Recent advances to scaling up production of these high-efficiency perovskite solar cell modules have introduced organics into the perovskite precursor—allowing a uniform thin film to be deposited across the entire photovoltaic module area (Huang et al., 2021).

Figure 6. Panel of solar photovoltaic cells at the GSA Headquarters in Boulder, Colorado, USA; used with permission. Perovskite photovoltaics potentially replace the more common silica-based solar cells and have a higher efficiency.

Minerals with a rigid structure and channels that are flexible at different pressures and temperatures are vital to new, improved functional materials. Such mineral properties allow for ionic to superionic mobility, which is critical for developing the next generation of solid-state electrolytes, and power our transition toward a fully renewable future. The feldspathoid analcime is one such mineral, with its channel structure and sodium atoms, and has an onset of super ionic conductivity (D. Palmer, personal commun., 2021; Fig. 7 [see Supplemental Material[1]]). Zeolite minerals, which also have channel structures and flexible chemistry, have long been used as manufactured materials for molecular sieving and catalysis. For a newer perspective in mineral science, an inside view of a resource needed for transitioning to a renewable energy future is shown in Figure 7 (and see footnote 1). Two crystal representations display the crystal structure showing the position of the ions, the channels, and many of the bonds at an atomic view. One can transform in your mind between the two crystal structure representations, as do our students, to improve the ability to see in 3D. Such knowledge of minerals, their crystallography, and their thermodynamic properties translates through technology and engineering and leads to new advances for materials critical for saving planet Earth in a new, Earth-forward perspective.

DUCT TAPE

These examples show that mineralogy is like duct tape—knowing how to use it can solve many problems! Minerals can be part of the solution for some of today's stickiest challenges. By the

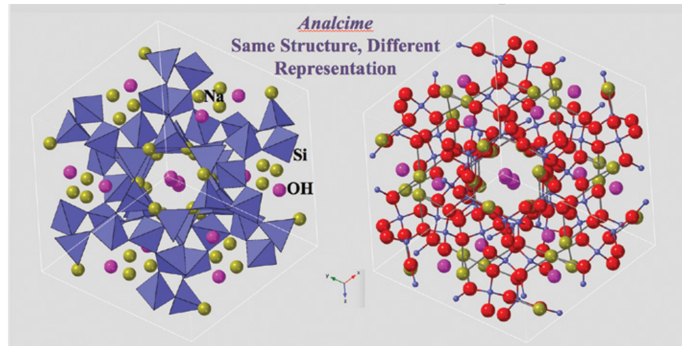

Figure 7. Two representations of the analcime ($NaAlSi_2O_6 \cdot H_2O$) structure, down [111], showing the location of the ions, the channel structure, and several bonds. Polyhedral model (left), ball and stick model (right). (Each representation can be transformed into the other to enhance an ability to see in 3D.) Such minerals have properties for superionic mobility of ions, needed for renewable energy systems. See footnote 1 for a link to the animation.

way, minerals are what make duct tape's stickiness so special. It's stickiness is due to zinc—a chemical element extracted from the mineral sphalerite (ZnS).

MINERALS ARE ESSENTIAL

Minerals are critically important for powering our future, and mineralogical expertise is essential for unleashing their full potential. Knowing where to explore for specific mineral constituents and how to protect the environment during extraction are paramount to safely securing critical minerals. Understanding minerals, crystal structures, structural constraints, elemental substitutions, and analytical techniques for analyses bridges the earth sciences to other STEM disciplines and leads to computational and experimental advances in new materials, patterned on natural minerals, as resources for transitioning to a cleaner, renewable, energy future. When you turn on the lights, use your cell phone, or start the car, think of the minerals that underlie our technologically rich society and impact our daily lives. "We don't buy minerals, we need their constituents" (USGS, 2021). Today, the vastness of minerals essential to our technological lifestyles cannot be overstated. Let's appreciate minerals in all their scientific enormity.

The time is now for minerals to move to the forefront as the domain of earth sciences and for the geoscientists to embrace this domain by teaching, learning, funding, exploring, and promoting an understanding of minerals for the future of society, as a technological imperative and as a scientific endeavor. Minerals matter!

ACKNOWLEDGMENTS

My appreciation to Darrell Henry, Nina Rosenberg, and Pamela Kempton for their thoughtful reviews, together with Wendy Bohrson, Dave Mogk, and many other colleagues for unwavering support of this topic. To my many mineralogy students over the years, who asked for more mineralogy classes and encouraged my development of minerals in context, thank you. David Palmer of CrystalMaker (TR) is thanked for sharing his insights on superionic conductivity, for developing the powerful visualization program Crystalmaker, and for making the animation (Fig. 7 [see footnote 1]). Mark Mauthner and Rob Sielecki generously provided photographs.

[1]Supplemental Material. Animation flies through the mineral structure of analcime, a mineral with ionic to superionic conductivity. Structure is represented by a ball (showing atoms) and stick (showing bonds) model. The beginning view is a "surface cell" perpendicular to the channel axis looking down <111> to view the pseudo-trigonal representation. Channel axes is 273 Angstroms wide. First image is about 23 times the channel width or 1288 unit cells. Courtesy of David Palmer, CrystalMaker. Go to https://doi.org/10.1130/GSAT.S.17320556 to access the supplemental material; contact editing@geosociety.org with any questions.

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NAGT

2021 Outstanding Earth Science Teacher Awards

The National Association of Geoscience Teachers (NAGT) has announced the 2021 Outstanding Earth Science Teacher Awards. 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 membership in GSA for three years. State winners receive a one-year complimentary GSA membership. Read bios at https://nagt.org/nagt/awards/oest/2021_oest.html.

SECTION WINNERS

Central Section: Christopher Bolhuis, Hudsonville Public High School
Eastern Section: James "JR" Bunner, Parkersburg High School
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Louisiana: Erin Nevala
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Pennsylvania: J Atkins
South Carolina: Hannah Quinley
West Virginia: James "JR" Bunner

2021 GSA J. David Lowell Field Camp Scholarship Awardee Report

Lauren Nickell

I find myself continuously blown away by the combination of extreme beauty coupled with the relentless heat of southern Utah's landscape. This summer marked my final semester as an undergraduate pursuing a B.S. in geology at Southern Utah University, and the five weeks only further cemented my desire to dedicate my life to this career path. Out of these five weeks, three and a half were spent wandering across large swaths of land to map highly complex and diverse lithologies. These four spots were in various areas across the southwest Utah region, including the Red Hill outside of Cedar City, First Lefthand Canyon on the Dixie National Forest, Goldstrike Mine, and finally Parowan Gap. Week one, spent on the Red Hill, was a complete shock to me. Despite having spent the past four years less than a 5-minute drive away from this location, the four days at this site were full of head scratching moments, friendly debates, and more sketching than I could have ever imagined. The intricacies of a site that I had gazed upon for eight prior semesters became apparent very quickly, and the experience only fueled my love of geology. This carried over into the following weeks as we explored farther out, taking time to comb through sites that I was unfamiliar with in the surrounding region.

What time wasn't spent mapping areas that have housed various tectonic activity over the past couple hundred million years was used to focus on more specific questions. The best example of this was our time spent at Bryce Canyon during week three, where our professor, Casey Webb, had conducted his master's research. Instead of trying to map an area that was entirely composed of the Claron Formation, we collected many measurements with Brunton compasses across different sections of the park and then used that to map out likely tectonic forces. The beach ball diagrams created through the class's measurements, along with our regional context of the area, allowed us to draw conclusions that aligned well with Professor Webb's research. The overlaying faults present due to both compressional and extensional forces on the Paunsaugunt Plateau had provided the perfect combination of strengths and weaknesses in the lacustrine Claron deposits to form the phenomenal hoodoos seen throughout Bryce Canyon National Park today.

Week three, Nickell on the Navajo Loop Trail looking toward the main amphitheater of Bryce Canyon with Powell Point (the Aquarius Plateau) in the distance.

Week three, on the Powell Ranger District of the Dixie National Forest. The class sits below an area of heavily exposed slickensides on the Claron Formation as Casey Webb conducts a lecture.

It has been an absolute gift to begin my career in geology in the Four Corners region. The opportunities I have been able to pursue over the past four years are incredibly unique and have provided me with the necessary reassurance to continue on to a graduate program in Vancouver, British Columbia, studying geomorphology in relation to wildfires. The scholarship I received gave me the ability to completely throw myself into the five-week-long field course offered by Southern Utah University, and I have walked away from this program—and my bachelors—with a profound love of a landscape that has shaped who I am and who I aim to be in the coming years. I can only hope that my engagement with this field sparks interest in the minds of those who have also faced adversity in a career path often dominated by a specific group, and that the individuals I meet along the way only contribute to the diversification of a field with so much left to explore. As a recipient of the GSA J. David Lowell Field Camp Scholarship, I would like to say thank you to both GSA and Brunton for supporting me in such a significant way this summer.

Note: If you are able to help students like Lauren attend field camp and pursue their geoscience training, you can make a gift now at https://gsa-foundation.org/fund/field-camp-opportunities or contact Debbie Marcinkowski at +1-303-357-1047, dmarcinkowski@geosociety.org, for more information. To apply for a J. David Lowell Field Camp Scholarship, go to **www.geosociety.org/field-experiences.**

J. David Lowell Field Camp Scholarships

GSA and the GSA Foundation are proud to announce that J. David Lowell Field Camp Scholarships will be available to undergraduate geology students for the summer of 2022. These scholarships will provide students with US$2,000 each to attend the field camp of their choice. Applications are reviewed based on diversity, economic/financial need, and merit.

Application deadline: 25 Mar.

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Questions? Contact Jennifer Nocerino, jnocerino@geosociety.org.

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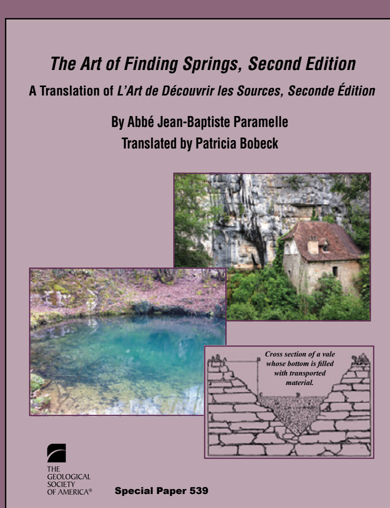

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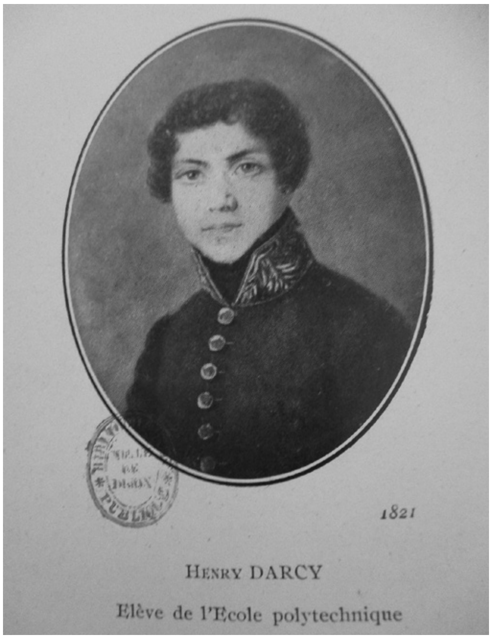


Henry Darcy, age 18. Student at Ecole Polytechnique, 1821. Courtesy: Bibliothèque municipale de Dijon.

INTRODUCTION: DARCY AND THE SOCIO-POLITICAL BACKGROUND OF 19TH CENTURY FRANCE

Henry Philibert Gaspard Darcy was born in Dijon, France, on 10 June 1803, during Napoleon's rise to power after the French Revolution. Napoleon's support for engineering and opportunity for talented youth made Darcy's career possible. Napoleon's educational reforms survived the Bourbon (deposed king's family) restoration from 1815 to 1830; Darcy completed his studies during these years. The 1830 revolution brought Louis Philippe, a member of the Orleans branch of the Bourbons, to power in a constitutional monarchy (1830–1848). During this period, Darcy proposed, planned, and built the Dijon water system. Between 1848 and 1858, Darcy was ousted from Dijon, was promoted to the highest rank of the engineering corps, worked in England and Belgium, conducted research on pipes and filtration, and published Darcy's Law.

DARCY'S YOUTH

Henry's father, Joseph, a Dijon tax collector, married Agathe Serdet, daughter of a Burgundy Parliament prosecutor, in 1802. Henry's younger brother, Hugues-Iéna, born in 1807, was named for a Napoleonic victory. Joseph died in 1817, leaving Agathe in difficult straits. When their father died, Henry, age 14, told Hugues that he, Henry, would "be the father." He asked Hugues to work hard so they could earn their bread and their mother's honor (P. Darcy, 1957). Agathe expended great effort to educate her sons, and the three remained close for life.

At age 12, Henry won a scholarship that led to further studies. At age 18, he won physics and math prizes and passed the entrance exam to the Ecole Polytechnique, established in 1794 (EP website). After graduation, Darcy entered the Ecole des Ponts et Chaussées (School of Bridges and Roads), and upon completion of his studies, joined the Corps des Ponts et Chaussées, where he spent his entire career.

At the request of the department of Côte d'Or, Darcy was assigned to Dijon in May 1827. In 1828, after promotion to ordinary engineer, he married Henriette Carey, daughter of an Anglican clergyman from the Isle of Guernsey, and sister of a childhood classmate. Henry and his wife had no children.

DARCY'S FIRST PROJECT: WATER FOR DIJON

In the early 1800s, Dijon had a meager supply of poor-quality water. Residents collected rain from rooftops and used well water from a shallow contaminated aquifer. Henry was sickened by the water he drank as a child, and he vowed to do something about it if he ever had the chance (P. Darcy, 1957). He was working in Dijon in 1829 when the city drilled a non-productive artesian well. An 1832 cholera epidemic further underscored the need for water.

In April 1832, the mayor of Dijon asked Darcy to prepare a report on ways to supply water to the city (Lochot, 2003). Darcy tackled the problem with enthusiasm; he studied all water supply ideas proposed since the 16th century and gauged all surface and groundwater resources. He consulted other cities to determine per capita water needs. The Rosoir spring, located in the Suzon valley northwest of Dijon, provided enough water (150 liters/person/day, considered sufficient at the time), and a chemical analysis showed the water to be pure. In 1833, at age 30, Darcy submitted a proposal to deliver Rosoir water to Dijon by gravity through a 12.7- km aqueduct. The French government approved the plan in 1837; land was purchased by 1838. Darcy began construction on 21 March 1839, and water arrived in Dijon on 6 September 1840.

The Dijon distribution system provided free, pure drinking water to 142 street fountains spaced at 100 m intervals. The water was also used to wash streets, flush a stream-turned-sewer that crossed the city, and fight fires. The system was completed in 1845, and the sewer was built by 1847. Dijon became Europe's second city (after Rome) for water quality and quantity.

RAILROAD FOR DIJON

Darcy's first rail transport project, in 1829, was a horse-drawn line to carry coal. In 1832, he was asked to consult on the Paris-to-Lyon rail line, a major artery of the proposed national system. Amidst political controversy, Darcy proposed a route that crossed the divide between Paris and Dijon via a 4.1-km tunnel.

Geologist Elie de Beaumont examined the Jurassic limestone along the route, excavated shafts to inspect it, and declared the rock competent. Darcy's plan was approved; he supervised more than 2,000 workers at the work site from January 1845 until July 1846. For several years, the Blaisy tunnel was one of Europe's longest. The rail line brought prosperity to Dijon, and the Paris-Dijon TGV uses the tunnel to this day.

LATER YEARS AND THE DEVELOPMENT OF DARCY'S LAW

The March 1848 revolution ended the government that had employed Darcy for 18 years. Darcy was popular in Dijon; he had provided water and the railroad, he was a city councilman and, mindful of human misery, he promoted projects to help the poor. The new regime feared his popularity and, despite protests by the Corps and the city, banished Darcy to a rural area where, during a short stay, he proposed major agricultural improvements.

A new government in June 1848 assigned Darcy to Paris as Chief of Water and Streets. The move gave Darcy a chance to do experiments that had interested him for years. Darcy and other engineers had observed that official formulas did not accurately predict water flow through pipes. So, between 1849 and 1851, Darcy conducted experiments at the Chaillot water plant to study the topic. The results were published in 1857.

In 1850, after promotion to divisional inspector, Darcy studied macadam roads in London and submitted a report on street paving later that year. In 1851–1852, Brussels invited him to consult on its water-supply system and awarded him the Order of King Leopold.

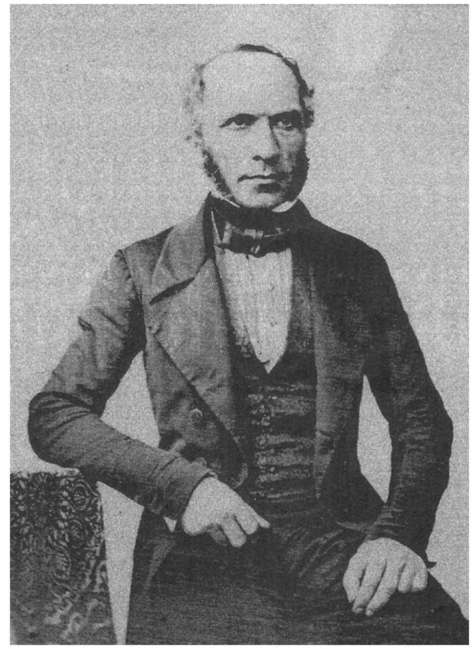
In 1855, after years of poor health and a few months of medical leave, Darcy retired on disability. Even so, he wanted to understand the mechanics of water filtration. In 1854–1855, he set up equipment in the Dijon hospital courtyard and did experiments on water flow through sand. These experiments led to Darcy's Law, which he presented in Appendix D of *Les Fontaines publiques de la ville de Dijon* (Darcy, 1856). His words, in translation, are "Thus it appears that for an identical sand, it can be assumed that the volume discharged is (directly) proportional to the head and inversely proportional to the thickness of the sand layer that the water passes through" (Bobeck, 2004).

Darcy's last project was a Burgundy Canal water-flow study with Henry Bazin (G. Bazin, 2005). During this research, Darcy continued to perfect the Pitot tube, a device used to measure fluid velocity.

Darcy died in Paris on 2 January 1858, at age 54. His body went home to Dijon on the rail line he had proposed, through the tunnel he had built. His admirers carried his coffin to the nearby cemetery. The next day, "Reservoir Square" was renamed "Place Darcy."

ACKNOWLEDGMENTS

I am indebted to Mme Lochot of the Archives Municipales de Dijon for her contribution to Dijon's bicentennial tribute to Henry Darcy, to R.A. Freeze for sending a copy of Paul Darcy's biography of his great-uncle Henry, and to Gabriel Bazin for the biography of his great-grandfather, Henry. I thank Henry Darcy V and the family for fact-checking the article and for their friendship over the years. I also thank Bob Kent who many years ago suggested I translate Darcy's Public Fountains.



Henry Darcy, circa 1845 (G. Bazin). Courtesy: Collection of Jean Darcy, Paris.

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Welcome New Members

The following new members joined between 24 February 2021 and 5 August 2021 and were approved by GSA Council at its fall meeting.

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Emily L. Cardarelli
Richard Cartwright
Joshua Castillo
Bellana Chemello
Ahmet Cilbir
Elizabeth G. Clark
Raistlin Contreras
Brian B. Cook
Fiona K. Couperthwaite
Archana Das
Maria Davalos Elizondo
Jason D. Dayley
Anne Tyler Deal
Patrick Desrosiers
Christopher Dipaolo
Gasper Dominici III
Scott D. Dyson
Mason Muir Einbund
Alison Evans
Sierra Nichole Ferguson
Lauren Gasior
Kaitlin Geary
Cody Grant Gibson
Arian Gonzalez
Samantha Faith Greenberg
Raphael Gromig
Christopher Haberle
Amanda Haddock
Matthew Hardman
Trevor Healy
Katie Hemmerlin
Haran Hennig
Holli Holmes
Christiano Bryce Irving
Tariq Jaser
Kenneth A. Jones
Donghui Kim
Janet S. Kodger
Rebecca Koll
Andrew F. Kopchynski
Vera A. Korasidis
Nicole Lapeyrouse
Robert Lengel

Kyle Lewis
Marsha Izabella Lidzbarski
Tao Liu
Sean Mahoney
Jiuliano Mamola
Mélissa Martinot
Jill McDermott
Siobhan McGoldrick
Patrick McMahon
Fernando Medina-Ferrer
Connor Phinney Miller
Pranabendu Moitra
Jennifer Monterrosa
Samuel T. Moorer
John David Morrow
Samer Naif
William Nanavati
Karma Nanglu
Jack Nolan
Rebecca Nunu
Rachel Ofili
Juan Carlos Olmo
Israel Ropo Orimoloye
Walter Scott Persons IV
Kapil Prasad Phuyal
Tom Pineda
Shaina Price
Lucia Profeta
Brendon Quirk
Matt Francis Rakovec
Rebecca Reagin
Alexis Rojas
Kelly C. Schnars
Juliet Sefton
Christine Simurda
Margaret Stewart
Jacob Stinson
Rebecca Tarbutton
Derek Thorn
Johan Vellekoop
Pia Viglietti
Linda Whitby
Penelope E. Wieser
David Wright
Hong Yong Wu
Shuang Zhang
Xu Zhang
Yipeng Zhang
Lingli Zhou

STUDENTS

(*Listed by Professional Interest*)

Archaeological Geology
Casey Cleaveland
Benjamin Cross
Sarah Heithaus
Naomi Elisabeth Nice
Alison Pitcher
Neil Van Kanegan

Biogeosciences
Alia Nina Al-haj
Luke A. Calderaro
Gwyneth Adelaide Chilcoat
Kelsey Elizabeth Doiron
Keitreice Kirksey
Carole Lakrout
Corinne Katherine Luksch
Cayla Martin
Julian Tomasz Nosarzewski
Amelia Olsen
Brandon Osorio
Nibedita Rakshit
Julia Frances Ricks
Sydney Elizabeth Shaner
Madison Tripp
Addien Wray

Climatology/Meteorology
Haley Hallett Coe
Sophia Lewis Dwyer
Miranda Rose Silano
Kelby L. Stallings

Economic Geology
Abdirahman Abdilahi Ali
Marcus Angus
Nathan John Carey
Daniel Addison Chafetz
Silas L. Goetz
Shiqiang Huang
Victoria A. Konieczka
Nikolas Kieran Kristoffersen
Steve Marrero
Timothy Allen Miller
Noe V. Munoz
Nicolas David Palma
Riley Allen Ross
Valente Octavio Salgado Munoz
Peyton B. Sanders
Carli Lynn Schmidt
Camille R. Sicker
Luke Wellman

Energy Geology
Jacob Edward Allen
Billy Baker
Daniela Bartels
Jacob Byerly
Marina Elizabeth Croy
Melia Marie Eaton
Isis Fukai
Omar Jbilou
Prionti Kundu
Martin Leipzig
Stephanie Leipzig
Michael Ruben Martinez
Gabriella Victoria Reiter
Sarai Beth Sharkey
David Tonner
Perla E. Vega

Engineering Geology
Michael G. Edelen
Andrew Jeremiah Edmonds
Javier Elizalde
Gerardo Hernandez
Joseph Kade Jackson
Lily Jung
Michael Tafadzwa Kutsanzira
Fehlandt A. Lentini
Alexia Mackey
Alec S. Mulkern
Arturo Sotomayor Jr.
Hayden Tackley
Meraf Zenebe

Environmental Science
Masoud A-Rostami
Sofia Almeida
Alana Andreoli
Sam C. Bagge
Veronica A. Balcer
Sydney Jeanette Benson
Collin J. Bogoski
Mana M. Bryant
Luz Arely Cadavid
Libby Callahan
Arisbeth Castañeda Medina
Elvin Cordero
Karen De La Garza
Kara Dempsey
Jack Fields Eason
Abdulgadir Ahamd Elnajdi
Shawn Israel Enstrom
Umme Fatema
Rachel Fricke
Henry Gage
Giancarlo Gomez
Sarah G. Gorman
Michael Allan Grossman
Timothy Gwynn
Morgan R. Haley
Alexis Breann Harford
Emily R. Hegedus
Lauren Holmes
Kailey Marie Hoving
Olivia Maya Jarvis
Kera Johnson
Gabrielle Kauffmann
Benjamin Peter Keel
Jacob King
Natalie Grace Kissner
Aran James Lovato
Katie Chunlei-Clark Mahorney

Top Professional Interests of new Student Members:

- Environmental
- MGPV
- Hydrogeology
- Paleo Sciences
- Planetary/Space Science

Celia A. Meyer
Lillian Minnebo
Michelle Moczulski
Jerri R. Moore
Grace Morel
Jennifer Bauer Morton
Simon Nguyen
Teresa Norman
Norma A. Portillo
Manuel Santos Quispe Villaverde
Meghan Raines
Hemwattie Rampersaud
Eric Regan
Marissa Lee Rossi
Ethan Trey Rumbaugh
Glen Ryan
Tyler P. Sacks
Karen Santana
Blake Logan Smalley
Jeri Stoller
Kinshuk S. Tella
Brandi Leigh Trantham
Amin Ullah
Michael Valencia
Andrew Brian Vandentop
Kierianna S. Wells
Audrey Virginia White
Cindy J. Zapata

Geography
Mary Chen
Hilary Taylor Johnson
Michael Shinkle
Diana A. Valdez

Geoinformatics
Curtis V. Price

Geology and Health
Rafael Angel Chavez
Nicholas Anthony Cipra
Adrita Dhar
Morgan Gayler
Laurel Serayna Goulbourne
Cody Pope

Geophysics/Tectonophysics
Saeed Alrsasmah
Miguel E. Castillo
Nicholas Dergazarian
Marie-Andrée Dumais
Stacy Dwain Gifford
Devin James Horvat
Denali Jivanjee Medina
Ryann Lam
Micah Mayle
Luke Michel
Eric Bruno Moukette Kabe
Uwodu Y. New-Gallo
Jada Nimblett
Linda Pan
Jake R. Parsons
Karl Joseph Schmidt
James W. Scofield
Kelli A. Scott
Ashutosh Shrivastava
Melissa M. Sikes
Abigail C. Travers
Harison Sandor Wiesman
Donald Zachary Wormington

Geoscience Education
Ronan Bartholomew Beltracchi
Clare Madelyn Bunton
Veronica Lee Dau
Mallory Grace Ford
Grant Fore
Anthony Gachetti
Judith Hoyt
Silvia Jessica Mostacedo Marasovic
Cora Raye Paul
Jenna Grace Paulsen
Indeewari Amanda Perera
Christ Ramos
Allyson Randall
Amanda A. Rosenberg

Geothermal
Abagail M. Hanson
Megan Kerr

Hydrogeology/Hydrology
Bedour Alsabti
Alexandra Arimes
Kolawole Isaac Arowoogun
William Blitch
Cole Robert Bowman
Robert Patrick Carpenter
Kyle Chaudoir
Mazvita M. Chikomo
Dylan Alexandeer Childs
Omar Colon
Claudia Dawson
Brandon Thomas Dunn
Isabella Ergh
Patrick J. Faynor
Karlee Foster
Alexa Franks
Ethan Gaddy
Daniela Galeano
Md Fahim Hasan
Nazmul Hasan
Olivia Kay Helinski
Daniel Jefferson Holder
Adrian A. Jimenez
Zoe Kanavas
Jesse Beau Kane
Celeste Kenworthy
Katarina Kieffer
Caroline Korterud
Kesego Pearl Letshele
Reane Loiselle
Kathleen Meiner
Jasmine Lee Morejon
Cheyenne Morgan
Maggie Morgan
Kevin Eugene Morphis
Matthew B. Norwood
Andrew Oberhelman
Raquel Oliva
Venkata Sailaja Pappala
Jacob Porta
Adam N. Price
Maiya C. Rizzo
Pamela Ann Rodriguez
Kristina Sasser
Heather B. Scheetz
Jesse Michael Schewe
Julia Florence Schwartz
Ben Seely
Nathan P. Shelnick
Christopher Timothy Sims
Annilese Q. Stewart
Nicole Isabel Stine
Keevan Patrick Tallon
Willow Teipel
Phillip Telgen
Emmanuel I. Ugwu
Wesmond C. Williams

Karst
Ethan William Oleson
Nick J. Soto-Kerans

Limnogeology
Haixiang Mao

Marine and Coastal Geosciences
Aaron Avery
Samuel Shayne Bond
Caroline Cassese
Erin A. Culver-Miller
Keira Heilpern
Amanda Adair Hicks
Jordan Julia Jontz
Bumsoo Kim
Charles Nathan Wesley Linder
Rachel Meyne
Neda Auzeen Mobasher
Austin Oishi-Yamamoto
Lillian W. Petsinger
Helena Pfluger
Emma Lauren Tegert
Sophia Truempi
Linah Turner-Chism
Carson Williams

Mineralogy/Geochemistry/Petrology/Volcanology
Tushar Prakash Adsul
Brynn Anderson
Julianna Benson
Brianna Bocook
Kyle C. Broley
Odalys Callejas
Allison Chen
Maya Connell
Alexander Cox
Casey James Crawford
Erica Cung
Hanh-Tu Ella Do
Harold Thomas Dossett III
Mitchell P. Duncan
Jarelys Gonzalez
Collin Paul Goulart
Desiree Guzman
Richard Moore Gwyn
Mable Hagans
Anita Jean Hall Frost
Rhiana Elizabeth Henry
Alina Hernandez
Cassidy Hill
Jamie Lynn Hoffman
Jenna Howard
Kaitlyn Elizabeth Hulsey
Holly Rae Hytrek
Megan Rose Jackson
Kendall John
Bear Jordan
Alexander K. Karrasch
Owen T. Kaufman
Austin Michael Keirs
Kristina Marie Kohl
Ben Kolland
Stepan Krasheninnikov
Allison Kubo Hutchison
Alyssa Lindsey
Jesuina Lopez
Cooper Maitoza
Tanner Manvydas
Madeline R. Mennenga
David William Miller
Brent L. Niece
Bailey J. Nordin
Jackson Oakey
Thomas Ott
Madison Marie Rafter
Sherri Buxton Randall
Madisyn Noel Rex
Anna Rae Richey
Andrew T. Saylor
Andrea Scroggs
Che Shen
James Simonini
River W. Taylor
Patrick Francis Tomasic
Judith Grace Topham
Brennan Trantham
David W. West
Lauren Elizabeth Wratchford
Mingyue Yu
Tianyi Zheng

Paleo Sciences
Sean E. Arias
Koen Arthaud-Day
Aletha Hope Bailey
Horus Balogh-Zanin
Russell Nathan Benoy
Dylan C. Brandt
Roxanne Riley Buck
Kassidy Chatterton
Wolf Gordon Clifton
Kiera D. Crowley
Meig Dickson
Deepa Dwyer
Xavier Omar Espinosa-Betancourt
Matteo Fabbri
Martin Luca Fernandez
Erin E. Fitzgerald
Derek Mena Godoy
Virginia Gold
Caleb Matthew Gordon
Louis John Grimmelbein V
Stephen Christopher Groff
Grady Nicholas Grudzinski
Amanda Harding
Theodore Butler Herring
Celeste Hofstetter
Brittney M. Hoskins
Christiane Jacquemetton
Lindsey MiKayla Jordan
Molly Karnes
Yaiza Arjona Kinney
Cheyanne Koran
Isaac Magallanes
Carlos Josue Martinez
B. Michelle Mayes
James G. Napoli

Jeremy Thomas Nunnonorod
Ashlyn Oh
Megan O'Quin
Britton Spencer Pearson
Jacob James Potter
Emma Nicole Puhalski
Eden E. Rakes
Janeddies Ramos
Siera S. Reick
Danni Sidle Riggs
Ashley Rivas
Dorothy Elizabeth Rodarte
Roman D. Ruiz
Chantel V. Saban
Gabriela Marie Diaz Santana
Giles D. Sukkert
Valerie Trinidad
Mikayla Walker
Jeremy-Louis Webb

Planetary/Space Science
Lavontria Miche Aaron
Anuva Anannya
Cynthia Andrade-Lerma
Peter Aurelio
Wynnie Melinda Avent II
Alexandra Jade Banks
Ritesh Bhakta
Haley Olivia Boles
Sydney Briggs
Mitchell Brown
Margaret LeSesne Burdell
Tsai-Wei Chen
Sara Camila Cuevas-Quinones
Thomas Dehais
Jacen L. Duplain
Tytrice J. Faison
Colin Kent Glaze
Mohini Jeetendra Jodhpurkar
Emily Johnson
Rudi Renee Lien
Benjamin Edward Mckeeby
Connor Mclaughlin
Eli Usei Nauda
Elizabeth Orlando
Rutu Parekh
Sebastian Perez-Lopez
Megan Piquiet
Camillo Rapparini
Anjelica Rodriguez
Evan Schneider
Mayank Shukla
Helle Leth Skjetne
Andrew Nicholas Sneed
Isaiah P. Spring
Tara L. Sweeney
Johanna Erika Valdueza

Policy/Regulatory
Noelle Christensen
Alexandra G. Dixon
Kimberly Dunlap

Quaternary Geology/ Geomorphology
Crey M. Ackerson
Kelsey Barker
Daniel David Bloch
Jason Steven Drebber
Alexander Gorr
Gwenn L. Harsha
Erin Harvey
Dylan Robert Jones
Lily Catherine Kuentz
Will Bridger Larson
Laura Lopera Congote
Theodor Rex Hartmann Lowe
Jason E. Mueller
Lauren Nickell
Clay Henry Robertson
Ryan Scott Swapp
Donny Rio Wahyudi
Jacob Woodard

Seismology
Yaqi Jie
Jennifer Kirk
Joses Bolutife Omojola

Soil Science
Susannah Claire Budd
Daniel Ryan Goddard
Tyler Hacking
Maya Lucille Karlan
Jessica Landesman
Madison Grier Williams
Elissa May Wobig

Stratigraphy/Sedimentology
Logan M. Ashurst-McGee
Lauren Bergeron
Matthew Bourdon
Samantha Dittrich
Jeffrey Duxbury
Chloe Geddes
Stacey Gerasimov
Holden Owen Hague
Jenna Roxanne Harker
Hannah Hogan
Renee Louise Homan
Elliott Wallace Jackson
Alexander Philip Barron Johanson
Anna Lesko
Robert Manta
Dustin Morris
Pooja Patel
Justin Sharpe
Mason Bruce Wade

Structural Geology/ Tectonics
Hanna Asefaw
Luka Basich
Leah Carson Boccignone
Adrianna Alyse Buxrude
Emily Carroll
Michael Cieslik Jr.
Gillian Clark
Matthew Czupski
Dannielle Morgan Fougere
Keerthi Gummidipundi
Makayla Hutchinson
Afolabi Olubunmi Jayeola
Charles F. Memmott
Haley Elisabeth Meyrowitz
Roberto Cesar Nepomuceno
Alix Osinchuk
Erin R. Pimentel
Gavin Pirrie
Gerson Francisco Quintanilla Navarro
Felipe R. Ferroni
Addison Kaye Richter
Alexia Peretz Rojas
Edward L. Vinis
Abigail Lynn Watson
Marissa A. Wiggins
Andrew Bernard Yokel-Deliduka
Terri A. Zach

Other Professional Interests
John Chibundu Akudike
Jordan J. Allen
Maram Alrehaili
Spiro Stephen Bogdanos
Danielle Marie Cottrell
Haley R. Culbertson
Ethan Dandurand
Lane Maligro Davis
Katherine Ryann Dowling
Elise Gabrielle Felt
James Bryan Futty Jr.
Natalie Grace Girlinghouse
Mikelia Heberer
Kathryn Henning
Lillian Howie
Benite Ishimwe
Keaton Cade Jenkins-Joyce
Hailey Renee Jerew
Saige Jost
Ireland Killen
Brittany Lanham
Filzah Amni Binti Latiff
Sarah Rose Lesmann

New members by member type:

- 149—Professionals
- 108—Early Career Professionals
- 544—Students
- 13—K-12 Teachers
- 54—Affiliates

Juliet Bel Liscomb
Isaac Lopez
Samuel G. Marcus
Madalyn Massey
Holly McCrory
Morgan Mellum
Zoe Morgan
Benjamin Pollock Morse
Alexander Paladino
Juliana Grace Peckenpaugh
Melissa Dawn Perkins
Owen Sainiak
Katie Seals
Addison Seidler
Anna Danielle Sivils
Allison Sowers
Jimmy Robert Swift Jr.
Emily True
Julia Chin Walker
Patrick J. Walston
Veronica Del Carmen Zermeno

K–12 TEACHERS
Rodney Baumbach
Kristina Brody
Bethany Marie Busch
Mariah Jordan Doll
Michael Bruno Dubaldi
Brian Murphy
Jeanette Kaur Ralph
Morgan James Salisbury
Monique Chanteh Somma
Kimberly Sullivan
Luke Tayler
Matthew J. Wilcott

AFFILIATES
German Harvey Alferez
Cody Michael Anderson
John Erich Anderson
Richard Anderson
Alexander Arrendale
Joe A. Baldwin
William Barany
Jeff D. Barlow

Kevin J. Barry
Charles E. Bartberger
Stefanie D. Cannan
Elisabeth Carver
John Cerniglia
Michele Dunham
Andrew Ek
Charles Erwin
René Estes
Charles Fivash
Terri L. Fivash
William Frohmberg
Kenneth Giles
Ushan Govender
Michael L. Hogan
Kyle Holgate
Nicole Huang
Rex Hunt
Guy E. Jette
Kent Karnofski
Bill Keffer
Randal T. Laney
Layla Merritt
David W. Meyer
Dean Miller
George Herald Miller
Teresa Mitchel
Susan Murphy
David L. Naylor
Alexander Pacubas
Randy Pendergrass
Paul Post
Michael L. Raftery
Mark Rice
Frederick Rosso Jr.
Richard F. Silber
Boris Stefanov
Christopher Sullivan
Ryan Driskell Tate
Ann Judith Tautz
Michael Thacker
Avana Vana
Glenn Waite
Richard Williams
Morgan Woodle

Top Employment Sectors of new members (excluding Students):

- Four-year University
- Federal
- Environmental

Submit Your GSA Experience Essay Today!

Let us know how GSA has made an impact on your life. Write an essay of about 500 words and send us your high-resolution photo. We'd love to hear from you, and so would your colleagues!

Email gsatoday@geosociety.org with your submission.

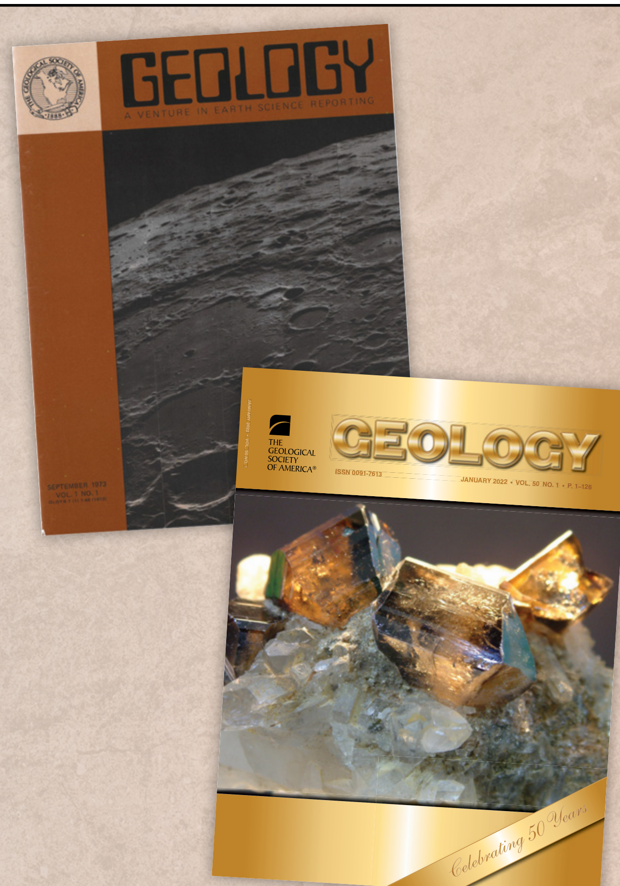
Why GSA Membership Is Important to Me

I joined the GSA in 1986, shortly after having started my Ph.D. My research was facilitated by a GSA Graduate Student Research Grant (my very first grant), and my attendance at a GSA Cordilleran Section meeting in Hilo, Hawaii, was fundamental to my development as a scientist: After my talk, a senior member of the audience took the time to talk to me and convince me that my interpretations were wrong (he was correct—I was wrong). That meeting also featured my first GSA field trip: scaling Mona Loa with J.P. Lockwood as our guide. It was an epic field trip, one that I will never forget. Those early experiences—the financial support, the mentorship by established members of the earth-science community, and the shared love of geology—were fundamental to my development as a geologist. And for that, I am forever grateful to the GSA.

Stephen Johnston, University of Alberta, GSA Member since 1986, GSA Fellow since 2013

Geology Celebrates 50 Years in 2022

Volume 1, issue 1, of *Geology* was published in September 1973. In 2022, the journal will publish its 50th volume. A bit of an upstart at the time, *Geology*'s mission was to be a "short-note, rapid publication journal." Along with short, peer-reviewed articles, early issues included book reviews, letters, and summaries of *GSA Bulletin* papers. In 1975, a section called "GSA news & information" was added. (*GSA News & Information* became its own publication in 1979; was ultimately replaced with *GSA Today* in 1991.) Read more about *Geology*'s beginnings at **https://pubs.geoscienceworld.org/geology/issue/50/1.**



September 1973 cover. Lunar Orbiter V, Photo 65 M, showing Hess Lunar Crater.

January 2022 cover, celebrating Geology's 50th year of publication.

GeoCareers Programs at the 2022 Section Meetings

CAREER WORKSHOPS

Geoscience Career Workshop Part 1: Career Planning and Networking. Your job-hunting process should begin with career planning, not when you apply for jobs. This workshop will help you begin this process and practice your networking skills. This workshop is highly recommended for freshmen, sophomores, and juniors. The earlier you start your career planning the better.

Geoscience Career Workshop Part 2: Geoscience Career Exploration. What do geologists in various sectors earn? What do they do? What are the pros and cons of working in academia, government, and industry? Workshop presenters and professionals in the field will address these issues.

Geoscience Career Workshop Part 3: Cover Letters, Résumés, and CVs. How do you prepare a cover letter? Does your résumé need a good edit? Whether you are currently in the market for a job or not, learn how to prepare the best résumé possible. You will review numerous examples to help you learn important résumé dos and don'ts.

MENTOR PROGRAMS

GSA student members will have the opportunity to discuss career prospects and challenges with applied geoscientists from various sectors.

South-Central Section Meeting
Shlemon Mentor Program: Monday, 14 March
Mann Mentors in Applied Hydrology Program: Tuesday, 15 March

Joint Cordilleran and Rocky Mountain Section Meeting
Shlemon Mentor Program: Wednesday, 16 March
Mann Mentors in Applied Hydrology Program: Thursday, 17 March

Northeastern Section Meeting
Shlemon Mentor Program: Sunday, 20 March
Mann Mentors in Applied Hydrology Program: Monday, 21 March

Joint North-Central and Southeastern Section Meeting
Shlemon Mentor Program: Thursday, 7 April
Mann Mentors in Applied Hydrology Program: Friday, 8 April

THE GEOLOGICAL SOCIETY OF AMERICA®

2022 GSA SECTION MEETINGS

SOUTH-CENTRAL SECTION

14–15 March
McAllen, Texas, USA
Meeting chairs: Juan González, juan.l.gonzalez@utrgv.edu; Chu-Lin Cheng, chulin.cheng@utrgv.edu
https://www.geosociety.org/sc-mtg

A resistant layer of the Roma sandstone is exposed crossing the Rio Grande. Photo by Juan González.

JOINT CORDILLERAN–ROCKY MOUNTAIN SECTION

15–17 March
Las Vegas, Nevada, USA
Meeting chairs: Michael Wells, michael.wells@unlv.edu; Alexis Ault, alexis.ault@usu.edu
https://www.geosociety.org/cd-mtg

Red Rock Canyon, Nevada.
Photo by Daniel Halseth on Unsplash.

NORTHEASTERN SECTION

20–22 March
Lancaster, Pennsylvania, USA
Meeting chairs: Andy deWet, adewet@fandm.edu; Chris Williams, cwillia2@fandm.edu
https://www.geosociety.org/ne-mtg

Susquehanna River, southern Lancaster County.
Photo by Emily Wilson.

JOINT NORTH-CENTRAL–SOUTHEASTERN SECTION

7–8 April
Cincinnati, Ohio, USA
Meeting chairs: Craig Dietsch, dietscc@ucmail.uc.edu; Rebecca Freeman, rebecca.freeman@uky.edu
https://www.geosociety.org/nc-mtg

Cincinnati skyline at night.
Photo by Jake Blucker on Unsplash.

Partners in Science, in Life, and in Giving Back

A lifelong commitment to promoting young geoscientists is a passion for a couple who met early in their geophysics careers.

When Carol and Seth Stein crossed paths at the California Institute of Technology in the late 1970s, Carol was an undergraduate whose brother shared an office with fellow grad student, Seth. One of the first women to receive a degree in geophysics at Caltech, Carol explained that at the time, most computing was done in a computing center: "You handed in your cards and waited an hour." Those hours allowed time for the two young geoscientists to get acquainted, although it wasn't until Seth was working on his post-doc and Carol went to grad school that the two started dating. Seth took Carol on her first backpacking trip in the Sierras; with smiles, they still recall the bear who went to great lengths to devour their tree-stashed food in Yosemite.

Carol and Seth Stein at Rocks National Lakeshore (above the Midcontinent Rift), 2014.

Now married 39 years, the Steins are grateful to have benefitted from enormous encouragement early in their training. Both are esteemed geophysicists: a professor in the University of Illinois at Chicago's Department of Earth & Environmental Sciences, Carol has been an editor for AGU's *Eos*, is a GSA Fellow, and served as chair of GSA's Geophysics and Geodynamics Division. Seth, William Deering Professor of Geological Sciences at Northwestern University, has received prestigious medals and awards from GSA, AGU, EGU, and the Royal Astronomical Society. He has served as scientific director of UNAVCO and as a visiting senior scientist at NASA's Goddard Space Flight Center.

Much of their careers have been spent working side-by-side, maintaining the scientific integrity that sometimes means brutal honesty and vigorous articulation of differing perspectives, while recognizing that scientific disagreement and spirited discussion did not translate to animosity in their personal life and family. This understanding has allowed for an unusual extent of gratifying scientific work together.

For all of their shared work and interests, their differences contributed to rewarding scientific collaboration. Although their greatest research interest is in plate tectonics, Carol was trained as a marine geophysicist, and Seth's training was heavy in mathematics and physics. Carol describes her husband as more process oriented, while Seth values her field-based background. The couple has found it "very useful to bring different ways of thinking about the world" into their shared work. They learned to appreciate the value of jointly looking for a solution, rather than one or the other being right, and carried this guiding principle over from work to their home lives.

Carol and Seth Stein at Arches National Park, 2019.

For the past decade, the Steins' vacations around Lake Superior have led to extensive research on the 2,000-mile-long Midcontinent Rift that underlies the lake and is responsible for much of the region's beauty and growth. As their work focused on this major feature of North American geology, their involvement with GSA increased. Although the Steins have both been heavily involved in other organizations, the greatest overlap between them is with the Society. With this new project, they started attending GSA's annual meetings together and discovered many things they enjoyed. Seth appreciates GSA as a "human-scaled entity." For instance, he often meets GSA officers and leadership sitting next to him at technical sessions.

During Carol's service as chair of the Society's Geophysics and Geodynamics Division, she started the Division's best student presentation awards based on talks and posters at the annual meeting: "It's a way of acknowledging that this is very important. It's saying 'We really value our young people.'"

Now, Carol and Seth are generously giving back as a couple through the *Seth and Carol Stein Early Career Award in Geophysics and Geodynamics*. The Steins are passionate about encouraging and supporting the next generation of scientists, and these efforts are an important part of what they do together.

If you are interested in learning how you can help the next generation of geoscientists thrive and flourish in your footsteps, please contact Debbie Marcinkowski at +1-303-357-1047 or dmarcinkowski@geosociety.org. We are grateful for those in a position to give back like the Steins, and we are pleased to help you find the right fit for your interests.

Bookmark the Geoscience Job Board at **www.geosociety.org/jobs** for up-to-the-minute job postings. Job Board ads may also appear in a corresponding monthly print issue of *GSA Today*. Send inquiries to advertising@geosociety.org, or call +1-800-427-1988 ext. 1053 or +1-303-357-1053.

OPEN POSITION

Director of The Mississippi Mineral Resources Institute, and (Associate or Full) Professor of Geology and Geological Engineering, University of Mississippi

The School of Engineering at the University of Mississippi is seeking an experienced researcher, administrator, and faculty member for the position of Director of the Mississippi Mineral Resources Institute and tenured/tenure-track faculty in the Dept. of Geology and Geological Engineering. The faculty appointment will be at a rank commensurate with qualifications and experience. Position details and instructions to apply can be found here: [https://careers.olemiss.edu/job/University-Director-of-MMRI-and-FullAssociate-Professor-of-Geology-&-Geological-Engineering-MS-38677/822335400/]. Screening of applications begins February 15, 2022, and continues until the position is filled. The University of Mississippi embraces a meaningful and holistic commitment to advancing diversity, equity, and inclusion. The University of Mississippi is committed to embracing a collaborative, innovative, and inclusive community that affirms all employees.

Hiring?

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Analysis of Skills Sought by Employers of Bachelors-Level Geoscientists

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INTRODUCTION

Bachelors-level geoscientists make up the majority of the geoscience workforce, and positions for entry-level geoscientists are expected to grow rapidly over the next decade, with some jobs anticipating upward of 10% growth (National Center for O*NET Development, 2021). Are geoscience departments adequately preparing undergraduate students to succeed in these positions?

Answering this question requires examining the alignment of undergraduate program outcomes and workforce needs. The results allow faculty to identify strengths and weaknesses in their programs with respect to workforce preparation (e.g., Viskupic et al., 2020). How well do we know workforce needs? *Vision and Change in the Geosciences* (Mosher and Keane, 2021) provides a list of competencies and skills necessary for new graduates to succeed in the workforce; the list was generated by academics (n ~200) and employers (n = 46) in a series of workshops. This list, while comprehensive and insightful, represents input from a relatively small sample of geoscience employers and may overrepresent the petroleum industry (26% of industry workshop participants), which has not been a significant employer of bachelors-level geoscientists (Gonzales and Keane, 2021). Our goal was to characterize the skills sought by the full range of bachelors-level geoscience employers and how these skills are communicated to potential applicants—with an eye toward providing information that would allow academic leaders to examine the alignment between their programs and workforce needs.

WHAT WE DID

We designed a systematic study to code online geoscience job advertisements (hereafter referred to as "ads") for workforce skills. Ads were retrieved between May and November 2020 from four online job search engines: CareerBuilder.com; USAJobs.gov; CollegeRecruiter.com; Indeed.com. We limited our analysis to ads that preferred a bachelor's degree in geoscience or a related field and required less than five years of experience. A total of 1,214 unique ads met these criteria. Occupation names and industry sectors, described in AGI's 2018 Status of the Geoscience Workforce report (Wilson, 2018), were assigned to each ad based on job title and description of duties. The most common occupations in our sample were geologist, environmental scientist, and natural resource specialist, following a distribution similar to the AGI report (Table 1).

Ads were coded for 34 skills; many were listed by Mosher and Keane (2021) and others emerged through multiple rounds of coding ad subsamples. We defined the skills and organized them into categories (e.g., data skills, communication skills) according to the classification of Viskupic et al. (2020). We coded a subsample of ads to establish interrater reliability among the three co-authors; we had 90% or greater agreement on all codes and Cohen's Kappa value of 0.84.

WHAT WE FOUND

Fourteen skills occurred in a third or more of the 1,214 ads analyzed (Fig. 1), with four of those—written communication, field skills, data collection, and computer skills—occurring in more than half of the ads. Several skill categories were represented by the most commonly occurring skills, but seven of the most common skills were in Data Skills and Communication. Three of the most common skills were emergent codes that were not identified by Mosher and Keane (2021): ability to drive, planning skills, and record keeping/documentation. Two skills in *Vision and Change in the Geosciences* were rarely coded in any ads: systems thinking and managing uncertainty.

TABLE 1. PERCENT OCCUPATIONAL DISTRIBUTION BY INDUSTRY SECTOR

Industry sector	Study sample (%)	2018 AGI data (%)
Professional, scientific, and technical services	39.0	35.9
Federal government	15.9	10.2
State government	9.4	14.2
Construction	6.6	0.2
Waste management and remediation services	4.5	1.5
Information services	4.0	0.0
Mining	3.8	0.7
Local government	3.6	8.7
Testing laboratories	2.0	N.D.
Utilities	1.9	1.5
Computer systems and design	1.8	N.D.
Manufacturing	1.7	3.6
Education*	1.5	13.4
Oil and gas	1.5	7.6
Scientific research and development	1.2	N.D.
Finance and insurance	0.7	0.0
Transport and warehousing	0.5	1.1
Agriculture, forestry, fishing, and hunting	0.4	1.5

N.D. = no data.
*Jobs in K–12 education are largely not advertised using the search engines included in this study and thus are underrepresented in our data compared to the AGI data.

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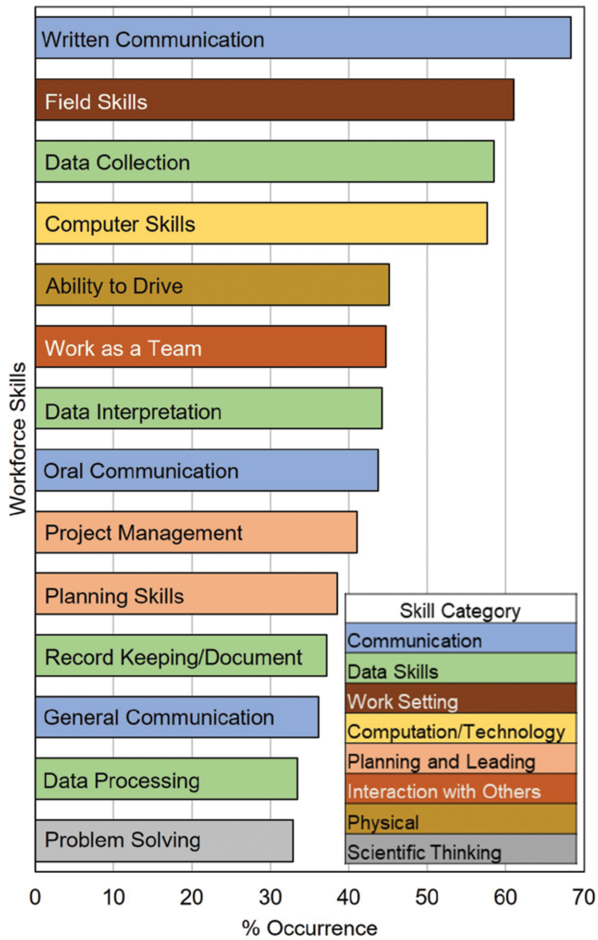

Figure 1. The most common skills by percent occurrence from the job advertisement analysis. Skills are colored to correspond to skill categories outlined in Viskupic et al. (2020).

The most common skills varied greatly among employment sectors. For example, teamwork skills were found in 60% of mining ads but only 22% of oil and gas ads.

HOW CAN OUR WORK BE USED?

Our results provide geoscience departments with current representation of the most sought-after workforce skills that bachelors-level graduates need to be successful in the current job market. Proficiency in the whole spectrum of data skills—from data collection and record keeping to interpretation—is critical; these skills are practiced across many geoscience courses (Viskupic et al., 2020) and can be highlighted as workforce skills. We also note the emphasis on communication skills, leadership, project management, and planning. None of these skills are content-specific and may be less commonly explicit in curricula. Written communication skills are more commonly practiced in geoscience courses than oral communication skills (Viskupic et al., 2020), but we are unaware of any data describing the practice of planning and management skills in geoscience programs.

WHAT IS NEXT?

These initial results are intriguing and provide a glimpse into a rich data set that we are continuing to explore. Additional analyses will probe:

1. Differences between industry sectors (e.g., oil and gas, government): How do skills vary across industry sectors?
2. Geographic distribution of jobs: Where are the majority of bachelors-level jobs? Do skills vary geographically?
3. Further analysis of field skills: Are the field skills sought by most employers geologic mapping, installing, and monitoring field instrumentation, collecting samples, or other?
4. The presence of physical abilities in job ads and their potential impact on recent graduates: Do advertisements that require physical abilities present unnecessary barriers to applicants with disabilities?
5. The articulation of systems thinking in job ads: Systems thinking is emphasized in *Vision and Change in the Geosciences* but was not found in any ads. How do employers articulate systems thinking skills in job ads?
6. Dispositions sought by employers: Dispositions (e.g., attention to detail, taking initiative) were distinct from skills, and appeared in many job ads. Which dispositions are most frequently sought, and to what extent can these be developed as part of geoscience programs?

SUMMARY

Our analysis of job advertisements presents a comprehensive view of the workforce skills sought by geoscience employers. Geoscience departments can use these results to inform their curriculum planning and incorporate opportunities for students to practice and develop competencies. The work presented here is a critical step in ensuring that the geoscience community is adequately preparing new graduates to succeed in the workforce.

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Learning from the COVID-19 Pandemic: How Faculty Experiences Can Prepare Us for Future System-Wide Disruption

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The COVID-19 pandemic provided education researchers with a natural experiment: an opportunity to investigate the impacts of a system-wide, involuntary move to online teaching and to assess the characteristics of individuals who adapted more readily. To capture the impacts in real time, our team recruited college-level geoscience instructors through the National Association of Geoscience Teachers (NAGT) and American Geophysical Union (AGU) communities to participate in our study in the spring of 2020. Each weekday for three successive weeks, participants (n = 262) were asked to rate their experienced disruption in four domains: teaching, research, ability to communicate with their professional community, and work-life balance. The rating system (a scale of 1–5, with 5 as severely disrupted) was designed to assess (a) where support needs were greatest, (b) how those needs evolved over time, and (c) respondents' capacity to adapt. In addition, participants were asked two open-response questions, designed to provide preliminary insights into *how* individuals were adapting—what was their most important task that day and what was their greatest insight from the previous day. Participants also provided information on their institution type, position, discipline, gender, race, dependents, and online teaching experience (see supplemental material[1]).

When it was evident that disruptions would continue through the 2020–2021 academic year, we issued a one-time follow-up survey to participants (n = 109) in October 2020 to inquire about teaching practices in the fall semester (see supplemental material). Survey questions asked about usefulness of supports available to faculty (i.e., instructional designers, internal and external colleagues, online resources) using a Likert-scale (1–5, with 5 as very helpful). Participants also responded to short answer prompts regarding what has been most helpful and what they have learned and will continue to do. From this group, we interviewed 22 participants in early 2021 to gain further insight into the challenges and triumphs they had experienced over the previous 10 months (see supplemental material). Data from both surveys and the interviews were analyzed through a grounded theory approach, iteratively coding the data and extracting themes. Here, we address one question that emerged from our work: ***How did disruption to teaching and capacity to adapt evolve over the course of the pandemic?***

REAL-TIME DISRUPTION EARLY IN THE PANDEMIC

In the spring 2020 15-day survey, average ratings of perceived teaching disruption (one of the four domains about which we inquired) were moderate (mean = 2.98, SD = 1.28). It is possible that the moderate disruption level is biased, and that those faculty experiencing the greatest disruption were less likely to complete the daily survey. Regardless, we found patterns that provide insight into individuals' capacity to adapt.

Levels of reported disruption did not differ significantly by participants' institution type or by their experience: In fact, disruption to teaching was pervasive and experienced even by those with extensive online teaching experience. On the other hand, non-tenure-track (NTT) faculty reported increasingly more disruption over time than tenure track (TT) faculty (increases over the 15 days of 0.37 and 0.03, respectively, $t = 1.69$, $p < 0.10$).

We hypothesize that the greater disruption experienced by NTT faculty results from a sense of the precariousness of their positions, a theme seen in open responses such as this one:

> "My career plans may have to drastically change, even though I love teaching. I am on an 18-month contract, and I doubt the academic job market will look good in Jan/Feb 2021 when I planned to look. … universities around the world are losing money, implementing hiring freezes, and laying off employees." —Female Geology Faculty, NTT, Doctoral Granting Institution, Day 12

Data collected later showed that ~90% of faculty members remained employed throughout the COVID-19 pandemic, with the highest rate of unemployment being among students and post-doctoral fellows (Gonzalez and Keane, 2021). However, during our spring 2020 survey, longterm outcomes were unknown and weighed on the minds of respondents.

Though at least one study has shown the negative long-term impacts of the pandemic

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[1]Supplemental Material. Demographic information for participants in all phases of the study and the survey and interview questions for all phases of the study. Go to https://doi.org/10.1130/GSAT.S.17209481 to access the supplemental material; contact editing@geosociety.org with any questions.

on female faculty (NASEM, 2021), using two-way ANOVA, we found no statistically significant interaction between the effects of gender and dependents on level of disruption reported by instructors, ($F(1,96) = 0.449$, $p = 0.504$). Respondents mentioned children and childcare often as the "most important thing" they needed to do that day (as below), but the frequency of such responses did not correlate with gender identity, nor did gender correlate with number of dependents in disruption ratings:

> "I needed to re-arrange my schedule to do extra childcare this week because my wife (also an academic) has more commitments this week. Every week ends with a conversation about how to balance both of our schedules. My wife is pre-tenure and I'm tenured, so every plan is run through that filter as well because we need to maximize her time more than mine." —Male Professor, Doctoral Granting Institution, Day 2

This male participant's family unit was making decisions about childcare grounded in the tenure process rather than traditional gender roles. A female participant described another non-gendered approach: Her extended family moved closer so that four adults could rotate responsibility for the children, increasing each adult's dedicated working time.

The survey specifically asked faculty to report dependents under the age of 15, but participants also reported caregiving for teenagers, adult children, and aging parents:

> Our son is depressed and it's getting harder and harder for him to find any joy with online learning in high school. Being around him all day I can understand how isolating this type of education is. I don't recommend it for a single child. —Female Professor, Doctoral Granting Institution, Day 15

Family caregiving therefore extended beyond the typical gender roles and age ranges normally examined.

ONGOING DISRUPTION

College-level teaching comes with inherent variability as courses and students change each term. In our interviews, participants reported that the advance notice and time over the summer to prepare for the fall influenced their perception of the fall as less disruptive than the preceding spring, particularly when re-teaching courses. One participant reflected:

> I spent the summer working with the instructional design people, they helped me redesign my Blackboard shells, so I have them organized. —Female, NTT Geology at Doctoral Granting Institution

For some, summer allowed time for preparing new materials, learning new tools, and thinking deeply about instructional needs.

However, some participants did not recall fall as more or less stressful, saying the two semesters were incomparable. When asked, they described the two as "apples and oranges" (Female Associate Professor, Geology, Doctoral Granting Institution). This was due to changes in course type, class sizes, and level of students. When surveyed in the fall, participants reported a higher level of disruption to teaching responsibilities when the delivery format for two or more courses changed (mean = 3.80) rather than for a single course (mean = 3.31) ($F(1, 98) = 5.83$, $p < 0.001$). However, neither the timing of the decision to change the delivery format, nor the level of involvement in making the decision to change the delivery format, predicted disruption ratings, both $p > 0.05$. In other words, advance notice did not help those who were teaching different courses or multiple courses feel less disruption in their teaching when format changed, despite the experience of the previous term.

In addition, participants reported minimizing or even completely ignoring their research agendas to be able to adapt to teaching and that greater amounts of time spent grading was a common theme. These shifts in the amount of time dedicated to teaching are not unexpected in a new course or setting but are not sustainable in the long term.

PREPARING FOR FUTURE DISRUPTIONS

A better understanding of how participants' disruption and capacity to adapt evolved over time can help departments and institutions better support their faculty in future disruptions. Our data show that capacity to adapt to disruption was influenced by the entire family unit's capacity to adapt: Individuals with strong family networks were able to establish new systems for childcare, for example, but when caregiving responsibilities extended beyond childcare to older children or parents, the system was less adaptable. In addition, our data show that a variety of physical, social, and cognitive resources aided faculty in adapting to their evolving situation, including instructional design professionals, digital learning communities, quality learning management software—and that not everyone needed the same thing. Departments and institutions need to pay particular attention to NTT faculty, who may experience greater despair in the face of perceived uncertainty.

Not surprisingly, a common theme in the qualitative reports is time. When provided the summer to prepare to teach their specific geoscience course online, most participants felt less disrupted, yet they still reported dedicating more time to teaching. Departments and institutions can do some things to give faculty time, such as making decisions early about course modality to allow faculty to prepare, but this is not always possible. Other ways to provide time include extending the tenure clock and hiring graduate students or post-docs to support teaching.

We continue to analyze this data moving forward to examine the ways in which faculty have described the dilemmas to teaching (Windschitl, 2002) in their daily diary responses. We hope from this in-progress analysis to offer more detailed support structures for geoscience faculty to navigate future disruptions to teaching.

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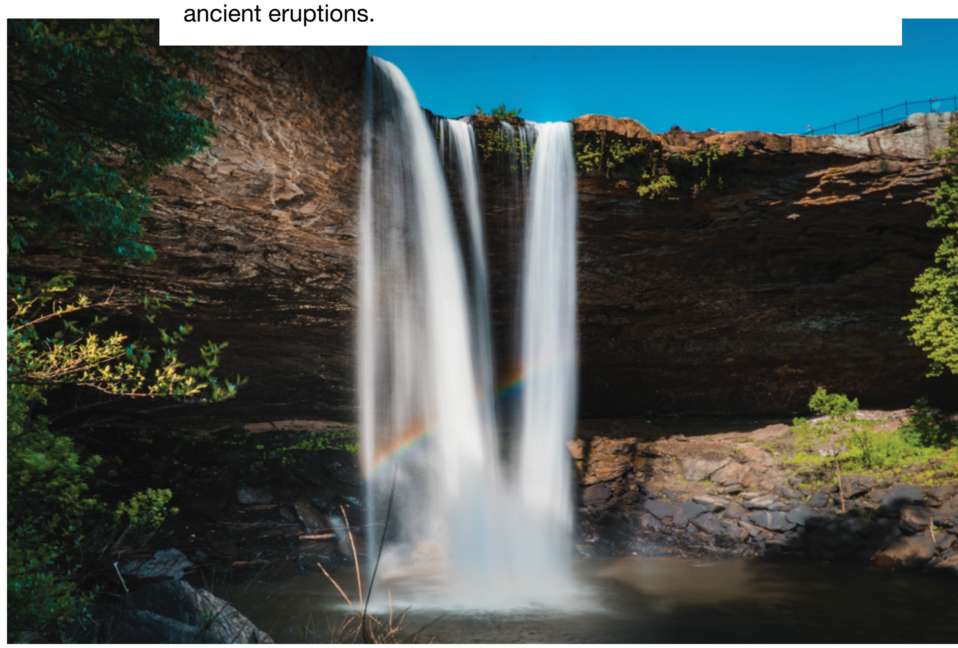

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