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The Mesoproterozoic Single-Lid Tectonic Episode: Prelude to Modern Plate Tectonics

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SCIENCE

Cover: Typical coarse-grained to pegmatitic, orthopyroxene-bearing anorthosite (leuconorite) from the 1765–1630 Ma Mealy Mountains Intrusive Suite (Labrador, Canada). This Mesoproterozoic anorthosite massif intrudes the Mealy Mountains Terrane and is one of several classic intrusive complexes in the Grenville Province of eastern North America. The hammer is ~40 cm long. Photo courtesy of Grant Bybee, Univ. of the Witwatersrand. See related article, p. 4–10.

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The Mesoproterozoic Single-Lid Tectonic Episode: Prelude to Modern Plate Tectonics

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ABSTRACT

The hypothesis that the Mesoproterozoic (1600–1000 Ma) tectonic regime was a protracted single-lid episode is explored. Single-lid tectonic regimes contrast with plate tectonics because the silicate planet or moon is encased in a single lithospheric shell, not a global plate mosaic. Single-lid tectonics dominate among the Solar System's active silicate bodies, and these show a wide range of magmatic and tectonic styles, including heat pipe (Io), vigorous (Venus), and sluggish (Mars). Both positive and negative evidence is used to evaluate the viability of the Mesoproterozoic single-lid hypothesis. Four lines of positive evidence are: (1) elevated thermal regime; (2, 3) abundance of unusual dry magmas such as A-type granites and anorthosites; and (4) paucity of new passive continental margins. Negative evidence is the lack of rock and mineral assemblages formed by plate-tectonic processes such as ophiolites, blueschists, and ultra high-pressure terranes. Younger plate-tectonic–related and Mesoproterozoic mineralization styles contrast greatly. Paleomagnetic evidence is equivocal but is permissive that Mesoproterozoic apparent polar wander paths of continental blocks did not differ significantly. These tests compel the conclusion that the Mesoproterozoic single-lid hypothesis is viable.

INTRODUCTION

Earth's modern plate-tectonic regime emerged from earlier tectonic regimes (Sleep, 2000; Cawood et al., 2018; Stern, 2018; Holder et al., 2019). This paper tests the hypothesis that the Mesoproterozoic was a protracted single-lid tectonics. Below, I briefly outline what single-lid tectonics is before presenting positive and negative evidence to test this hypothesis and explore some implications.

PLATE TECTONICS AND SINGLE-LID TECTONICS

Five concepts are central to this paper:

1. Active silicate bodies have convecting mantles. Tectonics is the lithospheric expression of mantle convection.
2. Plate tectonics is lithosphere divided into a mosaic of strong plates, which move on and sink into weaker ductile asthenosphere as a result of subduction. Plates move relative to each other across three types of boundaries: divergent, convergent, and transform (Bird, 2003). The negative buoyancy of old dense oceanic lithosphere sinking in subduction zones mostly powers plate movements (Forsyth and Uyeda, 1975).
3. Single-lid tectonics contrasts with plate tectonics by having a single, unfragmented, all-encompassing lithosphere.
4. There are many types of single-lid behavior but only one type of plate tectonics (Fig. 1).
5. We are only beginning to explore the range of active silicate body single-lid behaviors, and terminology is confusing. O'Neill and Roberts (2018) refer to stagnant, sluggish, plutonic squishy, or heat pipe variants, whereas Fischer and Gerya (2016) refer to plume-lid tectonics. "Sagduction"—the vertical sinking of weak lithosphere—is another vigorous non-plate tectonic–style (Nédélec et al., 2017).

In 2015 we finished taking a first look at all of the large (= semi-spherical) bodies in the Solar System using a variety of spacecraft (Stern et al., 2018). Four out of five tectonically active silicate bodies in the Solar System show single-lid behavior; that is, they have an all-encompassing lithospheric lid (Stern et al., 2018): Venus and Mars and the two Jovian inner moons, Io and Europa. We have imaged the surfaces of Venus, Mars and Io, but not Europa because it is encased in an icy shell. Venus, Mars, and Io show a wide range of single-lid tectonic behaviors. Io is subjected to strong tidal forces from Jupiter, which heats its interior so that it is very active volcanically and tectonically (McGovern et al., 2016). Io is characterized by heat pipe volcanism, where basaltic layers erupted from randomly distributed volcanoes are buried and remelted a few kilometers below the surface. Venus exhibits vigorous single-lid behavior dominated by mantle plumes and rifts (Ghail, 2015); the upward magma flux is presumably matched by drips and delamination. Mars is a good example of sluggish single-lid behavior, with a few great volcanoes and one great rift.

From studying other active silicate bodies of the Solar System we have learned three important things: (1) there are two distinct tectonic styles: single lid and plate tectonics; (2) there are many single-lid tectonic styles; and (3) only Earth has plate tectonics. Because single-lid tectonics is so common among active silicate bodies, it seems likely that Earth experienced single-lid tectonic episodes in the past.

THE MESOPROTEROZOIC

The Mesoproterozoic (1600–1000 Ma) is the heart of the "Boring Billion," a term coined by Holland (2006) for the interval between 1.85 and 0.85 Ga when atmospheric oxygen levels changed little (Fig. 2A). The term "Boring Billion" is now used to describe many more aspects about this time period than Holland (2006) intended. Cawood and Hawkesworth (2014) called this "Earth's middle age" and marshalled evidence that the Mesoproterozoic was a time of environmental, evolutionary, and lithospheric stability distinct from the dramatic changes documented for other times.

I have argued elsewhere (Stern, 2005; Stern, 2018) that Earth's modern plate-tectonic regime began in Neoproterozoic time. If Earth did not have plate tectonics, it had some type of single-lid tectonics. Earth has always experienced deformation and magmatism, but studying Io, Venus, and Mars shows that this could have been caused by single-lid as well as plate tectonics. An active silicate body's tectonic evolution is likely to be complicated, with multiple different episodes. Earth may have ex-

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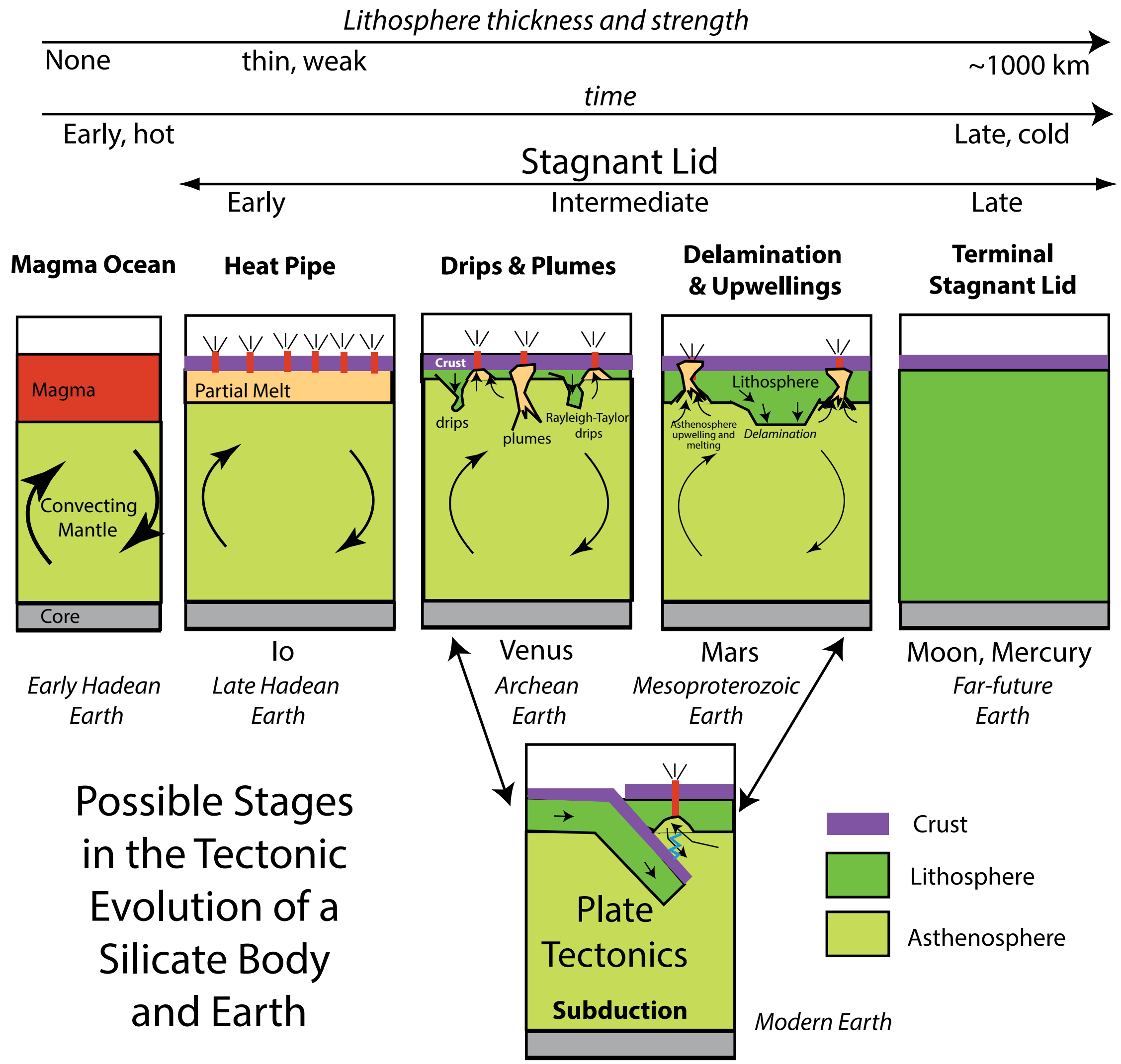

Figure 1. Possible evolution of magmatotectonic styles for a large silicate body like Earth. Examples from active Solar System bodies Io, Venus, and Mars are shown. Possible evolution of Earth is also shown. Strength of mantle convection is indicated by arrowed curve thickness. Plate tectonics requires certain conditions of lithospheric density and strength in order to occur and is likely to be presaged and followed by different styles of stagnant lid tectonics. See text for further discussion. Modified after Stern et al. (2018).

perienced multiple episodes of different kinds of single-lid behavior and of plate tectonics. Different tectonic regimes produce different structures, metamorphic rocks, and igneous rocks that, if preserved, provide evidence about the tectonic regime that produced them. Erosion, alteration, and burial destroy some but not all of the evidence of past tectonic regimes, at least for the past 3 Ga. Erosion may remove shallow features such as porphyry copper deposits and ophiolite nappes but cannot extirpate intrusive and metamorphic rocks, which extend to depth. Microscopic, geochemical, and isotopic evidence is useful for identifying when a change occurred in Earth's convective style but cannot reliably constrain when plate tectonics began. Condie's (2018, p. 58) admonition "… recycling of crust into the mantle does not necessarily require subduction, and it may be possible for such recycling to occur in stagnant [single]-lid regimes…" should be kept in mind.

EVIDENCE THAT THE MESOPROTEROZOIC WAS A PROTRACTED SINGLE-LID EPISODE

Geologic evidence—both negative and positive—should guide our interpretation of Mesoproterozoic tectonics. Negative evidence shows an absence of key plate-tectonic indicators (Figs. 2B–2D). Positive evidence specifies geologic features expected for single-lid behavior (Figs. 2E–2H). The first approach is straightforward because we know the kinds of rocks produced by plate tectonics. The second approach is more difficult because we are only beginning to think about what kinds of rocks should be produced by active single-lid tectonics.

Consider the negative evidence first. Stern (2018) identified three groups of rocks and minerals that only form by plate-tectonic processes. These are (1) ophiolites, indicators of subduction initiation and seafloor spreading; (2) blueschists, lawsonite-bearing metamorphic rocks, and jadeitite, indicators of subduction; and (3) ultra-high pressure (UHP) metamorphic rocks along with ruby and sapphire, indicators of continent-continent collision (Figs. 2B–2D). All of these are abundant in Phanerozoic and Neoproterozoic time and all are missing from the Mesoproterozoic. Brown and

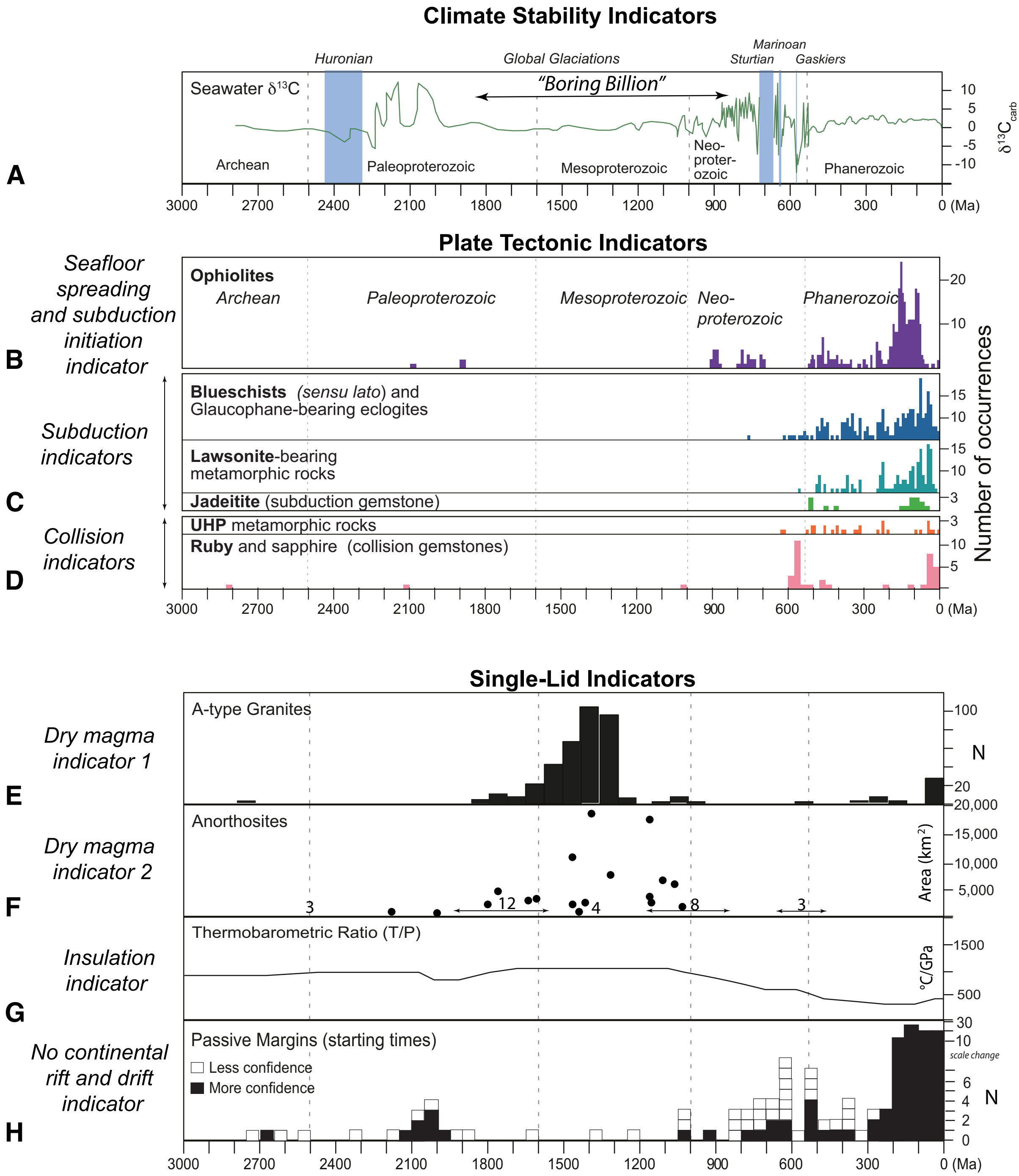

Figure 2. (A) Climate, (B–D) plate-tectonic, and (E–H) single-lid indicators for the past 3.0 Ga of Earth's history. Climate stability and plate-tectonic indicators from Stern (2018). "Boring Billion" from Holland (2006). Single-lid tectonic indicators include (E) A-type granites (Condie, 2014), (F) massif-type anorthosites (Ashwal, 2010), (G) thermobarometric ratios ($n = 564$; best fit curve from Brown et al., 2020), and (H) numbers of passive continental margins (Bradley, 2011). Fourfold confidence subdivision of Bradley (2011) is simplified into two intervals of higher and lower confidence. UHP—ultra-high pressure.

Johnson (2018) compiled data for 456 metamorphic terranes from the Eoarchean to the Cenozoic and classified these into three groups. Low dT/dP (which approximates the geothermal gradient at the time of metamorphism) metamorphic environments correspond to blueschist and eclogite, metamorphic rocks that only form in subduction zones. There are a few low dT/dP metamorphic rocks ca. 1.9 Ga but almost none in the Mesoproterozoic. There are a lot of Neoproterozoic and Phanerozoic low dT/dP metamorphic terranes. An independent assessment by Palin et al. (2020) confirms that there were two great episodes of low dT/dP metamorphism: one at 1.8–2.1 Ga and the second episode that began 0.7 Ga and continues today.

Positive evidence for single-lid behavior includes three types of indicators: (1) geochemical evidence of unusual, dry magmatism; (2) metamorphic evidence of elevated heat flow; and (3) sedimentological evidence for formation of passive continental margins. These are considered in greater detail below.

Because plate tectonics and subduction zones deliver large quantities of water deep into the mantle (van Keken et al., 2011) and single-lid episodes deliver less water, magmas generated during single-lid episodes should be drier than arc magmas generated by plate tectonics. I-type granitic rocks should dominate during plate tectonic regimes. In contrast, A-type granitic rocks are anhydrous, alkali-rich, and anorogenic (dall'Agnol et al., 2012). Mesoproterozoic A-type granites are unusually abundant compared to earlier and later times (Fig. 2E).

Massif-type anorthosites are another positive single-lid indicator that reflect anhydrous magmas. These were rarely emplaced in Neoproterozoic and Phanerozoic times but were placed abundantly in the Mesoproterozoic (Fig. 2F). Mesoproterozoic anorthosites may reflect deep-crustal ponding of basaltic magmas, crystallization and sinking of mafic silicates, and flotation of plagioclase in an Fe-rich magma (Namur et al., 2011; Ashwal and Bybee, 2017). Formation of Fe-rich magmas requires fractionation under low-oxygen fugacity conditions (Skaergaard trend). Low-oxygen fugacities are associated with dry magmas, not those generated above subduction zones (Cottrell et al., 2021).

A second line of positive evidence is that the lithosphere heated up. This is shown by the metamorphic thermobaric ratios (temperature/pressure, *T/P*) for Paleoarchean to Cenozoic metamorphic rocks (Brown et al., 2020). Thermobarometric ratios over the past 3.0 Ga are highest for Mesoproterozoic time (Fig. 2G). Heating up of the upper mantle (and the overlying lithosphere) is expected for single-lid tectonic regimes. Plate tectonics better cools Earth because it injects cold lithosphere deep into the mantle in subduction zones at the same time it releases asthenospheric heat at spreading ridges. An all-encompassing single lid, in contrast, insulates the interior and traps heat in the asthenosphere. Heat release is accomplished by magmatic outbursts and thinning the lithosphere (van Thienen et al., 2005). Lithospheric thinning leads to an elevated thermal gradient that is preserved in metamorphic rocks.

The third line of evidence is the paucity of new passive continental margins that formed in Mesoproterozoic time (Fig. 2H; Bradley, 2011). Passive continental margins form when continents rift and drift apart. They form frequently in a plate-tectonic regime but not in a single-lid tectonic regime.

There are distinctive Mesoproterozoic ore deposits that do not form in younger times when we can be confident that plate tectonics occurred, including sedimentary rock-hosted U, Kiruna magnetite-apatite, iron oxide-copper-gold, and ilmenite ore deposits. Correspondingly, the Mesoproterozoic lacks ore deposits that are common to younger assemblages formed by plate-tectonic processes such as orogenic gold and porphyry copper deposits (Goldfarb et al., 2010). Different mineralization styles are expected to accompany different tectonic styles. The contrast between younger plate tectonic–related and Mesoproterozoic mineralization styles couldn't be greater, which is consistent with an interpretation of different tectonic styles for these intervals.

Finally, there is paleomagnetic evidence. Paleomagnetic measurements could resolve the controversy because single-lid behavior should show that all continental blocks moved together. Unfortunately, paleomagnetic data that bear on this question are equivocal. Evans and Mitchell (2011) compiled and reported new paleomagnetic data and used these to conclude that there were "… minimal paleogeographic changes across Earth's first supercontinent cycle, in marked contrast to the dramatic reorganization implied between such Rodinia configurations and the subsequent assembly of Gondwana" (p. 445). This is consistent with the compilation of O'Neill et al. (2013), who found low plate-motion velocities through Early and Middle Mesoproterozoic time, although a rapid increase in plate velocity was noted for Late Mesoproterozoic time (see Discussion). On the basis of an independent compilation of paleomagnetic data, Piper (2013) identified the 1.7–1.25 Ga time period as a single-lid episode. Piper (2013) further inferred from paleomagnetic evidence that the transition to modern plate tectonics began ca. 1.1 Ga. These conclusions are controversial; for example, Pisarevsky et al. (2014) argue that Nuna/Columbia assembled by 1600 Ma and broke up at 1400 Ma. Meert and Santosh (2017) noted that "… despite the exponential increase in available [paleomagnetic] data, knowledge of the assembly, duration and breakup history of the supercontinent are contentious" (p. 67). Clearly, more paleomagnetic work is needed to resolve this controversy.

DISCUSSION

Given that plate tectonics emerged from a single-lid episode, how does this happen and how long does it take? Studies of Io, Venus, and Mars' single-lid episodes compel the conclusion that plate tectonics is a "Goldilocks" tectonic style. Oceanic lithosphere must be strong and dense, but not too strong or it cannot break to form new subduction zones; too weak and the lithosphere will break off in subduction zones. Single-lid tectonic regimes dominate when conditions for plate tectonics do not exist and when a lid with appropriate strength and density cannot be ruptured to form the first subduction zone, spreading ridge, and transform faults.

Sleep (2000) explored how an active silicate planet was likely to evolve through three different tectonic styles as a result of changing heat flow and mantle potential temperature: magma ocean, plate tectonics, and single-lid behavior. Magma ocean only happens early in planetary evolution, but cycling between plate tectonics and single lid may happen after that. Specifically, as plate tectonics cools the planet, lithosphere thickens and strengthens, ultimately transitioning into single lid. Single-lid regimes insulate the mantle, trapping heat and leading to lithospheric weakening, favoring plate tectonics.

O'Neill et al. (2016) argued that Earth may have started in an Io-like heat-pipe tectonic regime that evolved into short-lived alternating single-lid and plate-tectonic regimes over the next few billions of years (Fig. 1). As Earth-like planets cool, they may evolve into a plate-tectonic regime before eventually decaying into a terminal single-lid regime. The evidence presented here suggests that the Mesoproterozoic era was one such single-lid episode, separating an episode of Paleoproterozoic plate tectonics from the modern episode that began in Neoproterozoic time.

Evidence for cycling between single-lid and plate-tectonic styles is preserved in the rock record. Preservation of some ca. 1.8–2.0 Ga ophiolites and low dT/dP metamorphic belts indicates a brief plate-tectonic interval during this time. This episode ended with formation of a supercontinent called Columbia (Rogers and Santosh, 2002) or Nuna (Hoffman, 1997) and Earth entered the Mesoproterozoic single-lid episode. Immediately after a supercontinent forms is optimal for establishing a single-lid tectonic regime because supercontinent assembly destroys subduction zones between them to stop plate tectonics (Silver and Behn, 2008). Silver and Behn argued that formation of the Columbia/Nuna supercontinent led to the Mesoproterozoic single-lid episode.

Given the wide range of possible single-lid behaviors, how should we characterize the Mesoproterozoic episode? There was little orogenic activity during especially the first two-thirds of Mesoproterozoic time (Fig. 3). There was significant if unusual igneous activity but a low rate of crustal growth; Brown and Johnson (2018) infer that Mesoproterozoic crustal growth rates were 20%–50% that of other eons/eras. The Mesoproterozoic single-lid episode seems to have been somewhat between the vigorous style of Venus and the sluggish style of Mars today; perhaps "ponderous" single lid is an apt description.

THE GRENVILLE OROGENY AND MIDCONTINENT RIFT SYSTEM

The end of Mesoproterozoic differs significantly from the beginning and the middle. In Early and Middle Mesoproterozoic time there was a lot of igneous activity but little deformation, while the Late Mesoproterozoic experienced much more deformation (Figs. 3–4; Condie et al., 2015). Late Mesoproterozoic orogeny is known as Grenville in North America, Kibaran in Africa, and Sveconorwegian or Dalslandian in Europe. All of these expressions of ca. 1.2–0.95 Ga compressional deformation are called the "Global Grenville Orogeny" (GGO here for brevity). The GGO is generally accepted to manifest continental collisions to form the supercontinent Rodinia (Li et al., 2008). If this interpretation is correct, then plate tectonics operated in earlier Mesoproterozoic time, falsifying the central hypothesis that the Mesoproterozoic was a single-lid tectonic episode. Are there alternative explanations for the GGO that are consistent with a Mesoproterozoic single-lid episode? I think so. We know that few plate-tectonic indicators are associated with the GGO (Figs. 2B–2D), suggesting that it was somehow different than younger continental collision events, where such evidence is preserved.

Another difference between the GGO and younger continental collisions is that GGO compression was coeval with strong foreland extension and large igneous province (LIP) formation. This is best shown by the Mid-Continent Rift System (MCRS) of North America. The MCRS is at least 3000-km long, comparable to the modern East African and Baikal rifts, but is not a linear rift. Instead, it defines an upside-down "U" centered on Lake Superior with one arm that can be traced southwestward continuously as far as Kansas and discontinuously as far as west Texas and another arm that extends southeastward at least through Michigan. Stein et al. (2015) contrast the MCRS gravity signature with that of other continental rifts that have negative gravity anomalies because they are mostly filled with low-density sediment. Instead, the MCRS is filled with mostly mafic igneous rocks. Modeling of seismic and gravity profiles across the MCRS indicates a total magma volume of ~1–2 × 10^6 km^3 (Merino et al., 2013), an order of magnitude larger than the threshold for large igneous provinces (10^5 km^3) defined by Ernst (2014).

The MCRS trends discontinuously south in the subsurface from Kansas into west Texas, where igneous rocks can be traced south into the buried GGO deformation front. MCRS-related igneous rocks can be identified farther west. Late Mesoproterozoic (1140–1040 Ma) mafic and felsic magmatism affected a broad, ~1500-km-long region along the southwestern U.S. (Bright et al., 2014). Similar igneous suites are found elsewhere around the globe, including the 1078–1070 Ma Warakurna LIP of Australia, the 1112–1102 Ma Umkondo LIP in southern Africa, and mafic intrusions in Bolivia and northern India (Bright et al., 2014).

The relationship between global occurrences of the 1200–980 Ma GGO and 1150–1040 Ma LIP is unclear. Stein et al. (2018) argue that much of what has been called "Grenville" in the U.S. is actually buried MCRS. I concur with their assessment that the GGO and Late Mesoproterozoic LIPs need to be considered together, evidence that important changes happened in the solid Earth system at that time. I also conclude that the unusual nature of the GGO—including its lack of plate-tectonic indicators and association with coeval LIPs—indicates that consideration of a non–plate-tectonic origin for this activity is warranted. It is beyond the scope of this paper to explore in depth what that origin was, but the evidence for strong coeval compression, and extension suggests that the Late Mesoproterozoic GGO-LIP system marks the beginning of the transition from Mesoproterozoic single-lid to Neoproterozoic and younger plate tectonics.

CONCLUSIONS

Solar System exploration shows that most active silicate bodies have some kind of single-lid tectonic style and that only Earth has plate tectonics. Single-lid tectonic styles can range widely and will evolve from more to less deformation and magmatism as the body cools. Single-lid tectonic regimes can evolve

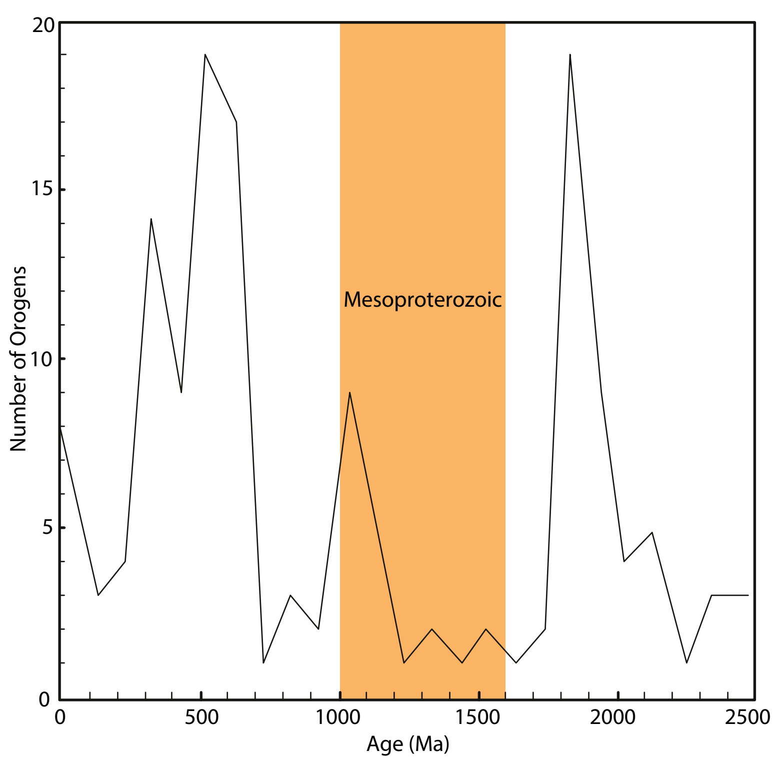

Figure 3. Numbers of orogens through time back to 2.5 Ga; from Condie et al. (2015).

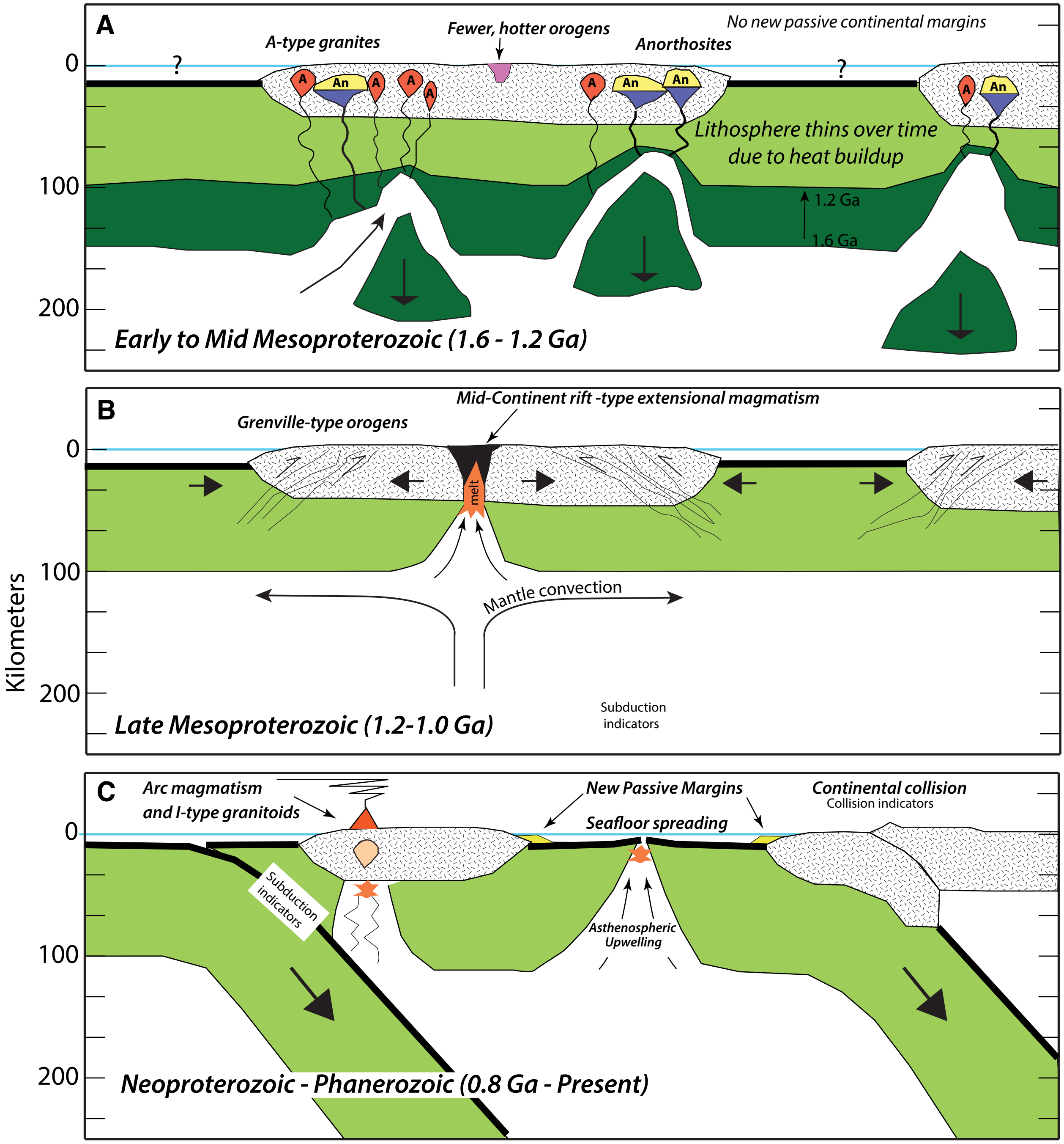

Figure 4. Cartoon showing three tectono-magmatic episodes and key characteristics of each discussed in this paper. (A) Early to Mid-Mesoproterozoic single-lid episode; (B) Late Mesoproterozoic regime; and (C) Neoproterozoic and younger plate-tectonic regime. A—A-type granites; An—anorthosite.

into plate tectonics. We can't understand the evolution of plate tectonics without better understanding Earth's episodes of single-lid behavior, when these were, and what the magmatic and tectonic styles of each were. The single-lid tectonic history of our planet needs to be explored if we are to understand how the modern solid Earth came to be. Negative evidence that plate tectonics did not occur should be combined with positive evidence for a single-lid tectonic regime. The Mesoproterozoic is the best interval of Earth history for this exploration to begin.

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CALL FOR NOMINATIONS

2021 GSA Awards & Medals

GSA selects individuals based on track record and commitment to integrity and promise to continue living up to the ethical standards embodied in GSA's Code of Ethics & Professional Conduct in addition to their many accomplishments. For details, see the October issue of *GSA Today* or go to **https://www.geosociety.org/awards.** The deadline for receipt of all medal, award, and recognition nominations is **1 Feb. 2021.**

Penrose Medal
Arthur L. Day Medal
Young Scientist Award (Donath Medal)
Florence Bascom Geologic Mapping Award
The Bromery Award for Minorities
Doris M. Curtis Outstanding Woman in Science Award
GSA Distinguished Service Award
GSA Public Service Award
Honorary Fellow

Also Coming Up:

John C. Frye Environmental Geology Award
Deadline: 31 Mar. 2021

In cooperation with the Association of American State Geologists, GSA makes an annual award for the best paper on environmental geology published either by GSA or by one of the state geological surveys. **Please send your nominations to** GSA Grants and Awards, P.O. Box 9140, Boulder, CO 80301-9140, USA; or send digital documents to awards@geosociety.org.

For more information, go to **www.stategeologists.org/award/frye.**

Call for GSA Fellowship Nominations

Deadline: 1 Feb. 2021

Nominate a deserving colleague with the honor of GSA Fellowship. GSA members are elected to Fellowship in recognition of distinguished contributions to the geosciences. See the election requirements at **https://www.geosociety.org/Fellowship.**

How to Nominate

The primary nominator, who must be a GSA Member and Fellow, (1) writes a letter of support; (2) collects two additional letters of support (one must be from a Fellow; both must be GSA members); (3) obtains nominee's current CV or résumé (two-page limit); and (4) completes online nomination form and uploads letters and CV/résumé at **https://www.geosociety.org/FellowNoms.**

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Scientists in Parks: A New Program for the Next Generation of Stewards

Scientists in Parks (SIP) is a new National Park Service (NPS) program that provides immersive, meaningful work experiences in natural resource fields so aspiring professionals, especially those underrepresented in science, can cultivate their career potential and connection with America's national parks.

What Happened to Geoscientists-in-the-Parks (GIP)?

We are uniting with related NPS programs to create Scientists in Parks, a new NPS program that will offer the opportunities previously found through the GIP program and much more. The new program model helps strengthen the framework for providing science-related, career-building experiences in partnership with NPS.

The SIP program brings the long-standing successes of three NPS programs—the Mosaics in Science Diversity Internship Program, Future Park Leaders of Emerging Change, and Geoscientists-in-the-Parks—into the same fold. The simplified program model unifies the strengths of earlier programs and builds capacity for hosting up to 200 opportunities with national park units annually.

SIP affords more options to consider for exploring careers in science and land management. Undergraduate students, graduate students, and recently graduated individuals will find it easier to align with opportunities based on their career stage and future goals.

One of SIP's core goals is to broaden diversity within the professional levels of the NPS workforce in natural resource fields. The program offers authentic opportunities to find mentorship, learn new skills, network with career professionals, and engage in leadership development as part of the participant experience. All projects help address the current natural-resource management needs of national parks.

"I think these are incredible opportunities to gauge where your passions and interests are, and what a wonderful place to do it."
—Jessie Pearl, past participant of Geoscientists-in-the-Parks and Future Park Leaders of Emerging Change

Project areas will encompass the physical, biological, and social sciences and will address a spectrum of topics—including air quality, climate change, geology, hydrology, night skies, paleontology, communication, and outreach. The program also invites science-related projects that intersect with the human dimensions of managing natural resources.

GSA is excited to join NPS, Stewards Individual Placement Program, Environment for the Americas, and the Ecological Society of America as program partners in providing SIP opportunities for the next generation of diverse park stewards.

Jessie Pearl (left) joined Saguaro National Park through Geoscientists-in-the-Parks (2018) and Future Park Leaders of Emerging Change (2019), two of the programs now merging with Mosaics in Science to create Scientists in Parks. Her project-related work investigated critical water sources in low-elevation and high-elevation desert settings over time. Pearl also received a 2017 GSA Graduate Student Research Grant while earning her Ph.D. in geoscience at the University of Arizona. Photo credit: Conservation Legacy.

Like GIP, Scientists in Parks will host an application period twice a year for project opportunities in the summer and winter seasons. Prospective participants can begin to review and apply for summer 2021 projects this month.

Learn more about Scientists in Parks:

1. Visit GSA's new website for the SIP program, **https://www.geosociety.org/sip;**
2. Check out the new NPS resources related to the program: **https://go.nps.gov/scientistsinparks;**
3. Receive updates about upcoming deadlines and program-related resources in the GeoScene, GSA's emailed monthly newsletter for students and early career professionals. Subscribe at **https://www.geosociety.org/geoscene;**
4. Find out more about all available projects and where to apply at **https://www.nps.gov/subjects/science/current-projects.htm.**



Scientists in Parks

Scientists in Parks provides all aspiring professionals—especially those underrepresented in science—with a unique opportunity to work on important real-world projects while building professional experience and a life-long connection to America's national parks.

Spring/summer 2021 opportunities are now posted—Apply by 24 Jan.

https://www.geosociety.org/sip

Learn more from the national parks about the program and related opportunities at **https://go.nps.gov/scientistsinparks.**

Questions? Contact us at sip@geosociety.org.

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2019–2020 GSA-USGS CONGRESSIONAL SCIENCE FELLOW FINAL REPORT

Knowledge, Persistence, and Trust: *My Congressionally Inspired Roadmap to a Successful 2020*


Mike O'Connor

Like so many others, I had no idea that my 2019–2020 GSA Congressional Fellowship would include, well, 2020. I wasn't aware that my year on the Hill would be interrupted on either end by an impeachment, which completely derailed the Congress, and a pandemic, which also completely derailed the Congress. I didn't know that the Aaron Sorkin–inspired fantasy that I was so happy to be living, where I spent my days briskly walking the marbled corridors of the Capitol complex in nice suits while scribbling notes on cards and talking to scores of people darting in and out of frame, would be shockingly, abruptly shattered in March, never to return. I didn't know that Congress, and the world, would be run from couches and dining rooms for the rest of my year. I didn't realize how much would be totally thrown off, upended, and in some cases, destroyed by this year. If I knew this all a year ago, I really might have rejected the whole thing.

I'd have been a moron to do that.

Working in government in 2020 was a great gift because it forced me to strip down every bell, whistle, frill, or perk that would usually come with the job and focus solely on the reason to do the job in the first place: to use the power of the people to improve lives. Despite, and in some cases because of, the unrest and uncertainty of this year, I found myself immersed in a job that was as meaningful and consequential as any ever could be. Government in 2020 taught me how to work hard, and be successful, when the roof is on fire. Three qualities are most crucial: You must know what you're doing; you must not stop doing it; and you must trust that if you know what you're doing and you don't stop doing it, progress will occur.

Everyone knows that in the sciences, knowledge IS currency. Conversely, many may look at the government today, recognizing how many policies exist that are incongruous with the current best-available science, and conclude, reasonably, that knowledge is seemingly without a place in our democracy. From my experience, I've seen knowledge as a still-relevant player in policy making, at least at the small scale. The job of Congress is to legislate on every single topic in existence. "Everything" is a fairly big ask for congressional offices, which average about nine people plus interns. Thus, in most cases, offices rely as much on the word of experts they trust, and those experts carry with them substantial knowledge. I was lucky enough to draft three bills and three amendments while working in Congressman Paul Tonko's office. Each of those legislative products has the endorsement of ten organizations considered thought leaders in their area of expertise. Those endorsements are often the hardest-earned agreements to be made, because each group has, in addition to an agenda, an extremely nuanced understanding of the issue being legislated. It was up to me, as the legislative staffer, to garner enough knowledge about a problem to put together bills that representatives of outside organizations could agree would be necessary.

One example from my year is very clear: I was asked in January to write a bill that would improve the recycling of lithium-ion batteries in America. I had to determine what the primary barriers were to recycling these batteries today, so that when I sent a bill to the Energy Storage Association or the Electric Drive Coalition for their support, they would agree. Based on my outreach and research, the BATTERY Act ended up becoming a bill to improve the infrastructure surrounding lithium-ion recycling (collection, sorting, transportation, etc.), rather than the recycling process itself. Because I was able to highlight a true issue in the industry, I was able to acquire a dozen groups and the ultimate support of a Republican cosponsor (Rep. John Curtis, UT-3). On a small scale (US$22 million annual appropriation over five years), knowledge won.

The BATTERY Act provides a perfect segue to the second pandemic-crucial quality: persistence. We hear at our fellowship orientation that "you should never hear a 'no' when there isn't one." Particularly now, people are more sporadic, burdened, and difficult to get ahold of. I learned through workshopping these pieces of legislation that non-response does not mean they are not interested. I emailed more than forty groups for support and more than thirty members of Congress for cosponsorship of the legislation I was working on. Fewer than ten percent responded to my first email, and less than half responded to my second. Most of the groups, and many of those members, are now supporting these bills. A formal training in science is not the ideal environment to learn persistence; however, in my experience this year, it proved crucial.

Finally, this year required us to have so much trust. As the walls of society crumbled around us, and our settings and livelihoods were upended, it was our responsibility as professionals to continue to work. To continue to have meetings. To continue to have deadlines. To continue to connect with colleagues, even on a bizarre and new platform—to trust that it was still worth it to put in the work. I have watched a slew of good legislation arise during this pandemic, both related to COVID-19 and apart from it, because people were able to put aside the uncertainty and the fear and just do the work. The comprehensive energy package being addressed in the House and Senate, which includes substantial climate provisions and now seems likely to become law, is one clear example of this.

2020 has not been easy, but I am lucky that it has been quite rewarding. I am so thankful to the thousands of members of GSA who, collectively, have made this fellowship happen, and I hope that the work I've done this year, and the many transferable skills acquired, will help promote the geosciences in the future. I am thankful to my host office, that of Congressman Paul Tonko, for integrating me into the team like few ever could. And, finally, I am so thankful to the board, selection committee, and Kasey White, for being the champions of a program that an increasing number of us owe our livelihoods to. Thank you for the best year of my life.

The manuscript is submitted for publication by Mike O'Connor, 2019–2020 GSA-USGS Congressional Science Fellow, with the understanding that the U.S. government is authorized to reproduce and distribute reprints for governmental use. The one-year fellowship is supported by GSA and the U.S. Geological Survey, Department of the Interior, under Assistance Award No. G19AP00110. The views and conclusions contained in this document are those of the author and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. government.

O'Connor worked in the office of Rep. Paul Tonko (D-NY) and can be contacted by e-mail at mtoconnor12@gmail.com.

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2020 By the Numbers:
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- 55% success rate

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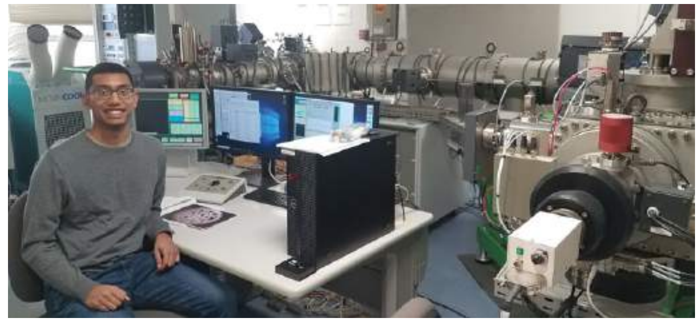
- +1-303-357-1025

GSA strongly encourages women, minorities, persons with disabilities, and other groups that are underrepresented in the geosciences to participate fully in this program. This program is supported by the National Science Foundation under Grant No. 1949901.



More Research Grants for Graduate Students and Others

GSA provides members with additional opportunities to apply for research funding. Applications for these programs will be accepted between now and 1 Feb. 2021, at 5 p.m. MST.
- Farouk El-Baz Student Research Grant (desert studies)
- Awards for Geochronology Student Research2 (AGeS2) Program (geochronology). Supported by the National Science Foundation under Grant No. 1759201.

More Information:
- Apply by 1 Feb. 2021
- **https://www.geosociety.org/grants**
- researchgrants@geosociety.org
- +1-303-357-1025

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NSF

Awards for Students to Attend GSA's Northeastern Section Meeting

Students nationwide who work full-time, care for dependents, or are considered non-traditional are eligible to apply for an award to attend the 2021 Northeastern Section Meeting, 14–16 March. Funding will cover meeting registration, educational costs, and dependent care. Deadline to apply: 1 Feb. 2021. Contact Tahlia Bear, tbear@geosociety.org, with questions.

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 2021. 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: 19 Mar. 2021. Learn more at **https://www.geosociety.org/GSA/Education_Careers/Field_Experiences/GSA/fieldexp/home.aspx.** Questions? Contact Jennifer Nocerino, jnocerino@geosociety.org.

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POSITIONS OPEN

Chair Search, California State University, San Bernardino

The Department of Geological Sciences at California State University, San Bernardino invites applications for a Department Chair, tenure track position, at the rank of Associate or Professor to begin service in July 2021.

The successful candidate must have a Ph.D. in the geosciences, excellent leadership, communication and interpersonal skills, as well as an excellent record of teaching and scholarship, preferably with a record of significant research funding. Applicants with prior success in fundraising and development are particularly encouraged to apply.

The area of the candidate's specialization is open. We seek a candidate with a strong commitment to undergraduate and graduate teaching and diversity, a record of research funding, and a commitment to excellence that will enhance the Department. Preference will be given to candidates with administrative experience as a department chair or similar leadership experiences.

The Department Chair reports to the Dean of the College of Natural Sciences and is a 12-month, 0.5 time department chair and 10-month 0.5 time faculty member appointment. The Chair will provide strong academic leadership in the planning and administration of graduate and undergraduate programs in Geology, assist the entire faculty in developing new initiatives and a viable strategic vision, mentor faculty in the promotion and tenure process, supervise support staff, teach courses (at a half-time load), maintain an active research program involving undergraduate and/or graduate students, work with the CSUSB Office of Advancement in fundraising, and maintain and build upon our existing strong relationship with industry and government agencies.

Typical Activities: Responsibilities of the Chair include participation and leadership in the faculty duties of teaching, mentoring, research, service, and program development. The Chair serves as an advocate for the Department in the College and the University, and vice versa. The Chair, in collaboration with the faculty, plans and executes a strategic direction for the department, builds and staffs the schedule of classes, oversees the department budget, fosters team building, manages the department and its staff, and works with diverse faculty and students in the department and across campus to enhance interdisciplinary collaboration. For additional information, please visit https://senate.csusb.edu/FAM/Policy/(FSD87-28.R3) Recruit_Chairs&Directors.pdf .

Minimum Qualifications: A Ph.D in Geological Sciences or a related field is required by time of appointment. July 1, 2021.

The Chair is encouraged to develop and participate in activities that support the University's strategic plan, available at https://www.csusb.edu/strategic-plan. This plan emphasizes: a) student success; b) faculty and staff success; c) stewarding resources; d) community engagement and partnerships; and e) enhancing the campus identity.

Qualified candidates must demonstrate a commitment to excellence in teaching and mentoring a diverse student population and to working effectively with faculty, staff and students across a wide range of disciplines.

If you are interested in this opportunity, we invite you to apply at: https://www.governmentjobs.com/careers/csusb/transferjobs. A link is also available on the Department's website: https://www.csusb.edu/geology. Salary is commensurate with experience. Formal review of applications will begin January 4, 2021 and continue until the position is filled.

The Department has four full-time faculty members and one faculty in the Faculty Early Retirement Program with a variety of research interests and offers B.A., B.S., and M.S. degrees. CSUSB is located in one of the most geologically rich and diverse regions of North America.

California State University, San Bernardino (CSUSB) is located in San Bernardino in the Inland Empire, 60 miles east of Los Angeles and operates a satellite campus in Palm Desert located in Coachella Valley. CSUSB serves approximately 20,000 students, of which 81% are first-generation college students, and graduates about 5,000 students annually. As a designated Hispanic Serving Institution, CSUSB reflects the dynamic diversity of the region and has one of the most diverse student populations of any university in the Inland Empire, and the second highest Hispanic enrollment of all public universities in California. CSUSB employs 467 full-time faculty and offers 48 undergraduate, 35 graduate, and 1 doctoral degree programs and 14 academic programs with national accreditation.

Geoscience Education, California State University, Fullerton

The Department of Geological Sciences invites applications for a tenure-track Assistant Professorship in Geoscience Education beginning August 2021. CSUF is a Hispanic-Serving Institution and an affirmative action and equal opportunity employer with a strong commitment to increasing campus diversity. We seek a geoscience educator who develops, applies, and evaluates new geoscience teaching innovations and curricula, and conducts innovative geoscience education research. We expect candidates to show evidence of an existing or developing, active, externally funded, student-centered research program. We seek a scholar who demonstrates interest and ability to teach courses in geoscience education and general geology at various levels including; general education, lower- and upper-division undergraduate, and graduate courses. The successful candidate shall: (1) coordinate geoscience education courses; (2) help facilitate the integration of teacher preparation; and (3) be involved in program-level assessment for our department. Applicants should submit a cover letter, separate teaching and research statements, as well as a statement discussing past and/or potential contributions to diversity through research, teaching, and/or service, a CV, and a list of three individuals who will provide letters of reference if requested. To be assured full consideration, all application materials must be received by December 15, 2020. Submit materials online at: https://apps.fullerton.edu/facultyrecruitment. Questions concerning the application or receipt of application materials should be sent to: Dr. W. Richard Laton Geoscience-ed-search@fullerton.edu.

Assistant Professor (Tenure Track) in Biogeochemistry of Terrestrial Ecosystems and Environmental Change, University of Lausanne

The Faculty of Geosciences and the Environment (FGSE) of the University of Lausanne invites applications for a professorship in biogeochemistry of terrestrial ecosystems and environmental change, to be based in the Institute of Earth Surface Dynamics (IDYST).

We are looking for a soil biogeochemist with expertise on ecosystem-level biotic and abiotic mechanisms driving the elemental cycles in terrestrial environments. The ideal candidate will further a process- and/or model-oriented understanding of terrestrial environments and their response to human activities and climate change. We welcome candidates who wish to integrate new research and teaching perspectives into our existing programs.

The successful candidate will actively participate in the research activities of the Institute of Earth Surface Dynamics, will teach in the Bachelor of Geosciences and Environment and Masters programs taught by the FGSE, and will supervise masters and doctoral students.

Appointment will be at the Assistant Professor level (tenure track). However, exceptionally, we will consider outstanding candidates for direct appointment to the Associate or Full Professor level, notably if this corresponds with our equal opportunity objectives.

The application should be in English and include a cover letter (max 1 page), a full Curriculum Vitae, a research statement (max. 4 pages), a teaching statement (max. 2 pages), a list and links to the three most significant publications and a statement on the personal contribution to each, and the names and contact information of five referees. For further information, contact Prof. Frédéric Herman, Dean of the FGSE (frederic.herman@unil.ch).

Application deadline: 15th of December 2020 (23:59 Swiss time GMT+1).

A full description can be found on the following link: https://bit.ly/33x33qm.

Or www.unil.ch/central/en/home.html –> Careers at UNIL –> Emplois –> Postes ouverts–> English –> Keywords biogeochemistry (or ad 16430).

Department Head, Biology, Geology, and Environmental Science, University of Tennessee at Chattanooga

The University of Tennessee at Chattanooga (UTC) College of Arts & Sciences invites applications for the position of Head of the Department of Biology, Geology, and Environmental Science (BGE) at the rank of associate or full professor. This is a tenure-track, 12-month position with appointment to begin August 1, 2021. The field of specialization is open, but candidates must have an earned Ph.D. in Biology, Geology, Environmental Science, or a related discipline to be considered. Applicants must have administrative experience and demonstrate the ability to support and integrate our large, complex, multidisciplinary department while promoting our disciplinary identities and strengths. The successful candidate should be a forward thinker who is able to motivate the department to pursue a long-term vision that will grow our strengths and capitalize on our uniqueness. We are especially interested in candidates with strong communication skills that will encourage open conversation within the department and facilitate advocacy of departmental needs to the upper administration. Applicants should have a history of teaching accomplishment and scholarly productivity and a sustained commitment to diversity, equity, and inclusion in higher education with a focus on increasing the participation of underrepresented students and faculty in the sciences. We encourage applications from members of under-represented groups, including but not limited to women, people of color, LGBTQ+, gender-nonconforming individuals, first generation college graduates, and people with disabilities.

For detailed information about this position, including minimum and preferred qualifications and application procedure, refer to the position announcement using the following link:

https://ut.taleo.net/careersection/utc_faculty/jobdetail.ftl?job=20000000X1.

Review of applications begins Friday, November 6, 2020 and will continue until position is filled.

Geosciences Instructor, Tarleton State University

The Department of Chemistry, Geosciences, and Physics at Tarleton State University, in Stephenville, Texas, invites applications for a non-tenure track Instructor of Geosciences (9 month) starting Fall 2021. The successful candidate will support the Geosciences program through engaging, student-centered teaching, and actively contribute to service and outreach initiatives that advance the department, college, and university. Candidates will be expected to instruct in introductory geoscience and related discipline courses and laboratories, and be competent in face-to-face and online instruction. All application submissions must be made electronically through Tarleton's employment site, https://www.tarleton.edu/jobs/.

Review of applications will begin immediately, and continue until the position is filled. Position availability is contingent on budgetary approval. Tarleton State University is an Equal Opportunity/Affirmative Action/Veterans/Disability Employer. As a member of the Texas A&M System, Tarleton will provide equal opportunity for employment to all persons regardless of race, color, sex, religion, national origin, age, disability, genetic information, veteran status, sexual orientation or gender identity and will strive to achieve full and equal employment opportunity through the Texas A&M System.

Required Qualification: Candidates must hold a Master's Degree in geology, geological sciences, environmental science, or a related field at the time of employment. Must demonstrate potential for outstanding teaching, and strong verbal and written communication skills. Physical activity will involve sitting, standing, bending, climbing stairs and walking, 20/20 corrected eyesight, and occasional lifting of moderate loads (50 lbs) in an office and field environment.

Preferred Qualifications: Experience and ability to teach additional courses from wider background is preferred, but not essential.

Environmental Science Tenure Track Assistant Professor (9 Month), Tarleton State University

The Department of Chemistry, Geosciences, and Physics at Tarleton State University, in Stephenville, Texas, invites applications for the tenure-track position of Assistant Professor of Environmental Science (9 month) starting Fall 2021. The successful candidate will support the Environmental Science Masters of Science program through engaging, student-centered teaching, establishment of a competitive research program, and actively contribute to service and outreach initiatives that advance the department, college, and university. Candidates will be expected to instruct in graduate-level environmental science courses in both a face-to-face and virtual format, as well as assist in teaching undergraduate courses as appropriate, while assisting in the expansion and management of the Master's program at Tarleton State University. Research specialization areas are broad, and candidates with experience in climate, remediation, or compliance are especially encouraged to apply. All application submissions must be made electronically through Tarleton's employment site, https://www.tarleton.edu/jobs/.

Review of applications will begin immediately, and continue until the position is filled. Position availability is contingent on budgetary approval. Tarleton State University is an Equal Opportunity/Affirmative Action/Veterans/Disability Employer. As a member of the Texas A&M System, Tarleton will provide equal opportunity for employment to all persons regardless of race, color, sex, religion, national origin, age, disability, genetic information, veteran status, sexual orientation or gender identity and will strive to achieve full and equal employment opportunity through the Texas A&M System.

Required Qualification: Candidates must hold a Ph.D. in environmental science or a related field at the time of employment. Must demonstrate potential for outstanding teaching, research, and strong verbal and written communication skills. Physical activity will involve sitting, standing, bending, climbing stairs and walking, 20/20 corrected eyesight, and occasional lifting of moderate loads (50 lbs) in office and field environments.

Preferred Qualifications: Experience and ability to teach additional courses from wider background is preferred, but not essential.

Mendenhall Postdoctoral Research Fellowships, U.S. Geological Survey

Various Locations

The U.S. Geological Survey (USGS) is seeking candidates for Mendenhall Research Fellows. The postdoctoral fellows are appointed to the USGS for two years and receive full salary and benefits at the GS-12 level, step 1. Mendenhall Fellow appointments are time limited, not to exceed two years, and are full-time. Under certain circumstances, the appointment may be extended up to an additional two years.

Open – Thursday 10/1/20, Close – Monday 1/4/21

The USGS Mendenhall Research Fellowship Program provides an opportunity for postdoctoral fellows to conduct concentrated research in association with USGS scientists, often as a final element to their formal career preparation. The Program also provides: 1) research experiences that enhance the scientific stature and credentials of the Fellows; and 2) scientific expertise to assist in the implementation of the USGS Strategic Plan and the science strategy of its programs. Mendenhall Fellows are expected to publish their results in peer-reviewed scientific outlets.

Applicants are encouraged to contact the Research Advisor(s) for the Research Opportunity of interest to coordinate the development of a research proposal.

More information on Research Opportunities and specific application requirements can be found at https://www.usgs.gov/centers/mendenhall/research-opportunities.

For more information, contact the Mendenhall mailbox at mendenhall@usgs.gov.

The U.S. Geological Survey is an Equal Opportunity Employer.

OPPORTUNITIES FOR STUDENTS

Graduate Student Opportunities at Case Western Reserve University. Students with backgrounds in geology, physics, chemistry, biology, engineering, and related fields are encouraged to apply for our Ph.D. and MS programs in Earth, Environmental, and Planetary Sciences. Areas of active research in the Department include planetary geology and geodynamics, planetary materials, high-pressure mineral physics and geochemistry, core and mantle processes, environmental science, sedimentary geology, and sediment transport. For more information, please visit http://eeps.case.edu or write to eeps-gradinfo@case.edu. Financial assistance is available. Application deadline: 1/15/2021.

Graduate Student Opportunities (MS), Ohio University. The Department of Geological Sciences at Ohio University invites applications to its research thesis-based MS degree in Geology for the Fall of 2021. The Geological Sciences faculty at Ohio University collaborate in three research clusters: paleobiology and sedimentary geology, solid earth and planetary dynamics, and environmental and surficial processes. Prospective students are encouraged to contact faculty directly to discuss potential research topics. Qualified students are eligible to receive teaching assistantships that carry a full tuition scholarship and a competitive stipend. For program and application information, visit the department website at http://www.ohio.edu/cas/geology/graduate or contact the graduate chair, Dr. Daniel Hembree (hembree@ohio.edu). Review of applications begins February 1, 2021.

Graduate Student Opportunities (online MS), Ohio University. The Department of Geological Sciences at Ohio University invites applications to its online, non-thesis MS degree in Geology for the Spring or Fall of 2021. The program includes courses on research methods, paleobiology and sedimentary geology, Earth materials and planetary geology, and environmental and surface processes. The program is designed for students planning to enter or already in the geoscience workforce (industry, government, non-profit) that do not require research experience as well as K-12 educators seeking additional training in the geosciences. For program and application information, visit the department website at http://www.ohio.edu/cas/geology/graduate or contact Dr. Xizhen Schenk (xschenk@ohio.edu).

Summer 2021 Community College Internships (CCI). Are you a community college student in science, technology, engineering, or math looking to develop your technical skills?

Then the CCI program is for you. Gain hands-on experience in a technical project under the guidance of a mentor and build your professional network at a national lab. Present your work to scientists and peers, join in social activities, and engage in a variety of professional development activities to enhance your career skills.

The CCI program is sponsored and managed by the Department of Energy (DOE) / Office of Science's Workforce Development for Teachers and Scientists (WDTS) program in collaboration with 16 DOE national laboratories and facilities across the U.S.

Benefits: $600/week stipend; Housing accommodations or housing allowance; Round-trip travel reimbursement.

Learn how to apply at https://science.osti.gov/wdts/cci/How-to-Apply.

Applications are due January 12, 2021 at 5:00 PM ET.

For full eligibility requirements, place visit https://science.osti.gov/wdts/cci/eligibility.

Summer 2021 Science Undergraduate Laboratory Internships (SULI). Are you an undergraduate student or recent graduate in science, technology, engineering, or math looking to develop your research skills?

Then the SULI program is for you. Gain hands-on research experience on an exciting project under the guidance of a mentor and build your professional network at a national lab. Present your research to scientists and peers, join in social activities, and engage in a variety of professional development activities to enhance your career skills.

The SULI program is sponsored and managed by the Department of Energy (DOE) / Office of Science's Workforce Development for Teachers and Scientists (WDTS) program in collaboration with 17 DOE national laboratories and facilities across the U.S.

Benefits: $600/week stipend; Housing accommodations or housing allowance; Round-trip travel reimbursement

Learn how to apply at https://science.osti.gov/wdts/suli/How-to-Apply.

Applications are due January 12, 2021 at 5:00 PM ET.

For full eligibility requirements, please visit https://science.osti.gov/wdts/suli/eligibility.

Graduate student opportunities in Geosciences at Baylor University. The Department of Geosciences at Baylor University invites applications for full-time PhD and MS students starting in August 2021. Admission to the program includes 5 years of support for PhD students and 2 years of support for MS students through graduate assistantships and fellowships, a full tuition waiver, 80% health insurance subsidy, annual travel funding for conference attendance, and research funding for graduate students on a competitive basis. Candidates should have at least an undergraduate degree in geology, geophysics, or in a related area and excellent analytical and writing skills. Students holding a BS degree may apply directly to the PhD program.

Faculty research covers a broad spectrum of Earth sciences, with strengths in biogeosciences, energy geoscience, hydrological and surface processes, lithospheric processes, paleoclimate, and solid Earth and planetary sciences. For more information about the Department of Geosciences, our research areas, and the graduate program please visit www.baylor.edu/geosciences.

Applications are due by January 15, 2021, with a priority application deadline of December 1, 2020. Details about the application process and the priority deadline can be found here: https://www.baylor.edu/geosciences/index.php?id=952059. Applications to the Department of Geosciences must be submitted online here: https://grad.baylor.edu/apply/. Please contact our Graduate Program Director for more information or with questions at geosciences@baylor.edu

M.S., Ph.D. in Earth Sciences (full-tuition and stipends), Syracuse University. The Department of Earth and Environmental Sciences at Syracuse University invites applications for full-time M.S. and Ph.D. students starting in August 2021. Interdisciplinary research opportunities leading to M.S. and Ph.D. degrees include: biogeochemistry, computational geophysics, environmental geology, geomorphology, global environmental change, hydrogeology and hydrology, isotope geochemistry, paleobiology, paleolimnology, petrology, sedimentology, tectonics, and thermochronology. For more information on our programs: https://thecollege.syr.edu/earth-sciences-department/graduate-programs-earth-sciences/

Ph.D. and M.S. students are supported by full-tuition scholarships and stipends through teaching assistantships, research assistantships, and/or fellowships. The Department only admits students that have identified faculty advisors, so it is recommended you contact potential advisors in your field of interest either before or after application. For more information on our faculty and research groups: https://thecollege.syr.edu/earth-sciences-department/research/

Applications for Fall 2021 admission are strongly encouraged by January 15, 2021. To apply: https://thecollege.syr.edu/earth-sciences-department/graduate-programs-earth-sciences/application-information/

M.S. and Ph.D. Graduate Student Assistantship Opportunities, Clemson University. Clemson University Department of Environmental Engineer and Earth Sciences seeks students interested in pursuing a M.S. or Ph.D. in the areas of tectonics, sediment transport, applied geochronology, and surficial processes. A strong foundation in the geosciences is required. Prior research in the above-mentioned areas of interest would be beneficial. Possible research topics include, but are not limited to, provenance analysis of Cenozoic continent-scale fluvial systems, Pliocene–Pleistocene dust production and loess deposition in South America, and improving geochronology-based sediment provenance analysis. Outstanding applicants will be offered support in the form of a research and/or teaching assistantship. Students offered an assistantship are expected to start Fall 2021. Interested geoscientists should contact Dr. Alex Pullen (apullen@clemson.edu; https://www.clemson.edu/cecas/departments/eees/people/facultydirectory/pullen.html) this fall to discuss opportunities.

Two NSF-funded Ph.D. Assistantships to study beaver dam analogues impacts on floodplain hydrology. Syracuse. We are seeking two Ph.D. students to start May or June 2021 for an NSF project focused on understanding the hydrologic impacts of beaver dam analogues in semi-arid landscapes using a combination of fieldwork (Wyoming), numerical modeling, and UAV image analysis. If interested, please contact Dr. Christa Kelleher (Syracuse University, Earth and Environmental Sciences) or Dr. Philippe Vidon (SUNY-ESF, Sustainable Resources Management) ahead of the application deadline (Jan 15, 2021) with a current CV, information about your interest in pursuing a graduate degree, and research or other relevant experience.

MERC MSc Graduate Opportunity at Eldorado Gold's Ormaque gold Discovery, May 2021. MERC, in partnership with Eldorado Gold, is seeking a MSc student to undertake a field-based structural MSc project at Eldorado's Ormaque zone, a new discovery at the Lamaque Gold Mine. This project is within southeastern Abitibi greenstone belt near Val d'Or, Quebec. The goal of this project is to provide a structural context for gold mineralization at Ormaque focused primarily on structural observations in drill core and underground mapping, when available. These will be combined with standard petrography (transmitted and reflected light) and SEM observations. The project will also address host lithologies, alteration systematics and relative timing of the hydrothermal event. The project will be supervised by Drs Bruno Lafrance, Ross Sherlock and Tim Baker, at MERC and Eldorado Gold. The successful candidate will integrate within the Lamaque exploration team adhering to their health and safety standards while in the field and working collectively to advance an understanding of the Ormaque deposit. Experience in greenstone belt geology and a working knowledge of French is an asset. To apply, please forward your application and cover letter to Courtney Folz at merc@laurentian.ca. The application should include a CV including academic transcripts, contact details and the names of three referees. Review of applications will begin immediately, but applications will be accepted until the position is filled.

MERC MSc Graduate Opportunity at Argonaut Gold's Magino gold project, January 2021. MERC, in partnership with Argonaut Gold, is seeking a MSc student to undertake a field-based structural thesis project at the Magino gold project within the GoudreauLochalsh district of the Michipicoten Greenstone Belt near Wawa, Ontario. The goal of this project is to provide a structural context for gold mineralization at the Magino deposit. This project will focus primarily on structural field observations, drill core observations and mapping combined with standard microstructural petrography (transmitted and reflected light) and SEM observation with the goal of characterizing gold mineralization at microscopic scale. The project will be supervised by Drs Bruno Lafrance, Ross Sherlock and Stefan Kruse, at MERC and Argonaut Gold. The successful candidate will integrate within the Magino exploration and development team adhering to their health and safety standards while in the field and working collectively to advance an understanding of the Magino deposit. To apply, please forward your application and cover letter to Courtney Folz at merc@laurentian.ca. The application should include: a CV including a list of publications, academic transcripts, contact details and the names of three referees. Review of applications will begin immediately, but applications.

A Three-Dimensional, Virtual Tour of the Johnston Geology Museum

*Marcia K. Schulmeister** and ***Briana Edwards,*** *Earth Science Program, Emporia State University, Emporia, Kansas 66801, USA*

As a need for online communication grows, digital 3D models provide an effective strategy for teaching shape- and orientation-based concepts that are essential for understanding geology. While developing our department's first, all-online section of an introductory earth-science class, we created a low-cost, 3D, virtual tour that simulates a traditional, on-campus visit to our University's geology museum. When combined with 360° images, the tour allows both traditional and online museum visitors to view mineral, rock, and fossil samples on cell phones, tablets, or computers. The new approach extends the use of an established museum assignment that is regularly used in our introductory face-to-face geology classes to our online students. Digital rotation and magnification of samples encourages in-depth examination of the specimens and materials that is not possible when looking through glass displays, enriching the museum experience for both online and traditional museum visitors. The new approach also provides audio tracks and alternative viewing access for differently abled or small museum patrons and expands the museum's visibility to a broader online audience.

MATERIALS AND METHODS

The Johnston Geology Museum features rocks, fossils, mining history, and Native American artifacts of relevance in Kansas. Used by both the university and a regional public audience, it has hosted thousands of open houses and school and scout field trips, in addition to supporting our earth-science curriculum. The collection is organized in display cases and as free-standing specimens that are accompanied by maps, drawings, and written explanations. We created virtual displays of ten cases using 3D modeling software (Agisoft, 2018) that aligns, masks, and renders multiple digital photos into clusters that form the basis of our models. Individual specimen models were generated from 30 to 200 digital photographs, while entire display cases required five to 10 photos, for smaller cases, and up to 150 photos for the large displays. Photos were taken at 18 megapixel resolution using a standard digital SLR camera. The rendered model files were edited and viewed using a commercially available viewer on a public-access server (Sketchfab, 2018). Three-dimensional subjects can be rotated, enlarged, and navigated using a mouse or two-finger swipes on a computer, tablet, or cell phone. Software used to create the models costs US$15 to US$550 (depending on license type), and the 3D viewer may be accessed for free or at a minimal cost. Our online virtual tour can be viewed for free wherever the Internet is available.

The virtual museum exercise begins with a 360° photograph of the museum. Ten "stops" (Fig. 1) along the tour include clickable links that provide access to 3D models of individual specimens, and expanded dialog boxes containing relevant background and explanations. Because most students in our introductory geology classes are not earth-science majors, and many museum visitors have minimal science background, we took advantage of an opportunity to amend the physical displays with digital materials of relevance to our exercise by adding links to new content. Additional explanations of plant and animal life modes, environmental conditions, and geologic time help to clarify concepts emphasized in our class through links to relevant short videos, location maps, and updated geologic time scales. The option of adding new questions and advanced material would allow for use of the 3D images in our upper-level geology courses. Students were able to complete the introductory virtual tour assignment in one to two hours.

OUTCOMES AND APPLICATIONS

After two semesters of its use, we have observed several positive outcomes and one limitation of the virtual experience. Online students scored higher than traditional students on exercise questions about fossil preservation and life modes, probably owing to the superior viewing angles and in-depth examination of subtle details that were possible when viewing the 3D models. By revising the original exercise so that the oldest fossils are visited first, and embedding links to a geologic time scale at various places within the exercise, we noted more thoughtful answers to questions about important events in earth history. Links to images or videos of modern environmental analogues helped allow students who have not traveled extensively beyond the Midwestern United States to better visualize the landscapes and environments of ancient Kansas. Because our assignment features only select display cases, the discovery that takes place when casually browsing an entire museum is lost; many valuable exhibits that are not part of our tour can only be accessed through a face-to-face visit.

The use of 3D models is emerging in the growing field of online geoscience education (e.g., Brande and McDaniel, 2018; Nesbit et al., 2020). Our exercise is the first to combine a virtual museum tour with 3D models that illustrate the geologic history of Kansas. The tour provides access to mid-continent geologic history that may not otherwise be available to students and geologists living outside of our region. The potential use of our exercise in online secondary education teaching may help teachers communicate earth history concepts to a younger audience and inspire future earth-science majors.

To take a 3D tour of the Johnston Geology Museum visit https://sites.google.com/view/

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Figure 1. Stop 7—The Cretaceous Fossils of Kansas. The 3D display (A) is superimposed on a map of the Cretaceous Seaway, which is visible when the model is open. Explanations (B), videos, enlarged images, and audio tracks are linked to special display features as circled numbers.

schulmeister-hydrogeology/virtual-tour-of-the-johnston-geology-museum, or scan the QR code provided below.

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It's Time to Defuse the Cambrian "Explosion"

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Volcanoes may erupt explosively. Meteoroids may explode on entering the atmosphere. A microwaved grape may explode (Conover, 2019). However, a growing body of research suggests that biodiversity at the dawn of the Cambrian Period did *not* explode. Data, amassed in the century and a half since Charles Darwin (1859) agonized that the apparent absence of Precambrian lifeforms was the weakest link in his theory of evolution by natural selection, support the view that biological diversity at the beginning of the Cambrian Period did not burst violently, detonate, shatter, or blow up. In this contribution, we trace the origin of the phrase "Cambrian explosion," give reasons for moving away from using it, and offer an alternative for describing intervals of significant increase in the diversity of life.

The bibliographic pedigree of the phrase "Cambrian explosion" is uncertain; its origin is not clearly established in peer-reviewed literature. By the early twentieth century, the abrupt appearance of abundant (macro-) fossils in the Cambrian was canon in historical geology textbooks (Schuchert and Dunbar, 1933). The earliest use of the adjective "explosive," with reference to an evolutionary rate, was likely George Gaylord Simpson's "explosive evolution" to describe a general pattern of rapid diversification early in the history of a lineage (Simpson, 1944). Mid-twentieth-century contemporaries echoed use of this phrase in characterizing a general evolutionary pattern (Henbest, 1952; Colbert, 1953).

Use of the phrase "explosive evolution" to describe rapid diversification during the early Cambrian morphed into "The Cambrian Explosion" under obscure circumstances. The earliest published occurrence known to us is a section heading in an early version of an experimental high school biology curriculum (BSCS, 1961). Three years later, the phrase, "Cambrian evolutionary explosion," with the middle, qualifying adjective "evolutionary," to distinguish it from physical or chemical processes, was used in a paper describing the evolution of oxygen in Earth's early atmosphere (Berkner and Marshall, 1964). Ultimately, the binomial form prevailed, referring to the biosphere, and the "Cambrian explosion" has propagated ever after without explicit authorship attribution.

Eminent Precambrian geologist and paleobiologist Preston Cloud was an early critic of the adjective "explosive" to describe the Cambrian biodiversification. Cloud noted that the time scale involved could have been millions of years, hardly "explosive" in the widely understood use of the word (a point reiterated by Marshall, 2006). Cloud also remarked, presumably facetiously, that such episodes probably were not accompanied by a loud noise (Cloud, 1948).

The images conjured by "Cambrian explosion" are vivid and Internet-ready; a Google search on "Cambrian explosion memes" returned more than 300K results. However, the concept implied by the word "explosion" does not do justice to advances in our understanding since the Modern Synthesis (Huxley's 1942 coinage describing the merger of natural selection with Mendelian genetics) was modern. A few examples: molecular phylogenetics (Suárez-Díaz and Anya-Muíoz, 2008) makes possible construction of hypotheses for evolutionary development during the "prelude" to the Cambrian (Valentine, 2002); the ability to resolve biosignatures and Proterozoic biogeochemical cycles (Rothman et al., 2003) pushed the appearance of complex biological processes deeper into the pre-Cambrian past; measures of morphological disparity (that is, the variety of different metazoan body plans) show that biological innovation was not limited to the Cambrian but proceeded apace as life expanded from the marine environment into new terrestrial ecospace (Deline et al., 2018); new fossil discoveries point to evolutionary continuity of biomineralizing animals across the Ediacaran–Cambrian transition (Cai et al., 2019); integration of biostratigraphical and geochemical records indicates that biological transitions of the late Proterozoic and early Phanerozoic were a series of successive radiations that built upon each other (Wood et al., 2019). In sum, the processes and the time scale over which these processes acted were more complex than implied by a phrase that signals a single event.

But perhaps the most compelling reason to reassess the use of the word "explosion" to describe biodiversification during the Cambrian, separate from linguistic lineage and disciplinary developments, is its appropriation by followers of non-scientific explanations for life's origin. Authors of anti-evolution tracts were among the earliest adopters of the phrase (Ridenour, 1967). Misuse of the concept of an early, explosive episode of evolution continues today (exchanged life discipleship, http://exchangedlife.com/); in this arena, the Cambrian explosion is commonly styled as falsifying evolutionary theory and flummoxing "evolutionists," neither of which accusations are accurate, correct, or true.

"Diversification" and "radiation" may not have the visceral appeal of "explosion," but both alternatives are suitable, fitting, apt, proper, and applicable (Marshall, 2006; Sperling and Stockey, 2018) without carrying the implication of catastrophic rate or otherworldly mechanism. Certainly, biodiversification at the beginning of the Cambrian was unique (Erwin et al., 1987)—all those new

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body plans—*but no evolutionary rules were broken*, nor is there mystery or discipline-dividing controversy, as is claimed by anti-science concerns who seize on the term "explosion."

After the Cambrian, the next major expansion in biodiversity occurred during the middle Ordovician, a chapter in the history of life referred to as the Great Ordovician Biodiversification Event or GOBE (Webby et al., 2004; Harper et al., 2015; Servais and Harper, 2018; Stigall et al., 2019). The term "event" may be as problematic as "explosion" in its implication of a short time period. We note that the word "event" in GOBE is redundant, as "biodiversification" is itself an event. (Similar pleonastic phrases encountered in other venues include "sales event" and "birth event.") We suggest, as an alternative to "Cambrian explosion," the *Great Cambrian Biodiversification* (GCB), a construction parallel to that for the Ordovician episode, absent the redundant and problematic "event" suffix. Because the phrase "mass extinction" is applied to multiple biodiversity crises through time, even though each event is unique in the organisms affected and the contributing causes, so might "great biodiversification" become a less volatile descriptor for intervals of notable increase in life's diversity.

We submit that, for scientific, semantic, and societal reasons, it is time to lay the term "Cambrian explosion" to rest for any use other than historical reference.

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Join Us in Support of Field Camp Experiences

We talk with you a great deal about field camp because it remains a critical component for students pursuing geoscience, and it is an area in which we can substantially provide assistance. The cost can be prohibitive, particularly now when the COVID-19 pandemic has made already difficult financial situations that much worse. Geoscience students will need support to gain this essential experience whether next year's camps are virtual, in-person, or hybrid. With your help, they can focus on having a memorable and transformative experience in whatever form it may take.

Several recipients of the 2020 J. David Lowell Field Camp Scholarships shared with us the challenges and rewards of attending virtual field camps and how receiving the scholarship helped them navigate those challenges. Selena Kimball considers the University of South Florida's virtual field camp to be the capstone of her geology degree, and she now feels prepared to continue her academic and professional career. Maria Solis discovered the interesting and diverse geology in her home state of Texas when her field camp decided to stay local instead of going to Montana. Natalea Cohen's virtual field camp through Fort Lewis College in Durango, Colorado, challenged her to apply all of the geologic knowledge she's learned in the past three years as she and her classmates remotely mapped the nearby geologic features. You can read the full stories from all three of these students right now on the Foundation blog at **https://gsa-foundation.org/news-events/.**

2020 has been a year full of changes and uncertainty. Many of us have had to cancel our own travel plans. We hope we can resume our travel before too long. Until then, please consider donating those unused personal funds to be used to help geoscience students navigate their careers during this challenging time—including their field camp experiences, even if they, too, don't include travel.

Join us to help students like Selena, Maria, and Natalea attend field camp as they continue to pursue geoscience in the midst of all the uncertainty. You can make a gift now at **https://gsa-foundation.org/fund/field-camp-opportunities/** or contact Debbie Marcinkowski, dmarcinkowski@geosociety.org, +1-303-357-1047, for more information.

From left: Selena Kimball at Little Glass Mountain, California, USA, in fall 2019. Maria Solis mapping conglomerates in Wilson County, Texas, USA, in summer 2020. Natalea Cohen, Molas Pass, Colorado, USA, holding a map of the area, summer 2020.

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William J. Samford Hall, Auburn University. The George F. Landegger Collection of Alabama Photographs in Carol M. Highsmith's America, Library of Congress, Prints and Photographs Division.

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Downtown Springfield Park Central Square. Photo courtesy of the Springfield, Missouri, Convention and Visitors Bureau.

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