Elements

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Cratons to Continents

CAROL D. FROST and PAUL A. MUELLER, Guest Editors

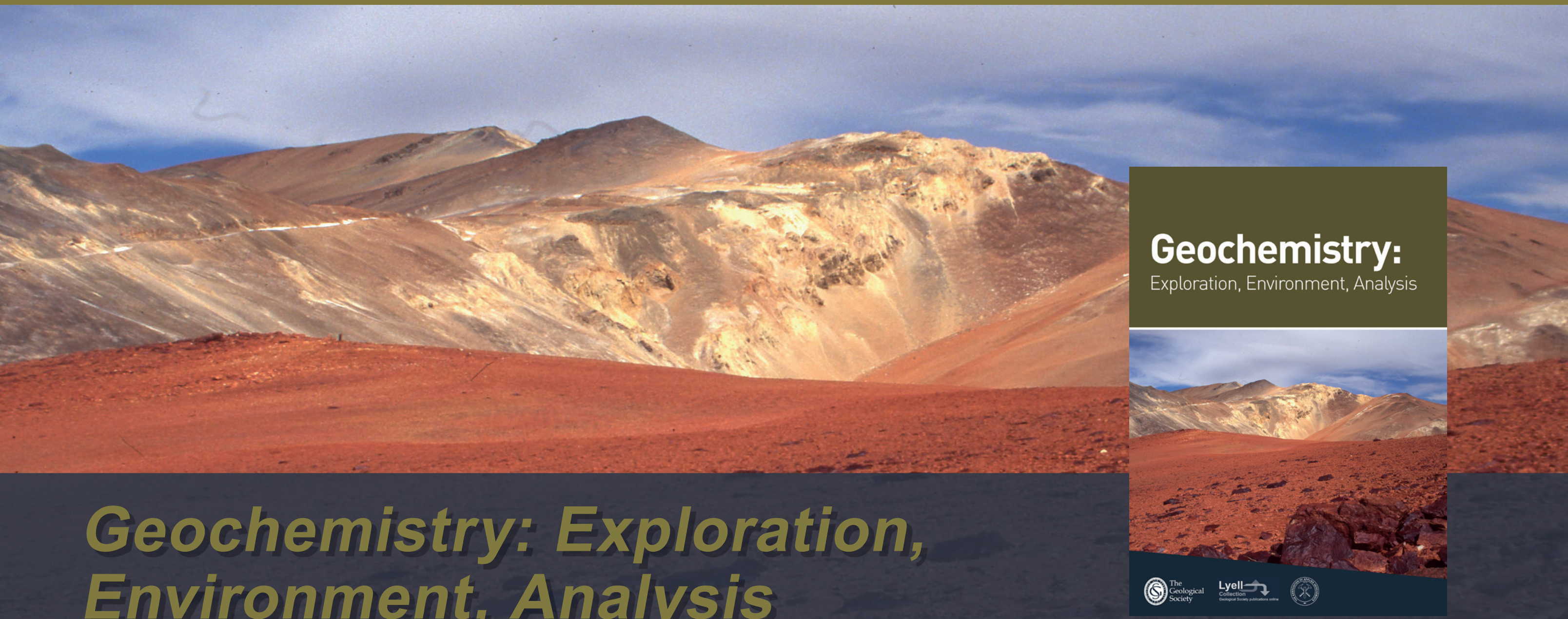
Archean Cratons:
Time Capsules of Early Earth

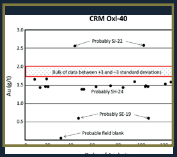
Earth's Earliest Crust

At the Dawn of Continents

Archean Geodynamics Under Flat
and Flooded Continents

Embracing Craton Complexity at Depth


Geochemistry:
Exploration, Environment, Analysis
The Geological Society
Lyell Collection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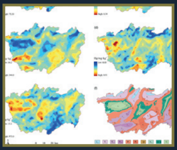

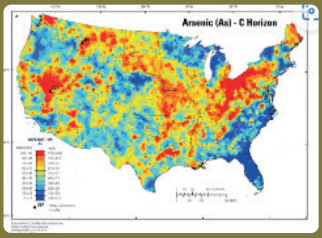
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Elements
An International Magazine of Mineralogy, Geochemistry, and Petrology

Elements is published jointly by the Mineralogical Society of America, Mineralogical Society of the UK and Ireland, Mineralogical Association of Canada, Geochemical Society, The Clay Minerals Society, European Association of Geochemistry, International Association of GeoChemistry, Société Française de Minéralogie et de Cristallographie, Association of Applied Geochemists, Deutsche Mineralogische Gesellschaft, Società Italiana di Mineralogia e Petrologia, International Association of Geoanalysts, Polskie Towarzystwo Mineralogiczne (Mineralogical Society of Poland), Sociedad Española de Mineralogía, Swiss Geological Society, Meteoritical Society, Japan Association of Mineralogical Sciences, and International Association on the Genesis of Ore Deposits. The magazine is provided as a benefit to members of these societies.

Elements is published six times a year. Individuals are encouraged to join any one of the participating societies to receive *Elements.* Institutional subscribers to either of the following journals—*American Mineralogist* and *Canadian Journal of Mineralogy and Petrology*—also receive one copy of *Elements* as part of their subscription. Institutional subscriptions are available for US$185 (US$200 non-US addresses) per year in 2024. Contact the Executive Editor (editor@elementsmagazine.org) for information.

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Cratons to Continents

Guest Editors: **Carol D. Frost** and **Paul A. Mueller**

Archean rocks of the Wyoming craton are exposed in Late Cretaceous to Eocene basement-involved uplifts of the Rocky Mountains. This issue's cover image is a WSW view of Continental Tower from the south flank of Wind River Peak, Wind River Mountains, Wyoming. A Paleoproterozoic mafic dike crosscuts Neoarchean granite of the Louis Lake Batholith. PHOTO: CAROL FROST.

DEPARTMENTS

The Mineralogical Society of America is for individuals interested in mineralogy, crystallography, petrology, and geochemistry. Founded in 1919, the society promotes—through research, education, and publications—the understanding and application of mineralogy by industry, universities, government, and the public. Membership benefits include *Elements* magazine, access to the electronic version of the *American Mineralogist*, as well as discounts on journals, Reviews in Mineralogy & Geochemistry series, textbooks, monographs, reduced registration fees for meetings and short courses, and participation in a society that supports the many facets of mineralogy.

Website: **www.msaweb.org**

Contact: business@minsocam.org

Society News Editor: Ann Benbow (abenbow@minsocam.org)

The Mineralogical Society of the UK and Ireland is an international society for all those working in the mineral sciences. The society aims to advance the knowledge of the science of mineralogy and its application to other subjects, including crystallography, geochemistry, petrology, environmental science, and economic geology. The society furthers its aims through scientific meetings and the publication of scientific journals, books, and monographs. The society publishes *Mineralogical Magazine* and *Clay Minerals*. Students receive their first year of membership free of charge. All members receive *Elements*.

Website: **www.minersoc.org**

Contact: info@minersoc.org

Society News Editor: Kevin Murphy (kevin@minersoc.org)

The Mineralogical Association of Canada was incorporated in 1955 to promote and advance the knowledge of mineralogy and the related disciplines of crystallography, petrology, geochemistry, and economic geology. Any person engaged or interested in these fields may become a member of the association. Membership benefits include a subscription to *Elements*, a reduced subscription to *The Canadian Mineralogist*, a 20% discount on volumes in the Topics in Mineral Sciences series (formerly the Short Course series), and a discount on the registration fee for annual meetings.

Website: **mineralogicalassociation.ca**

Contact: office@mineralogicalassociation.ca

Society News Editor: Lucy McLay (lucynjmclay@gmail.com)

The Clay Minerals Society (CMS) began in 1952 as the Clay Minerals Committee of the US National Academy of Sciences – National Research Council. In 1962, the CMS was incorporated with the primary purpose of stimulating research and disseminating information relating to all aspects of clay science and technology. The CMS holds annual meetings, workshops, and field trips, and publishes *Clays and Clay Minerals* and the CMS Workshop Lectures series. Membership benefits include reduced registration fees to the annual meeting, discounts on the CMS Workshop Lectures, and *Elements*.

Website: **www.clays.org**

Contact: cms@clays.org

Society News Editor: Bhabananda Biswas (Bhabananda.Biswas@newcastle.edu.au)

The Geochemical Society (GS) is an international organization founded in 1955 for students and scientists involved in the practice, study, and teaching of geochemistry. Our programs include cohosting the annual Goldschmidt Conference®, editorial oversight of *Geochimica et Cosmochimica Acta* (*GCA*), supporting geochemical symposia through our Meeting Assistance Program, and supporting student development through our Student Travel Grant Program. The GS annually recognizes excellence in geochemistry through its medals, lectures, and awards. Members receive a subscription to *Elements*, special member rates to *GCA* and to *G-cubed*, and publication and conference discounts.

Website: **www.geochemsoc.org**

Contact: gsoffice@geochemsoc.org

Society News Editor: Kevin Johnson (kjohnson@geochemsoc.org)

The European Association of Geochemistry was founded in 1985 and is a non-profit organization dedicated to promoting geochemistry internationally. The society is a dynamic association that organizes the Goldschmidt Conference® in Europe; publishes *Geochemical Perspectives* and *Geochemical Perspectives Letters*; recognizes scientific excellence through awards; supports early career scientists; sponsors workshops and conferences in Europe; organizes distinguished lecture and outreach programs; publishes job opportunities, newsletters, and blogs; and partners with other learned societies to strengthen geochemistry internationally.

Website: **www.eag.eu.com**

Contact: office@eag.eu.com

Society News Editor: Alice Williams (awilliams@eag.eu.com)

The International Association of GeoChemistry (IAGC) has been a preeminent international geochemical organization since 1967. Its principal objectives are to foster cooperation in the advancement of applied geochemistry by sponsoring specialist scientific symposia and the activities organized by its working groups and by supporting its journal, *Applied Geochemistry*. The administration and activities of IAGC are conducted by its council, comprising an executive and ten ordinary members. Day-to-day administration is performed through the IAGC business office.

Website: **www.iagc-society.org**

Contact: businessoffice@iagc-society.org

Society News Editor: Devin Smith (BusinessOffice@IAGC-Society.org)

The Société Française de Minéralogie et de Cristallographie (French Mineralogy and Crystallography Society) was founded 21 March 1878. The purpose of the society is to promote mineralogy and crystallography. Membership benefits include the *European Journal of Mineralogy*, *Elements*, and reduced registration fees for SFMC meetings.

Website: **www.sfmc-fr.org**

Contact: sfmc@ccr.jussieu.fr

Society News Editor: Mary-Alix Kaczmarek (mary-alix.kaczmarek@get.omp.eu)

The Association of Applied Geochemists is an international organization founded in 1970 that specializes in the field of applied geochemistry. It aims to advance the science of geochemistry as it relates to exploration and the environment, further the common interests of exploration geochemists, facilitate the acquisition and distribution of scientific knowledge, promote the exchange of information, and encourage research and development. Membership with the AAG includes the AAG journal, *Geochemistry: Exploration, Environment, Analysis*; the AAG newsletter, *EXPLORE*; and *Elements*.

Website: **www.appliedgeochemists.org**

Contact: office@appliedgeochemists.org

Society News Editor: John Carranza (ejmcarranza@gmail.com)

The Deutsche Mineralogische Gesellschaft (DMG; German Mineralogical Society) was founded in 1908 to "promote mineralogy and all its subdisciplines in teaching and research as well as the personal relationships among all members." Its great tradition in geoscience is reflected in its list of honorary fellows, which include M. v. Laue, G. v. Tschermak, P. Eskola, C.W. Correns, P. Ramdohr, and H. Strunz. Today, the subdisciplines in the DMG are also bridging the gap with other communities, such as materials science, solid state chemistry/physics, and the environmental sciences. The DMG especially tries to support young researchers, e.g., to attend conferences and short courses. Membership benefits include the *European Journal of Mineralogy*, *Elements*, and *GMit*.

Website: **www.dmg-home.org**

Contact: post@dmg-home.org

Society News Editor: Klaus-Dieter Grevel (klaus-dieter.grevel@rub.de)

The Società Italiana di Mineralogia e Petrologia (Italian Society of Mineralogy and Petrology), established in 1940, is the Italian national body representing all researchers dealing with mineralogy, petrology, and related disciplines. Membership benefits include receiving *European Journal of Mineralogy*, *Plinius*, and *Elements*, and a reduced registration fee for the annual meeting.

Website: **www.socminpet.it**

Contact: segreteria@socminpet.it

Society News Editor: Costanza Bonadiman (bdc@unife.it)

The International Association of Geoanalysts is a worldwide organization supporting the professional interests of those involved in the analysis of geological and environmental materials. Activities include the management of proficiency-testing programmes for bulk-rock and micro-analytical methods; the production and certification of reference materials; and the publication of the association's journal, *Geostandards and Geoanalytical Research*.

Website: **geoanalyst.org**

Contact: jmc@bgs.ac.uk

Society News Editor: Jennifer Cook (jmc@bgs.ac.uk)

The Polskie Towarzystwo Mineralogiczne (Mineralogical Society of Poland), founded in 1969, draws together professionals and amateurs interested in mineralogy, crystallography, petrology, geochemistry, and economic geology. The society promotes links between the mineralogical sciences, education, and technology through its annual conferences, field trips, invited lectures, and publishing. Membership benefits include subscriptions to *Mineralogia* and *Elements*.

Website: **www.ptmin.pl**

Contact: ptmin@ptmin.pl

Society News Editor: Anna Pietranik (anna.pietranik@uwr.edu.pl)

The Sociedad Española de Mineralogía (Spanish Mineralogical Society) was founded in 1975 to promote research in mineralogy, petrology, and geochemistry. The society organizes annual conferences and furthers the training of young researchers via seminars and special publications. The *SEM Bulletin* published scientific papers from 1978 to 2003, the year the society joined the *European Journal of Mineralogy* and launched *Macla*, a new journal containing scientific news, abstracts, and reviews. Membership benefits include receiving the *European Journal of Mineralogy*, *Macla*, and *Elements*.

Website: **www.ehu.es/sem**

Contact: npvsem@lg.ehu.es

Society News Editor: Nuria Sánchez-Pastor (secretaria@semineral.es)

The Swiss Geological Society was founded in 1882 and comprises specialist groups in geophysics, mineralogy and petrology, sedimentology, tectonics, and paleontology. The society is part of the Swiss Academy of Sciences and promotes the advancement and dissemination of Earth sciences in Switzerland. The society coorganizes the annual Swiss Geoscience Meeting (SGM) and publishes the *Swiss Journal of Geosciences* (*SJG*), which is now fully "open access." Members receive discounts for publishing in the *SJG* and participating at the SGM.

Website: **https://geolsoc.ch**

Contact: office@geolsoc.ch

Society News editor: Julien Allaz (julien.allaz@erdw.ethz.ch)

The Meteoritical Society is an international organization founded in 1933 for scientists, collectors, and educators to advance the study of meteorites and other extraterrestrial materials and their parent asteroids, comets, and planets. Members receive our journal, *Meteoritics & Planetary Science*; reduced rates for *Geochimica et Cosmochimica Acta*, which we cosponsor; the *Meteoritical Bulletin*; and *Elements*. We organize annual meetings, workshops, and field trips, and we support young planetary scientists worldwide. Through our medals and awards, we recognize excellence in meteoritics and allied fields.

Website: **meteoriticalsociety.org**

Contact: meteoritical.org/contact

Society News Editor: Cari Corrigan (corriganc@si.edu)

The Japan Association of Mineralogical Sciences (JAMS) was established in 2007 by merging the Mineralogical Society of Japan, founded in 1955, and the Japanese Association of Mineralogists, Petrologists, and Economic Geologists, established in 1928. The JAMS covers the wide field of mineral sciences, geochemistry, and petrology. Membership benefits include receiving the *Journal of Mineralogical and Petrological Sciences* (*JMPS*), the *Ganseki-Koubutsu-Kagaku* (*GKK*), and *Elements*.

Website: **jams.la.coocan.jp**

Contact: KYL04223@nifty.ne.jp

Society News Editor: Yusuke Seto (seto.y@omu.ac.jp)

The International Association on the Genesis of Ore Deposits (IAGOD) was established in 1964 to promote international cooperation and to increase knowledge in the field of the genesis of ore deposits: it is affiliated with the International Union of Geological Sciences (IUGS). The society organizes quadrennial symposiums and cosponsors sessions at the International Geological Congress and SGA Biennial Meetings. The IAGOD working groups and commissions promote ore deposit research and sponsor an international speaker series. Membership includes reduced fees at our meetings, discounted subscriptions to our flagship journal *Ore Geology Reviews* and other publications, and a subscription to *Elements*.

Website: **www.iagod.org**

Contact: webmaster@iagod.org

Society News Editor: Jens Andersen (J.C.Andersen@exeter.ac.uk)

Affiliated Societies The International Mineralogical Association, the European Mineralogical Union, and the International Association for the Study of Clays are affiliated societies of *Elements*. The affiliated status is reserved for those organizations that serve as an "umbrella" for other groups in the fields of mineralogy, geochemistry, and petrology but that do not themselves have a membership base.

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EARLY—AND FUTURE—PLANETARY ENVIRONMENTS

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Janne Blichert-Toft

The topic of this newest *Elements* issue that you are about to embark on is particularly close to my heart because it is all about the early Earth, which is one of the main reasons I became a geologist and a geochemist in the first place and which has taken up a big part of my ensuing almost 40-year-long research career. Becoming a geologist was a choice no one from the medical world I grew up in as an only child of two doctors, one a surgeon, expected I would make, especially given the poor prospect at the time (in Denmark) of ever being able to make a living out of it, at least compared with practicing medicine. But as it turned out, everything worked out although none of it—like not a *single* thing—according to any of my carefully laid plans (admittedly made at 18, which, unbeknownst to this 18-year-old exactly forty years ago to the date, more than guaranteed a "man plans, God laughs" scenario to play out—which was exactly what happened). I have never regretted making the choice that I made and, in hindsight, the lesson I learned—and have lived by ever since—is to follow one's interests and prioritize one's passion *if* one is fortunate enough to encounter the right initial opportunities—always created by other people—and happens to be in the right place and career stage at the right time and to be welcomed. Those are a lot of ifs but I was one of the lucky ones and I have many people to be grateful to for that. This, one can never pay back. One can only pay forward by creating opportunity for others in return—therein lies the beauty!

I was always fascinated by Greenland, which of course is innate to a Dane, and always dreamt of traveling to this enigmatic island. That dream came true in 1987 after my third year as a geology undergraduate at the University of Copenhagen, when I was given the rare opportunity of going to remote, cold, ice-covered, and polar bear–populated East Greenland for three months during the Arctic summer to work for a Canadian mining company prospecting for platinum in the, to me, back then and still today, mythical Skaergaard Intrusion (Fig. 1). I still remember the incredulous feeling and thrill of standing on and walking along the actual, almost cartoon-like layers (Fig. 1) of the actual famous Skaergaard Intrusion that I had read so much about during the first part of my undergraduate training—and, remarkably, the layers looked just like the photos I had seen in my geology textbooks! My dream had come true! In case you wonder, and to everyone's surprise, we actually did find the coveted platinum, the first traces of which had been detected the year before and were now being reconnaissanced, but, thankfully, not at high enough grades to be financially exploitable given the logistically challenging location, thereby mercifully saving the Skaergaard Intrusion and its magical beauty and peaceful site from destruction and pollution.

Greenland, of course, is not only a craton (i.e., a large stable block of the Earth's crust that forms the core of a continent—although, technically speaking, Greenland is considered an island, the world's biggest, not a continent) but *the* craton hosting some of the oldest, most famous rocks on Earth, the Isua supracrustal belt located in southwestern Greenland, dated to be 3.7–3.8 billion years old and still vigorously debated in the

Figure 1 Layering in the Skaergaard Intrusion, East Greenland. Geologist for scale. Photo: Janne Blichert-Toft (1987).

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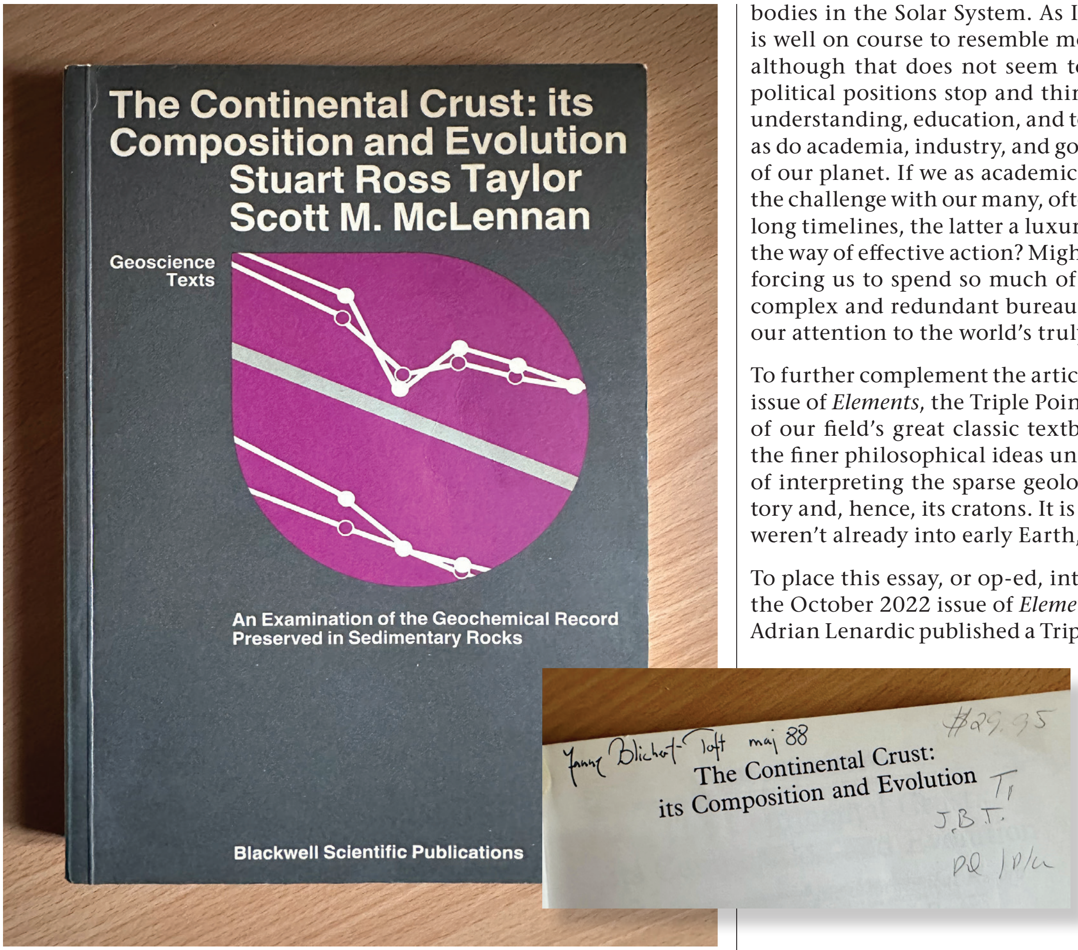


Figure 2 My personal copy dates back to 1988—the first textbook I acquired after returning from my first trip to East Greenland in 1987, where, in addition to the young (Tertiary) Skaergaard Intrusion, I was exposed to some legendary ancient (Archean) basement crust, which I now wanted to learn all about—bought at the 1988 AGU Spring Meeting in Baltimore for $29.95! As an aside, that meeting had the largest attendance (a whopping 2814 attendees!!) of any AGU Spring Meeting up until that point—translating into a rather modest carbon footprint at the time compared with today's gigantic AGU meetings; the same goes for the Goldschmidt conferences, which, over the same time period, grew from 400 attendees in the 1990s to 4000 today! The elephant in the room is hard to miss from the perspective of the sustainability of "future planetary environments"!

literature (and in just about every other forum) as holding one of the keys to understanding the origin of life—the Holy Grail of many a geobioscientist. After that first summer in East Greenland, the most stunningly beautiful place, other than Iceland, I have ever been, I never looked back and life just happened, determinedly steering me further and further away from my original plans; one of the outcomes being that I never returned to Denmark again, except to visit. This was not an end result I was ever conscientiously striving for as I love (and miss) Denmark and its laid back and socially responsible way of life, but on the upside, I got to learn about other cultures and languages hand-in-hand with science.

While the articles and supporting Toolkit of the present thematic issue of *Elements* focus on *terrestrial* cratons, such as Greenland but not only, its Perspective column goes looking for cratons on other rocky planets in our Solar System, thereby placing the development of Earth's crust into a larger planetary context. It turns out that journeying to other planets significantly broadens our perspective on Earth processes. What particularly surprised me was how, of all planets, infernally hot Venus leads back to the early Earth in ways I did not expect. The point being that we can learn a lot, sometimes in the most basic ways, about Earth, particularly Earth's early history, which is the part most similar to our neighbors in space, by looking closely at other solid planetary-type bodies in the Solar System. As I write this Editorial, Earth, of course, is well on course to resemble more and more its hotter sister planet—although that does not seem to make many of those sitting in key political positions stop and think, even less act. Our dated sectors of understanding, education, and technology delivery all need to change, as do academia, industry, and government if we are to tackle the future of our planet. If we as academics were to set an example, are we up to the challenge with our many, often increasingly obsolete traditions and long timelines, the latter a luxury we can no longer afford, standing in the way of effective action? Might administrations at large one day stop forcing us to spend so much of our time and energy on increasingly complex and redundant bureaucracy and instead allow us to redirect our attention to the world's truly existential problems at hand?

To further complement the articles on Archean cratons making up this issue of *Elements*, the Triple Point column, written by an author of one of our field's great classic textbooks (Fig. 2), thoughtfully discusses the finer philosophical ideas underlying the challenges and subtleties of interpreting the sparse geological record from Earth's earliest history and, hence, its cratons. It is fascinating and inspiring reading! If I weren't already into early Earth, I would be now!

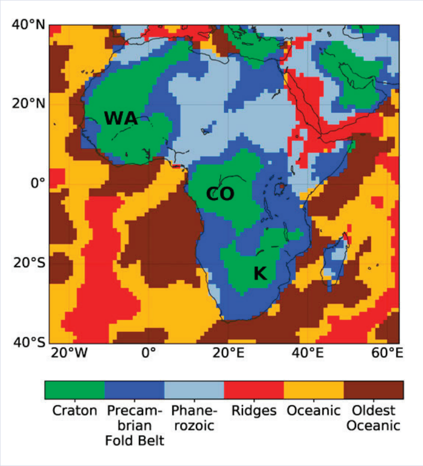
To place this essay, or op-ed, into context, here is what preceded it. In the October 2022 issue of *Elements* (vol. 18, no. 5), Mark Harrison and Adrian Lenardic published a Triple Point column entitled "Burke's Law: Toward a Reasoned Discussion of Deep Time." This essay took note of the difficulties with the evidence that can be mounted in the study of deep time for which there is little geological record, while the record that we do have is highly biased, and urged greater restraint when formulating interpretations. They suggested some new rules to help guide research into deep time and ended their essay with an invitation to the community to "continue this discussion." In their essay, the approaches employed by several workers were called into question, including some of the efforts of Ross Taylor (deceased) and Scott McLennan, and so it was no surprise that several months after publication, McLennan took Harrison and Lenardic up on their invitation "to discuss." The present *Elements* issue, focusing on Archean cratons and the development of the earliest continental crust, is particularly appropriate for McLennan to "continue the discussion," which he does by offering a timely new Triple Point contribution entitled "Scientific Laws and Myths, Ockham's Razor and Multiple Working Hypotheses." In this essay, he mounts some defense of the work on early Earth history by Taylor and McLennan, but also broadly engages with the major concerns discussed in the Harrison and Lenardic essay on deep time and offers some new insights into the issues raised.

To sum up: this issue of *Elements* constitutes yet another eloquent primer on a captivating topic put together by a strong, knowledgeable, and creative team of authors and Guest Editors that I hope the magazine's diverse readership will enjoy diving into and learning something from.

Janne Blichert-Toft
Principal Editor

ABOUT THIS ISSUE

This "Cratons to Continents" issue of *Elements* provides insights into the multiple ways geoscientists explore the 45% of Earth history encompassed by the Hadean and Archean eons. The contributions provide examples of geochemical, petrologic, and geophysical approaches to unraveling the origin and evolution of continents. Our authors explore the craton-to-continent journey from the darkly shrouded mysteries of the Hadean from 4.6 to 4.0 billion years ago through the merely old Archean eon, 4.0 to 2.5 billion years ago. Over these roughly two billion years, the Earth accreted from planetesimals, and developed its core, mantle, oceans, and earliest crust. The nature of the Hadean crust can be explored only indirectly as none has survived. Archean cratons preserve a legacy of crust with deep mantle lithosphere keels composed of greenstones and high-grade felsic gneiss. Toward the end of the Archean, these rock suites gave way to continental crust we'd recognize today. Archean cratons are the oldest pieces of continental crust on the planet and form the nuclei of many continents, as shown in the image depicting the cratonic nuclei of Africa (bright green), which stand out against the background of younger crust. To quote the Beatles, "it has been a long and winding road!"



Craton abbreviations: WA = West Africa, CO = Congo, K = Kalahari. Reproduced from Haas et al. (2021) with permission from Frontiers.

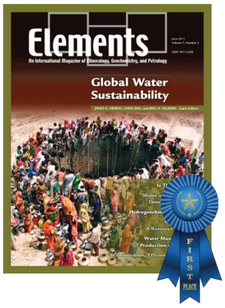
REFERENCE

Haas P, Ebbing J, Celli NL, Rey PF (2021) Two-step gravity inversion reveals variable architecture of African cratons. Frontiers in Earth Science 9, doi: 10.3389/feart.2021.696674

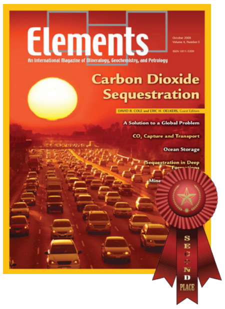
AGING LIKE A FINE WINE

Time flies when you're reading *Elements*—at least it does for us!—and in the most educationally enjoyable way. Since its visionary launch in 2005, *Elements* has published an astounding 742 review papers in 116 different thematic issues within the geosciences, ranging from the subatomic to the planetary scale, from the deep-time birth and evolution of planets to the modern-day throes of mining and waste management, from atomic jumps to building mountains—and there is still so much more to explore, learn, and discuss. Here we recognize *Elements*' top cited papers according to Google Scholar.

ELEMENTS' TOP CITED PAPERS



Water management challenges associated with the production of shale gas by hydraulic fracturing by Kelvin B. Gregory, Radisav D. Vidic, and David A. Dzombak, published in *Elements* June 2011 issue, "Global Water Sustainability" (vol. 7, no. 3), edited by Janet G. Hering, Chen Zhu, and Eric H. Oelkers **(1095 citations)**.

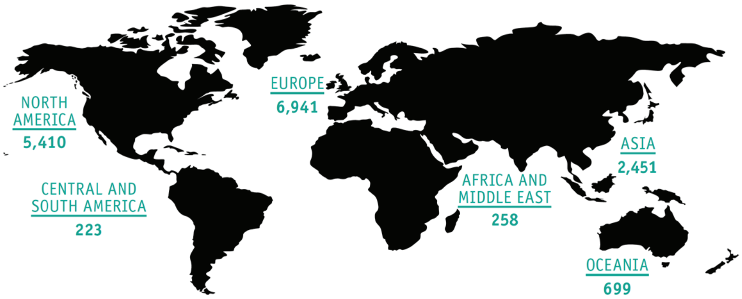


CO_2 sequestration in deep sedimentary formations by Sally M. Benson and David R. Cole, published in *Elements* October 2008 issue, "Carbon Dioxide Sequestration" (vol. 4, no. 5), edited by David R. Cole and Eric H. Oelkers **(985 citations)**.

Re-equilibration of zircon in aqueous fluids and melts by Thorsten Geisler, Urs Schaltegger, and Frank Tomaschek in *Elements* June 2007 issue, "Zircon: Tiny but Timely" (vol. 3, no. 1), edited by Simon L. Harley and Nigel M. Kelly **(893 citations)**.

DID YOU KNOW?

Since October 2023, *Elements* has been printed at the Sheridan Ohio facility in the outskirts of Brimfield, Ohio, USA, a suburb of Cleveland near the freshwater shores of Lake Erie. Approximately 25% of *Elements* print magazines are distributed domestically by the U.S. Postal Service, while the remaining majority is picked up by *Elements*' international distributor, APC Postal Logistics, and shipped to over 100 countries worldwide (see map). Approximately 43% of *Elements* readers are based in Europe, followed by North America (~34%) and Asia (~15%), and the remainder are scattered across the expanses of Africa, South America, and Oceania. After the United States, the second and third highest proportions of *Elements* readers are based in Germany (~15%) and Japan (~9%), respectively, while Swiss readers boast the highest number of subscribers per national population (~96 subscribers per 10^6 inhabitants [SPI]) followed by Icelanders (~39 SPI).



WHAT'S COMING NEXT

AUGUST 2024 (vol. 20, no. 4)	**The Invisible Ocean: Hydrogen in the Deep Earth**
OCTOBER 2024 (vol. 20, no. 5)	**Behind and Beyond Luminescence Imaging**
DECEMBER 2024 (vol. 20, no. 6)	**Himalayan Leucogranites**

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Janne Blichert-Toft, **Sumit Chakraborty**, **Tom Sisson**, and **Esther Posner**

SCIENTIFIC LAWS AND MYTHS, OCKHAM'S RAZOR, AND MULTIPLE WORKING HYPOTHESES

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Harrison and Lenardic (2022; hereinafter HL22) argued in a Triple Point article entitled "Burke's Law: Toward a Reasoned Discussion of Deep Time" (published in *Elements* vol. 18, no. 5) that special issues exist in the research of deep time and when trying to understand early Earth, for which the geological record is increasingly sparse as one descends into that abyss. They questioned the approaches, especially regarding the role of plate tectonics and nature of the earliest crust, taken by several workers including, prominently, Taylor and McLennan (2009). I have not worked in these areas for some time and, regrettably, my co-author is no longer with us (McLennan and Rudnick 2021), but some response seems appropriate. Relevant to my recent efforts in planetary science, HL22's essay got me thinking more generally about evaluating natural phenomena on Earth or other planetary bodies (including exoplanets) for which it is difficult or even impossible to make key measurements relevant to the important questions, that under more favorable circumstances might be routine, or for which resources needed to make measurements are inadequate or unavailable. In other words, cases where it is not possible to undertake decisive experiments to test hypotheses—a hallmark of vigorous scientific advance (Platt 1964)—regardless of whether or not they can be devised in principle. Accordingly, this contribution is not merely concerned with defending against pointed criticism, although there is some of that, but rather to pursue HL22's recommendation to *"continue this discussion."*

HL22 balked at words like "myth" to characterize suggestions of extensive Hadean continental crust (although tagging ideas with a cacophonous acronym SANMLM, embedding a charge of being a *"self-affirming … misconception,"* feels equally egregious to me!). The irony seemed rich upon reading this, as one inspiration for this label comes from the most unrepentant proponent of early continental crust, the late Dick Armstrong, in his paper *"The Persistent Myth of Crustal Growth"* (Armstrong 1991). This word is rather common in scientific discourse: a Web of Science search for "myth" under science topics revealed >10,000 entries. But one can turn the question of rhetoric around with HL22's promulgation of what they "informally" call "Burke's Law." Kevin Burke was indomitable in promoting plate tectonics, but "Burke's Law" (i.e., assuming plate tectonics has operated since initial differentiation until there is evidence otherwise) is not really a law at all, as HL22 recognize, but rather an application of Ockham's razor to a specific case. Indeed, a law—scientific or legal—has special weight that is broadly agreed upon. But, as the HL22 essay also notes, Ockham's razor is not without controversy (nor is the cited Hume's Law [i.e., the is–ought problem], which also carries the ominous moniker Hume's guillotine). Asserting a new "law," fully aware that it is not really a law, to support a point of view strikes me as also being an effective rhetorical device. (Has any paper been rejected for relying on the First Law of Thermodynamics?) Scientific literature is replete with extreme and perhaps no longer acceptable discourse; nevertheless, there remains a time and place for both neutral and precise wordsmithing and some measure of rhetorical flair—involving myths and misconceptions, laws and aphorisms, razors and guillotines. To this end, I direct readers to Ross Taylor's counsel derived from writing 10 books (also applying to review papers): *"Books should reflect the opinion of the authors. It is no service to readers to provide a list of ongoing controversies or of problems without making some assessment of a likely resolution or outcome. This is indeed not without hazard"* (Taylor and McLennan 2009, p. xviii).

Few scientists would disagree with the famous antimetabole/aphorism that provides one leg supporting "Burke's Law": absence of evidence is not evidence of absence. However, arguments about Hadean crusts or timing of plate tectonics mostly are not quite so banal. A more charitable characterization might be that absence of evidence, ***that should be present and observable given the available geological record***, may be evidence of absence (e.g., Sober 2015, p. 252–253). In other words, at least attempting classic Popperian falsification based on failed predictions (philosophy that for theories to be considered scientific, in principle, they must be testable and conceivably falsifiable). Taylor and McLennan (2009) did not argue that there simply was an absence of evidence for extensive Hadean continental crust and, therefore, it did not exist, but rather that extensive continents should produce Hadean-aged zircons that persisted during repeated cycles of cannibalistic sedimentary recycling and be more abundant than observed in Archean sedimentary rocks. Interpretations of the Hadean detrital zircon record certainly may evolve as more data are collected or simply may differ among workers—and so my point here is not to again argue the evidence, but simply to point out that it was indeed the evidence that was argued.

Similarly, the issue of Archean plate tectonics is more involved than opposing camps of pro- and anti-Archean plate tectonics. Many geologists have examined the Archean record (hopefully accumulating evidence in the "Burke's Law" sense) and found modern plate tectonic models wanting. However, debates are more along the lines of what exactly constitutes "modern-style plate tectonics"—there is much room to maneuver between immobile stagnant lids and Earth's current regime (e.g., unstable lids, squishy lids, sluggish lids, overturns, platelets, delamination, drip tectonics, flake tectonics, sagduction, hot subduction)—and exactly when modern conditions began: apparently sometime between T_0 and the Neoproterozoic (Palin and Santosh 2021). From my vantage, this range of views suggests a state of affairs more like multiple working hypotheses run amok! But even "Burke's Law" recognizes some kind of transition from an earlier state to a plate tectonic regime: *"we should assume (plate tectonics) was operating* ***since*** *global silicate differentiation…"* (HL22, p. 354; emphasis added). If recent planetary exploration has taught us anything, it is that the nature of initial silicate differentiation on rocky planetary bodies, involving a variety of magma ocean and other complex igneous processes, is remarkably diverse (e.g., contrast the earliest anorthositic crust of the Moon, graphitic crust of Mercury, and eucritic [basaltic] crust of 4-Vesta) and provides little comfort for imposing a unitary assumption that Earth's first crust resembled the current continental crust (McLennan 2022). As such, there seems to be some agreement that a transition from an original crust, related to initial differentiation, to modern-style plate tectonics occurred with ensuing debate essentially being haggling over the details.

Over the past two decades, I have been involved with Mars exploration, especially using rovers (e.g., McLennan et al. 2019). Mars rovers serve as "robotic field geologists" and operate under strict resource constraints involving time, data volume, and power. Prioritizing and obtaining observations are by design hypothesis-driven processes needed to justify resource allocations on both tactical and strategic timelines. Analytical capabilities are chosen well before landing site selection and therefore not fine-tuned to the specific geological problems encountered and, hence, often cannot carry out what on Earth would be routine measurements. These circumstances may lead to operationally unfalsifiable hypotheses—those that can be tested in principle but not in practice (i.e., spacecraft do not or cannot deploy appropriate instruments—synchrotrons come to mind). For example, in a recent review of Mars' sedimentary geology, one of my co-authors observed that *"many outstanding questions … could be resolved with a single thin section!"* (McLennan et al. 2019, p. 93). In my experience, just like the nature of Archean plate tectonics, hypotheses tend to accumulate over time (sustained by the guise of multiple working hypotheses) but because it is rarely possible to make decisive measurements leading to falsification, it can be very difficult to reduce an ever-growing number of acceptable hypotheses, each of which may be considered deserving of precious resources. This, in turn, could pose a risk of resource-limited missions becoming bogged down.

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There are many reasons—some scientifically objective and others less so—why some theories are more accepted than others (Hoffmann 2003). But in my judgement, embedded within these discussions are the competing roles of three fundamental concepts underpinning scientific discourse: (1) Karl Popper's doctrine of falsification (Popper 1962), (2) the method of multiple working hypotheses (Chamberlin 1890), and (3) Ockham's razor (principle of parsimony). The first two are widely understood (although some details perhaps less so), but among the difficulties with Ockham's razor is that its meaning is largely in the eye of the beholder (Sober 2015). At one extreme, it is improperly thought to suggest that simpler theories are more likely correct. After all, nature abounds with complexity. HL22 boil it down to *"simpler is better"* (p. 354). Hoffmann et al. (1997) concluded that rather than *"simpler is better,"* a preferable expression is that simpler is pragmatically more useful (Fig. 1). Thus, *"Ockham's razor merely keeps science on the straightest path to the truth, crooked as it may be"* (Kelly 2008, p. 350).

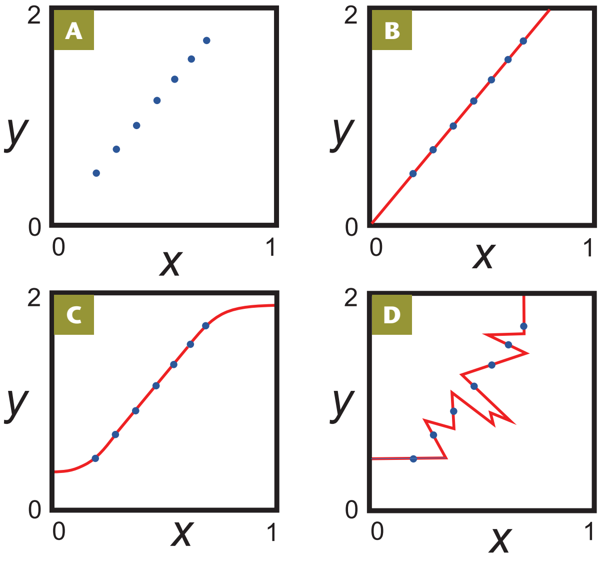

Figure 1 One formulation of Ockham's razor to evaluate multiple working hypotheses. Modified from Hoffmann et al. (1997). (**A**) Measurements from experiments or samples. (**B**) Linear regression explaining all variation ($r^2 \approx 1.0$). (**C**) High-order polynomial tracking the data but deviating beyond the data range. (**D**) "Chaotic" relationship but also fitting the data. Ockham's razor does not state that (**B**) is necessarily correct, but only that it is the most useful model to adopt with available information. Where resources are limited (e.g., planetary exploration), making additional observations to further test models (**C**) or (**D**), rather than directing resources to another problem, is questionable. For example, if a measurement at $x = 1$ fell on the linear trend, ad hoc adjustments to hypothesis (**C**), changing the number of terms, degree, and/or coefficients of the polynomial, or to hypothesis (**D**), adding another "zig" or "zag," could be made, reducing them to what Lakatos (1969) would term "degenerating" theories.

HL22 provide ten *"different rules"* (p. 355) to guide investigations of deep time, many being behavioral in nature. Earth science research in general is heavily burdened by weak (i.e., practical) underdetermination (Kleinhans et al. 2010) and, accordingly, it is probably not coincidental that the method of multiple working hypotheses was devised by a geologist. Hence, rather than formulating different rules to address specific problems (where might that end?), perhaps we should refresh our memories about long-standing thinking on the general nature of scientific investigation. Such problems may well fall in the shadow of Popper's rather murky concept of the demarcation between science and metaphysics, which is founded on the ability to test and falsify hypotheses, or uncomfortably along the continuum between progressive and degenerating problem-shifts (Lakatos 1969). Being falsifiable in principle, Popper probably would consider many questions about early Earth or those arising during planetary exploration to be scientific in nature, but I think he might remind us that the intrinsic confirmability of any hypothesis is fundamentally limited by its testability (Popper 1962, p. 256). This is very much in line with Platt's (1964) approach of strong inference. Platt embraced a version of multiple working hypotheses but tempered it with the necessity of having *"crucial experiments"* (*experimentum crucis* of Robert Hooke and Isaac Newton?) to test and, where possible, exclude hypotheses in order to make robust scientific progress. Indeed, for nearly a century prior to the lead up to the plate tectonic revolution, geology itself was largely moribund because it did not have the tools to implement relevant experiments to test its hypotheses (Menard 1971).

But in the absence of such crucial experiments, or until breakthroughs (likely technological or discovery-based) allow us to devise such experiments, what is a practical path forward? HL22 considered Ockham's razor the weaker second leg supporting "Burke's Law," but I would instead argue that vigorous use of Ockham's razor, when aptly framed, should indeed be a key tool in reducing the number of multiple working hypotheses, thus allowing us to focus our resources (and attention) on the most prospective subset of models. The late geophysicist Don Anderson (2002, p. 59) suggested *"Occam's razor can be used to improve, simplify, and discard theories, but is most useful when it is used to compare theories."* Hoffmann et al. (1997) argued that the razor is best used as a pragmatic tool serving as an operational principle and *"is not a metaphysical statement about the way the universe is"* (p. 14), a view I find compelling. It has even been suggested that we best reserve Ockham's razor for trimming *"Plato's beard"* only when it *"is sufficiently tough, and tangled by many entities"* (Popper 1972, p. 301). For cases such as early Earth that lacks an adequate geological record, planetary exploration that lacks adequate or appropriate resources, and no doubt many other underdetermined scientific problems (e.g., origin of life), perhaps the razor is also well used to help prune overgrowths of multiple working hypotheses for which no decisive experiments can be reasonably or practically devised to test their predictions.

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THE QUEST FOR EXTRATERRESTRIAL CRATONS

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Here I explore our Solar System's rocky planetary bodies as possible Archean craton (AC) analogs. Why? If other bodies host AC-like features, we might learn things about early Earth that we cannot learn from Earth itself. Typically, we look to Earth for planetary analogs. I propose the reverse—let us look to other planets for Earth analogs. Planets are likely most similar in their *early* histories. Earth developed plate tectonics, but this elegant global cooling process destroyed most of Earth's early geological record. No other planets developed global plate tectonics and, therefore, might preserve records of early global processes that shed light on our own planet's workings.

First, we need to define 'Archean craton' so that it is clear what we are looking for. Second, we will abandon strict uniformitarianism (the concept that Earth has always changed in uniform ways and, hence, that the present is the key to the past), which bolsters familiar concepts but stifles novel ideas. Third, we will formulate thought experiments armed with first-order scientific principles and being mindful of operative boundary conditions (i.e., primary variables that control processes we wish to explore).

Archean cratons (quasi-circular masses of ancient lithosphere ≥500 km in diameter) consist of coupled crustal granite-greenstone terrains (GGTs) and strong, buoyant cratonic lithospheric mantle (CLM). GGTs owe their preservation to CLM, without which GGTs would be recycled to the mantle by subsequent plate tectonics. Coupled GGT-CLMs formed contemporaneously and likely by a uniquely Archean process, although ACs were variably modified over geologic time by plate tectonics. Eroded GGTs expose a snapshot of mid-crustal processes and evidence of once higher-standing terrain. Models to explain the formation of ACs, and their planetary analogs, if such exist, must address 1) their large size and high-standing, quasi-circular shape; 2) their unique crustal signature and buoyant mantle root which formed together; and 3) their ability to survive for billions of years.

Regional topographic highs can be supported in three different ways: 1) thermally, 2) by mantle upwelling, and 3) by compositionally lower bulk density. The first two form domical topography with gradual surface slopes, indicative of the role of flow (heat and material, respectively), and represent contemporary processes. These actively supported features are not good analogs for ACs due to their transient nature (remove heat or flow and topography decays). Compositionally supported topography, typically marked by steep sides and flat tops (plateaus), is more resilient and will not decay over time, as needed for ACs. Erosion, a dominant process on Earth (but not on all planets) might modify an AC, exposing the mid-crust as in Earth's GGTs.

Many Solar System bodies *lack* geomorphic features appropriate to be AC analogs. Mercury and the Moon have no AC-like features; impact craters dominate both bodies. Among Jupiter's moons, volcanically dominated Io is much too young. Europa hosts small quasi-circular 'chaos terrain' surfaces crisscrossed with overlapping lineaments of seemingly random orientations cut by sharp breaks that leak material from below, like broken ice refrozen on a pond; their small size and low topography are not AC-like. Ganymede and Calisto also lack fitting geomorphic features; again, impact craters dominate both. Saturn's moons Enceladus and Titan likewise lack features resembling ACs. And despite new data for Pluto, no AC-applicable features stand out.

Although none of those bodies host plausible AC analogs, Mercury and the Moon's vast ancient impact basins remind us that large bolides traversed the early inner Solar System. Bolides, bodies of unspecified composition—stony, metallic, gaseous, or a combination—form large craters upon collision with target bodies and are a principal driver of exogenic (versus endogenic) processes. Mars also preserves gigantic ancient impact basins. These three bodies—all smaller than Earth and hence cooling significantly faster—developed thick target lithospheres. The high crater density on their impact-basin fills, resulting from subsequent pummeling by smaller bolides, confirm the ancient ages of these enormous impact basins. Large ancient bolide impacts are therefore something we should bear in mind for early Earth.

Mars, bigger than Mercury and the Moon, preserves a richer geologic history, including potential AC analogs. The Tharsis bulge (~5000 km in diameter and 7 km high) and Olympus Mons (~1600 km in diameter and a whopping 22 km high) are extensive highland features meeting some of the AC-analog criteria. However, their domical forms and gradually sloping topography indicate thermal topographic support and relative youth, consistent with their young glacial and volcanic surfaces marred by only a few small impact craters (Neukum et al. 2004). Rather, Tharsis and Olympus Mons, potentially the longest-lived volcanic provinces in the Solar System, seem more analogous to Hawaiian volcanoes underlain by a deep mantle plume than to ancient cratons.

This leaves Venus. Venus is considered Earth's sister planet due to its similar size, density, bulk composition, and heat budget—all factors critical to planetary differentiation and first-order dynamic endogenic cooling processes. Like siblings, these planets were most similar at 'birth', yet Venus now differs dramatically from Earth. It is hotter (~475 °C) and drier, therefore with stronger silicate rocks and little erosion, has a dense atmosphere, and it never developed plate tectonics. Without plate tectonics, evidence of early lithospheric processes could have been preserved such that Venus' early geologic history might stand in for Earth's.

Venus and Earth lack the vast impact basins seen on other planets; their largest impact craters are a mere ~300 km in diameter. Why? Surely, they must have experienced the same early large-bolide impacts recorded on Mercury, the Moon, and Mars, and their larger masses should have attracted even more numerous and larger bolides. But because Venus and Earth are bigger, they cooled more slowly, resulting in early thin, hot lithospheres, and lithosphere thickness plays a critical role in bolide-impact response. A large bolide impacting thick lithosphere forms a crater, whereas a large bolide impacting thin, hot lithosphere can generate millions of cubic kilometers of melt, which forms in the mantle, not in the crust; thinner lithosphere, larger bolides, and hotter mantle each contribute to greater melt volumes (Jones et al. 2005; Elkins-Tanton and Hager 2005).

Venus hosts two types of quasi-circular craton-sized features—volcanic rises and crustal plateaus—both >1500 km in diameter and ~4 km above mean planetary radius. Volcanic rises are domical with extensive lava flows reflecting contemporary thermal support by large mantle plumes, making them unlikely AC analogs. In contrast, crustal plateaus are characterized by steep sides and flat tops that host distinctive tessera terrain (see Box 1); tessera is widely accepted as Venus' oldest surface. A plateau shape indicates compositional support which, together with tessera surfaces, imply ancient formation. Crustal plateaus on Venus are therefore a viable AC analog. But how did they form? Tessera may provide critical clues. Distinctive tessera fabric consists of parallel-trending short- and medium-wavelength folds (~1 to 5 km) that record thin-layer shortening and orthogonal periodic ribbon structures (1–3 km spacing) formed by thin-layer extension. Venus' lowlands host isolated tessera inliers that display coherent fabric patterns across 1000s of kilometers, interpreted as remnants of collapsed crustal plateaus.

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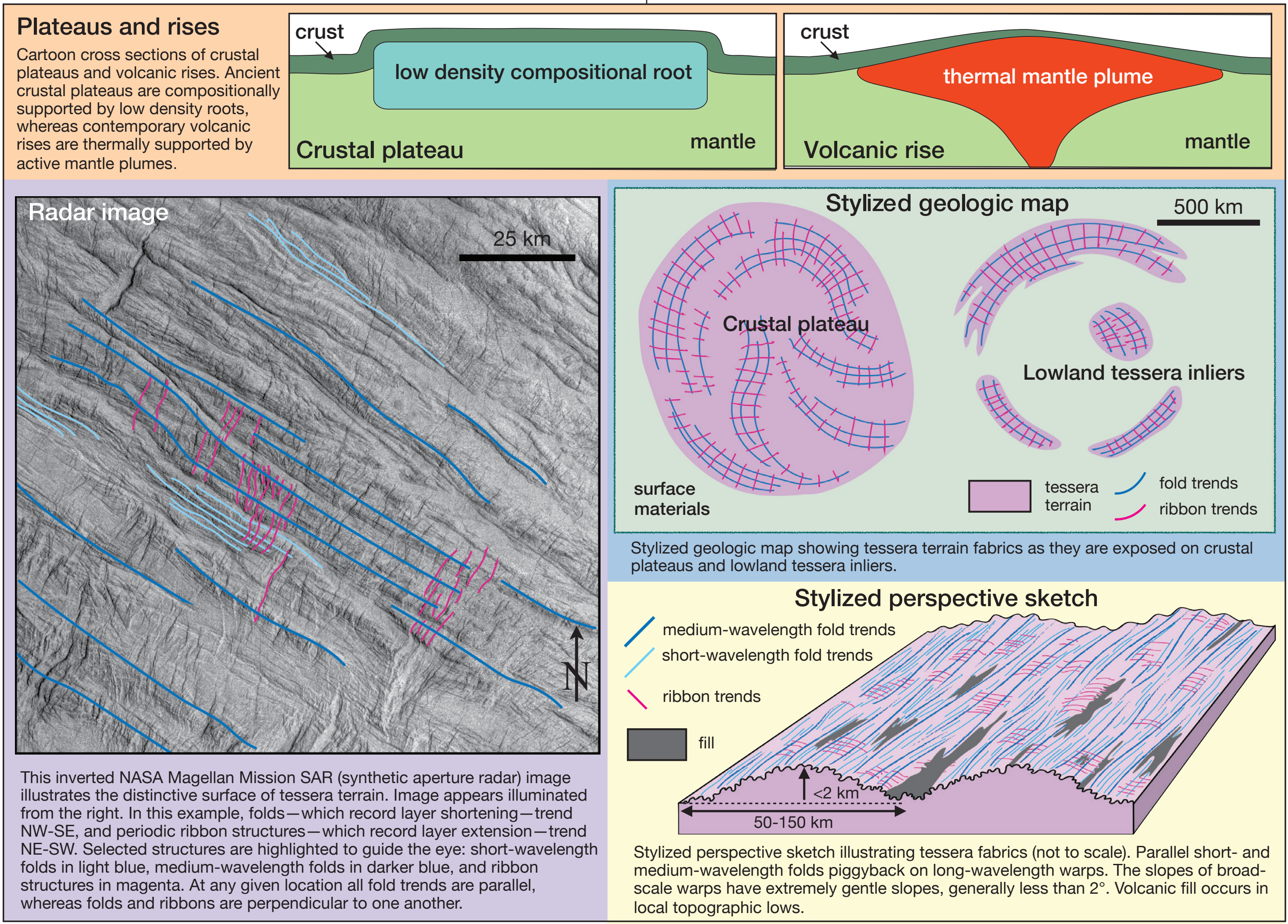

Cartoon cross sections of crustal plateaus and volcanic rises. Ancient crustal plateaus are compositionally supported by low density roots, whereas contemporary volcanic rises are thermally supported by active mantle plumes.

This inverted NASA Magellan Mission SAR (synthetic aperture radar) image illustrates the distinctive surface of tessera terrain. Image appears illuminated from the right. In this example, folds—which record layer shortening—trend NW-SE, and periodic ribbon structures—which record layer extension—trend NE-SW. Selected structures are highlighted to guide the eye: short-wavelength folds in light blue, medium-wavelength folds in darker blue, and ribbon structures in magenta. At any given location all fold trends are parallel, whereas folds and ribbons are perpendicular to one another.

Stylized geologic map showing tessera terrain fabrics as they are exposed on crustal plateaus and lowland tessera inliers.

Stylized perspective sketch illustrating tessera fabrics (not to scale). Parallel short- and medium-wavelength folds piggyback on long-wavelength warps. The slopes of broad-scale warps have extremely gentle slopes, generally less than 2°. Volcanic fill occurs in local topographic lows.

Box 1 CHARACTERISTICS OF VENUSIAN CRUSTAL PLATEAUS AND THEIR DISTINCTIVE TESSERA TERRAIN.
Crustal plateaus are supported by a compositionally low-density root. Tessera terrain, defined by perpendicular folds and ribbon structures, decorates all crustal plateaus and also occurs as lowland inliers thought to represent the remnants of collapsed crustal plateaus. Note the disparate scales of tessera fabrics and crustal plateaus (see radar image and geologic map).

Crustal plateau formation is highly debated. I focus here on a mind-stretching bolide impact hypothesis (Hansen 2006), contending that tessera fabric, so characteristic of individual crustal plateaus, evolved as the 'scum' of a vast lava pond (1500–2000 km in diameter and perhaps >5 km thick), which formed due to a large bolide impact on Venus' early hot, thin lithosphere. Bolide impact resulted in extensive high-temperature, high-fraction partial melting (30% to >50%) in the mantle; juvenile mantle melt rose to form an immense lava pond (>1.77 × 10^6 km^2) on thin lithosphere. As the pond solidified, progressive formation of tessera ribbons and short- and intermediate-wavelength folds recorded increasingly thicker pond scum. As the pond melt crystallized, differentiated melts (as opposed to juvenile melts) leaked through to the surface, embaying local structural lows in the developing tessera scum. Petrologic evolution of such a huge igneous province would result in a wide range of melt compositions; this complexity, however, has yet to be modeled. In the mantle, melt residuum formed a strong and compositionally buoyant sublithospheric root (e.g., Jordan 1981). Residuum strength resulted from its extremely high temperature of melting and dry nature (fluids would concentrate in the melt), while residuum buoyancy resulted from it being chemically less dense than the surrounding mantle. This melt-residuum root ultimately uplifted the partially solidified lava pond, producing a crustal plateau decorated with tessera. Each crustal plateau represents a separate large bolide impact event. Tessera that lost its buoyant residuum root (e.g., via mantle convection) could be locally buried, forming lowland tessera inliers. Tessera coupled to its buoyant residuum would escape burial, preserved atop a crustal plateau. Subsequent secular cooling and thickening of the global lithosphere would 'lock' resilient low-density residuum roots in place, assuring geologic preservation of crustal plateaus. Lowland tessera inliers could be subsequently uplifted above a mantle upwelling, but would not fit the definition of a crustal plateau.

What are the implications for Earth? Can we extrapolate directly from Venus to the early Earth? Let us start with what early Earth and its neighborhood were like, and what might result. During the Archean, large bolides that struck Earth's thin, hot lithosphere would cause massive fractional (i.e., partial) melting of the mantle (30% to >50%), instantly creating two new reservoirs—juvenile melt and strong buoyant residuum (Hansen 2015, 2018). Some melt, lost to a vapor-rich ejecta plume (Jones et al. 2005), would rain down as vapor-condensate spherules (Lowe et al. 2003; Glass and Simonson 2012). Neither melt nor residuum reservoirs would communicate chemically with their parent mantle. The melt reservoir, concentrated with parent-mantle components that chemically partitioned into the melt (radiogenic elements, fluids, precious metals, etc.), would rise, forming a vast crustal igneous province. Igneous evolution would form rock types spanning the entire spectrum from ultramafic to felsic compositions, and intrusive to volcanic rocks, further enriching the evolved melts. The residuum—a buoyant, isolated solid mantle reservoir—would remain unchanged.

I suggest that Venus' crustal plateaus represent plausible analogs of Earth's ACs. Both could have formed as a result of large bolide impacts on ancient hot, thin lithosphere—an exogenically driven process leading to rapid, simultaneous formation of distinctive GGT-type crustal igneous complexes coupled with low-density mantle melt-residuum roots (CLM). The ensuing evolution of Venus' and Earth's igneous complexes would differ as a function of the ancient environmental boundary conditions of each planet. A bolide impact/melt mode of GGT-CLM formation appears consistent with isotopic signatures related to formation of one of Earth's oldest cratons, the Pilbara (Kemp et al. 2023; Petersson et al. 2023) indicating 1) linkages between mantle–crustal processes throughout craton history; 2) coupled evolution of granites and greenstones; 3) felsic rocks formed mostly by differentiation of juvenile mantle material; 4) little evidence for remelting of Hadean crust; and 5) a distinctive style of Archean crust production. A bolide impact/melt hypothesis for Archean craton formation hence seems worthy of consideration.

Seemingly outlandish hypotheses can lead us to consider unforeseen implications, surprising connections, and novel solutions. In this case, the Venus perspective 1) challenges geologists to reconsider the importance of bolides in Earth's early evolution; 2) presents a mechanism by which Archean cratons (like crustal plateaus) are the product of large bolide impacts on ancient thin lithosphere during a unique period in Earth history; 3) explains how a GGT could lose its CLM root and be recycled to the mantle; and 4) accounts for Earth's (and Venus') lack of gigantic impact basins. Further, it 5) potentially addresses the uniqueness of Archean mineral deposits; 6) suggests that ancient GGT topography might be supported, at least in part, by mantle melt residuum, not solely by thick silicate crust; and 7) stimulates us to consider other implications stemming from processes and conditions not usually envisaged for the early Earth.

Is mind travel between Earth and other planetary bodies relevant to better understanding the formation of terrestrial Archean cratons? Because Earth offers geochemical clues, whereas other bodies, like Venus, preserve rich geological and structural evidence the equivalent of which has been lost on Earth due to plate tectonics, I believe it is. Given that the early (Archean) Earth's lithosphere was thin and large bolides traversed the heavens, logic tells us that large bolides hit the early Earth. Spherule layers in the geological record represent the vapor-plume ejecta of impact events and provide evidence of large Archean events, despite the lack of corresponding crater basins (Lowe et al. 2003; Glass and Simonson 2012). Geochemical, isotopic, and geophysical data combined with modeling (see Table 1 in Johnson and Melosh 2012) provide timing (3.5–2.5 Ga), bolide size (11–58 km), and velocity (18–25 km/s) of these Archean impact events. Modeling further suggests that large bolide impact with thin lithosphere yields extremely high-fraction (30% to >50%) partial melting in the mantle, and that just a 50 °C increase in the potential temperature of the mantle leads to the production of 2–3 times more melt volume (Jones et al. 2005; Elkins-Tanton and Hager 2005). Mantle potential temperature, a theoretical concept geologists use to compare mantle temperatures in different situations, is the temperature of the mantle if it ascended to the surface without melting. Imagine the amount of melt a hot Archean mantle could generate! Voluminous high-fraction melting would also leave behind a substantial low-density residuum (see Box 3 in Pearson et al. 2021).

Implications often lead to new questions, or new thought experiments. Three immediately come to mind. 1) *What would happen if a bolide 50 km in diameter struck hot, thin Archean lithosphere overlying mantle with a high potential temperature? How much melt volume would result and what would be the chemical composition of that melt?* 2) *Given Archean mantle and environmental conditions, how would this large melt pool evolve physically and chemically during solidification? Would evolution differ under Venus conditions?* 3) *Would melt evolution be different if there were two or more spatially adjacent, but temporally distinct, large bolide impacts?*

In closing, we should ask '*What happened* when *large bolides impacted Earth's early thin lithosphere?'*—not *if*. Geologically, Earth is not a closed system, particularly during its early phase in the larger Solar System, so it is important to consider the influence of exogenic processes on geodynamics and, likely, the origin of life.

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Vicki Hansen is a structural geologist with a strong belief that important questions (and answers) lie in the field. Her initial inquiries focused on the North American Cordillera from Arizona to Alaska. She serendipitously ventured to Venus, experiencing geologic 'field mapping' and structural analysis at global scales, made possible through incredible NASA Magellan high-resolution radar data. New collaborations further expanded her world from planetary crusts and lithospheres to mantle dynamics and core–mantle boundaries. Her appreciation of deep endogenic processes grew, as it did for exogenic processes. Venus research led Hansen back to Earth—particularly early Earth—motivated by global-scale evolution of 4.5-billion-year-old planetary systems, and driven by questions that start with geological relationships embedded in planetary crusts. Hansen is Emeritus Professor at University of Minnesota Duluth, USA, and Senior Scientist with the Planetary Science Institute, Arizona, USA.

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Carol Frost began studying Archean cratons when she started her faculty career at the University of Wyoming (UW, USA) and found herself living on the Wyoming craton, beautifully exposed in Late Cretaceous to Eocene basement-involved uplifts. She combines field study with petrologic and isotopic approaches to understand the formation and evolution of the continental crust in general and the origin of granitic and anorthositic intrusions in particular. In addition to teaching and research, she has held a variety of leadership positions at UW, the National Science Foundation, and in professional societies. She holds a PhD from the University of Cambridge (UK).

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Meghan Miller is an observational seismologist enthusiastic about solving outstanding questions in plate tectonics that range from the formation of cratons to earthquake processes on active faults. To achieve this, she combines the use of novel seismological techniques, including the collection of new data in regions where none are available, integrated with other, sometimes disparate, geologic and geophysical data. Currently, she has seismic deployments out in Alaska, Western Australia, and New Zealand. She is the Director for AuScope Earth Imaging and currently on an ARC Future Fellowship focusing on the use of distributed acoustic sensing (DAS) in seismic imaging.

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Paul A. Mueller is a professor emeritus at the University of Florida (USA) in the Department of Geological Sciences. He obtained his AB in Earth science from Washington University (St. Louis, Missouri) and his MS (meteoritics) and PhD (geochemistry) from Rice University (Houston, Texas, USA). He also held post-doctoral appointments in the Department of Geology at the University of North Carolina (USA) and in the Division of Geochemistry and Planetary Materials at Johnson Space Center (Houston, Texas, USA). His research focuses on the application of trace element and isotopic systems to understand early crustal genesis and the evolution of mountain belts.

Jonathan O'Neil is an associate professor at the University of Ottawa (Canada) in the Department of Earth and Environmental Sciences. He obtained his BSc and MSc at the Université du Québec à Montréal (Canada) and his PhD in 2009 at McGill University (Montreal, Canada). He is an isotope geologist using a combination of fieldwork, petrology, geochemistry, radiogenic isotope systems, and geochronology to study the early Earth and its evolution through time. His research aims to better understand the different geological processes in the Hadean and Archean that formed Earth's most ancient crust and the evolution of the early mantle.

Jesse Reimink is an assistant professor at The Pennsylvania State University, USA. He completed his PhD at the University of Alberta (Canada) before working as a postdoctoral fellow at the Carnegie Institute of Washington's Department of Terrestrial Magnetism (now Earth and Planets Laboratory, USA). His research focuses on the petrology of the early Earth, zircon geochemical proxies, Earth system change in the Archean, geochronology, and mass spectrometer development. Jesse co-directs the LionChron geochronology laboratory at Penn State and teaches courses on introductory geoscience, geochronology, and geoscience entrepreneurship.

Patrice Rey is a professor in the School of Geosciences at The University of Sydney (Australia). Combining fieldwork and numerical experiments, he documents the processes shaping the evolution of the lithosphere over the Earth's history. He obtained a PhD from the École Normal Supérieure de Lyon and the University Joseph Fourier (Grenoble), both in France. He was a postdoc at the University of Wyoming, USA (1992–93) and at the GeoForschungsZentrum (Potsdam, Germany, 1994), and a lecturer at Monash University, Australia (1995–2000). He was elected a Fellow of the Geological Society of America (2014) and awarded the A.B. Edwards Medal (2013) and the Bruce Hobbs Medal (2022) from the Geological Society of Australia.

Hanika Rizo is an associate professor in the Department of Earth Sciences of Carleton University (Canada). Leading a dedicated research group, she focuses on addressing fundamental questions in Earth and planetary sciences. Their inquiries include the formation and evolution of the Earth's mantle, the timing and processes of Earth's differentiation, and the stabilization of contents along with the emergence of life. To accomplish these objectives, Rizo's research team utilizes techniques that enable the identification of isotope variations resulting from extinct radioactivities, offering valuable insights into planetary processes and Earth's geological history.

ARCHEAN CRATONS: TERMS, CONCEPTS, AND ANALYTICAL APPROACHES

Paul A. Mueller[1] and Carol D. Frost[2]

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The articles in this *Elements* issue highlight various aspects of the formation and evolution of the Earth's earliest crust. This Toolkit includes a glossary of terms, concepts, and analytical approaches important to the study of Archean cratons to provide context for the methodologies discussed in these articles.

TIMESCALE OF EARLY EARTH

Geologic timescales are rarely presented without compressing the Precambrian portion of Earth history. For this reason, it is easy to overlook the fact that the time between Earth formation and the end of the Archean at 2.5 Ga (billion years ago)—the time period covered by the articles in this issue—represents fully 45% of Earth history (FIG. 1).

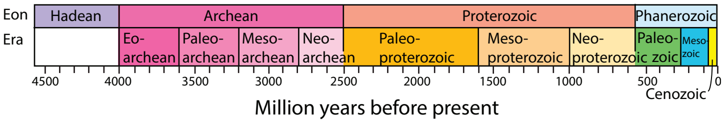

FIGURE 1 Geologic timescale.

The geologic timescale for the earliest part of Earth history is divided into two eons: the Hadean (4.6 to 4.0 Ga) and the Archean (4.0 to 2.5 Ga) (FIG. 1). The Hadean is defined as the time from Earth formation to the earliest part of the rock record. We use the 4.568 billion-year-old age of the oldest grains condensed from the solar nebula found in meteorites (Ca-Al-rich grains included in chondritic meteorites) to mark the start of Earth accretion (Bouvier and Wadhwa 2010). The beginning of the Archean has been established at 4.031 Ga based on the 10 oldest U-Pb zircon ages from the Acasta gneiss complex in the Slave craton of northern Canada (Bowring and Williams 1999). Consequently, we refer to all ages older than this as Hadean.

The Archean eon is divided into the Eoarchean (4.03–3.6 Ga), the Paleoarchean (3.6–3.2 Ga), the Mesoarchean (3.2–2.8 Ga), and the Neoarchean (2.8–2.5 Ga). Unlike the Phanerozoic, where the timescale is related to the evolution of fossil life forms, these time divisions are arbitrary, as is the end of the Archean eon at 2.5 Ga. The geologic timescale is updated periodically by the International Commission on Stratigraphy (www.iugs.org/ics).

EARTH'S COMPOSITION AND RESERVOIRS

It is not possible to determine the average geochemical composition of the entire Earth directly, so its overall composition—often expressed as the bulk Earth composition—is estimated from the composition of Type-1 carbonaceous chondrite meteorites, a class of meteorites that is thought to have formed during condensation of the solar nebula and formation of the Solar System and has not undergone melting or metamorphism since that time. This composition is also referred to as the chondritic uniform reservoir (CHUR).

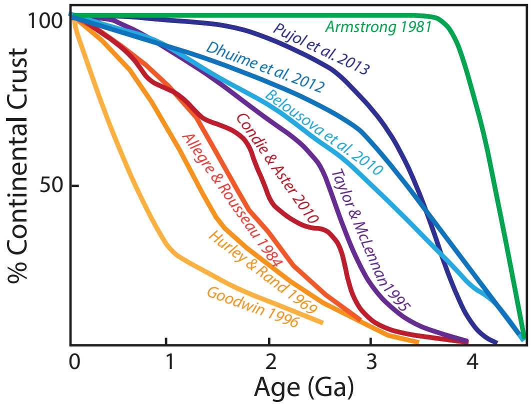

FIGURE 2 Crustal growth models. Estimates of the time at which the crust first separated from the mantle vary greatly, as does the volume of crust present throughout Earth history, which on this figure is expressed as a percentage of present-day crustal volume. This figure illustrates a variety of models ranging from those that envision abundant crust formation early in Earth history (i.e., green curve) to many other models that suggest that the volume of continental crust has increased over time, albeit at different rates. MODIFIED FROM HAWKESWORTH ET AL. (2019).

Very early in its history, the metallic core separated from the silicate portion of the Earth (Nimmo and Kleine 2015). Thus, it is useful to define the geochemical composition of the bulk silicate Earth as the composition of the entire Earth minus the core. The composition of the bulk silicate Earth is equivalent to that of the primitive mantle.

Today, the Earth is composed of a number of geochemically distinct components, including the core, mantle, and crust. These are commonly referred to as reservoirs. The portion of the mantle that partially melted to produce magmas that contributed to forming the Earth's crust is known as the depleted mantle. The time when the depleted mantle reservoir began to form and the evolution of its composition and volume over Earth history are intricately related to the formation and evolution of the complementary crustal reservoir (FIG. 2). These processes are incompletely resolved in time and space, as discussed by O'Neil et al. (2024 this issue) and Rey et al. (2024 this issue).

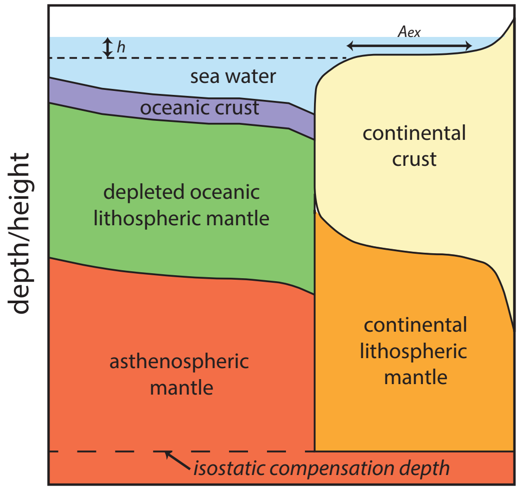

FIGURE 3 Schematic illustration of continental freeboard (Korenaga et al. 2017). If sea level rises by height h, more of the continental shelf will be submerged, the area of exposed landmasses decreases by area A_{ex}, and continental freeboard decreases.

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The Earth's oceans constitute another reservoir that appears to have formed early, likely by 3.7–3.8 billion years ago when pillow basalts are first preserved in the rock record (Nutman et al. 2013). The concept of crustal growth is intimately linked to the concept of continental freeboard, which refers to the mean height of the continental landmasses with respect to sea level at any given time (Fig. 3; Korenaga et al. 2017). This concept is important because freeboard reflects a balance between the volume of the oceans, the shape of ocean basins, and the volume, density, and thickness of the oceanic and continental crust. See Rey et al. (2024 this issue) for a broader discussion of changes in sea level during the Archean.

GEODYNAMICS OF THE EARLY, NON-UNIFORMITARIAN EARTH

Geologic processes are commonly assumed to be *uniformitarian*, that is, we can infer how ancient rocks were formed and modified by looking at modern processes, including plate tectonics, that affect the Earth today. This assumption cannot be applied to the first 1.5 to 2 billion years of Earth history. For example, the formation of Earth's core, silicate magma oceans, and the Moon were early, one-time events. Exponential, secular cooling of the Earth as radioactive heat production decreased produced different temperature regimes at different times in the past (Korenaga 2013). This cooling also likely affected Earth's geodynamics, a general term that refers to the physical stresses that deform Earth's surface and interior. Instead of stiff plates of crust moving horizontally above a convecting mantle in a modern so-called mobile lid process, Hadean and Archean tectonics may have been driven by mantle plumes beneath a weaker, stationary crust, in a so-called stagnant-lid scenario (Fig. 4A). Instead of subduction, the early crust may have been disrupted and even relocated in response to mantle upwellings and downwellings that have been linked to processes such as sagduction and drip tectonics (Fig. 4B; Martin and Arndt 2021).

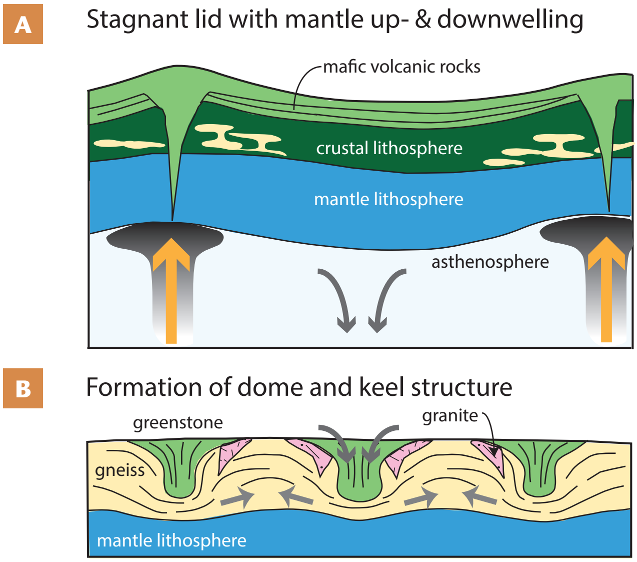

Figure 4 Earth currently dissipates >90% of its internal heat via a "multi-plate mobile lid" system (plate tectonics) driven by the sinking of cold dense lithosphere into the convecting mantle. In the Archean-Hadean, higher mantle temperatures and more rapid convective heat loss may have occurred in a "stagnant lid" system, which transitioned to plate tectonics over time. Two possible transitional stages include: (**A**) Hadean mafic crust with nascent TTG differentiates (yellow) formed over broad mantle upwellings (orange arrows) and (**B**) An Archean stage when dense volcanic rocks of greenstone belts sank through warm, weak felsic crust, displacing older felsic crust as diapirs with melt (purple) that intruded the foundering greenstones. This process, often labeled "sagduction," produced the dome and keel pattern shown in Figure 2. of Frost and Mueller (2024 this issue).

In addition, studies of the lunar surface indicate by analogy that impacts of large, extraterrestrial bodies (e.g., planetesimals and large meteorites) strongly affected the early Earth, but the rate of these impacts tailed off by the end of the Archean (see recent compilation on Fig. 2 in Tai Udovicic et al. 2023). Large impacts on the early Earth, including the Moon-forming impact, may have generated enough heat to wholly or partially melt large parts of the mantle. The resulting "magma oceans" may have persisted for millions of years and greatly influenced the chemical and physical evolution of the mantle.

The time at which modern plate tectonics initiated is a subject of considerable debate (Korenaga 2013). As Rey et al. (2024 this issue) point out, it is possible that there was a period when both stagnant and mobile tectonic processes were operating in parallel, a situation they refer to as dual-mode geodynamics. The transition from stagnant to mobile lid tectonics need not have been synchronous globally, but likely occurred at different times in different parts of the Earth and affected individual cratons differently (Frost and Mueller 2024 this issue).

AGE DETERMINATIONS OF ARCHEAN AND HADEAN EVENTS

U-Pb in Zircon

The U-Pb system in zircon has evolved to become the most reliable method for obtaining accurate and precise ages of events in the geologic past, particularly the Precambrian. The two radioactive isotopes of uranium (^{235}U and ^{238}U) decay at vastly different rates, providing two independent age determinations and an opportunity to compare ages from one decay system to the other in a unique cross-check. When the ages agree within analytical errors, the ages are considered concordant, implying that the zircon has behaved as a closed system since it formed. The data are often depicted on concordia diagrams, on which curved lines give the ages of concordant data regardless of the ratios used to define concordia. Two different common concordia plots are shown in Figure 5. Discordant ages (ages from the two decay systems that do not agree) are also valuable because the lack of agreement often can be related to loss of Pb from the system (e.g., a zircon grain). Straight lines through discordant points (discordia; Fig. 5) on the concordia plots may intersect concordia at two times, and can then identify both the time of original crystallization and the time of the event that caused Pb-loss, such as metamorphism. Because ancient zircons likely experienced more than one Pb-loss event, the lower intercept of the discordia line with concordia may have only limited or no geologic meaning.

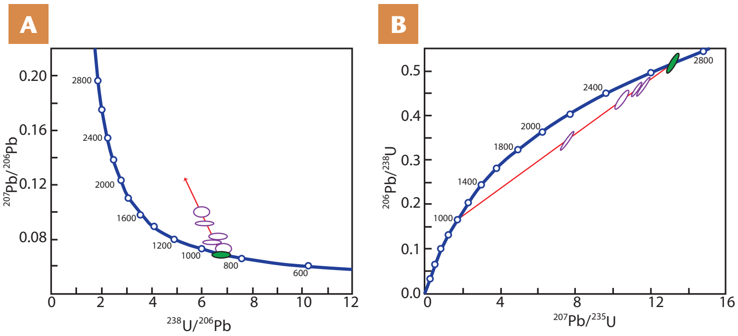

Figure 5 Two commonly used types of concordia diagrams. (**A**) Tera-Wasserburg concordia diagram and (**B**) Wetherill concordia diagram. In each, the concordia is shown as the blue curve. Samples plotting on the concordia (green ellipses) give the same age in both the $^{238}\text{U} \rightarrow {}^{206}\text{Pb}$ and $^{235}\text{U} \rightarrow {}^{207}\text{Pb}$ decay systems. Arrays of discordant points (open purple ellipses) may form a chord (discordia) that intersects the concordia at the crystallization age. See Figure 4 in Laurent et al. (2024 this issue) for an example of data interpreted on a Tera-Wasserburg diagram.

Common Pb and the Age of the Earth

Common Pb isotopes are those found in "common" rocks and minerals that have not necessarily remained closed systems since they formed. The Pb isotopes produced by decay of ^{235}U (^{207}Pb) and ^{238}U (^{206}Pb) are typically reported as ratios relative to the non-radiogenic isotope ^{204}Pb. Lead produced from decay of ^{232}Th is similarly reported as ^{208}Pb/^{204}Pb from the single decay of ^{232}Th to ^{208}Pb. The Pb isotopic composition of an individual rock or mineral evolves with time to higher ratios of radiogenic Pb (^{206}Pb, ^{207}Pb, ^{208}Pb) to non-radiogenic ^{204}Pb along curved paths called growth curves (FIG. 6). The relatively rapid decay of ^{235}U means that ~80% of all ^{235}U on Earth had decayed by the end the Archean and is the reason why the growth curves shown on FIGURE 6 flatten out at younger ages. Consequently, rocks and minerals with high ^{207}Pb/^{204}Pb relative to ^{206}Pb/^{204}Pb indicate interaction with high-U/Pb reservoir(s) that must have formed in the Hadean or Archean. These are referred to as high-μ or early enriched reservoirs. These reservoirs likely formed by magmatic differentiation within the crust because U is preferentially partitioned into magmas to a greater extent than Pb in crustal and mantle melts.

Common Pb isotopes have played an important role in our evolving understanding of Earth and Solar System history. For example, Pb isotopic data from galenas, oceanic sediments, and meteorites were combined to provide the first viable determination of the age of the Earth (FIG. 6B; Patterson 1956).

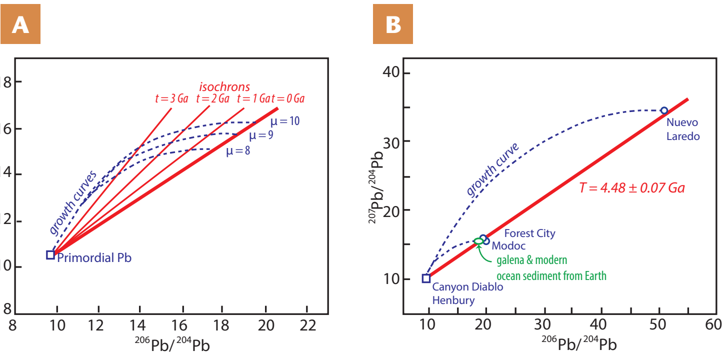

FIGURE 6 (**A**) Evolution of Pb isotopes in Earth reservoirs with different U/Pb ratios (μ = ^{238}U/^{204}Pb) over Earth history from an initial bulk Earth Pb isotopic composition estimated from iron meteorites (Blichert-Toft et al. 2010). At any given time, rocks from reservoirs of the same age, but with different μ-values, will define a straight line (an isochron) with a slope that is a function of age. (**B**) The slope of the red line defined by the Pb isotopic composition of meteorites (blue symbols; blue square = iron meteorites; blue circles = stony meteorites) gives the time of Solar System formation. Because average deep-sea sediment, taken as a proxy for average continental crust, and recently formed galena samples (μ = zero) from ore deposits lie on the same isochron as meteorites, the Earth and meteorites were interpreted to have the same age (Patterson 1956).

ISOTOPIC SYSTEMS USED TO INFER EARTH DIFFERENTIATION PROCESSES

In addition to the U-Pb system, many other radiogenic parent-daughter isotope pairs are used to determine both the timing and nature of events on Earth. Most of these involve parent isotopes with slow decay rates, such as ^{147}Sm-^{143}Nd (half-life ($T_{½}$) of ^{147}Sm = 107.0 billion years), ^{176}Lu-^{176}Hf ($T_{½}$ of ^{76}Lu = 37.2 billion years), and ^{187}Re-^{187}Os ($T_{½}$ of ^{87}Re = 41.6 billion years). As with Pb isotopes, the daughter isotope is reported relative to a stable isotope of the same element. Examples include ^{143}Nd/^{144}Nd (shown on FIG. 7A), ^{176}Hf/^{177}Hf, and ^{187}Os/^{188}Os. The variation in these ratios for Earth materials is very small, so it has become customary to report measured values relative to a standard such as CHUR (the chondritic uniform reservoir, which approximates the bulk silicate Earth composition). This is called the epsilon notation, and is given by the formula:

$$\varepsilon\mathrm{Nd}(t) = \left[\frac{\left(\frac{^{143}\mathrm{Nd}}{^{144}\mathrm{Nd}}\right)_{\mathrm{sample}(t)}}{\left(\frac{^{143}\mathrm{Nd}}{^{144}\mathrm{Nd}}\right)_{\mathrm{CHUR}(t)}} - 1\right] \times 10{,}000$$

where (*t*) is the time of interest. Multiplying by 10^4 results in values for εNd(*t*) commonly between +15 (depleted mantle) and −50, (old felsic crust), where positive values denote samples with higher ^{143}Nd/^{144}Nd than the bulk Earth, and negative values identify samples with lower ^{143}Nd/^{144}Nd than the bulk Earth (FIG. 7B). This is the case because mantle melts have lower Sm/Nd than the residual (depleted) mantle. Analogous expressions give εHf(*t*). In the ^{187}Re-^{188}Os system, the γOs(*t*) notation refers to percent deviation from CHUR of ^{187}Os/^{188}Os (multiplying by 100 instead of 10,000).

When evaluating diagrams and/or text that use the epsilon notation, it is important to remember that the relative rate of change of a sample compared to a model reservoir or another sample is related to the half-life of the parent isotope, the time since mineral/rock formation, the parent/daughter ratio, and the assumptions used to calculate the ε of model reservoirs. For example, the depleted mantle formed at 4.6 Ga with an epsilon of zero and has evolved to a range of values centered about +13 εNd. Evolution diagrams may be plotted with measured isotope ratios (FIG. 7A) or derivative ratios such as epsilons (FIG. 7B). Although Hf and Nd isotopic compositions of rocks and minerals can be measured very precisely today, extrapolating these values back over 3–4 billion years involves uncertainties beyond analytical errors.

Model Ages

As shown in FIGURE 7B, a model age is simply an estimate of the time that a sample was extracted from a model reservoir. For example, a given sample's measured ^{143}Nd/^{144}Nd is extrapolated back in time using

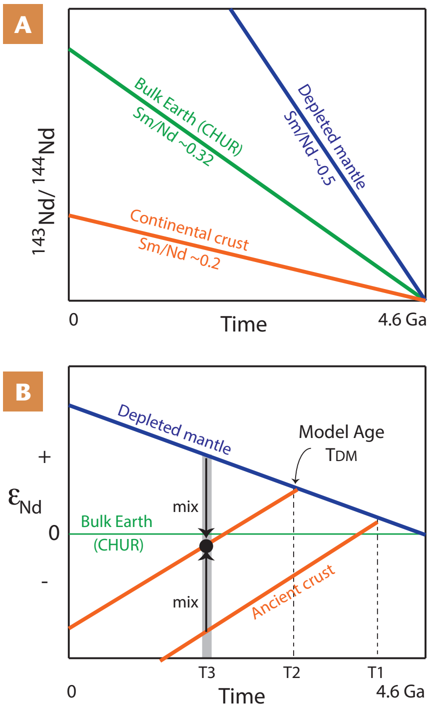

FIGURE 7 The Sm-Nd isotopic system is used to illustrate the change in isotopic composition over time, expressed as the isotopic ratio ^{143}Nd/^{144}Nd (**A**) and epsilon notation (**B**). (**A**) Effect of different Sm/Nd ratios in bulk Earth, crust, and depleted mantle on the accumulation of ^{143}Nd by decay of ^{147}Sm. (**B**) The εNd(*t*) notation and calculation of model ages. In the example shown, ancient crust formed at time T1 evolves to negative epsilon values, while the depleted mantle evolves to positive epsilon values. At T3, a magma forms by melting and mixing both depleted mantle and crustal sources (black circle). The model age of the mixture is T2. Model ages do not represent the time of a specific event, but instead are a weighted average age of the model sources. FROM MURPHY AND NANCE (2005). See also FIGURE 3 in Laurent et al. (2024 this issue) and FIGURE 3 in O'Neil et al. (2024 this issue).

the sample's measured $^{147}Sm/^{144}Nd$ until its Nd isotopic composition matches that of the evolving reservoir, commonly the depleted mantle. That time is referred to as the depleted mantle model age: T_{DM}. A graphic representation of this concept is shown as point T_{DM} on FIGURE 7B, where the model mantle evolution curve is intersected by the evolution curve of an individual sample at time T2.

Extinct Radionuclides

Some radioactive isotopes produced during stellar processes have such short half-lives that they have completely decayed and are no longer present in our Solar System. These are known as extinct radionuclides. Extinct radionuclides are especially well suited for understanding events that took place on the early Earth while these short-lived radioactive isotopes were still "alive." For example, consider the decay of lithophile (crust-loving) ^{182}Hf ($T_{1/2}$ = 8.9 million years) to siderophile (iron-loving) ^{182}W. In this system, W is fractionated into the core and Hf into the mantle during core formation. The fact that $^{182}W/^{184}W$ is not completely homogenized in the modern mantle after 4.5 Ga of convection and is more heterogeneous in Archean rocks than modern mantle-derived rocks help us understand the timing of core formation and the extent of mantle mixing over time (FIG. 8). Another extinct radionuclide, ^{146}Sm, has also been applied to the chronology of early Archean rocks. Note that instead of the ε notation, the $\mu^{142}Nd(t)$ notation is used with μ referring to parts per million (1×10^{-6}). See O'Neil et al. (2024 this issue) for more discussion.

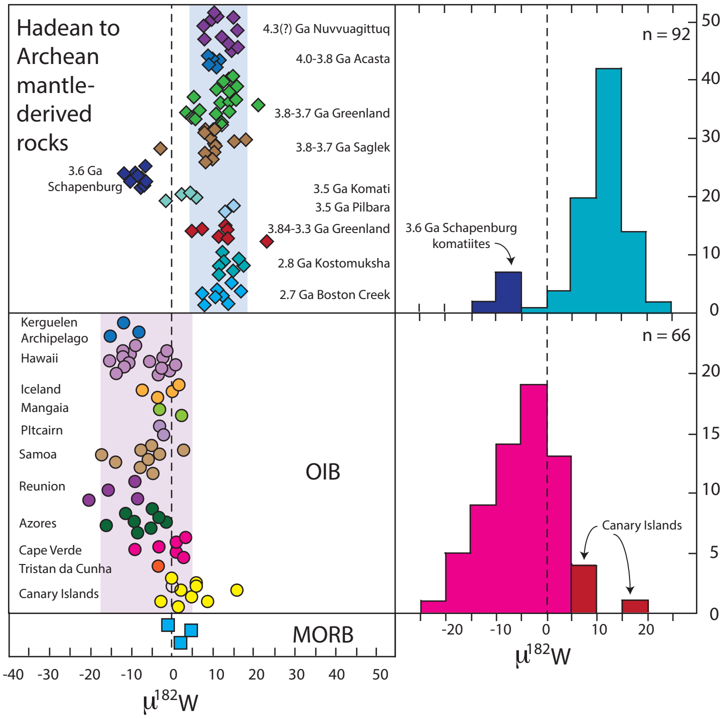

FIGURE 8 Compilation of $^{182}W/^{184}W$ data shown with the $\mu^{182}W$ notation. Data from Hadean and Archean mantle-derived rocks indicate that the Hadean-Archean mantle had $\mu^{182}W$ different from that of modern mantle-derived ocean island basalts (OIB) and mid-ocean ridge basalts (MORB). The difference in $\mu^{182}W$ between Hadean-Archean mantle-derived rocks and modern mantle-derived magmas has been variously attributed to incomplete mantle homogenization in the Archean; core–mantle chemical interaction, possibly related to the crystallization of the inner core; and/or initiation of post-Archean deep slab subduction. FROM RIZO ET AL. (2019).

Oxygen Isotopes

The most abundant element in the silicate Earth is oxygen. The isotopes of oxygen are all stable, yet their abundance varies in Earth materials because the mass difference between isotopes results in different equilibrium and kinetic behavior. A delta notation (δ) is used for oxygen isotope ratios, which most commonly compare the $^{18}O/^{16}O$ of a sample to a standard material, typically "standard mean ocean water" (SMOW), and is expressed as per mil deviations (10^3) from the standard's ratio. Samples with positive $\delta^{18}O$ have higher $^{18}O/^{16}O$ than the standard, and samples with negative $\delta^{18}O$ have lower $^{18}O/^{16}O$ than the standard. In zircon, $\delta^{18}O$ higher than values for the depleted mantle (5.3‰ ± 0.6‰) can indicate incorporation of a sedimentary component and/or interaction of their parent magmas with meteoric water. FIGURE 9 shows a compilation of oxygen isotope data for zircons of different ages depicting a distinct change across the Archean-Proterozoic boundary.

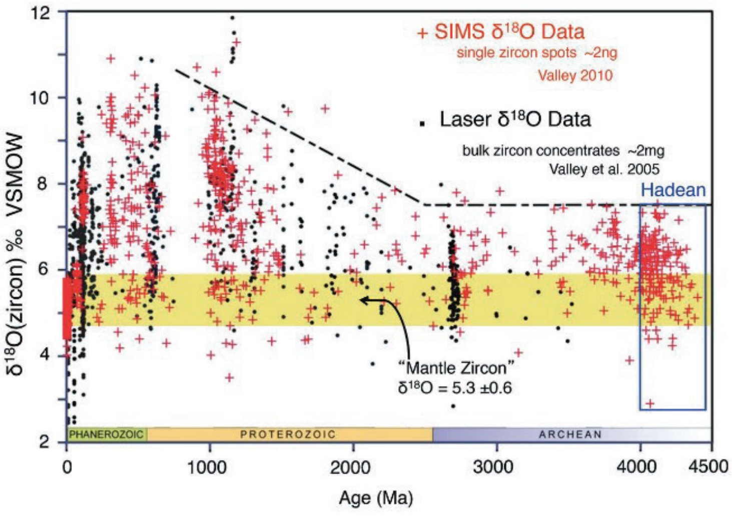

FIGURE 9 Values of $\delta^{18}O$ of zircons plotted as a function of their U-Pb age. Values of $\delta^{18}O$ > 8 are very rare in Archean and Hadean zircons, but rise during the Proterozoic to become much more common in younger samples. SIMS refers to secondary ion mass spectrometry, a method that yields data from an individual micro-domain in the zircon (2 ng as shown). Laser data require much larger samples and are acquired using a laser to heat the sample and then purify the evolved oxygen before analyzing the isotope ratios of the purified gas. REPRODUCED FROM VALLEY ET AL. (2015) WITH PERMISSION FROM THE MINERALOGICAL SOCIETY OF AMERICA.

Presentation of Trace Element Geochemical Data

A common approach to constraining the origin of (meta)igneous and (meta)sedimentary rocks is through the use of trace elements, i.e., elements present below 0.1% by weight. These abundances are often reported in parts per million (ppm) and shown graphically as ratios relative to chondritic meteorites and major Earth reservoirs, such as estimates of the primitive mantle, average crust, average shale, etc. (FIG. 10). The regular behavior of the rare earth elements (REE) is particularly useful because the contraction of ionic size with increasing atomic number leads to predictable behavior in many systems, from igneous to sedimentary. Be aware that the normalizing composition grossly affects the shape of the patterns and that the *y*-axis is always logarithmic. Moreover, the REE are often discussed under the broader term "incompatible elements," which refers to elements that do not readily substitute for the major cations in rock-forming minerals. Depending on a rock's mineralogy, an element may be incompatible in one rock, but not in another.

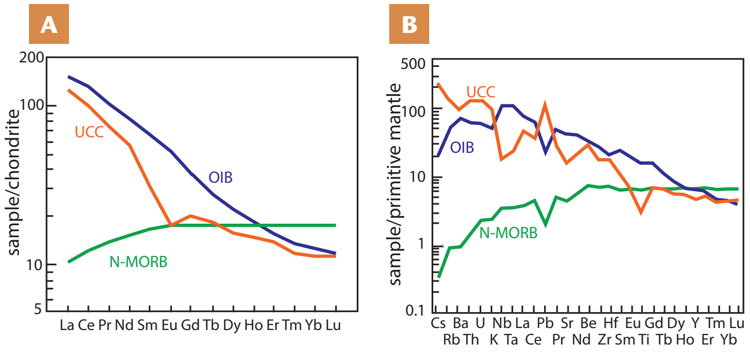

FIGURE 10 (**A**) Rare earth element compositions of typical ocean island basalts (OIB), average upper continental crust (UCC), and normal (depleted) mid-ocean ridge basalt (N-MORB) normalized to the CHUR composition. (**B**) Trace element compositions of typical OIB, UCC, and N-MORB expressed relative to a primitive mantle composition. DATA FROM SUN AND MCDONOUGH (1989), MCDONOUGH AND SUN (1995), LUNDSTROM ET AL. (2003), AND RUDNICK AND GAO (2014). The more irregular pattern for the UCC pattern in (**B**) reflects strong contrasts in the concentrations of many trace elements in accessory minerals such as zircon and monazite that can fractionate from, or accumulate in, more felsic rocks.

GEOPHYSICAL IMAGING OF THE EARTH'S STRUCTURE

Seismic tomography is not only a method to image the Earth's interior, but also a term that refers to a collection of different modeling methodologies centered around an inverse problem. Solutions to inverse problems involve using observations to create a model of the conditions that created the observations. For imaging crustal- or lithospheric-scale structures, tomographic methods are dependent on the number and distribution of seismometers or seismic stations that record the observations. The data recorded on these instruments, such as earthquake waveforms, or even "noise" generated by the oceans, can be used to illuminate the changes in seismic velocities of materials in the subsurface. Body wave tomography, which uses the arrival times of P or S waves, and surface wave tomography, which uses the dispersive nature of Rayleigh or Love waves, have quite different resolutions and sensitivities. The resolution of the models generated is primarily controlled by the wavelength of the seismic waves used in the tomographic inversion, regardless of the specific technique or seismic wave type analyzed. Seismic waves are only sensitive to, or able to detect, heterogeneities that have length scales that are similar to the seismic waves themselves. For example, a 1-second (1-Hz) P-wave with a velocity of 5 km/s has a wavelength of 5 km, which roughly corresponds to the size of the smallest detectable heterogeneity. Surface wave tomography can produce cross sections similar to those shown in FIGURE 3 of Cooper and Miller (2024 this issue). These cross sections are based on much longer wavelength Rayleigh waves, providing lateral resolution on the scale of 10s of kilometers. Because of the way these waves propagate through the Earth, they are most sensitive to lateral variations in the lithosphere and less sensitive to sub-horizontal structures, such as the crust-mantle boundary (Moho). Other types of seismic imaging techniques that use body waves (P and S waves), which travel along more vertical paths, are more sensitive to boundary layers. These methods, typically referred to as receiver functions, are more often used for determining the depth to the Moho or the lithosphere-asthenosphere boundary. Regardless of methodology, these seismic images can then be tested against the temperature and pressure estimates provided by crustal and mantle xenoliths.

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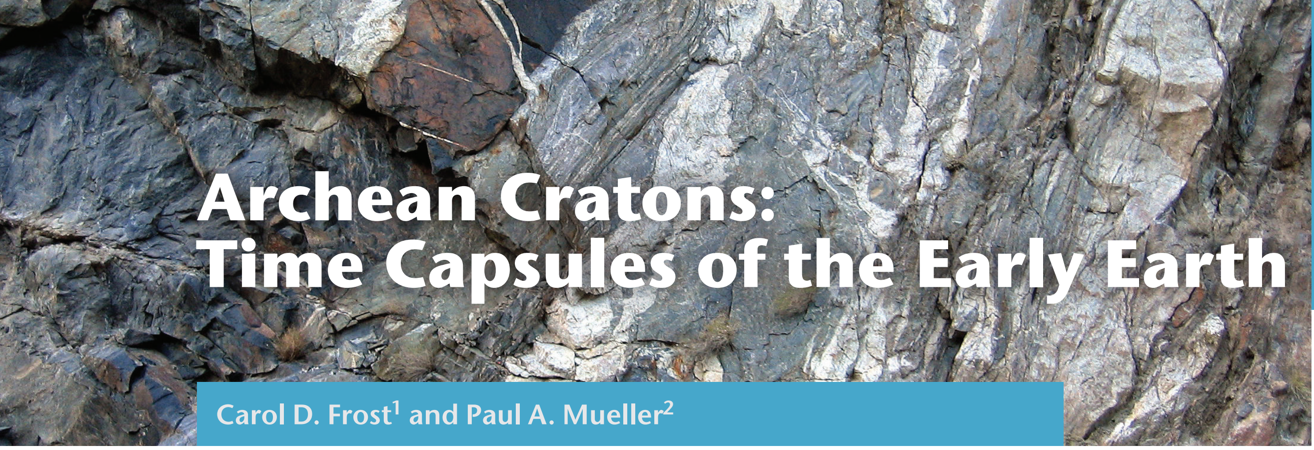

Archean Cratons: Time Capsules of the Early Earth

Carol D. Frost[1] and Paul A. Mueller[2]

Outcrop showing complex middle-crustal history of the Archean rocks of Yankee Jim Canyon, Beartooth Mountains, Wyoming craton. PHOTO: DARRELL HENRY.

1811-5209/24/0020-0162$2.50 DOI: 10.2138/gselements.20.3.162

Studies of Archean cratons, and the rocks and minerals they contain, help us understand the processes that occurred on the early Earth, our place in the Solar System, and how the planet we live on today came to be. The articles in this issue examine different aspects of early Earth evolution from multiple perspectives relying on both theory and observation. We hope they will encourage you to investigate further this most fascinating time in Earth history. Here we introduce the basic characteristics of cratons, the challenges of inferring Earth evolution from the sparse Archean rock record, the concept of cratonic clans, the development of supercratons, and, by the end of the Archean, continents, supercontinents, and plate tectonics.

KEYWORDS: Archean; Hadean; craton; crustal evolution

INTRODUCTION

The first 2 billion years of Earth history were an unparalleled period of dynamic change for our planet. As the Earth formed by accretion of planetesimals, energy from impacts and the radioactive decay of short-lived and long-lived radioisotopes strongly heated the early Earth. One result was segregation of the core, a process that released gravitational energy in the form of heat when metal sank to the center of the Earth. These processes combined to heat the Earth sufficiently that magma oceans formed at both regional and planetary scales. Collision with a Mars-sized impactor (Theia) led to formation of the Moon as debris from the collision coalesced in near-Earth orbit. All this took place within about the first 100 million years of our Solar System's history (Nimmo and Kleine 2015). But rapid change did not stop there as the rate of impacts decreased and early magma oceans solidified. By 4.4 billion years ago (Ga), grains of the mineral zircon ($ZrSiO_4$) crystallized in magmas that solidified to become part of an early silicate crust (Wilde et al. 2001; Valley et al. 2014). The oceans may have been present by this time (Wilde et al. 2001), certainly by 3.8–3.7 Ga when the first pillow basalts appear in the geologic record (Nutman et al. 2013), and the fossilized remains of early microbial life forms are also present in the rock record by 3.7–3.5 Ga (Hickman-Lewis et al. 2023).

This early history of our planet has been pieced together over many years from studies of Archean (4.0–2.5 Ga) rocks that preserve the oldest record of early Earth evolution and from meteorites, which provide the strongest evidence for the age and overall chemical composition of the Earth. We now know that by the end of the Hadean (4.57–4.03 Ga), silicate crust began aggregating to form what became cratons. These cratons are the oldest physical components of our planet that can be sampled and studied. Using various techniques, we continue to tease out the early history of the Earth and how it became the habitable planet it is today.

THE SURVIVORS: ARCHEAN CRATONS

Cratons are parts of the Earth's crust and lithospheric mantle that have not experienced significant penetrative deformation or calc-alkalic magmatism for hundreds of millions to billions of years. Their long-term stability is related to their 150–250 km thick, cool, and viscous lithospheric mantle roots (Bedle et al. 2021; Cooper and Miller 2024 this issue). Archean cratons are found on every continent (FIG. 1).

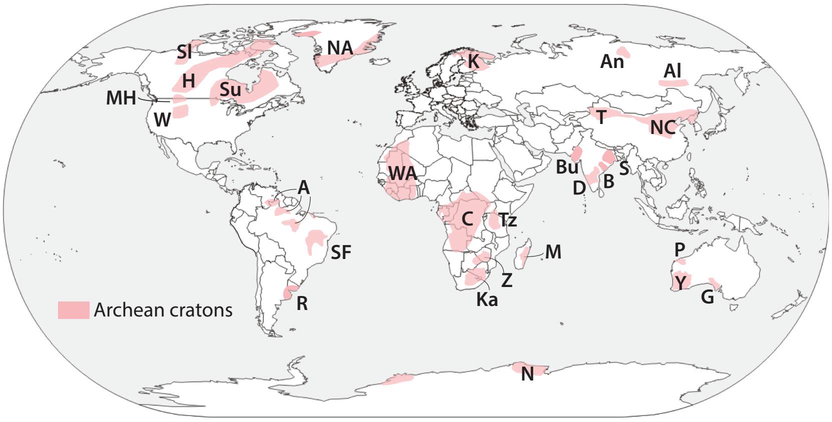

FIGURE 1 Global distribution of Archean cratons, after Frost et al. (2023). A = Amazonia, Al = Aldan, An = Anabar, B = Bastar, Bu = Bundelkhand, C = Congo, D = Dharwar, G = Gawler, H = Hearne/Rae, K = Kola/Karelia, Ka = Kaapvaal, M = Madagascar, MH = Medicine Hat, N = Napier, NA = North Atlantic, NC = North China, P = Pilbara, R = Rio de la Plata, S = Singhbhum, SF = Sao Francisco, Sl = Slave, Su = Superior, T = Tarim, Tz = Tanzania, W = Wyoming, WA = West Africa, Y = Yilgarn, Z = Zimbabwe.

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Archean cratons typically are composed of two distinct rock assemblages: high-grade gneiss terranes and greenstone belts. High-grade gneiss terranes are composed of complex suites of metamorphosed intrusive rocks sometimes referred to as "grey gneiss." These terranes, which typically include rocks of multiple ages, are commonly metamorphosed at amphibolite- to granulite-facies and show evidence of partial melting at the higher grades. Although these terranes are dominated by tonalite-trondhjemite-granodiorite (TTG) gneisses, calc-alkalic intermediate to felsic rocks, tholeiitic and calc-alkalic mafic rocks, and ultramafic rocks such as komatiites and pyroxenites are commonly present in limited volumes. Larger intrusions of calc-alkalic granodiorite and granite tend to be younger and to have formed by partial melting of the sodic TTG suite (Moyen 2011; White et al. 2017). High-grade gneiss terranes and their TTG suites are typical of the time period spanning the Eoarchean to the Mesoarchean (4.03–2.8 Ga) crust (Frost et al. 2023; Laurent et al. 2024 this issue).

In contrast, greenstone belts are characterized by a wide variety of supracrustal rocks, both volcanic and sedimentary. Overall, most are elongate, synformal structures and appear on all cratons (Anhaeusser 2014). Their name derives from the greenish color imparted to metabasalts by greenschist metamorphism. In addition to greenstones, these belts also contain ultramafic volcanic rocks with minor intermediate to felsic intrusive, volcanic, and volcaniclastic rocks. The volcanic rocks are typically overlain by sedimentary rocks, including greywacke, tuff, pelite, chert, minor carbonate, and iron formations. Spherule layers in some greenstone belts have been interpreted as fallout from impact events (Anhaeusser 2014). Some greenstone belts also contain >3.5 Ga metacarbonate rocks with stromatolites and filamentous microfossils that may record primitive life. Archean greenstone belts host globally important mineral deposits, including massive sulfide Ni–Cu–Zn deposits, magmatic cumulate Cr deposits, iron-formations, and placer and magmatic lode gold. Structurally, many greenstone belts are characterized by a "dome and keel" structure (Fig. 2), in which shallowly-emplaced granitic plutons intrude the metasupracrustal rocks such as typically found in the Pilbara, Superior, and Zimbabwe greenstone belts (Anhaeusser 2014).

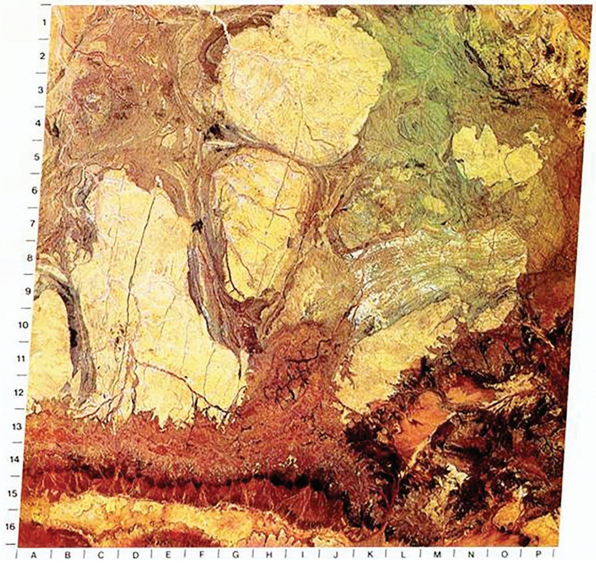

Figure 2 Landsat image of domes (pale yellow) and surrounding keels of metavolcanic rocks in the Pilbara craton. Image dimensions are 175 × 175 km. Image credit: CSIRO Mineral Physics, Satellite Images of Australia, www.xnatmap.org.

CHALLENGES IN STUDYING ARCHEAN CRATONS

Studying Earth's oldest rocks can be like trying to learn one's family history by consulting the oldest living relative with a failing memory: some facts may be reliable, but others are difficult to untangle and place in correct chronological order and geographic location, some reminiscences may be misleading, and for some significant events, there may be no recollection at all. Like geoscientists studying younger rocks, geologists studying Earth's oldest rocks use a combination of analytical approaches that include field studies, petrology, geochemistry, geophysics, and numerical modeling to try to reconstruct the family history of the planet. However, unlike those who study the Phanerozoic (541 Ma to present), geologists who study the Archean encounter severe challenges that make this task especially difficult, as discussed throughout this issue's thematic articles and Triple Point.

The Non-uniformitarian Earth

Geologic processes are commonly assumed to be *uniformitarian*, that is, we can infer how rocks formed and were modified in the past by looking at modern processes that affect the Earth today. This assumption cannot, however, be applied to the first 1.5 to 2 billion years of Earth history. For example, the formation of the core, silicate magma oceans, and the Moon were early, one-time events. Exponential, secular cooling of the planet occurred as the energy of accretion dissipated and radioactive heat production decreased. This cooling led to a continually evolving temperature regime within the early Earth, which likely included a 100–250 °C hotter mantle. This higher temperature regime surely affected the nature and rates of geologic processes, including global tectonics. Instead of rigid plates of crust moving horizontally above a convecting mantle in a modern "mobile lid" regime, Hadean and Archean tectonics may have been driven by mantle upwellings beneath a stationary crust, in a "stagnant lid" scenario similar to that thought to exist on Mars (see Toolkit and Perspective in this issue). Instead of subduction, the early crust may have responded to mantle upwelling and downwelling, including a process called sagduction, and a range of other proposed forms of "drip tectonics" (see Laurent et al. 2024 this issue). In addition, studies of the lunar surface indicate by analogy that extraterrestrial impacts strongly affected the early Earth, but tailed off by the end of the Archean (see Toolkit). The lesson here is that we cannot allow our interpretations of Archean environments or processes to be constrained by our experience with the modern Earth. Rather, we must keep an open and creative mind when trying to imagine and understand its early history.

It is also important to remember that although the geodynamic environment of the Hadean-Archean Earth may have been different than today, basic thermodynamic principles still applied. For example, the temperature and pressure at which hydrated basalt melts would be the same in the past as it is today. How and where these conditions were met in the early Earth could have varied: instead of by subduction of oceanic crust, melting may have occurred at the base of thick oceanic plateaus. Although such melts do not form at the base of these plateaus today, the higher geotherms in the Archean suggest that melting was possible at that time. In addition, impacts of large bolides (extraterrestrial bodies of unspecified composition—stony, metallic, gaseous, or a combination) could lead to decompression melting, much as basaltic magmas filled impact craters on the Moon (see Perspective). In short, the tectonic environments in which rocks reach their melting temperature change over time, but the basic laws of physics and chemistry do not—they are timeless and universal.

Preservation Bias

Another important aspect of placing early Earth evolution in context is to keep in mind that we only have the "leftovers" to examine, which is referred to as *preservation bias*. Whereas many models of crustal evolution suggest that >50% of the continental crust formed in the Archean (see Toolkit), Archean and older crust available for study make up only ~3% of Earth's exposed surface. Just as most of the Phanerozoic oceanic crust has been subducted and is no longer available for direct study, tectonic processes may have preferentially destroyed certain Archean rock assemblages, leaving those that survived over-represented in the rock record. We cannot assume, therefore, that what is left of the Archean crustal record is representative of what was present more than 2.5 billion years ago. The fact that cratons are associated with thick lithospheric mantle keels may have helped them survive at the expense of other crust that was more easily recycled or removed by erosion. Consequently, we cannot take for granted that the TTG suite that dominates the high-grade gneiss terranes typical of many cratons was as prevalent in the Archean as the rock record suggests.

Overprinting by Subsequent Events

The older the craton, the more likely it is that subsequent events have obscured its origin and evolution. For example, consider the world's oldest known rocks of the Acasta gneiss complex in the Slave craton of northwestern Canada. The gneiss that yields the 4.03 Ga zircons for which the gneiss is famous occupies a relatively small (~25 km^2) area. Even a cursory look at these exposures shows that this area has experienced a complex history of intrusion, metamorphism, and deformation (Fig. 3). It is little wonder that it took a generation of studies to sort out the complex history of the Slave craton, which would not have been possible without the robustness of the mineral zircon and its ability to yield precise U-Pb geochronologic and isotopic information about magma sources and metamorphic events (see Toolkit; Reimink et al. 2016).

Figure 3 Acasta gneiss outcrop, Slave craton, showing the complexity of the geologic field relations. Photo: J. Reimink.

CRATON CLANS AND SUPERCRATONS

As indicated in Fig. 1, Archean cratons vary considerably in size, from relatively small, e.g., Tanzania, Wyoming, Rio de la Plata, and Kola, to larger ones like Superior and Yilgarn. These cratons are found worldwide, embedded within younger continental collages. For example, Laurentia (ancestral North America) is a continental landmass that was assembled around 10 or more Archean cratonic nuclei (Fig. 4). Most surviving cratons have Proterozoic rifted or faulted margins, suggesting they are fragments of what were once larger landmasses. Present-day cratons have been grouped into "clans" based on common geologic histories and isotopic characteristics (Bleeker 2003). These clans may identify cratons that originally composed "supercratons," which, in turn, may be precursors to the well-known supercontinents Gondwana, Rodinia, and Nuna/Columbia. These supercontinents aggregated, broke up, and reformed in different configurations in repeated cycles over geologic time, resulting in the dispersed locations of these Archean cratons today.

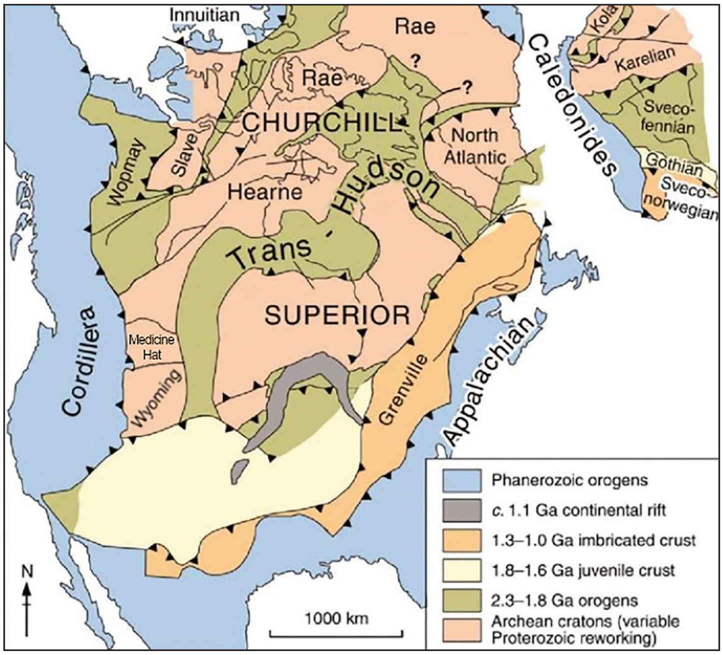

Figure 4 Ancestral North America, also known as Laurentia, was built around 10 or more Archean cratonic fragments of varying size. Modified from St. Onge et al. (2009).

APPROACHES FOR IDENTYFYING ARCHEAN CRATON CLANS

Geologic Histories

Similar geologic histories have long been used to propose correlations among cratons. Bleeker (2003) used a detailed examination of Archean timelines of igneous, metamorphic, and sedimentary events to suggest specific correlations of cratonic fragments with similar geologic histories. He proposed possible correlations between the Slave, Dharwar, Zimbabwe, and Wyoming cratons and suggested they might together make up the Slave "clan" that comprised a supercraton he named Sclavia. The oldest rocks in cratons may also help identify members of a clan. Nutman et al. (2015), for example, proposed that 10 cratons, each containing >3.6 Ga rocks, could have been part of an ancient continent that they called Itsaqia. In contrast, the Superior province is made up of terranes that preserve a geologic history dominated by Neoarchean

(2.8–2.5 Ga) crust formed from juvenile mantle reservoirs (Percival et al. 2012). It represents the archetypal craton of Bleeker's Superia clan. Another distinguishing feature of craton clans is the time of cratonization, which is the time after which the cratons became tectonically stable with minimal, if any, further penetrative deformation or magmatism. According to Bleeker (2003), the Kaapvaal and Pilbara cratons cratonized around 3 Ga, the Superior craton around 2.65 Ga, and the Slave clan cratons by 2.5 Ga. Similar geologic histories only suggest, rather than prove, which cratons were once together in one landmass. In fact, the plethora of different proposals for "supercratons" composed of various combinations of cratons suggests that geologic history alone is not sufficient to classify cratons into clans.

Evidence from Common Pb

In addition to geologic histories, the initial Pb isotopic composition of cratons can also be used to help identify clans. The initial Pb isotopic composition of the Earth is taken to be that of iron meteorites (see Toolkit). The Pb isotope evolution of the mantle begins with an initial composition well constrained by data from meteorites. Data from feldspars and sulfide ores, such as galena, feed into forward models of crustal evolution (see Mueller et al. 2014). Because continental crust has higher $^{238}\text{U}/^{204}\text{Pb}$ than the mantle, it evolves to higher $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{207}\text{Pb}/^{204}\text{Pb}$ than coeval mantle (Fig. 5). Because ^{235}U decays to ^{207}Pb much faster than ^{238}U decays to ^{206}Pb, growth curves are steep early in Earth history (see Toolkit Fig. 6A), and early-formed reservoirs can quickly evolve to elevated $^{207}\text{Pb}/^{204}\text{Pb}$ for a given $^{206}\text{Pb}/^{204}\text{Pb}$. Significantly, the initial Pb isotopic compositions of Archean igneous rocks from some cratons require that these rocks formed from a reservoir with a substantially higher $^{238}\text{U}/^{204}\text{Pb}$ than coeval mantle and model continental crust. Thus, the initial Pb isotopic composition can be the basis for grouping cratons into those from high-μ sources (where $\mu = {}^{238}\text{U}/{}^{204}\text{Pb}$) and those derived from low-μ reservoirs such as contemporary depleted mantle. This is possible because feldspar, particularly potassium feldspar, is characterized by relatively high Pb contents (tens of ppm) and very low U/Pb ratios. These low U/Pb ratios mean that feldspar Pb isotopic compositions do not change much, if at all, over time from radiogenic ingrowth and can hence preserve their initial Pb isotopic compositions. Initial Pb isotopic compositions can also be calculated for rocks of known age from their U and Pb contents and present-day Pb isotopic compositions, assuming no loss or gain of either element.

An example of how Pb isotopic compositions discriminate cratons formed from reservoirs with different μ is shown in Fig. 5. Feldspars and Neoarchean TTG rocks from the high-grade gneiss terrane of the northern Wyoming craton define an array that corresponds to an age of 2.8 Ga, which matches the U-Pb zircon ages of 2.79–2.83 Ga. This agreement means that the measured U, Pb, and Pb isotopic compositions are primary. In the case of the Wyoming craton, first-order modeling suggests that a Hadean reservoir with at least an average crustal μ value (μ ~ 10–11) is required. This in turn suggests that the northern Wyoming craton was built on Hadean lithosphere. This hypothesis is supported by the presence of 4.0 Ga detrital zircons in the metasedimentary rocks intruded by the Neoarchean batholiths (Mueller et al. 2014). The high-μ character of the Wyoming craton contrasts strongly with the low-μ character of the Superior craton (e.g., Mueller and Wooden 1988), but is compatible with the high-μ character of the Slave craton (Thorpe 1972). These observations support a Wyoming-Slave connection reaching back to the Hadean, but do not support a connection with the Superior or other low-μ cratons. In terms of clans, other cratons with high-μ terranes in addition to Wyoming include the western Slave, Kaapvaal, and North China cratons.

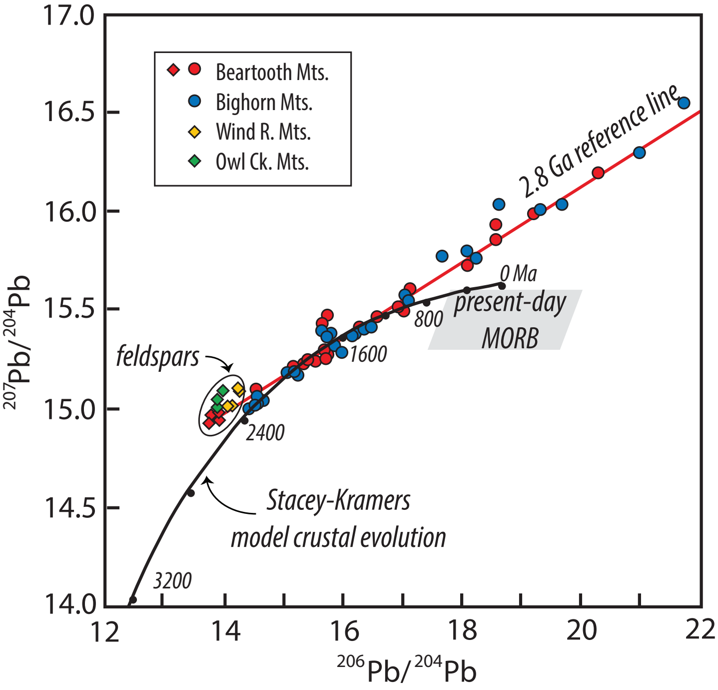

FIGURE 5 Common Pb isotopic compositions of Neoarchean granitoids (circles) and feldspar separates (diamonds) from the northern Wyoming craton plotted with the Stacey and Kramers (1975) average crustal growth curve and the field for mid-ocean ridge basalts (MORB). The feldspar data show that the initial Pb isotopic composition of these magmas was above the average crustal growth curve and, therefore, must have interacted with an ancient, high-μ reservoir. Data from Wooden and Mueller (1988) and Frost et al. (2006).

Evidence for Hadean Crust from Detrital Zircons

Beyond the high- and low-μ characteristics suggested by Pb isotopes, we can consider the possibility of linking cratons that contain evidence of Hadean crust using the U-Pb age and Hf isotopic compositions of detrital zircons (see Toolkit; Laurent et al. 2024 this issue; O'Neil et al. 2024 this issue). All Hadean zircon grains are detrital, i.e., they have been removed from their host-rock and hence their original geologic context, and have been transported unknown distances from their sources. They provide an interesting, but biased, sample, revealing information only about magmas that crystallized zircon. Nevertheless, they and their inclusions provide important information about the early Earth (Harrison et al. 2017). To date, Hadean zircons have been reported from Australia, India, North America, South America, and Asia. The best-known suite is from the Jack Hills region of the Yilgarn craton of Western Australia, which contains grains up to 4.4 Ga (Harrison 2020). Even so, Hadean grains have not been reported from every craton, including the Superior craton, despite thousands of analyses. Although the Yilgarn is the Pilbara craton's nearest cratonic neighbor (Fig. 1) and both cratons contain Paleoarchean crust (3.6–3.5 Ga), Hadean zircons have not been reported from Pilbara.

Evidence from Mafic Dike Swarms and Paleomagnetic Data

Radiating mafic dike swarms have been interpreted as originating from mantle plume centers that may be associated with the break-up of supercratons (Ernst and Bleeker 2010). If so, correlation of well-dated dikes across two cratons may indicate that they once were contiguous. The lateral motion of cratons can then be quantified from information about the direction of the Earth's magnetic field recorded in igneous and sedimentary rocks at the time they acquired their magnetization. Because magnetic poles rarely lie far from the geographic poles, the changes in orientation of the craton in relation to the poles track the motion of the craton across the Earth's surface. Unfortunately, high-quality paleomagnetic data are sparse in the Archean compared with the Proterozoic and Phanerozoic. Extant data have, however, been used to suggest a Vaalbara supercraton between 2.8 and 2.2 Ga, that break-up of Superia did not occur until 2.1 Ga, that break-up of Sclavia occurred at 2.0 Ga, and that these two supercratons were not likely adjacent from 2.4 to 2.2 Ga (Salminen et al. 2021).

CRATON CLANS AND SHIFTING ALLEGIANCES: WYOMING, SLAVE, AND SUPERIOR

The Wyoming craton has been grouped with the Sclavia clan because of the similar geologic histories between the northern part of the Wyoming craton and the western half of the Slave craton (Bleeker 2003). Both expose extensive 3.5–3.0 Ga TTG gneisses and their detrital zircon populations extend back to 4.0 Ga. They share high-μ common Pb isotopic signatures, and the negative initial εNd of the Paleoarchean gneisses in both cratons indicate derivation from an ancient evolved source (Wooden and Mueller 1988; Thorpe 1972; Davis et al. 2003; Frost et al. 2006; Mueller et al. 2014).

At the end of the Mesoarchean, sedimentary sequences interpreted to be rift-related were deposited on both the northern Wyoming and western Slave cratons. The southwestern Slave craton was covered by a supracrustal sequence composed of quartz arenite, sandstone-argillite, banded iron formation (BIF), quartz pebble conglomerate, and minor felsic volcaniclastic rocks and mafic volcanic flows (Corcoran 2012). Along the southern margin of the Wyoming province, similar supracrustal rocks (quartzite, BIF, metapelite, metabasalt, and minor felsic volcanic rocks) were deposited in the Neoarchean (Mogk et al. 2023). Subsequently, their geologic histories diverge, suggesting that if the two cratons were originally adjacent, they had moved apart by 2.85 Ga (FIG. 6). The later geologic histories of the two cratons are distinct: the Eastern Slave accreted to the western Slave craton between 2.7 and 2.6 Ga (Davis et al. 2003), and in the Wyoming craton, the southern accreted terranes docked at ~2.65 Ga (Mogk et al. 2023).

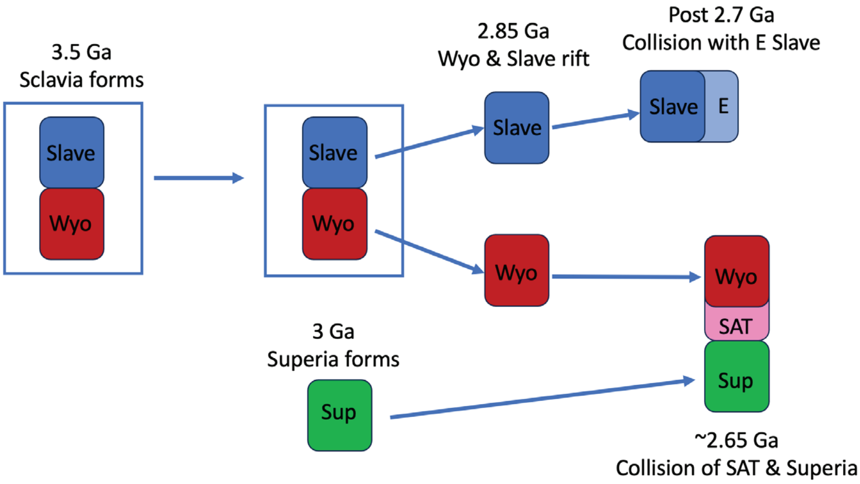

FIGURE 6 Cartoon summarizing the changing allegiances of the Wyoming craton. Originally part of the Sclavia supercraton, Wyoming (Wyo) rifted from Slave and accreted to the Superia (Sup) supercraton in the Neoarchean. SAT = southern accreted terranes.

What happened to Wyoming after it rifted from Slave? Correlated mafic dike swarms and paleomagnetic data suggest that the Wyoming craton may have changed allegiances and joined Superia by the end of the Archean (FIG. 6). The collision of accreted terranes along Wyoming's southern margin at ~2.65 Ga has been interpreted to be related to closure of an ocean between Superior and Wyoming (Ernst and Bleeker 2010). High-quality paleomagnetic data place Wyoming adjacent to Superia by 2.45 Ga (FIG. 6; Salminen et al. 2021).

IMPLICATIONS

Archean cratons represent an incomplete record of early Earth history. The surviving cratons almost certainly represent only a fraction of the original Archean crust. They may not be representative of Archean crust as a whole if cratons were preserved preferentially because of their thick, strong, lithospheric roots. Their geologic, petrologic, geochemical, and isotopic characteristics are complicated by a long history of deformation, partial melting, and metamorphism before cratonization. Consequently, detailed study using multiple approaches provides the best insight into early Earth processes and the protracted journey from craton to continent. Key insights include:

- *It appears that crust formation on Earth was not a global, synchronous event. Instead, different craton clans formed at different times from different reservoirs.* In the example we discussed, the Slave and Wyoming cratons formed in the Paleoarchean from a similar, high-U/Pb reservoir, incorporating detrital and xenocrystic zircon as old as 4 Ga. By contrast, most of the Superior craton is characterized by greenstone terranes formed from juvenile mantle sources in the Neoarchean.
- *By the end of the Hadean (if not earlier), the Earth had differentiated into a number of geochemical and isotopic reservoirs.* We discussed how common Pb isotope data suggest high- and low-μ reservoirs formed in the Hadean. Using excesses in ^{142}Nd, O'Neil et al. (2024 this issue) present evidence for multiple depletion events in the Hadean mantle. They note that these excesses are not a feature shared by all cratons, suggesting that early crustal genesis and mantle depletion may have been local, not global.
- *Rifted and faulted cratonic margins and paleomagnetic evidence for lateral movement of cratons suggest that mobile lid tectonics was operating by the Neoarchean.* Although paleomagnetic data indicate the possibility of far traveled cratons, they do not necessarily imply that plate tectonics was widespread in the Archean. As suggested by Rey et al. (2024 this issue), both mobile lid and stagnant lid tectonics may have operated simultaneously in the early Archean. As the planet cooled and rigid plates formed, this temporary dual-mode tectonic scenario eventually was replaced by plate tectonics at the expense of the stagnant lid regime.
- *The small volume of surviving Archean crust may mean that preservation bias affected the remaining array of cratons. It is likely significant that these survivors are characterized by thick mantle roots, which may have protected them from modification and destruction from the Archean to the present.* As pointed out by Cooper

and Miller (2024 this issue), sharp lateral changes in temperature between thick cratonic lithosphere and surrounding mantle can induce edge-driven convective instabilities that weaken, modify, and deform cratonic lithosphere. The lithosphere beneath the eastern part of the North China craton appears to have thinned as a consequence of Mesozoic flat-slab subduction (Bedle et al. 2021; Cooper and Miller 2024 this issue), suggesting that other cratons also may have been weakened and even destroyed by similar processes.

Understanding the evolution of the Earth's earliest crust and mantle is a challenging area of research for geoscientists at large. Using a variety of geologic, geochemical, isotopic, geophysical, and geodynamical tools and models, we continue to gain increasingly detailed insight into our planet's earliest history. This issue of *Elements* presents aspects of our current understanding that we hope will stimulate interest in the early Earth and spur future investigations.

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Field photo from the Saglek-Hebron Complex, northern Labrador, Canada (view from Big Island, looking south across the Saglek fjord). Outcrop showing the intricate relationship between multiple generations of felsic rocks and mafic amphibolites, illustrating the complex processes of early crustal formation.

Earth's Earliest Crust

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The scarcity of rocks preserved from the first billion years (Gy) of Earth's history hinders our ability to study the nature of the earliest crust. Rare >4.0-Gy-old zircons confirm that felsic crust was present within 500 million years of Earth's formation. Given that most of that ancient crust has been destroyed, geochemical and isotopic tracers applied to rocks from the oldest sections of continents can be used to provide insights into the nature of the predecessor crust. Evidence from Earth's oldest rocks and minerals suggests multiple early mantle depletion episodes, possibly linked to the formation of an initial, dominantly mafic, crust. This early crust was the precursor to evolved rocks that now constitute considerable portions of Earth's oldest surviving crust.

KEYWORDS: Hadean; Archean; early crust; Earth's oldest rocks; crustal reworking; depleted mantle; isotope geochemistry

INTRODUCTION

The Hadean Eon was named after Hades, the Greek god of the underworld, and viewed as a time when catastrophic events related to Earth's accretion prevented the survival of solid rocks on its surface. The Hadean encompasses almost 600 million years (My) of Earth's earliest history, from the Solar System formation 4.568 billion years ago (Ga), until the preserved rock record begins, currently defined by the International Commission on Stratigraphy at 4.031 Ga. However, the boundary marking the end of the Hadean at ~4 Ga is a moving target given the continuing discovery of increasingly old rock terranes.

Our ability to investigate the earliest crust and the geological processes responsible for its formation is greatly hindered by the near absence of preserved Hadean rocks and minerals. Hadean and early Archean (4.0–2.5 Ga) rocks and minerals provide a sparse, potentially biased, geological record, making extrapolation to planetary-scale processes and features challenging. Nevertheless, these small remnants record invaluable information about the nature of the early crust. Here, we review what is known so far about some of Earth's oldest rocks and focus on how geochemical and isotopic tracers can be used to better constrain the composition of our planet's most ancient crust and the impact of its formation on the early mantle.

WHAT REMAINS—THE OLDEST GEOLOGICAL RECORD

The oldest known terrestrial materials are Hadean detrital zircons as old as ~4.4 Ga (e.g., Wilde et al. 2001), first reported from the Jack Hills in the Yilgarn craton (FIG. 1; Cavosie et al. 2019 for review), with additional Hadean detrital grains being discovered globally.

With a crystallization age of up to 4.03 Ga based on zircon U-Pb data (Bowring and Williams 1999), the Acasta gneisses, located in the Slave craton (FIG. 1), represent the oldest evolved rocks known on Earth. Potentially older rocks, however, are included in the Nuvvuagittuq greenstone belt in the Superior craton (FIG. 1), a volcano-sedimentary sequence mostly composed of mafic metavolcanic rocks. The Nuvvuagittuq belt is at least 3.75 Gy old, as constrained by zircon U-Pb ages in intruding felsic rocks (Cates and Mojzsis 2007), but the ^{146}Sm-^{142}Nd isotopic systematics of its metavolcanic rocks (see *Toolkit*) suggest an older age of ~4.3 Ga, yet still debated in the scientific community (O'Neil et al. 2019 for review).

The Eoarchean (4.0–3.6 Ga) geological archive is similarly sparse. The best-known assemblage of Eoarchean rocks is the Isua supracrustal belt within the Itsaq Gneiss complex in the North Atlantic craton of southwestern Greenland (FIG. 1; Nutman et al. 2021 for review). Often considered as the best-preserved remnant of ancient supracrustal rocks (rocks deposited on existing basement rocks of the crust), the Isua supracrustal belt comprises 3.7–3.8 Ga mafic metavolcanic and metasedimentary rocks, and orthogneisses as old as ~3.85 Ga. On the Canadian side of the North Atlantic craton, the Saglek-Hebron complex (FIG. 1) also includes rare occurrences of Eoarchean rocks. The oldest rocks are ~3.9 Ga tonalite-trondhjemite-granodiorites (TTG; Laurent et al. 2024 this issue), but the complex is dominated by

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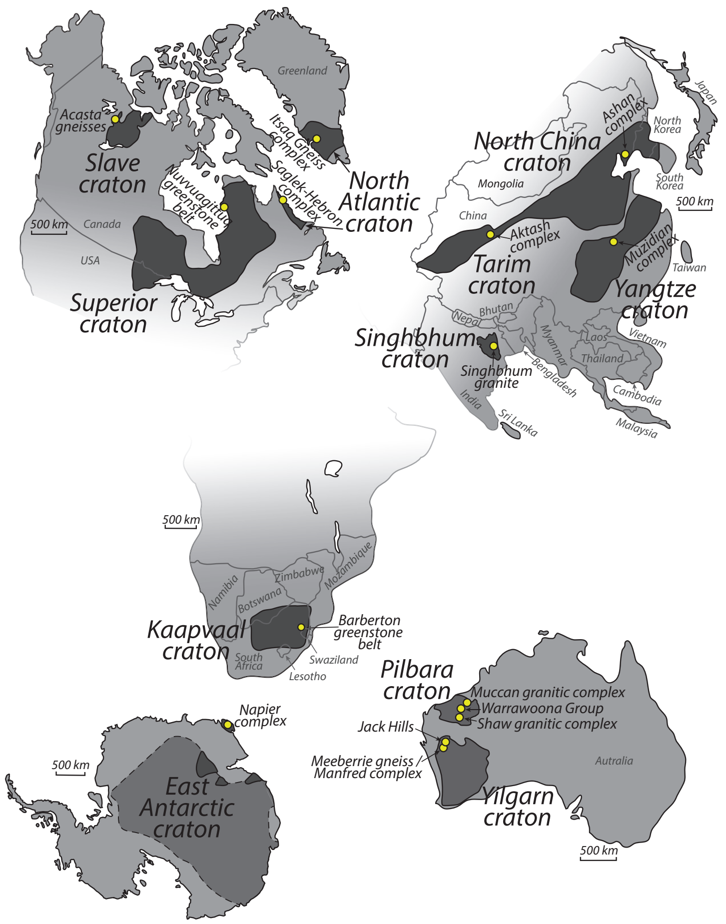

FIGURE 1 Location of some of Earth's oldest rocks and Archean cratons discussed here.

~3.75 Ga orthogneisses (e.g., Wasilewski et al. 2021) with numerous enclaves of mafic metavolcanic, ultramafic, and metasedimentary rocks as old as ~3.8 Ga (e.g., Morino et al. 2017).

Other sections of early Archean rocks are included in the Yilgarn and Pilbara cratons in Western Australia, as well as the Kaapvaal craton in southern Africa (FIG. 1). The Narryer terrane of the Yilgarn craton includes rocks as old as 3.73 Ga within the Meeberrie gneiss and Manfred complex (Kemp et al. 2019 for review). The Warrawoona Group of the East Pilbara terrane, mainly composed of basaltic to komatiitic volcanic rocks, was deposited between 3.53 and 3.43 Ga, but gabbroic rocks from the Shaw granitic complex and TTGs from the Muccan granitic complex were dated at 3.59 Ga (Wiemer et al. 2018; Petersson et al. 2019). The oldest rocks of the Kaapvaal craton are 3.66 Ga TTGs in the Ancient Gneiss complex (e.g., Hoffmann and Kröner 2019). The slightly younger supracrustal rocks in the Barberton greenstone belt, South Africa, include volcano-sedimentary sequences in the Fig Tree and Moodies groups (3.26–3.22 Ga) that contain detrital zircons in the Green Sandstone Bed as old as 4.1 Ga (Byerly et al. 2018), as well as komatiites in the Onverwacht Group (3.45–3.48 Ga). Less well documented occurrences of Eoarchean rocks include the 3.85 Ga rocks from the Napier complex of Antarctica (Black et al. 1986), the 3.7 to 3.8 Ga rocks from the Anshan and Muzidian areas of the North China craton (Liu et al. 2008; Wang et al. 2023), and the 3.7 Ga Aktash gneisses from the Tarim craton, China (Ge et al. 2020) (FIG. 1).

NEW TOOLS TO DECIPHER THE HISTORY OF ANCIENT CRUST

Most ancient crustal rocks have been subjected to complex thermal histories that have changed their original mineralogy and often their bulk chemical composition. Understanding the processes that formed these ancient rocks requires a combination of dating techniques that can distinguish crystallization ages from later events, along with chemical and isotopic approaches that help trace the nature of their sources. The tool of choice for geochronology has become U-Pb dating of zircon, while isotopic tracers based on the decay of ^{147}Sm to ^{143}Nd, or ^{176}Lu to ^{176}Hf, on whole rocks or the zircons themselves, are commonly used to constrain the age and composition of their source (see *Toolkit*).

Another recent advance has been the application of short-lived radionuclides, such as the decay of ^{146}Sm to ^{142}Nd (half-life of 103 My). Because the abundance of ^{146}Sm became too low (or "extinct") by ~4 Ga, measurable variations in ^{142}Nd due to ^{146}Sm decay were no longer produced after the Hadean. Hence, variations in ^{142}Nd provide a record of chemical fractionation between Sm and Nd before 4 Ga (FIG. 2). This tool is, therefore, ideal to highlight evidence of Hadean silicate differentiation preserved in younger rocks. Variations of ^{142}Nd/^{144}Nd are typically expressed as μ-values, representing parts per million deviations from a Nd standard with μ^{142}Nd = 0 (see *Toolkit*). Mantle-derived rocks with positive μ^{142}Nd indicate a mantle source that was depleted in incompatible elements (higher Sm/Nd) in the Hadean, while negative μ^{142}Nd imply a pre-4 Ga source enriched in incompatible elements (lower Sm/Nd). More than 500 samples have now been analyzed for ^{142}Nd and unequivocally show that most of Earth's oldest preserved crust was derived from sources that had been chemically modified by events occurring in the Hadean, long before the preserved rock record began (FIG. 2).

CRUSTAL ANCESTORS—EARTH'S LOST ANCIENT CRUST

Earth's first crust may have been a crystallization product of an early largely molten phase (e.g., magma ocean), analogous to the ancient crusts of the Moon and Mars, but surviving remnants of such crust on Earth are unknown. Although small amounts of >4 Ga terrestrial material confirm that Hadean crust existed on Earth, the extremely rare geological archive from this eon indicates that this early crust was either nearly entirely destroyed or of minimal volume. The processes responsible for its destruction remain debated, but include disruption of the early crust by meteoritic impacts or sinking into Earth's interior through mechanisms proposed to range from lithospheric "drips" to processes similar to modern plate subduction. The presence of Hadean zircons that crystallized from felsic, TTG-like magmas shows the existence of at least some felsic, continent-like crust early in Earth's history. Continental crust can survive at Earth's surface for billions of years because of the relatively low density of its Si-rich rocks, and because it is underlain by strong and buoyant residual mantle peridotite (e.g., Pearson et al. 2021). In contrast, under the current mode of plate tectonics, mafic oceanic crust is transient and survives for only 100–200 My before its subduction into the mantle; yet in the modern world, oceanic crust covers roughly two-thirds of Earth's surface. The proportion of Earth's crust in the Hadean that was continent-like or ocean-like is effectively unknown.

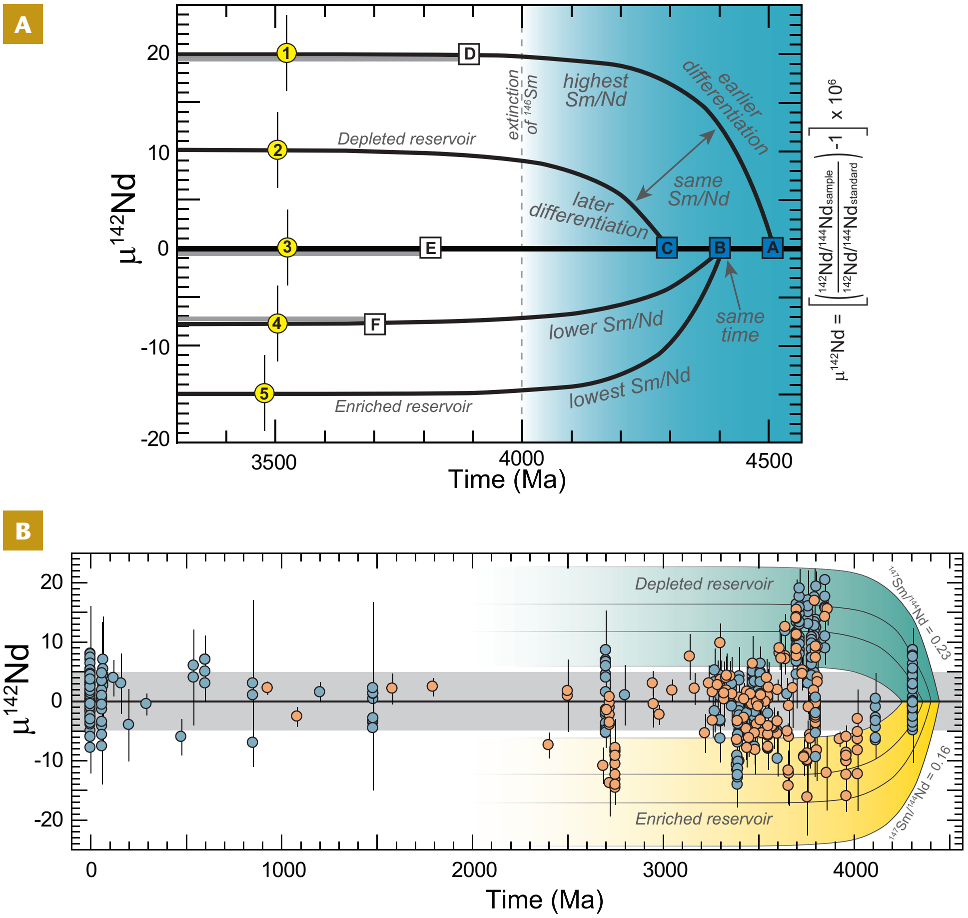

FIGURE 2 (**A**) Cartoon illustrating how μ^{142}Nd traces Hadean silicate differentiation. Yellow circles show ~3.5 Ga samples with different μ^{142}Nd. Squares represent differentiation events occurring in the Hadean (blue) and after 4 Ga (white). Reservoirs formed from events A, B, and C have a common precursor with μ^{142}Nd = 0. Events A and C show equal extent of Sm-Nd fractionation of a depleted reservoir at different times, producing the sources of rocks 1 and 2 with distinct positive μ^{142}Nd, where the earlier source evolves to higher μ^{142}Nd. Event B produces coeval enriched reservoirs with different Sm/Nd ratios, sourcing rocks 4 and 5 with distinct negative μ^{142}Nd, where the more enriched reservoir generates the rock with lower μ^{142}Nd. Differentiations D, E, and F occur after ^{146}Sm is extinct, producing reservoirs (grey lines) with the same μ^{142}Nd as their respective sources. Rocks 1, 3, and 4, derived from sources produced by post-4 Ga events, have different μ^{142}Nd due to the distinct Hadean evolution of their precursors. (**B**) Compilation of terrestrial ^{142}Nd data. Nuvvuagittuq samples are plotted as initial μ^{142}Nd at their interpreted Hadean ages. Mafic-ultramafic and felsic rocks are shown with blue and orange symbols, respectively. The typical external precision of the standard is represented by the grey bar. Evolution lines (thin black lines) for the depleted and enriched reservoirs have ^{147}Sm/^{144}Nd ratios of 0.23 and 0.16, respectively, derived at 4.45, 4.40, 4.35, and 4.25 Ga, from a reservoir with chondritic Sm/Nd and present-day μ^{142}Nd = 0. Data sources are given in the online supplement.

Beyond the rare Hadean materials, Archean rocks also record valuable information about the nature and age of their progenitors, although even here, the record is biased by what is preserved. Archean crust is dominated by felsic rocks such as TTGs and granites, along with Mg-rich rocks, referred to as "greenstones." Because felsic magmas cannot be derived by melting of mantle peridotite, they are commonly interpreted to stem from melting of an older crustal ancestor. Moreover, the geochemistry of Archean TTGs, notably their high silica contents, low K/Na ratios, and depletion in heavy rare earth elements, indicate their formation from melting of a metamorphosed basaltic precursor. The extent of TTGs in many Archean cratons, therefore, strongly implies the presence of an older mafic crust of potentially widespread distribution.

A combination of isotopic tracers applied to Archean rocks can shed light on what could have been Earth's early crust by better constraining the age and composition of their crustal ancestors. For example, Hf isotopes in zircons have been widely used for this purpose. As zircons crystallize, they record the Hf isotopic composition of their host magma, reflecting that of the magma source at the time of crustal melting. Combining U-Pb with Hf and Nd initial isotopic variability allows determination of the compositional characteristics of the progenitor(s) and whether they formed in the Hadean or later. FIGURE 3 shows the evolution of Hadean mafic and felsic sources, along with the Hf-in-zircon isotopic compositions (expressed as εHf, the deviation in parts per 10,000 of the sample relative to a chondritic reference value; see *Toolkit*) and μ^{142}Nd values of some of the oldest TTG, focusing on terranes that recorded negative μ^{142}Nd (i.e., a Hadean enriched source), and Eoarchean-Hadean detrital zircons. The trends defined by the Acasta gneisses, TTGs from the NE Superior craton, the Napier complex, and the Muzidian complex are consistent with melting of 4.25–4.35 Ga mafic crust. The detrital Jack Hills zircons show a wide range of initial εHf compositions; however, a subset of the least altered Jack Hills zircons and detrital zircons from the Green Sandstone Bed in the Barberton greenstone belt show an evolution broadly following a slightly older mafic progenitor, perhaps as old as 4.45 Ga (FIG. 3). Like the Hf isotope record, the negative μ^{142}Nd of many Eoarchean TTGs can be explained by the melting of a 4.25–4.35 Ga mafic crust, whereas a Hadean felsic precursor would have led to μ^{142}Nd much lower than what has been observed for TTG—suggesting limited remelting of Hadean felsic crust to create preserved Eoarchean evolved rocks.

The combined record of Hf isotopes in zircons and μ^{142}Nd of some of Earth's oldest crustal rocks thus points to the existence of an early, potentially wide-spread, mafic crust that served as their geological ancestor, and which appears to have not been directly preserved in the rock record. Moreover, given that TTGs are typically interpreted to represent 10%–50% partial melts of mafic amphibolite, this would imply the involvement of large volumes of mafic Hadean crust to produce the TTG-dominated Archean cratons. Although negative initial εHf and ε^{143}Nd (defined similarly to εHf) are common in many post-Eoarchean rocks, only some Neoarchean (2.8–2.5 Ga) TTGs from the NE Superior and Muzidian terranes currently display negative μ^{142}Nd. As negative μ^{142}Nd is a sign of Sm-Nd fractionation in the Hadean, these two terranes suggest the survival of some mafic Hadean crust for at least a billion years, some five times longer than the oldest modern oceanic crust. The signatures of this Hadean mafic crust seem to completely disappear as sources for crustal rocks younger than ~2.4 Ga ("enriched reservoir" in FIG. 2), implying the complete destruction of this early crust by that point in time, perhaps by subduction into the mantle.

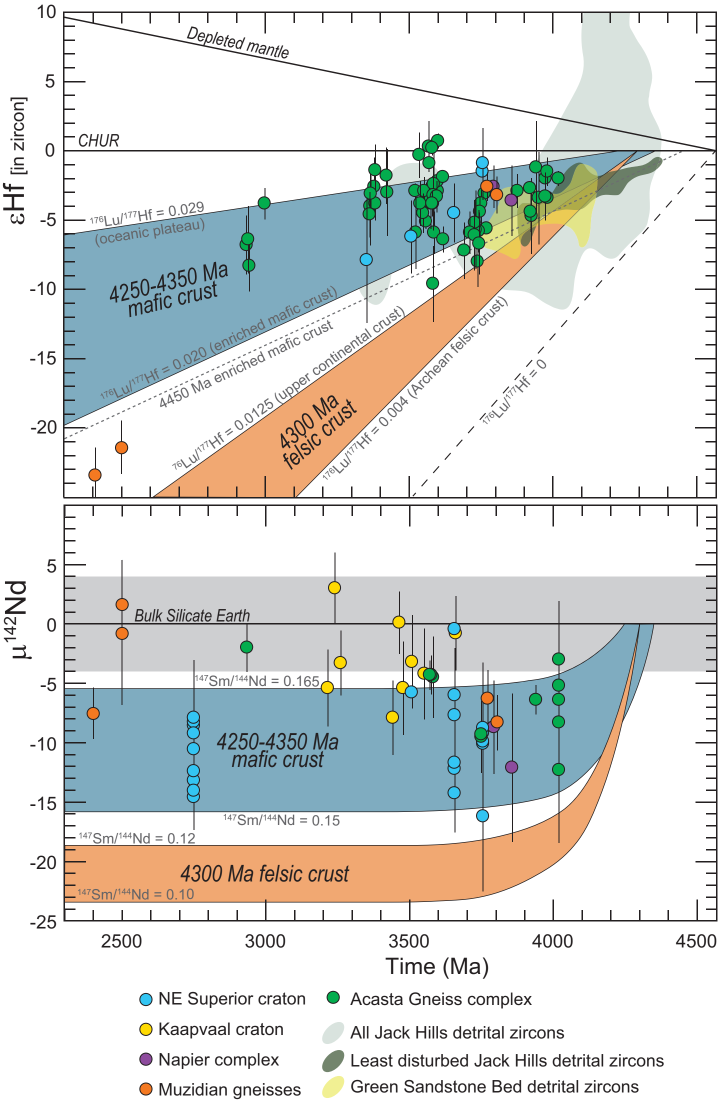

FIGURE 3 Initial εHf-zircon and μ^{142}Nd for some of Earth's oldest TTGs and early Archean to Hadean detrital zircons, focusing on samples that record negative μ^{142}Nd. Each zircon–εHf data point represents the average composition of several zircons from the same magmatic sample, calculated at the rock crystallization age. Irregular fields are for detrital zircons. The Green Sandstone Bed field only includes >3.80 Ga zircons. The Jack Hills lighter grey field includes all analyses. The least-altered Jack Hills zircons are shown by the darker grey field. Data points for μ^{142}Nd are for individual whole-rock samples. K-rich granitic samples are not included as they may result from multiple crustal reworking episodes. The ^{176}Lu/^{177}Hf and ^{147}Sm/^{144}Nd ratios of the modeled crusts are shown in grey. Data sources are given in the online supplement.

PERSPECTIVE FROM THE SEDIMENTARY RECORD

Terrigenous, fine-grained, clastic, sedimentary rocks concentrate the erosion products of land above sea level. They provide insights into the composition and history of Earth's earliest crust on the assumption that they depict a composite picture of large areas of ancient continental crust. The early Archean record for terrigenous sediment is sparse. It is therefore challenging to use this limited record to constrain the nature of the Hadean "lost" crust as discussed above. Later Archean terrigenous sequences are present in almost all cratons, making this archive particularly interesting for studying the nature and evolution of the global Archean crust. Sedimentary processes such as weathering, hydrodynamic sorting, and diagenesis can, however, significantly change the composition of sediments from source to sink and after deposition. The biggest challenge is thus to select and interpret the proper geochemical proxies to represent the composition and history of the eroded continental areas. The interpretation of the geochemical record preserved in the oldest sedimentary archive has been widely disputed, particularly regarding the relative proportions of felsic and mafic crust in the Archean.

From the pioneering work of Taylor and McLennan (1985) and subsequent studies (e.g., Tang et al. 2016), the Archean crust has long been thought to be dominantly basaltic, and that a major change, proposed to be the onset of plate tectonics, turned it to dominantly felsic at the end of the Archean. New insights may be obtained from re-evaluations of the meaning of trace element ratios in fine-grained sedimentary rocks (e.g., Ptaček et al. 2020) that integrate both (i) the compositional evolution of igneous rocks through geological time (Keller and Schoene 2012) and (ii) the propensity of trace element ratios involving Cr and Ni to be biased by contributions from komatiite (a rare ultramafic volcanic rock type with unusually high Mg, Cr and Ni contents), the consequence of which is overestimation of the contribution to the sediment from mafic rocks. These studies concluded that the oldest emerged crust preserved in Archean sedimentary rocks was, on average, almost as felsic as today. FIGURE 4 shows an estimation of the SiO_2 content of continents through time, based on the composition of fine-grained sedimentary rocks. Because the Sm/Nd ratios and SiO_2 contents are well correlated in igneous rocks, the Sm/Nd ratio of fine-grained terrigenous sedimentary rocks through time provides a good compositional (SiO_2) secular proxy for continents (Garçon 2021). From this perspective, the SiO_2 of continents appears to have been felsic (between 60 and 70 wt.%) throughout most of the Archean (FIG. 4). Additional evidence of a dominantly felsic crust above sea level as far as the sedimentary archive dates back was further provided by the record of Ti isotopes (Greber et al. 2017) and major element contents (Lipp et al. 2021) in ancient terrigenous rocks, all arguing for an average SiO_2 content > 60 wt.% for the emerged Archean crust.

Evidence of Hadean material is very subdued in the Archean sedimentary archives. Hadean detrital zircons appear absent from most Archean metasedimentary units, with a few exceptions (Green Sandstone Bed, South Africa; Jack Hills, Australia), and a record of Hadean mafic crust has not yet been found in Archean metasedimentary rocks. In fact, the available bulk-rock ^{147}Sm-^{143}Nd, ^{146}Sm-^{142}Nd, and ^{176}Lu-^{176}Hf data for the oldest terrigenous rocks point to a very limited contribution from Hadean crustal sources, (e.g., Garçon 2021; Boyet et al. 2021). This suggests that the Hadean mafic crust was either mostly below sea level, hence unable to form sediments due to lack of subaerial erosion, or was progressively reworked into more felsic lithologies through intra-crustal differentiation, or was recycled and mixed away into the mantle early in the Archean.

THE MANTLE VIEWPOINT—EARLY SILICATE DIFFERENTIATION

As the crust is primarily derived from partial melting of the mantle, a high mass ratio of crust to complementary melt-depleted mantle results in a residual mantle with a composition depleted in the most incompatible trace elements. Such signatures are commonly observed in samples of subcontinental mantle from beneath Archean cratons where Re-Os isotopes document a rough synchronicity of crust and lithospheric mantle formation, or at least preservation (e.g., Pearson et al. 2021). The broader influence of crust extraction from the mantle is evident in

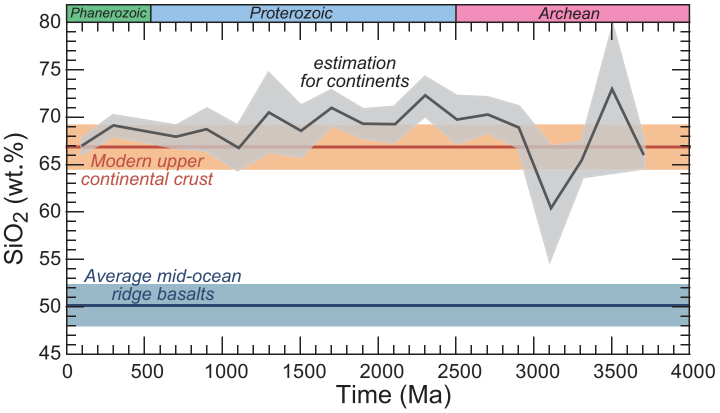

Figure 4 Estimated average SiO_2 of continents through time based on the correlation of the Sm/Nd ratios of fine-grained terrigenous sedimentary rocks and SiO_2 of igneous rocks. Modified from Garçon (2021). Data sources for upper continental crust and mid-ocean ridge basalt compositions are provided in the online supplements.

compositional and isotopic data from modern mid-ocean ridge basalts. However, isotopic data in this case suggest ages between 1.5 and 2.0 Ga that are often interpreted as reflecting the average age of a relatively continuous process of crust extraction and recycling throughout Earth history (e.g., Armstrong and Hein 1972). The existence of preserved early Archean crust, along with corresponding evidence discussed below for ancient sections of melt-depleted mantle, shows that crust–mantle differentiation began very early in Earth history.

A still unresolved issue regarding our understanding of the early differentiation history of the mantle stems from the observation that Hf isotopes in many ancient zircons, particularly in Eoarchean rocks from Greenland, are indicative of derivation from sources with minimal, if any, previous fractionation of Lu from Hf (Guitreau et al. 2012). In contrast, whole-rock Sm-Nd systematics indicate derivation of the same rocks from sources that experienced prior depletion of incompatible elements. One explanation of this paradox is that whole-rock samples may have undergone post-crystallization events that potentially fractionated the parent and daughter elements, leading to the erroneous calculation of initial isotopic compositions. The Lu-Hf system in zircon is less sensitive to such issues given the very high Hf concentrations and low Lu/Hf ratios of zircon, making the diffusion of Lu and/or Hf into or out of zircon unlikely. While alteration is possible, the observation that both μ^{142}Nd and initial ε^{143}Nd are positive in many of the Eoarchean Greenland rocks, makes the whole-rock disturbance explanation unlikely, given the fact that post-magmatic parent-daughter elemental fractionation does not affect the ^{142}Nd/^{144}Nd ratio after the extinction of ^{146}Sm.

A potential explanation is that the ancient chemical depletion recorded by Nd isotopes is valid, but not the result of typical crust–mantle differentiation where the magnitudes and directions of Sm-Nd and Lu-Hf fractionation are strongly coupled. For example, crystallization of a terrestrial magma ocean involving lower-mantle mineral phases, such as bridgmanite, that fractionate high-field strength elements (like Hf) very differently than rare earth elements (such as Nd, Sm, and Lu) could decouple Lu-Hf and Sm-Nd evolution (e.g., Rizo et al. 2011). The observation of unfractionated initial Hf isotopic compositions in Eoarchean rocks, however, is not universal, so the full explanation of the cause of this apparent decoupling of Nd and Hf isotope systematics remains unclear.

Compelling evidence for the existence of a Hadean depleted mantle comes from Eoarchean and Paleoarchean (3.6–3.2 Ga) rocks from several Archean cratons (e.g., Rizo et al. 2011; Morino et al. 2017; Maltese et al. 2022). Although these rocks formed after the extinction of ^{146}Sm, they contain excesses in ^{142}Nd that can only be produced in high Sm/Nd reservoirs formed in the Hadean. By coupling the initial ε^{143}Nd and μ^{142}Nd in the same rocks, the differentiation age and the degree of depletion of the mantle source involved in their formation can be estimated, as shown in Figure 5. With mantle differentiation ages ranging from 4.2 to 4.5 Ga coupled with variable ^{147}Sm/^{144}Nd ratios in the source, the data suggest that multiple episodes, or gradual, depletion were likely recorded in Earth's Hadean mantle. Moreover, while the degree of source depletion suggested by the mafic-ultramafic Archean rocks is similar to the present-day mantle source of mid-ocean ridge basalts, as reflected by the comparable ^{147}Sm/^{144}Nd source ratio, the Hadean depleted reservoirs recorded by the felsic TTGs appear to be more depleted (i.e., higher Sm/Nd). Possible processes generating these depletion events

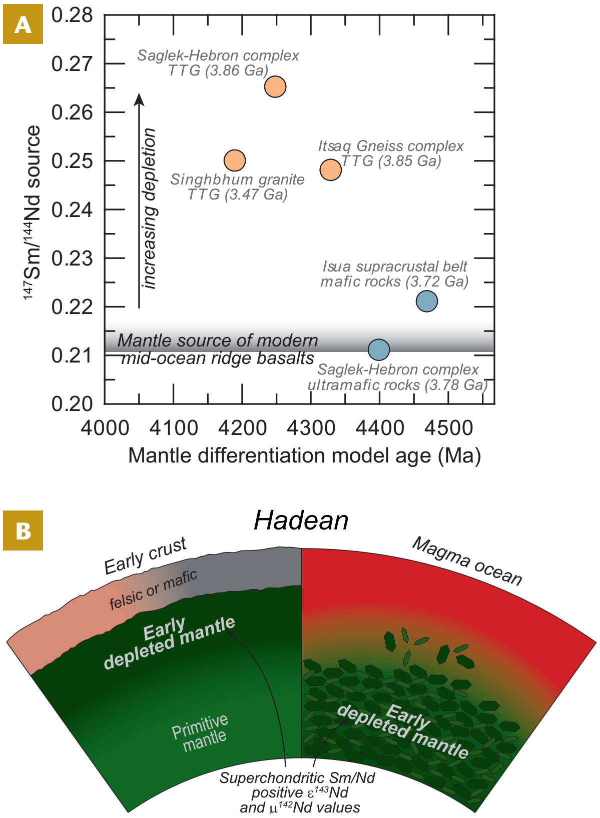

Figure 5 (**A**) ^{147}Sm/^{144}Nd ratios versus differentiation age for sources of Paleoarchean to Eoarchean suites of rocks for which initial ε^{143}Nd and μ^{142}Nd data are available, and for rocks that have been interpreted as not significantly affected by post-magmatic processes. Mantle differentiation ages and ^{147}Sm/^{144}Nd of the sources are calculated from coupled ^{143}Nd-^{142}Nd isotopic compositions. Data for mafic and ultramafic rocks include suites of samples. TTG data are individual samples. All samples yield positive μ^{142}Nd, indicative of a Hadean depleted source. The variation in source ^{147}Sm/^{144}Nd and ages spanning most of the Hadean suggests that no single event, but rather a combination of several or more-or-less continuous events, is responsible for the early depletion of the mantle. Ages in brackets are the rock crystallization ages. Data sources are given in the online supplements, including the composition used to calculate ^{147}Sm/^{144}Nd for the mantle source of mid-ocean ridge basalts. (**B**) Cartoon illustrating possible mechanisms responsible for the Hadean depletion of the mantle, such as episodic or progressive extraction of Earth's earliest crust (regardless of its composition) or the formation of depleted mantle domains following magma ocean solidification.

include episodic early crust extraction and/or solidification of Earth's magma ocean(s) producing depleted mantle domains (Fig. 5).

Excesses in ^{142}Nd have been observed in rocks from only a limited number of terranes, suggesting either poor preservation of such terranes, that early mantle depletion may not have occurred on a global scale, or that the database remains limited. If this early depletion was the result, at least in part, of the extraction of Earth's first crust, then the volume of early crust may have been either small or eradicated by the efficient recycling of such crust back into the mantle. Abundant ancient basaltic crust characterized by incompatible element enrichment is, however, likely required as a source for the formation of the voluminous TTG found in ancient terranes—so the record of positive (depleted mantle-like) and negative (enriched ancient mafic crust) ^{142}Nd signals may both reflect crust–mantle differentiation. Finally, evidence from ^{142}Nd for an early depleted mantle is subdued in rocks younger than 3.4 Ga (e.g., Bennett et al. 2007), perhaps due to the recycling of the incompatible element–enriched crust and mixing with its complementary depleted components in the mantle.

CONCLUDING REMARKS

Recent advances using the newest geochemical and isotopic tools provide insight into the geological ancestry of Archean cratons to better understand Earth's earliest crust and mantle. Although the crystalline and sedimentary records may depict different views of the nature of the dominant crustal progenitor of Archean cratons, crust–mantle differentiation, at least to some extent, clearly occurred in the Hadean. Contrary to the etymology of the word Hadean, crust existed on Earth before 4 Ga, and the rare remnants of surviving ancient crust are now beginning to yield information on the nature of Earth's earliest crust.

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At the Dawn of Continents: Archean Tonalite-Trondhjemite-Granodiorite Suites

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and Jean-François Moyen[2]

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Outcrop of the Goudplaats-Hout River grey gneiss suite (northern Kaapvaal craton, South Africa) comprising several units of 3.43 to 2.85 Gy-old TTGs.

Archean rocks of the tonalite-trondhjemite-granodiorite (TTG) suite are dominant constituents of Earth's earliest preserved silicic crust, while conversely rare in Phanerozoic continental crust. **Their formation represents the first critical step towards the construction and preservation of continents. Formation of most TTG magmas involved partial melting of hydrous, probably silicified, mafic rocks at various depths (20–50 km, possibly up to 100 km). Many possible tectonic scenarios fit the petrological and geochemical constraints on TTG formation, whether compatible with a global plate tectonic-like regime or not. Refining such scenarios is a major challenge that requires systematically integrating the constraints on TTG formation—relying especially on accessory minerals as key petrogenetic tools—with the geological context on a regional scale.**

Keywords: tonalite-trondhjemite-granodiorite suite; continental crust; grey gneisses; accessory minerals; Archean geodynamics

INTRODUCTION

The Earth is unique in the Solar System by the abundance of its silica-rich continental crust and the crucial role this crust has played in the physical, chemical, and biological evolution of our planet. Present-day continents consist of a patchwork of individual domains that show a range of crust formation ages from the Hadean or Eoarchean (4.4–3.6 billion years ago [Ga]) to the present day. Archean cratons generally contain remnants of the oldest continental nuclei, around which younger lithosphere has progressively aggregated and been preserved over time. Exposed crustal parts of these oldest nuclei are dominated by a *suite* of igneous silicic rocks that is archetypal of Archean cratons: the tonalite-trondhjemite-granodiorite (TTG) suite (Jahn et al. 1981). The construction of these TTG-dominated domains can therefore be regarded as the first critical step towards the preservation of significant volumes of continental lithosphere and, hence, the birth of cratons and continents.

The geological processes and tectonic settings in which TTG-dominated crust formed are fundamental to understanding continental crust evolution over time, the early Earth environment, and, therefore, how life arose on our planet. For these reasons, understanding the origin of TTGs has been an active research field over the past 50 years. In this contribution, we review the recent advances and persisting debates in TTG research, notably regarding their geological significance, magma-forming mechanisms, and general implications for crustal evolution and tectonic settings on the early Earth.

WHAT ARE TTGS?

Tonalite, trondhjemite, and granodiorite are quartz-rich igneous plutonic rocks in which plagioclase is more abundant than K-feldspar. The TTG suite hence includes rocks whose typical mineral assemblage consists of sodic plagioclase, quartz, and biotite, with minor to absent K-feldspar and amphibole, and accessory minerals (zircon, apatite, titanite, allanite/epidote, monazite, Fe-Ti oxides). However, Archean rocks fulfilling the mineralogical definition of TTGs do not all have the same geological significance. Some TTGs form intrusive igneous bodies ranging from small dykes to large zoned plutons, emplaced at shallow paleo-depths in the crust (within the first 10 km), some of which may be genetically linked with contemporaneous volcanic eruptions (e.g., Laurent et al. 2020; Fig. 1A). Other TTGs may represent mid-crustal (10 to 20 km depth) plutonic complexes (Kendrick et al. 2022; Fig. 1B) or magmas crystallized at or near their production site, comparable to "in-source" leucosomes in migmatites (Halla 2020; Pourteau et al. 2020; Fig. 1C).

The mineralogical assemblage of TTGs is stable over a wide range of crustal pressures and temperatures, such that the term also includes orthogneisses that have experienced metamorphism up to amphibolite-facies conditions. Therefore, due to their long geological history often characterized by several tectonic and thermal events, TTGs may crop out as components of heterogeneous, deformed, and metamorphosed "grey gneisses" (Moyen 2011). In this case, rocks that are not necessarily coeval or co-genetic may coexist on a small scale. For example, the outcrop in Figure 1D shows five distinctive igneous units, three of which are of TTG composition, emplaced over a time period exceeding 600 million years. Here, "TTG" should not be misused as a synonym for "grey gneiss" and, at best, represents a shortcut for "*part of a heterogeneous rock unit of TTG composition.*"

The plagioclase-rich and K-feldspar-poor nature of TTGs (Fig. 2A) imparts a distinctive geochemical signature characterized by a sodic character (Na_2O > 4 wt.% and K_2O < 2 wt.%; hence, K/Na ratios < 0.6) at high silica concentrations (>64 wt.% SiO_2) (Moyen and Martin 2012). TTGs

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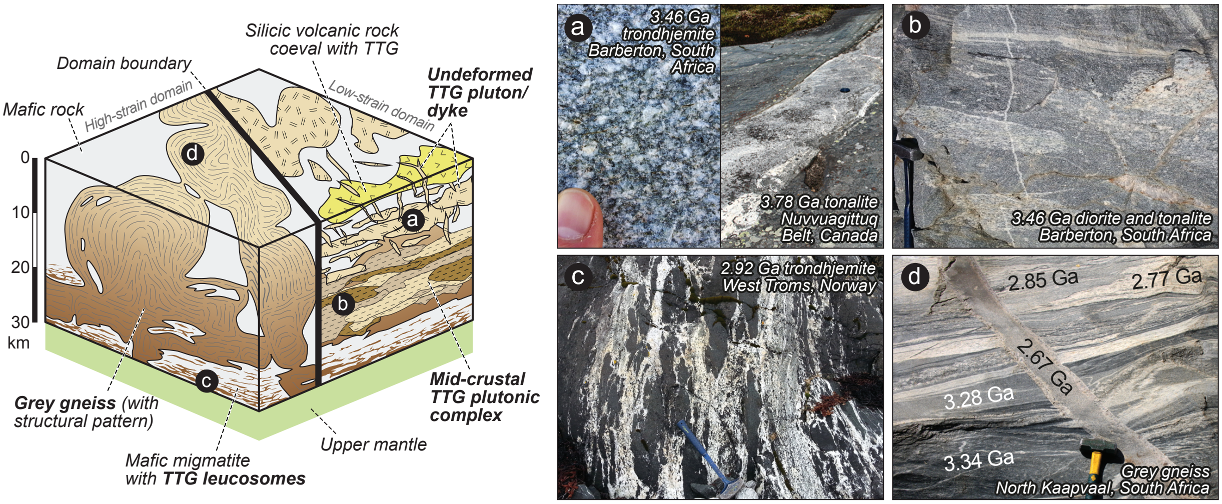

FIGURE 1 Sketch block diagram of Archean crust depicting the main structural settings in which TTG rocks can be found, with field examples.

also show moderately to highly fractionated rare earth element (REE) patterns (La/Yb > 15) with weak to no Eu anomalies, and elevated Sr/Y ratios (>15). Importantly, some geochemical variability exists within TTGs (FIG. 2B, 2C), which allows definition of several sub-groups from low-HREE-Y, high-Sr to high-HREE-Y, low-Sr end-members (Moyen 2011). The geochemical characteristics of TTGs distinguish them from granitoids formed in most post-Archean geodynamic settings (FIG. 2A, 2B). Although sodic tonalites and trondhjemites do form on the modern Earth, mainly in intra-oceanic environments (mid-ocean ridges, oceanic arcs), they constitute a negligible fraction of the preserved Phanerozoic continental crust. In contrast, TTGs dominate the Archean felsic crust. These observations point to specific distinctions between continental crust formation and preservation on the early and the modern Earth.

RECIPES FOR TTG MAGMAS

The Ingredients—Mafic Rocks from Undepleted Mantle

Experimental petrologists have long demonstrated that sodic silicate liquids of TTG affinity can be produced by 20%–30% (volume) melting of basaltic rocks, leaving an amphibolite or eclogite residue depending on pressure (review in Moyen and Martin 2012). Other studies have argued that fractional crystallization of basaltic melts would also produce TTG liquids (e.g., Smithies et al. 2019). Although this hypothesis is difficult to reconcile with the requirement that the source of TTG suites has undergone surficial alteration (see below), it is an alternative to generating at least some TTGs.

Regardless, the alkali (Na, K) and other lithophile and highly incompatible element (Rb, Ba, Th, U) contents of TTGs indicate that their mafic parental material must have been richer in these elements than the most common basalts on the modern Earth, i.e., mid-ocean ridge basalts (MORB) (e.g., Martin et al. 2014). This could indicate that the mantle source of Archean basalts was less depleted in these elements than the modern asthenosphere from which MORB are generated (Bédard 2018; Moyen and Laurent 2018), and/or slightly enriched in lithophile and incompatible elements by recycling pre-existing crustal material into depleted mantle (Smithies et al. 2019, 2021).

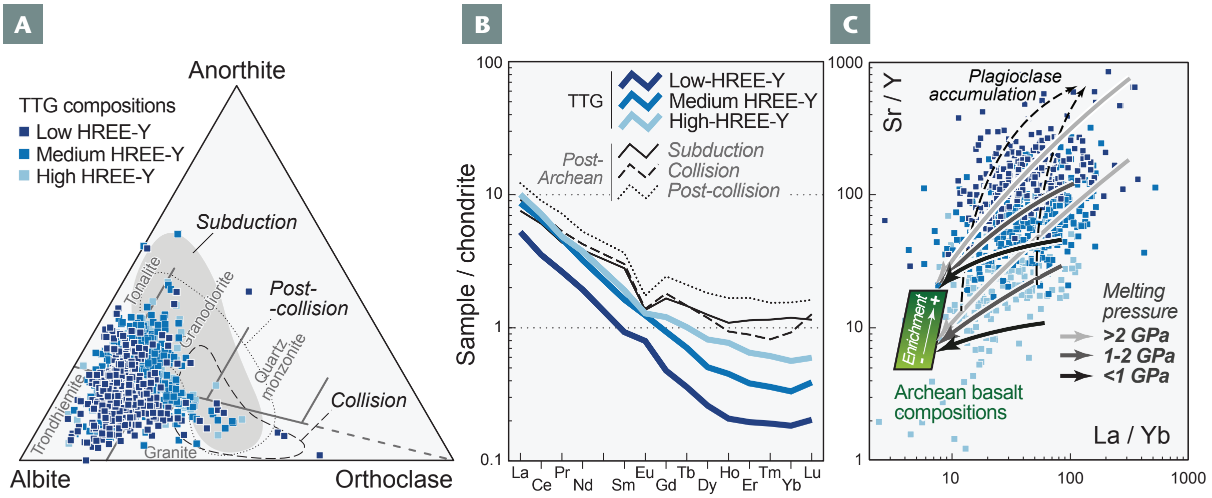

FIGURE 2 Mineralogical and geochemical characteristics of Archean TTGs, subdivided in three groups based on their HREE-Y (± Na, Sr, Eu) contents (Moyen 2011), compared to post-Archean granitoids. DATA FROM BONIN ET AL. (2020). (**A**) Normative ternary feldspar diagram; (**B**) chondrite-normalized REE diagram; and (**C**) Sr/Y versus La/Yb plot (values not normalized to chondrite). As depicted in (**C**), this geochemical diversity results from a combination of variables: source compositions (green box), different melting depths (arrows show the evolution of melts produced at different pressures from low to high melt fractions, after Moyen 2011), and plagioclase accumulation and/or amphibole fractionation (Kendrick et al. 2022).

The Seasoning—Water and Ocean-derived Silica

Water plays an essential role in the production of most silicic magmas. The high abundance of TTGs in Archean cratons, therefore, requires partial melting of hydrous, likely amphibole-rich, mafic source rocks. The actual origin(s) of the water is still debated, but Archean mafic rocks commonly show evidence of eruption under water, implying that seafloor-related alteration could account for the hydration of TTG sources. In support of this hypothesis, TTGs exhibit Si isotopic compositions compatible with silicification of their mafic source by seawater-derived silica during seafloor alteration (André et al. 2019; Deng et al. 2019). Some authors have further proposed that the mantle-like oxygen isotopic compositions of TTG-hosted zircon ($\delta^{18}O$ of +5‰ to +6.5‰) reflect reworking of a mafic parent that did not interact with the surface and already contained enough water to melt, due to its derivation from a non-depleted, volatile-rich mantle (Smithies et al. 2021). However, this interpretation overlooks isotope fractionation between zircon and its parental melt, which can vary significantly and may imply a higher $\delta^{18}O$ in TTG magmas (above +7‰; Lei et al. 2023) for the same $\delta^{18}O$ measured in zircon. This, in turn, would be consistent with surface hydration of the TTG mafic source before melting.

The Cooking Conditions—Pressure and Temperature of Partial Melting

Results from experimental petrology have shown that melts of TTG composition can be produced by melting mafic rocks at temperatures of 750 to 950 °C and pressures from 0.5 to 4 gigapascals (GPa) (review in Moyen and Martin 2012), corresponding to a wide depth range of about 20 to 150 km. Refining this depth range relies on the identification of trace element characteristics of natural TTG rocks that reflect the stability of pressure-sensitive minerals in the melting residue. Martin (1986) was among the first to demonstrate that the low HREE-Y and high Sr-Eu contents in TTGs (Fig. 2B, 2C) were diagnostic of an amphibole- and/or garnet-bearing, plagioclase-poor melting residue, as garnet and amphibole scavenge Y and HREE, whereas plagioclase preferentially incorporates Sr and Eu. In fact, the continuous compositional spectrum of TTGs in terms of HREE-Y and Sr-Eu contents (Fig. 2B, 2C) could be explained by variable proportions of garnet and plagioclase in the residue, indicating melting at a range of possible pressures (e.g., Moyen 2011) from 2.0–2.5 GPa for the lowest Y-HREE, highest Sr-Eu TTGs down to 0.5–1.0 GPa for the highest Y-HREE, lowest Sr-Eu TTGs (Fig. 2C).

However, the melting pressure required to produce a given TTG composition also depends on the source composition, which influences the trace element signature of the resulting melt. A TTG magma with a given set of Sr/Y and La/Yb ratios, for instance, could result from melting either an enriched mafic source (high Sr/Y and La/Yb) at pressures <1.5 GPa or a less-enriched (lower Sr/Y and La/Yb) source at higher pressures (>2.0 GPa) (Fig. 2C). In fact, phase equilibria calculations using undepleted to enriched Archean basalts as the source of TTG magmas, instead of modern basalts (e.g., MORB) as has commonly been considered, show that the TTG compositional spectrum could form through melting within a more restricted pressure range than previously thought, i.e., 0.7 to 1.8 GPa (Palin et al. 2016; Johnson et al. 2017). Additionally, water-fluxed melting would generate apparent "high-pressure" signatures at 1 GPa or even less (Pourteau et al. 2020), as high H_2O activity has effects comparable to those of pressure on melting residues (i.e., promoting amphibole and garnet stability and suppressing plagioclase crystallization).

Lastly, the observed range of TTG trace element compositions does not necessarily reflect only source compositions and the nature of residual mineral assemblages, but also derives to some extent from differentiation processes during magma transfer and crystallization. This includes fractional crystallization (Liou and Guo 2019; Smithies et al. 2019) and its consequences, such as crystal accumulation and concomitant loss of interstitial melt (Laurent et al. 2020; Kendrick et al. 2022). Amphibole fractionation and/or plagioclase accumulation hence could account for the composition of TTGs with the highest Sr/Y and La/Yb ratios (Fig. 2C). In such a case, primary melts would be represented by TTGs with intermediate to low Sr/Y and La/Yb ratios (Fig. 2C), entailing again a more restricted melting pressure range (0.5–1.5 GPa) than previously thought (Laurent et al. 2020). Alternatively, TTG parental melts could be represented by mafic magmas derived from melting of enriched mantle, i.e., already showing high Sr/Y and La/Yb ratios (Smithies et al. 2019).

In summary, most TTG magmas were formed through partial melting of hydrous, probably silicified, mafic rocks at temperatures between 750 and 950 °C and a range of possible melting depths spanning from 20 to >100 km. However, recent studies have emphasized that source composition, presence of water during melting, and magma differentiation processes all critically influence element abundances and ratios that were previously interpreted as melting pressure indicators. Based on these recent findings, a more restricted melting depth range of 20–50 km would also account for the geochemical diversity of TTGs.

ACCESSORY MINERALS IN TTGS: TINY CRYSTALS WITH LARGE IMPLICATIONS

Zircon Age and Hf Isotopic Records of TTG Crust Evolution

Zircon is a popular "time capsule" used to understand the evolution of Archean crust because it is highly robust and can preserve geochemical information about its parental magma through multiple metamorphic events and/or sedimentary cycles. In detail, zircon can provide reliable U-Pb crystallization ages for TTGs and information about their source(s) through Hf isotopes expressed as $\varepsilon Hf(t)$ (see *Toolkit*). Because most TTG magmas cannot be directly extracted from the mantle, their $\varepsilon Hf(t)$ signatures are generally interpreted in terms of crustal residence time of their mafic source and/or mixing between crustal and mantle sources. A compilation of Hf isotopic compositions of TTGs worldwide (i.e., excluding more granitic and mafic compositions) and their zircons shows that about 80% of the data are roughly centered on the chondritic value ($\varepsilon Hf(t)$ between −2 and +4; Fig. 3A). This indicates that the mafic precursor of TTGs was extracted from chondritic to mildly depleted mantle sources and re-melted to produce TTG magmas <100 My thereafter (Guitreau et al. 2012; Kemp et al. 2023).

However, a non-negligible amount of >3.2-Gy-old TTGs shows negative $\varepsilon Hf(t)$, pointing to the contribution of a relatively old crustal source (Fig. 3A). This is also true for detrital zircons of that age (Fig. 3), many of which probably derived from erosion of TTG-like crust (e.g., Laurent et al. 2022). When Hf isotopic data are examined on a local, as opposed to global, scale it appears that such >3.2-Gy-old TTG-hosted and detrital zircons from various cratons (e.g., Frost et al. 2017; Guitreau et al. 2019; Bauer et al. 2020; Kirkland et al. 2021; Mulder et al. 2021; Drabon et al. 2022) define an evolutionary trend characterized by a steady decrease of $\varepsilon Hf(t)$ to negative values, followed by an abrupt $\varepsilon Hf(t)$ increase to near-zero or positive values

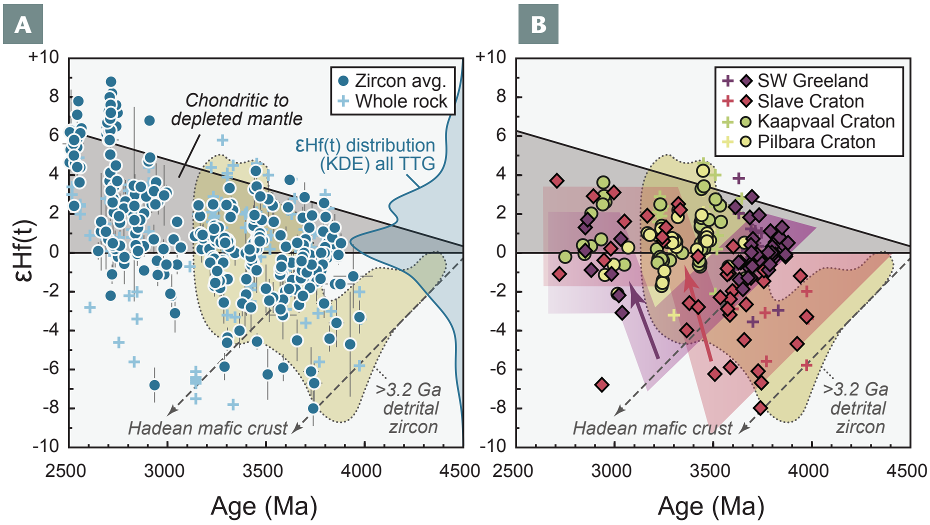

FIGURE 3 (**A**) Compilation of εHf(t) versus age data for Archean TTGs worldwide (data and references are available as online supplementary material); circles correspond to averages (*± 1 standard deviation)* of zircon analyses from single samples (average Hf isotopic composition of cogenetic zircon crystals, analyzed mainly by laser ablation, or solution MC-ICP-MS), crosses are bulk-rock values (Guitreau et al. 2012), all calculated at the respective rock crystallization age given by zircon U-Pb dating. The blue curve is the kernel density estimate (KDE) of the whole εHf(t) dataset; >3.2 Ga detrital zircon field is after Drabon et al. (2022). (**B**) Same plot containing data from selected cratons; colored fields and bold arrows correspond to the εHf(t)–time evolutions proposed for the Slave craton and SW Greenland by Bauer et al. (2020) and Kirkland et al. (2021), respectively.

(FIG. 3B). This observation has been tied to a transition in crust-forming mechanisms from closed-system reworking of mafic crust over hundreds of millions of years followed by rapid reworking of recently emplaced mafic material (Bauer et al. 2020; Kirkland et al. 2021) and formation of a complementary thick, buoyant depleted mantle, enabling craton stabilization (Guitreau et al. 2012; Mulder et al. 2021).

The transition visible in the εHf(t)–age trends has been attributed to global changes from so-called stagnant-lid to mobile-lid tectonics (Bauer et al. 2020; Kirkland et al. 2021; Mulder et al. 2021). However, the variable transition timing (e.g., 3.8–3.6 Ga in the Slave craton and 3.2–3.0 Ga in SW Greenland; FIG. 3B) most likely points to craton-specific evolution histories rather than synchronous events at a planetary scale. In support of this, note that the zircon εHf(t)–age trends observed in some cratons are missing from others (e.g., Pilbara and Kaapvaal; Kemp et al. 2023) (FIG. 3B). It is therefore emphasized that the global εHf(t) range can be explained by local variations in the composition, crustal residence time, and reworking histories of the mafic precursors of TTGs.

Unravelling the Complex History of TTGs using Multiple Accessory Minerals

Depending on the timing of their crystallization, different accessory minerals may provide "snapshots" of distinct magma and/or metamorphic evolution stages. For instance, TTG-hosted zircon can show homogeneous trace element compositions regardless of the geochemical diversity of the host rocks (from high-HREE-Y- to low-HREE-Y TTGs) and very low Ti contents, interpreted to record crystallization mainly from compositionally uniform (near-eutectic) melts formed within the last 100 °C of the TTG crystallization history (Laurent et al. 2022). In contrast, apatite compositions of some TTGs are in line with those of their host rocks: apatite from high-HREE-Y, low-Sr TTGs exhibit higher Y and lower Sr contents than those from low-HREE-Y, high-Sr TTGs (Bruand et al. 2020). This suggests that apatite compositions allow to discriminate between TTG types and possibly reflect distinct melt production mechanisms in the source.

Several studies of metamorphosed Eoarchean TTG gneisses have further shown that micro-analysis of accessory minerals has the potential to identify whether metamorphic events resulted in changes of whole-rock chemical and isotopic signatures. For example, apatite, titanite, and allanite from Eoarchean TTG gneisses document metamorphic re-equilibration of the Sm-Nd isotopic system at the sample scale, such that whole-rock Nd isotopic compositions no longer reflect those of the initial magma sources (Hammerli et al. 2019). In other cases, accessory minerals preserve information about the magma sources and their compositions, even in highly metamorphosed TTGs. For example, apatite inclusions encapsulated in zircon have been shown to partially or completely preserve U-Pb ages and chemical compositions of the parent magma, whereas matrix apatite was re-equilibrated at the age of the metamorphic event (Antoine et al. 2020; FIG. 4).

One important potential future outcome of studies on multiple accessory minerals will be a better understanding of the geochemical signatures of TTGs. In particular, this will allow focusing exclusively on observations pertaining to magma sources and petrogenesis, in contrast to using only whole-rock compositions, which represent the integrated, end-product of a complex array of magmatic and potentially metamorphic processes.

POSSIBLE GEODYNAMIC IMPLICATIONS OF TTG FORMATION

For the purpose of this discussion, it is important to distinguish (1) the *conditions* (temperature, depth) *of TTG magma generation*; (2) the *local tectonic site* through which the hydrated mafic source was transported to these conditions; and (3) the *global-scale geodynamic setting* that comprises this tectonic site, among others (e.g., in the case of modern plate tectonics, convergent margins coexist with mid-ocean ridges, hotspots, etc.). Critically, petrological and geochemical data on TTGs and their accessory minerals constrain the *conditions of magma generation* only, namely, temperatures of 750–950 °C and a range of possible melting depths. This range may either span from ca. 20 to >100 km or, as mentioned above, be more restricted (20–50 km), depending on the composition of the source, the presence or absence of water during melting, and the role played by magma differentiation processes.

FIGURE 5 shows a variety of tectonic sites that may satisfy these two end-members in terms of melting depth ranges, classified based on their likelihood to be found in a global geodynamic setting resembling modern plate tectonics. Melting of mafic crust along anomalously hot subduction zones (e.g., Martin 1986), characterized by continuous steep to flat-lying slabs (FIG. 5A, 5B), could take place in a plate tectonic environment. However, the relevant melting depth ranges can also be reached in situations still resembling convergent plate margins, yet characterized by processes

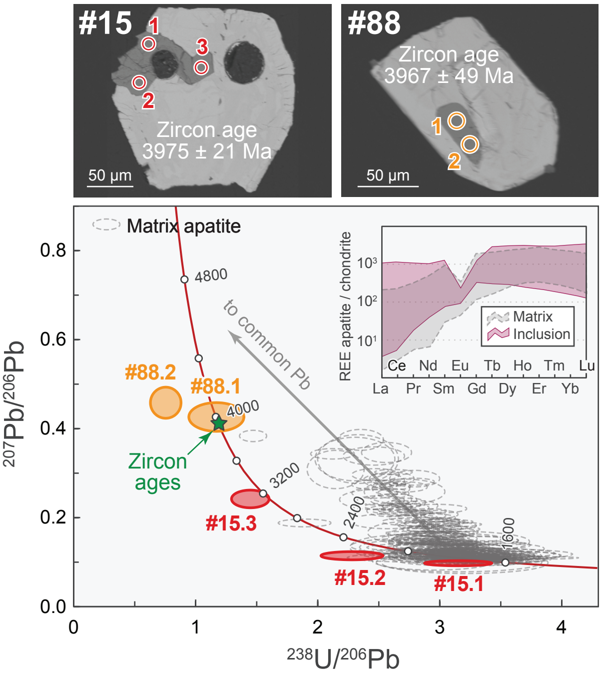

Figure 4 Zircon-hosted apatite inclusions as tools to distinguish primary from secondary information in metamorphosed TTGs. Modified from Antoine et al. (2020). The backscattered electron images show apatite (dark gray) inclusions in ca. 3.97 Ga zircons (light gray) from a TTG sample of the Acasta Gneiss complex in Canada. Circles represent micro-analytical (laser ablation ICP-MS) spots, with corresponding U-Pb data reported in a Tera-Wasserburg plot (see *Toolkit*). While fully included apatite (#88) has recorded U-Pb dates comparable to those of the host zircon, apatite partly connected to the matrix (#15) does not. Instead, it records dates near those of matrix apatite, which reflect regional metamorphism at ca. 1.72 Ga. Despite U-Pb resetting, the latter largely preserved magmatic REE compositions, as they overlap with those of apatite inclusions (inset plot).

unlike modern subduction, such as intermittent dripping of the lower plate (“dripduction”; e.g., Moyen and Laurent 2018; Fig. 5C) and under-thrusting of mafic slices at the leading edge of a drifting lithospheric block (“subcretion”; e.g., Bédard 2018; Fig. 5D). Finally, melting in an essentially “intraplate” environment is also possible, notably at the base of mafic plateaus and/or from rafts of lower crust “dripping” into the underlying mantle (e.g., Johnson et al. 2017; Smithies et al. 2019; Fig. 5E, 5F). These scenarios are unlikely to be found in a global plate tectonic environment, as shown by the paucity of silicic magmas produced in modern intraplate settings like oceanic plateaus.

It is stressed that all sketches presented in Figure 5 are only possible snapshots of transient and/or local tectonic processes that occurred within broader-scale geodynamic environments. Therefore, these scenarios are not mutually exclusive and could have either happened simultaneously, or successively in time, on both local and global scales. This is well illustrated by zircon Hf isotopes versus time systematics in TTGs, pointing to diachronous crust formation and evolution from one craton to another (see Fig. 3). For these reasons, to address the problem of early Earth geodynamics, it appears necessary to investigate the evolution of crust-forming processes on a local or regional scale (i.e., craton, or terrane within a craton) and draw comparisons between them. In general, a more robust understanding of Archean geodynamics would certainly arise from a more systematic integration of information about TTG petrogenesis (field observations; petrological and geochemical data, including geochronology and trace element/isotopic data on accessory minerals; thermodynamic modeling) with the regional geological context and independent constraints (e.g., data from other granitoid types, structural and metamorphic records of greenstone belts, thermo-mechanical modeling, study of cratonic mantle xenoliths, etc.).

CONCLUSIONS AND OUTLOOK

Rocks of the TTG suite represent the dominant, oldest preserved crustal lithology of Archean cratons. The term “TTG” applies to rocks that do not all have the same significance, including shallow intrusions, heterogeneous plutonic to migmatitic complexes, and deformed and metamorphosed “grey gneisses.” Considering these contextual differences and filtering out the effects of syn- to post-magmatic processes specific to each rock assemblage are critical tasks to retrieve the geochemical signals corresponding to magma-forming conditions and address the geodynamic significance of TTGs. Data from TTG accessory minerals hold promise of being highly relevant to address this issue (Fig. 4).

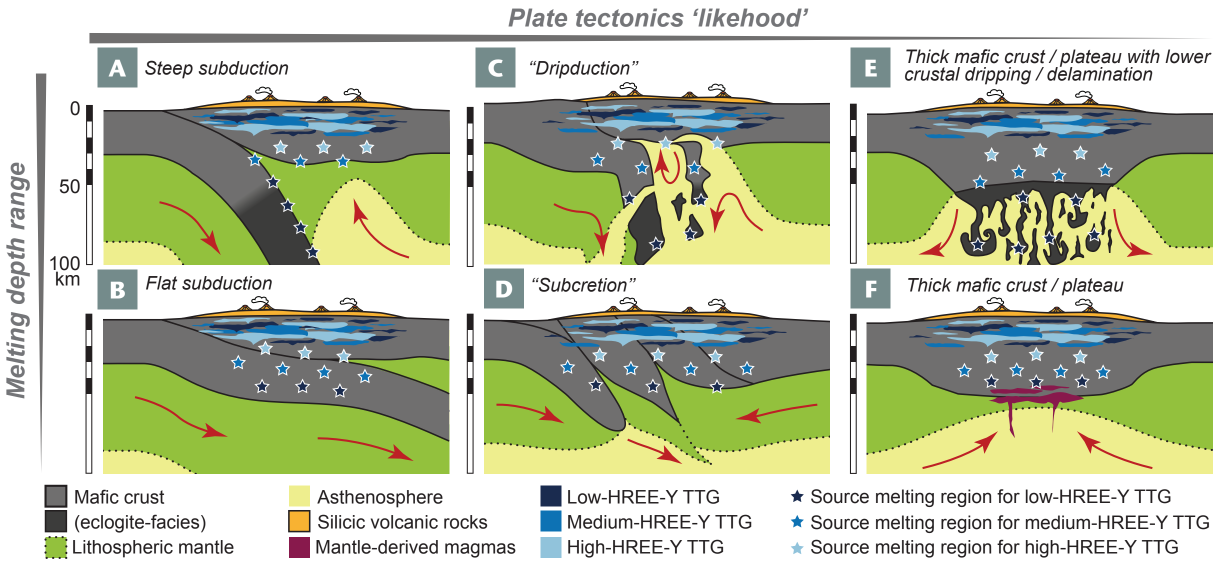

Figure 5 Possible tectonic sites for forming TTG magmas. The two rows of images correspond to the two end-member ranges of melting depths, from large (20–100 km; top) to restricted (20–50 km; bottom), as constrained by the petrological and geochemical data on TTGs and their minerals. The three columns of images depict the likelihood to find these sites in a global geodynamic environment similar to modern plate tectonics, from high (left) to intermediate (middle) and low (right).

The formation of TTG magmas requires two essential steps: (1) formation of a hydrous basaltic source and (2) transport of the source to depth to reach the pressure and temperature conditions required for partial melting: ca. 750–950 °C and a range of possible melting depths (from 20–50 km to 20–100 km) depending on source composition, water content, and subsequent magma differentiation processes. However, the mechanisms by which water was brought to the melting site (burial of mafic rocks hydrated at the surface or primordial water contained in mafic magmas from undepleted mantle) are still debated. Likewise, a variety of tectonic configurations may account for the melting conditions in which TTG magmas formed, involving or not a global plate tectonic regime.

Individual blocks of Archean crust, including distinct terranes from a given craton, have their own particular history of mafic and TTG crust formation, amalgamation, and reworking, that may last tens to hundreds of millions of years. These crustal evolution histories should be investigated through a systematic linkage between petrological and geochemical constraints on TTG magma formation, data from accessory minerals (e.g., zircon Hf isotopes; monazite/titanite/apatite Nd isotopes; and newly developed tools such as Si and triple O isotopes in zircon, S speciation in apatite, etc.), and local geological contexts.

Closing the knowledge gaps summarized above is an exciting challenge for future research, as this will enlighten our understanding of how Archean cratons and continents in general formed and became preserved. This understanding is fundamental to solve the enduring mystery of the emergence of life on Earth.

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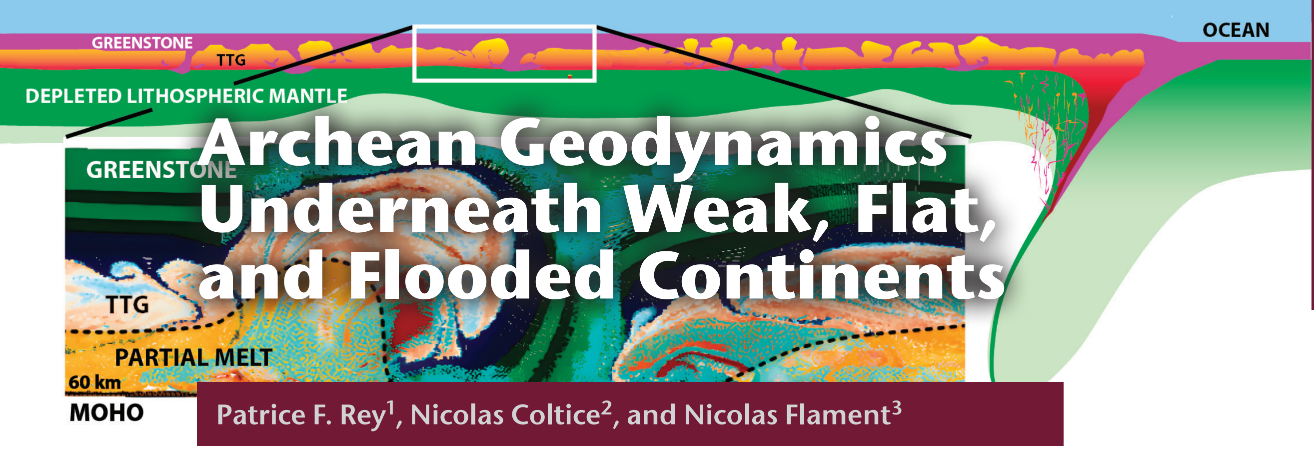

During the Archean dual-mode geodynamics, gravitationally unstable greenstone belts drove intracrustal tectonics, whereas spreading protocontinents forced the subduction of adjacent lithospheres.

Archean Geodynamics Underneath Weak, Flat, and Flooded Continents

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Although a significant volume of crust was extracted from the mantle early in Earth's history, the contribution of felsic rocks to the sedimentary record was minimal until ~3.0 Ga. On a hotter Earth, this conundrum dissipates if we consider that the felsic crust was buried under thick basaltic covers, continents were flooded by a near-global ocean, and the crust was too weak to sustain high mountains, making it largely unavailable to erosion. Gravitational forces destabilized basaltic covers within these weak, flat, and flooded continents, driving intra-crustal tectonics and forcing episodic subduction at the edges of continents. Through secular cooling, this dual-mode geodynamics progressively transitioned to plate tectonics.

KEYWORDS: Archean continents; geological record; geodynamics

INTRODUCTION

Continents exist for hundreds of millions of years and hold the memory of past tectonic and geodynamic processes. The continental crust itself is often presented as the cumulative outcome of plate tectonics because modern crust is typically created, reworked, and recycled at subduction zones. Some proxies for mantle depletion indicate that 50% to 75% of the continental crust had formed by 3.0 Ga (Campbell et al. 2003), which is consistent with the geologic evidence of the existence of pre-3.0 Ga felsic crust. Although this record extends back to 4.0 Ga (Bowring et al. 1989), other proxies indicate that recycling of the oceanic crust only started at 3.8–3.6 Ga (e.g., Kemp et al. 2010; Bauer et al. 2020). How much of the early crust was the product of plate tectonics is therefore uncertain. To advance this debate, we address here two important paradoxes. The first paradox stems from the surprisingly tenuous contribution early felsic sources had to the pre-2.5 Ga sedimentary record (Taylor and McLennan 1995). The second paradox arises because the recycling of oceanic crust left little trace in proxies sensitive to the recycling of sedimentary and weathered rocks until ~2.5 Ga (Valley et al. 2015).

To address the first paradox, we review crustal growth and corresponding mantle depletion, and present a model to explain the late appearance of felsic crust in the sedimentary record. To address the second paradox, we discuss key attributes of Archean (4.0 to 2.5 Ga) crust in the light of numerical experiments. These point to a dual-mode of geodynamics in the Archean. One tectonic mode involved episodic sinking of basalt covers into and through the felsic crust, a process called sagduction (Mareschal and West 1980), that could explain the second paradox. The other tectonic mode involved the gravitational spreading of weak continents, thereby forcing episodic subduction at their margins. While the first mode progressively disappeared because of the secular cooling of the Earth, the second mode evolved into modern plate tectonics.

PRODUCTION AND EVOLUTION OF THE CONTINENTAL CRUST

Crustal Perspective on Continental Growth

Fine-grained sediments provide global estimates of the average composition of Earth's emerged surface. The composition of Archean fine-grained sedimentary rocks suggests that the emerged crust was dominated by mafic-ultramafic rocks during most of the Archean and transitioned to more felsic compositions no earlier than ~3.0 Ga (Taylor and McLennan 1995). This is supported by the $^{87}Sr/^{86}Sr$ of marine carbonates, which identifies fluxes of weathered felsic crust into the oceans. Marine carbonates show a departure at ~3.0 Ga from the mantle trend they inherited from basalts, towards a more radiogenic trend recording an increased contribution of felsic lithologies to continental runoff (e.g., Flament et al. 2013). This is consistent with the lack of prominent pulses of crust production before ~3.0 Ga (e.g., Condie et al. 2017) recorded by the distribution of ages in detrital zircon, an igneous mineral resistant to erosion and alteration that can be dated using the U-Pb chronometer. Overall, the sedimentary record suggests no significant volumes of felsic crust at the surface before ~3.0 Ga, despite the well-documented presence of pre-3.0 Ga felsic crust in most cratons. In what follows, we discuss what we know about the origin of old felsic crust.

The stable oxygen isotope ratio $^{18}O/^{16}O$, expressed as $\delta^{18}O$, and radiogenic hafnium isotope ratio $^{176}Hf/^{177}Hf$, expressed as εHf (see Toolkit), measured in zircon, are tracers of the source of the melt from which the zircon crystallized. Whereas $\delta^{18}O$ of mantle zircon ranges from 5.5‰ to 5.9‰ today, zircon from sources that interacted with water at low temperature (e.g., sediments and altered crust) have $\delta^{18}O$ values reaching 12‰. The $\delta^{18}O$ of old zircons shows a change from values that remained stable

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and ≤ 7.5‰ before 2.5 Ga, to increasingly higher values in the Proterozoic (2.5 Ga to 541 Ma) (see Toolkit). δ^{18}O values between 6.5‰ and 7.5‰ point to a steady-state contribution between surface and mantle material in the source of old zircons. Increasing δ^{18}O values above 7.5‰ after 2.5 Ga indicate a shift towards a growing contribution of supracrustal lithologies to the production of felsic crust (Valley et al. 2015). Basaltic crust derived directly from partial melting of the mantle inherits its εHf(t). Recurrent partial melting of this crust in a closed system leads to felsic rocks with younger zircons showing increasingly negative εHf(t) values. This trend is observed in the oldest known suite of zircons from the Jack Hills of the Yilgarn craton and from the Acasta gneiss of the Slave craton, i.e., it began well before 3.8 Ga (e.g., Kemp et al. 2010; Bauer et al. 2020). In contrast, the involvement of juvenile magmas (i.e., magmas derived from the mantle or remelting of a short-lived basaltic crust) leads to a shift towards higher εHf(t) values. Such a shift is well-documented and occurs at different times on different cratons, beginning between 3.8 and 3.6 Ga (e.g., Kemp et al. 2010; Bauer et al. 2020). The shift towards higher εHf(t) points to increasing recycling of juvenile basaltic crust, whereas the shift to higher δ^{18}O points to increasing recycling of surface-altered rocks from 2.5 Ga onwards. Although both shifts might be explained by subduction of altered oceanic crust, the difference in their timing requires an explanation. Because no δ^{18}O shift is observed at 3.8–3.6 Ga, it is difficult to invoke modern style subduction to explain the εHf(t) shift at that time.

Mantle Perspective on Continental Growth

Over geologic time, the extraction of the crust from the mantle must have resulted in a corresponding depletion of incompatible elements (see Toolkit) in the upper mantle, the region where partial melting occurs most often. For example, the Nb/U ratios of juvenile mafic rocks (e.g., mid-ocean ridge basalts) are characterized by a current value of 47. Assuming Earth's primitive mantle initially had a Nb/U of 30, the increase to an average of 47 must have resulted from partitioning of U into the continental crust (e.g., Hofmann et al. 1986). Basaltic rocks as old as 3.5 Ga have slightly lower Nb/U ratios (43) than those of modern oceanic basalts (47), suggesting ~75% of the crust was extracted from the mantle by 3.5 Ga (Campbell et al. 2003). Further back in time, the U-Pb and Hf isotopic compositions of magmatic zircon older than 3.8 Ga show limited signs of early mantle depletion (Fisher and Vervoort 2018). This is rather puzzling because the 4.4 Ga Jack Hills zircon (Wilde et al. 2001), the Acasta gneisses (4.03 to 3.94 Ga) in the Slave province (Bowring et al. 1989), and small ^{142}Nd/^{144}Nd excesses (see Toolkit) in 3.8 Ga mafic rocks of the Isua supracrustal belt (Greenland) suggest that continental crust extraction had begun by 4.3 Ga, before ^{146}Sm went extinct (see Toolkit; Boyet et al. 2003; O'Neil et al. 2024 this issue). This apparent paradox can be resolved if we consider that before 3.8 Ga, large mantle plumes and an intense bombardment of the surface by planetesimal impacts could have efficiently re-mixed the early crust back into the convecting mantle. A model that does not require the dramatic recycling of the early lithosphere (the outermost layer of the Earth above the convective mantle) was recently proposed by Guo and Korenaga (2023). They noted that the depleted mantle is unlikely to melt before being well mixed with the undepleted mantle, which they calculated could take ~700 million years. Hence, the signal of a depleted mantle after 3.8 Ga is not incompatible with crustal growth before 4.0 Ga. Nevertheless, if 50% to 75% of the crust was extracted by 3.5 Ga, one needs to explain why there is little discernible evidence for felsic sources in the pre-3.0 Ga sedimentary record.

RECONCILING THE CRUST AND MANTLE RECORDS: THE WEAK, FLAT, AND FLOODED CONTINENTS HYPOTHESIS

The increasing εHf(t) in zircon beginning at 3.8–3.6 Ga supports an enhanced contribution of basaltic crust to the production of felsic magmas (Laurent et al. 2024 this issue). To explain this shift, it is tempting to invoke the initiation of a plate tectonic regime involving subduction and melting of oceanic crust and sedimentary rocks (Fisher and Vervoort 2018; Bauer et al. 2020). However, this scenario is in apparent conflict not only with the lack of a corresponding δ^{18}O shift in zircon (i.e., the second paradox), but also with the secular evolution of Archean fine-grained sedimentary rocks, carbonates, and detrital zircon showing limited emergent felsic continental crust before ~3.0 Ga (i.e., the first paradox). To address the first paradox and reconcile early growth from 4.0 to 3.0 Ga with the quasi-absence of felsic sources in the sedimentary record, one needs to revisit the implicit assumption that the early felsic continental crust was above sea level, and therefore available to influence the composition of detrital sediments. In other words, we need to envision the isolation of the felsic reservoir from the surface until ~3.0 Ga.

This isolation is conceivable because the felsic crust was likely buried under thick layers of basalt (Arndt 1999). The ubiquitous presence of pillow lava in preserved ancient basalts suggests that many of these basaltic rocks were emplaced below sea level and onto flooded continents (Arndt 1999; Flament et al. 2008). On a hotter Earth, flooding can be explained by the reduced water storage capacity of a warmer mantle (Dong et al. 2021), and a shallower seafloor forcing oceans to overspill onto continents (Flament et al. 2008). Furthermore, as the strength of rocks is strongly temperature-dependent, the hotter continental lithosphere was much weaker and unable to sustain significant orogenic topography (Rey and Houseman 2006; Duclaux et al. 2007), making Archean landscapes flatter and with a lower freeboard (see Toolkit; Arndt 1999; Rey and Coltice 2008). Overall, no more than 3% to 4% of the Earth's surface (i.e., equivalent to the surface area of South America today) was above sea-level before the late Archean (Flament et al. 2008). The hypothesis of weak, flat, and flooded continents solves the first paradox by reconciling the early extraction of a significant volume of continental crust with its late appearance in the sedimentary record. Consequently, the measured shift in the geochemical signatures of detrital sedimentary rocks, detrital zircons, and carbonates does not trace crustal growth, but rather the exhumation of the felsic crust to the surface, its exposure to alteration and erosion, and ultimately its coupling to other geochemical reservoirs such as the atmosphere, oceans, biosphere, and mantle (Flament et al. 2013). To solve the second paradox, one needs a process that can explain the recycling of basaltic crust without leading to a significant increase in the δ^{18}O in crustal magmas.

ARCHEAN DUAL-MODE GEODYNAMICS: INTRA-CRUSTAL MASS REDISTRIBUTION, TRANSIENT SUBDUCTION, AND THE SECOND PARADOX

Petrology and Structure of Archean Cratons

The geologic record of Archean cratons is unique in many ways. Archean crust consists of an association of volcanic rocks with minor sedimentary rocks (greenstone belts), structurally in contact with underlying felsic rocks from the tonalite-trondhjemite-granodiorite (TTG) suite (Laurent et al. 2024 this issue). The structural architecture of the Archean crust is dominated by either TTG domes (up to 100 km in diameter) surrounded by narrow greenstone belts and/or prominent ductile strike-slip faults juxtaposing TTG gneiss and greenstone belts (e.g., Rey and Houseman 2006; Duclaux et al. 2007). The geochemistry of TTG suggests that many were formed by melting of hydrated mafic sources at pressures compatible with the stability of amphibole or garnet (Moyen and Martin 2012). Although earlier models of TTG formation invoked melting of subducting oceanic crust, melting of a hydrated mafic crust at 25 to 50 km depths is generally consistent with TTG geochemistry (e.g., Laurent et al. 2024 this issue). Greenstone belts are typically 5 to 25 km thick and accumulated over tens of millions of years. They are mostly composed of high-Mg rocks ranging from komatiites (MgO > 18%) to komatiitic basalts (12% < MgO < 18%) and abundant tholeiitic basalts (6% < MgO < 12%). Polybaric decompression melting of the mantle at depths ≤ 150 km can explain the volume of basalts in greenstone belts, the large dispersion of their FeO/MgO ratio, and the formation of the melt-depleted lithospheric mantle (Griffin et al. 2009), which forms the thick (~200 km) and buoyant roots of Archean cratons. Geochemical data from mantle xenoliths and seismic tomography suggest a stratification of the lithospheric mantle with, from top to bottom, strongly depleted, moderately depleted, and undepleted mantle (cf. Griffin et al. 2009; Rey et al. 2014 and reference therein).

Interpretations of the geology of cratons are debated. Greenstone belts are often presented as either ancient oceanic crust formed in back-arc basins above a subduction zone, and later accreted onto continents, or as stacks of lava flows formed via decompression melting in mantle plume heads. There are difficulties with both propositions. On one hand, it is curious that so many back-arc basins have survived erosion at convergent margins. On the other hand, the short duration of plume head volcanism, typically less than 5 million years, is hardly compatible with the duration of greenstone volcanism, which often extended over tens of millions of years. The interpretation of the crustal architecture is also strongly debated, and often reduced to an opposition between "horizontal tectonics," a misnomer for plate tectonics, and "vertical tectonics," a misnomer for diapirism. While some interpretations of TTG domes invoke polyphase contractional tectonics, or post-collisional extension, others invoke intra-crustal gravitational tectonics involving the sinking of greenstone belts into a hot and weak felsic crust, a process named sagduction (e.g., Mareschal and West 1980; Thébaud and Rey 2013). Similarly, prominent Archean strike-slip faults are interpreted either as accommodating the syn-collisional lateral escape of rigid blocks, or in terms of strain partitioning in a hot crustal environment under convergence (e.g., Duclaux et al. 2007).

Making Sense of the Geological Record

Numerical modeling can help explain first-order petrological and structural attributes of Archean cratons. The internal and boundary conditions of numerical experiments are informed by the thermal and mechanical properties of rocks and by first-order geological observations. Their temporal evolution is constrained by the physics of heat and mass transfer. Tracking the temperature and pressure evolution of particles makes it possible to consider processes such as partial melting and phase changes, and, thus, to integrate magmatic and geochemical observations with geodynamic and tectonic processes (e.g., Rey et al. 2014). Hence, modeling outputs can deliver physically

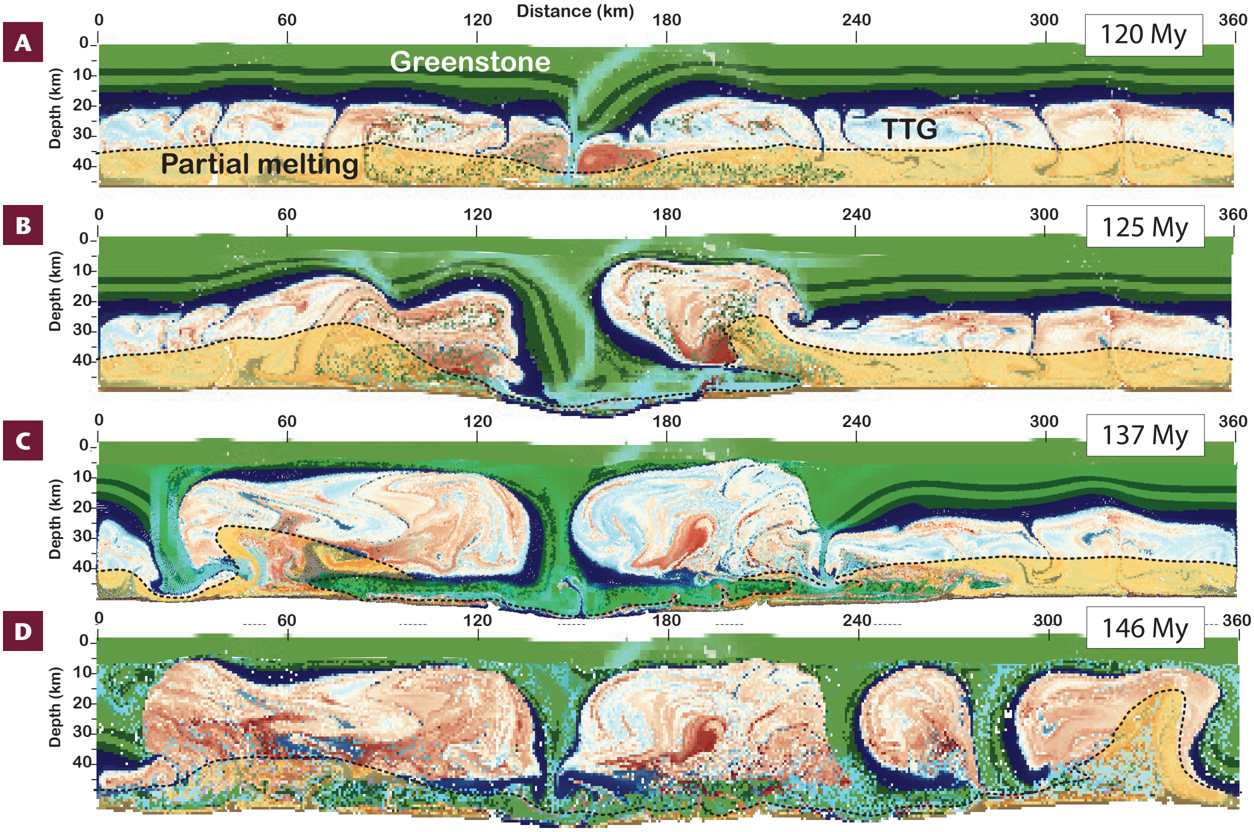

FIGURE 1 Accumulation of volcanic rocks (green to dark blue) leads to partial melting and TTG magmatism (A). The density inversion between greenstones (2840 kg·m^{-3}) and the TTGs (2720 kg·m^{-3}) drives sagduction of the cover and exhumation of TTG into domes. The slow build-up phase lasts ~120 million years (A) and precedes the instability phase during which a single dome can develop in a few million years (B), and multiple domes over ~100 million years. For modeling details see François et al. (2014).

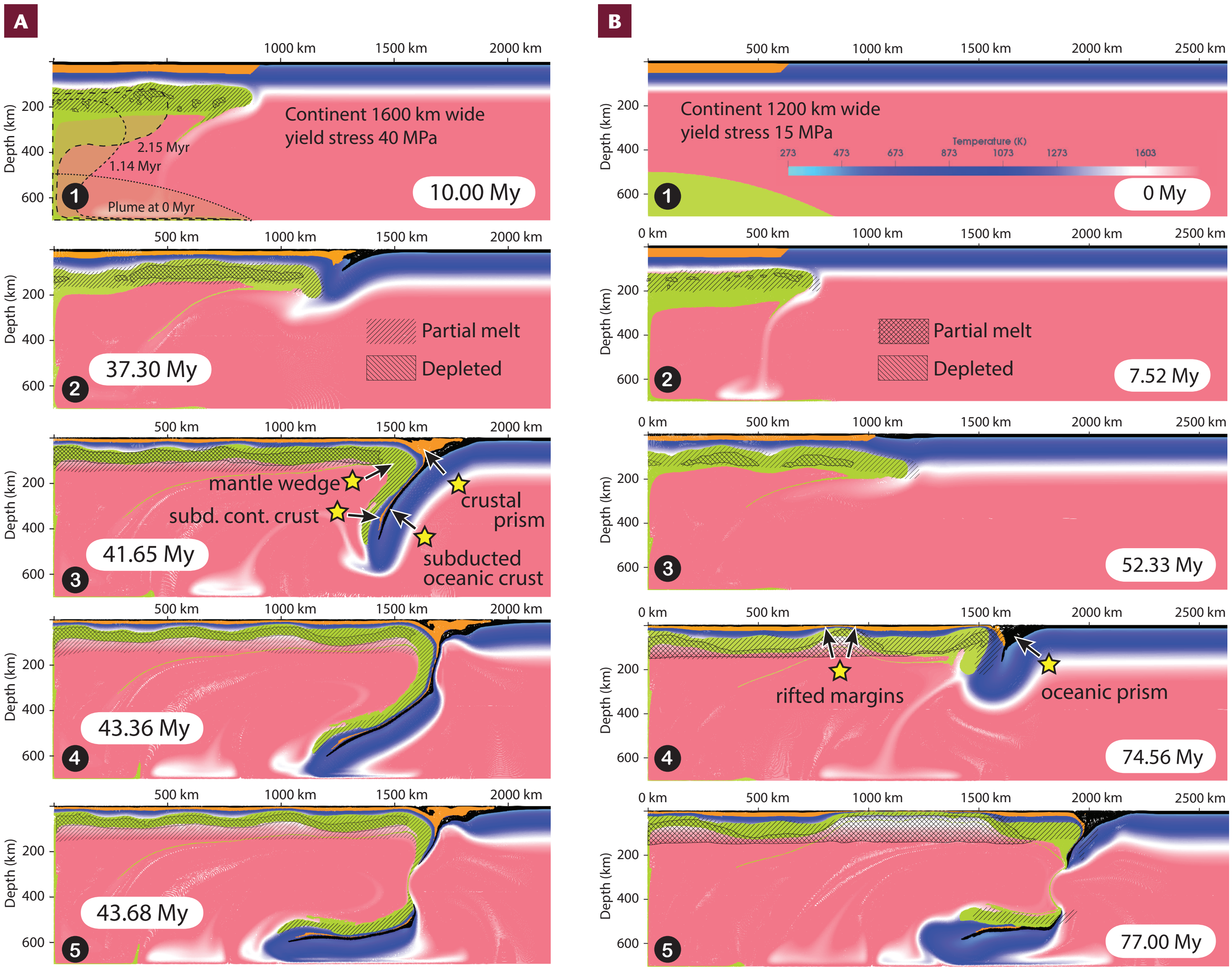

Figure 2 A numerical model with a mantle 200 °C hotter than present delivers a stagnant lid (blue) above a convective mantle (pink). Temperature is laterally averaged to remove convective stresses. A continental crust (orange) and a basaltic crust (black) are embedded into the lid. Plume material (pale green) is added at the bottom of the convective mantle (**A1**, **B1**). In (**A**), the protocontinent is wider and stronger than that in (**B**). Panels **A1** and **B1-2** show that the plume rises through the mantle in 2–3 million years and spreads laterally, forming a protocontinent in less than 10 million years. Gravitational spreading of these protocontinents forces subduction of the adjacent lid (**A2-5**, **B4-5**). Subduction drags portions of the protocontinent into the mantle (**A3-5**, **B4-5**). Thinning and rifting of the protocontinents lead to decompression melting of the underlying mantle. For modeling details see Rey et al. (2014).

plausible thermal, tectonic, and magmatic predictions that promote a better understanding of the composition and architecture of Archean cratons. A major advantage of this approach is that it mitigates the cognitive bias from our familiar imagery of the modern Earth, which prevents us from considering different, but plausible, scenarios.

Archean intra-crustal tectonics. Simple mathematical and analogue models have suggested that small lateral changes in the thickness of greenstone belts can drive their sagduction and the coeval exhumation of partially melted crust into gneiss domes (Mareschal and West 1980). In these pioneering experiments, sagduction led to diapirs rising vertically between sinking greenstone belts and delivered strain fields with a radial symmetry. In contrast, thermomechanical experiments using realistic thermal and mechanical properties (Fig. 1) show that, contrary to expectation, sagduction can deliver horizontal shortening and asymmetric strain fields like those generated by modern plate tectonics. In this setting, the stacking of asymmetric folds, layer-parallel folds, thrusts, and nappes, are not the signature of horizontal plate movement or plate tectonics (Thébaud and Rey 2013). Rather, they imply mass redistribution in a finite volume, where the downward motion of greenstone belts is accommodated by horizontal convergent transport in the upper crust to replace sinking material, and horizontal divergent flow in the deeper crust to make space for sinking material (Fig. 1). Therefore, sagduction tectonics is no more vertical than it is horizontal. Furthermore, thermal gradients in sagducted greenstones can be comparable to those in the subduction regime (François et al. 2014). Hence, at first glance, sagduction-related strain and temperature fields can mimic those of plate tectonic processes. Nevertheless, a key difference between modern and ancient strain fields is that strain in Archean cratons is often partitioned into

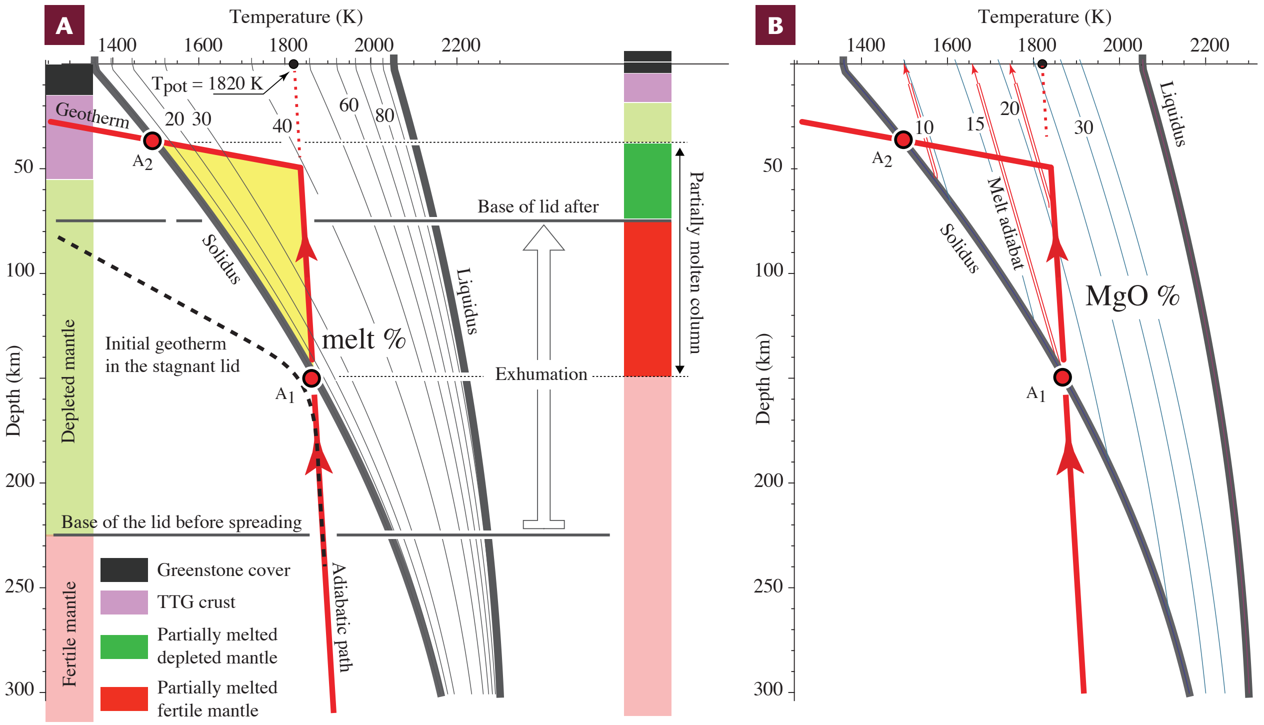

FIGURE 3 (**A**) Phase diagram showing how the spreading of a protocontinent triggers decompression melting of depleted and undepleted mantle. The columns on the right and left show the protocontinent structure before and after spreading. After spreading, the geotherm (in red) intersects the solidus at the base (A_1) and the top (A_2) of a partially molten layer. Whilst the base remains at 150 km depth, the top moves up (polybaric melting), leading to a basaltic layer whose thickness is given by the integration of the melt fraction in the yellow region (here ~20 km). (**B**) The MgO content of the melt extracted at various depths ranges from 9% to 21% (see Rey et al. 2014 for details).

adjacent domains of coeval extensional and contractional deformation (e.g., contractional greenstone belts adjacent to extensional domes; see Toolkit).

Because it involved the recycling of juvenile mafic rocks into TTG magmas, sagduction could explain the shift towards higher εHf(t) in TTG zircon from 3.8–3.6 Ga onwards. Sagduction could also explain the lack of a corresponding shift towards higher δ^{18}O. Compared with modern subduction zones, the volume of buried felsic sediments during sagduction was much more limited. In addition, whereas cold oceanic crust is buried in subduction zones, sagduction buried greenstones that evolved over a protracted period (>100 million years) under higher geothermal regimes (FIG. 1A), powering high-temperature (>230 °C) fluid–rock interactions (Thébaud and Rey 2013), which in turn may have lowered the δ^{18}O of rocks.

Although sagduction can explain Archean crust dominated by TTG domes and greenstone belts, Archean crust dominated by strike-slip tectonics suggests development under conditions of bulk shortening, which requires the existence of horizontal convergence. In what follows, we discuss the concept of mobile-lid geodynamics as a precursor to modern plate tectonics.

Archean Geodynamics

Secular cooling of the Earth and the transition from stagnant lid to mobile lid to plate tectonics. On a slowly cooling Earth, the geodynamics of the lithosphere–convective mantle system is expected to go through several regimes due to the strong dependence of rock viscosity with temperature. According to experiments and observations, hot rocks flow under low stresses, while cold rocks remain rigid, only breaking when a stress threshold (the yield stress) is reached. A strong temperature and stress dependence of viscosity with a stress threshold is required to achieve mantle convection coupled with plate tectonics (e.g., Coltice et al. 2017 for a review). Geochemical and petrological information on komatiites suggest that, during Archean times, the mantle was from 100 to 250 °C hotter than today. In numerical experiments that consider a mantle >150 °C hotter, the mantle vigorously convects underneath a cooler, rigid, and stable "stagnant lid" (Moresi and Solomatov 1998). The stagnant-lid geodynamic regime corresponds to the case where the lid and the convective mantle are mechanically decoupled. With secular cooling, the lid becomes progressively coupled to the convective mantle, and the stagnant-lid regime transitions to a "mobile-lid" regime, as convective stresses locally overcome the lid yield stress. Under a weak mechanical coupling, numerical experiments of mobile-lid systems produce only diffuse surface deformation, and at most, transient episodes of subduction (e.g., Coltice et al. 2017). The transition to a sustained plate tectonic regime, a particular mode of mobile-lid tectonics where deformation is strongly localized at plate boundaries, may have been achieved through further secular cooling and strengthening of the lid, as well as enhanced gravitational forces acting at continent–ocean boundaries in response to the deepening of the seafloor (Flament et al. 2008).

The role of protocontinents in Archean mobile-lid geodynamics. In the Archean, the lithospheric lid was compositionally distinct and hosted protocontinents that evolved into present-day cratons. Applying a simple decompression melting model to the hotter Archean mantle predicts that the oceanic crust would have been about three times thicker (see Flament et al. 2008 for a review) and the residual mantle more buoyant than today (Griffin et al. 2009). Geodynamic models developed to explore the stability of such a lithosphere show intermittent subduction with recurrent slab detachment (van Hunen and van den Berg 2008). However, in these models, subduction is imposed at the onset by embedding a slab ~250 km long. The initiation of subduction and the transition from a stagnant lid to a mobile lid can be achieved via a plume head 200 km in diameter piercing the entire lid (Gerya et al. 2015). However, such a plume head should begin to melt at a depth of 150 km and produce, in a few million years, a 50–60 km thick basaltic plateau. Neither of these predictions seem to fit the geological record as greenstone belts are at most 25 km thick and accumulated over many tens of millions of years. The presence of buoyant protocontinents embedded in the lid is a potential source of important horizontal gravitational stress that needs to be taken into consideration.

The model shown in FIGURE 2A1 considers that protocontinents developed through the accumulation of basaltic rocks extracted from a mantle plume, and from the accretion of the melt-depleted plume head at the base of the lid supporting the thick basaltic crust. Numerical experiments show that these hot, weak, and buoyant protocontinents could have spread under their own weight, forcing the initiation of subduction and the destabilization of the adjacent lid (Rey et al. 2014). This model predicts that the gravitational spreading and thinning of the protocontinent induces decompression melting of the underlying mantle (FIGS. 2 and 3). The parameters that control the dynamics of the lid are, on the one hand, its stress threshold and its viscous resistance to mechanical stresses, and, on the other hand, the buoyancy and size of the protocontinents. By varying these parameters within realistic limits, a range of mechanical behaviors is obtained from stable spreading of continents in a stable lid regime, through continental rifting accommodated by transient episodes of subduction (FIG. 2). These models suggest that protocontinents could have kick-started transient episodes of subduction, until plate tectonics became self-sustained.

Making sense of the geochemical and geophysical record. In the models presented in FIGURE 2, deep mantle melting occurs in the garnet stability field, and melting becomes progressively shallower (FIG. 3A), producing a range of mafic rocks (FIG. 3B) including small volumes of komatiites, komatiitic basalts, and abundant tholeiitic basalts. The model also predicts the formation of a second layer of moderately residual mantle under spreading protocontinents via partial melting of the undepleted mantle (red layer in FIG. 3A). The transient subduction zones that initiate at their edges could explain the co-occurrence of arc volcanism and high-Mg basalts in some greenstone belts. The timing, volume, and compositional range of these basalts are consistent with first-order observations in Archean greenstone belts. In addition, the model explains the presence of a strongly depleted and buoyant layer of mantle in the roots of Archean cratons (pale and darker green in FIG. 3A) above a layer of moderately depleted mantle, inferred from petrological and geochemical studies of mantle xenoliths (Griffin et al. 2009). The strengthening through cooling of these depleted roots would have helped preserve the cratons.

CONCLUSION: DUAL-MODE ARCHEAN GEODYNAMICS

We envision an early Earth with dual-mode geodynamics where intra-crustal tectonics, driven by sagduction, was independent from evolving geodynamics of the global lithosphere–mantle system. In this framework, the diachronous onset of sagduction and modern subduction is constrained by positive shifts of εHf(t) and δ^{18}O in zircon, respectively. The extraction of a primordial mafic crust, before ~4.3 Ga, left a melt-depleted, Mg-rich, buoyant upper mantle less prone to partial melting. Before 3.8 Ga, the primordial mafic crust evolved into TTG via recurrent partial melting in a largely closed system. The progressive mixing of the depleted mantle with the undepleted mantle, via impacts, convection, and mantle plumes, enabled the resumption of volcanism and the accumulation of greenstone basalts from ~3.8 Ga onwards. The shift towards higher εHf(t) of zircon beginning at 3.8–3.6 Ga would record the onset of sagduction. Spreading protocontinents could have triggered polybaric decompression melting, explaining the compositional range of greenstone basalts and the vertical structure of Archean cratons. Until ~3.0 Ga, the felsic crust was largely isolated from the surface by ongoing volcanism and a near global ocean. From 3.8 to 2.5 Ga, transient subduction at the edges of protocontinents did not affect the δ^{18}O of zircon in subduction-driven magmas. This could be explained by a combination of limited sediment supply at the margins of flat and flooded protocontinents, short-lived subductions restricting the amount of subducted material, and fluid–rock interaction at temperatures > 200 °C in hotter subduction zones on a hotter Earth. Protocontinents would have slowly emerged by 3.0 Ga due to secular cooling and the resulting deepening of the seafloor. The strengthening of the lithosphere would have enabled the formation of high mountains, enhancing erosion and sediment supply, and allowed for longer episodes of subduction, shifting the δ^{18}O in some arc magmas. Weathering and erosion would have exhumed the felsic crust from underneath the greenstones, and geochemically coupled the newly exposed TTG crust to the Earth's surface. Eventually, secular cooling strengthened the crust and inhibited the development of greenstone belts, and sagduction was eliminated from Earth's geodynamic repertoire.

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Embracing Craton Complexity at Depth

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Snapshot from a simulation demonstrating the effects of lateral variations on cratonic lithosphere stability.

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Variations within individual cratons, as well as across different cratons, are readily apparent at the Earth's surface, providing indirect insight into the processes governing the formation and evolution of the underlying regions. However, our views at depth are more limited. As such, there is a risk of interpreting the cratonic lithosphere as a monolith. Recent modeling and advances in seismological imaging have enhanced our perspective of vertical variations within the cratonic lithosphere, which has helped build a general conceptual model. While lateral variations also are increasingly identified, their significance still presents unanswered questions. In this review, we summarize the current state of knowledge of cratonic lithospheric structure and demonstrate the importance of lateral heterogeneity in craton evolution and stability.

Keywords: cratons; cratonic lithosphere; geodynamics; seismology

INTRODUCTION

Encapsulating several billion years of Earth's history, the cratonic lithosphere holds considerable potential and promise for understanding the evolution of the Earth's interior. The term lithosphere refers to the outermost region of the Earth that includes the crust plus some portion of the upper mantle which, together, comprise a "zone of strength" that typically behaves as a coherent unit. Much as the crust's rock record captures different geologic events, so does the deeper subcrustal portion of the lithosphere. Our goal in this chapter is to encourage the community to dig deeper into the complexity inside the oldest and typically most stable regions of the deep lithosphere—the cratonic lithosphere.

Tapping into the geologic history recorded in the deep cratonic lithosphere requires first unraveling a complex rock record only accessible by indirect methods that tend to smooth out and/or under-sample the cratonic lithosphere. Adding to that challenge is that the two primary methods of observation—geochemical and isotopic analysis of xenoliths and geophysical imaging—record different time periods with xenoliths capturing deep time (including events from their formation onward) and geophysical imaging documenting the present day, literally providing a snapshot of "now." We often rely on geodynamic modeling to fill in the gaps in space and time between these two approaches, although care must be taken in interpreting those models due to the uncertainties inherent to simulating complex and poorly constrained systems. Even if relying on *static* images of the current structure, *incomplete* sampling of rocks and minerals, and *non-unique* geodynamic models, much has been learned about cratons by peering into their deep structure. We know that cratonic lithosphere is old (Archean to Proterozoic), thick (200–300 km), cold (surface heat flux values of 30–40 mW/m^2) (all ranges from Lee et al. 2011 and references therein), and mostly resistant to deformation (e.g., Bedle et al. 2021 and references therein).

At first pass, cratonic lithosphere may seem passive and tectonically "boring" as it remains seemingly unscathed despite long and complex tectonic histories. That tectonic boringness provides a geologic puzzle—is the long-lived nature of cratonic lithosphere due to its inherent properties, changing mantle dynamics, or some combination of the two? For example, past stresses driven by mantle convection may have been lower in such a way that allowed for long-term survival of cratonic lithosphere, in addition to its inherent properties that promoted stability (Bedle et al. 2021). Alternatively, there could have been mechanisms that allowed for both the destruction and regrowth of cratonic lithosphere (Kusky et al. 2007; Peng et al. 2022) in a manner that mimics longevity in a changing dynamic interior. Both viewpoints, whether non-participatory and long-lived or actively reworking, demonstrate the potential to better understand the geologic history trapped within the deep cratonic lithosphere. The modern-day presence of cratons hence not only allows for the evaluation and constraining of past dynamics, but also for the investigation of the limits of lithospheric strength.

Much of the research on the cratonic lithosphere has focused on its thickest portion, referred to as the root, or the core, with less emphasis on its margins. This root-centered focus is because the root itself is likely the key to stabilizing cratons. Yet, it could also be because defining the lateral extent of cratons and cratonic lithosphere is challenging. Indeed, ask a room full of geologists, geochemists, seismologists, and geodynamicists to point out on a map the western edge of the North American craton and you will get wildly different answers depending on whether the edge should be defined by age, lithospheric thickness, lack of recent deformation, composition, some combination of the above, or yet other reasonings. It is important to point out that the inconsistency in answers does not mean that one group is "right" and another is "wrong." Rather, it is just a reminder of the messiness and heterogeneity that the dynamic, complex Earth brings about. The challenge

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in pinning down the lateral boundaries of cratons at the surface is not just a semantic argument of the best way to define a craton and cratonic lithosphere, it is also our ability to observe, interpret, and contextualize the variations within cratonic lithosphere.

At depth, cratonic lithosphere is as geologically complex as the surface exposures of cratons. Cratonic lithosphere is not homogenous nor uniform in composition, shape, rheology, or thickness, certainly not across regions (although there may be commonalities) and likely not within a single region either. Cratonic lithospheric structure reflects its formation and any subsequent events. As such, there may be portions within cratonic lithosphere with slightly or largely differing properties, each marking a different episode in that craton's history. If containing zones of weakness, these heterogeneities could change the trajectory of the cratonic lithosphere evolution by leading to regional or large-scale deformation; however, if the regions are only slightly modified, then they may just be an artifact of the past with limited impact on craton stability.

The margins themselves represent variations in the cratonic lithosphere as they are the lateral transitions between cratonic and surrounding lithosphere. These transitions could be an abrupt change in thickness, composition, rheology, or age; they could mark a more gradual deepening without a change in composition; or any combination of the above. Regardless, the margins of cratons are a great testament to why understanding heterogeneity in cratonic lithospheric structure is important. The margins of cratonic lithosphere serve as the first line of defense for cratons. When cratons do deform, the deformation often initiates at the margins (e.g., Currie and van Wijk 2016; Chin et al. 2021; Cooper et al. 2021). If the margins are sufficiently weaker than the cratonic core, then they may buffer the interior from deformation and destruction (Lenardic et al. 2000). Interestingly, a cratonic margin's propensity to deformation also leads to that area being the most likely to be reworked, reshaped, and, potentially, no longer as easily identifiable as "cratonic lithosphere."

Cratonic lithospheric margins are just one example of the complexity within the cratonic lithospheric structure. There are also zones of pre-existing weaknesses, sutures, vertical variations, phase transitions, and much more packed into these tectonically "boring" regions of the Earth's interior waiting to be carefully unraveled and have their stories told. In this chapter, we hope to lay the foundation for these stories by reviewing our current knowledge of the general cratonic lithospheric structure, expand on that framework with a discussion of some of the additional complexity mentioned above, and propose approaches to address that complexity in future work. While we may not be able to resolve the argument over any given map, we do hope that we can shift it to a deeper conversation about the *why* behind the differing answers.

GENERAL CRATONIC LITHOSPHERIC STRUCTURE

The basic vertical structure of the cratonic lithosphere can be described as a set of embedded boundary layers (Fig. 1). The term boundary layer comes from fluid mechanics and is used to define the region in a fluid near a surface wherein the fluid motion is affected by that surface; specifically, the boundary layer is the layer of fluid that encompasses the velocity gradient between the ambient fluid motion and the velocity of the fluid at the surface, assuming that the fluid and the surface are coupled ("no-slip" condition). In other words, it marks the transition between a background state (ambient fluid motion) and an abrupt change (surface).

The concept of a boundary layer has been adopted and expanded by the Earth science community to describe transitional regions due to large variations in various parameters near primary boundaries (typically the surface of the Earth and the core–mantle boundary). For example, the lowermost region of the atmosphere that is affected by the Earth's surface is described as a boundary layer. Likewise, within the interior of the planet, the transition between the surface of the Earth and the convecting mantle encapsulates large changes in many quantities including temperature, composition, rheology, and seismic velocity. The depth at which each quantity reaches average values associated with the ambient convecting mantle varies. In other words, defining the lithosphere, beyond a "zone of strength," as a single entity with a clear base connected to a single value is intractable. Indeed, this challenge may be an explanation for why terms such as mechanical lithosphere, seismic lid, thermal boundary layer, etc. are all used to represent the Earth's lithosphere with each term providing varying estimates of lithospheric thickness. Each term describes a region that encompasses a single, specific transition, which may not and need not be occurring at the same range of depths as another term. Instead of adhering to a single perspective, we therefore encourage the community to conceptualize the lithosphere as a collection of transitions, or nested boundary layers (Fig. 1), which is what we refer to when using "lithosphere" in a general sense within this chapter. In addition, when we provide estimates for values of lithospheric thickness, we delineate to which transition depth those thicknesses refer.

Early ideas on the cratonic lithosphere were framed on the premise of competing effects of a chemical versus thermal boundary layer in recognition of the observed lack of gravity anomalies over cratonic regions (Jordan 1978). Observations of surface heat flux and other indicators of thermal structure, such as temperature and pressure estimates from cratonic xenoliths, indicate that the cratonic lithosphere is at a cooler state than the surrounding mantle (Lee et al. 2011 and references therein). This cooler state would place the cratonic lithosphere in a state of negative thermal buoyancy with a net downward force (as well as increasing its temperature-dependent viscosity). Yet, this expected density excess, due to being in a cooler state, is not generally observed within gravity surveys over cratonic regions (Jordan 1978), meaning that the effect of thermal contraction is somehow compensated. In other words, the concept of solely a thermal boundary layer is inadequate to describe the cratonic lithosphere, as it tends to overestimate the density structure. Jordan (1978) reconciled this discrepancy with the isopycnicity hypothesis, which proposed that the negative thermal buoyancy resulting from a cooler thermal structure is exactly offset by a positive chemical buoyancy driven by a compositionally less dense cratonic lithosphere, compared with the surrounding upper mantle; the net result being that the craton is in a state of neutral buoyancy. Indeed, cratonic mantle lithosphere does have lower density than average mantle peridotite (e.g., Lee et al. 2011). Although providing an argument for the isopycnic hypothesis (Jordan 1978), the unique composition of cratonic mantle lithosphere may not provide for perfect isopycnicity wherein the negative thermal buoyancy is exactly offset by the positive chemical buoyancy of the cratonic lithosphere at every depth. Such a state would require a stratified compositional structure of increasing cratonic lithosphere density with depth that is not often observed in cratons (Lee et al. 2011). Instead, the integrated density structure of cratonic lithosphere on average may provide sufficient positive buoyancy to keep the craton neutrally buoyant (Lee et al. 2011), although there are some

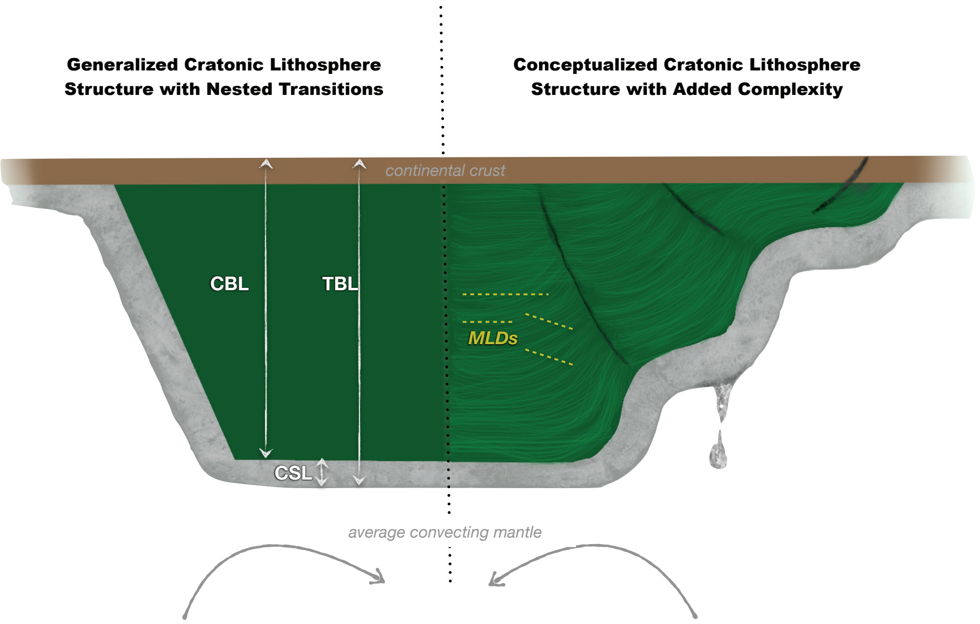

Figure 1 Cartoon illustrating the embedded boundary layers associated with cratonic lithospheric structure on the left with CBL = chemical boundary layer (green region plus continental crust in brown), TBL = thermal boundary layer (the region encompassing the CBL plus the gray region directly below the CBL), and CSL = convective sublayer (the gray region directly below the CBL). To the right of the dotted line is a rendering of the potential complex lateral structure within the cratonic lithosphere with sutures, folding, faults, additional seismic discontinuities (MLD = mid-lithospheric discontinuity), and small-scale convection/drips within the CSL.

arguments that cratonic lithosphere is negatively buoyant due to a denser composition (Wang et al. 2022), cooler state, or a combination of both (Mooney and Vidale 2003).

The distinct chemical compositions observed within cratonic xenoliths introduce an additional descriptor for the cratonic mantle lithosphere—a chemical boundary layer that encompasses the transition between mantle lithosphere with a unique composition (cratonic lithosphere) and the average composition of the upper mantle. The premise of a chemical boundary layer provides then an opportunity to conceptualize the processes that would produce a thick, compositionally distinctive lithosphere. Analyses of cratonic mantle xenoliths suggest that high degrees of melt extraction, likely due to hotter past mantle temperatures, are required to explain their geochemical signatures (Boyd 1989). This requirement has launched various interpretations of the tectonic settings (mid-ocean ridge, continental arc, plumes) that have provided the origins for cratonic mantle lithosphere (Lee et al. 2011). Regardless of the origin, the high degree of melt depletion also suggests a degree of devolatilization that would promote dry, viscous lithosphere (Lee et al. 2011 and references therein). As such, the chemical boundary layer may also act as a rheological boundary layer providing enhanced viscosity (beyond that provided by cooler temperatures) and buoyancy, both of which in turn promote resistance to deformation and longevity of the cratonic lithosphere.

If the chemical boundary layer represents the portion of the cratonic lithosphere that is rigid and resistant to deformation, then the chemical and thermal boundary layers are inherently linked. Heat transfer within the chemical boundary layer is limited to conduction if, indeed, it is resistant to deformation. The thermal boundary layer is the region that encompasses the temperature change between a surface and a convecting fluid, in this case, between the temperature at the surface of the Earth and that of the average convecting mantle. It can also be envisioned as the transition between two heat transfer modes—conduction and convection. As such, if rigid, then the presence and thickness of the chemical boundary layer control the portion of the thermal boundary layer wherein conduction is the primary heat transfer mode (Cooper et al. 2004). The thermal boundary layer extends past the chemical boundary layer. The region between the base of the chemical boundary layer and the base of the thermal boundary layer (often called the convective sublayer) is susceptible to small-scale deformation, convection, and dripping. The material within the convective sublayer could have the same composition and rheology (Cooper et al. 2004), or slightly different (e.g., Evans et al. 2011), as the average surrounding mantle, but at cooler temperatures and, thus, higher viscosities. This convective sublayer, which can deform, may then act as a protective barrier for the chemical boundary layer and cratonic lithosphere.

The thick, thermal boundary layer associated with cratonic lithosphere is inferred in part from low heat flow (e.g., Lee et al. 2011) within the cratons and in part, and more widely, from high seismic velocities. Global tomography models, such as Schaeffer and Lebedev (2013), depict high velocities that extend down to ~250 km within the mantle beneath cratons, helping to define the depth of the cratonic lithosphere, in this case, typically the depth of the base of the thermal boundary layer. Some cratonic mantle xenoliths sample the chemical boundary layer and, as such, estimates of cratonic lithospheric thickness based on these xenoliths provide the depth of its base. In addition to temperature, seismic waves are also sensitive to composition, providing additional insight into the nature of the chemical boundary layer, as well as outlining the extent of the thermal boundary layer. For example, in addition to the cooler temperatures, the observed high seismic velocities within cratonic lithosphere have been interpreted to also be due to the highly melt-depleted compositions measured in some cratonic mantle xenoliths (e.g., Jordan 1978; Lee et al. 2011). However, studies of melt extraction effects on seismic velocities have now shown that this compositional distinction results in only subtle changes (e.g., Afonso and Schutt 2012). Consequently, high cratonic velocities may be due to compositional factors driven by processes other than melt extraction (e.g., Dalton et al. 2017).

In addition to the above, there are several other ways to define and describe the cratonic lithosphere, including the electrical lithosphere, which describes observed changes within the electrical conductivity (Evans et al. 2011); for a more in-depth review, see Fischer et al. (2020). Each of the nested transitions that collectively comprise the cratonic lithosphere may contribute to, or elucidate, the controls on craton stability and longevity. For example, the cooler temperatures within the thermal boundary layer contribute higher viscosity values within the cratonic lithosphere (presuming a temperature-dependent rheology). Regions of lower conductivity may indicate less water or melt content (Evans et al. 2011), both of which would also promote higher viscosity values. As mentioned, both

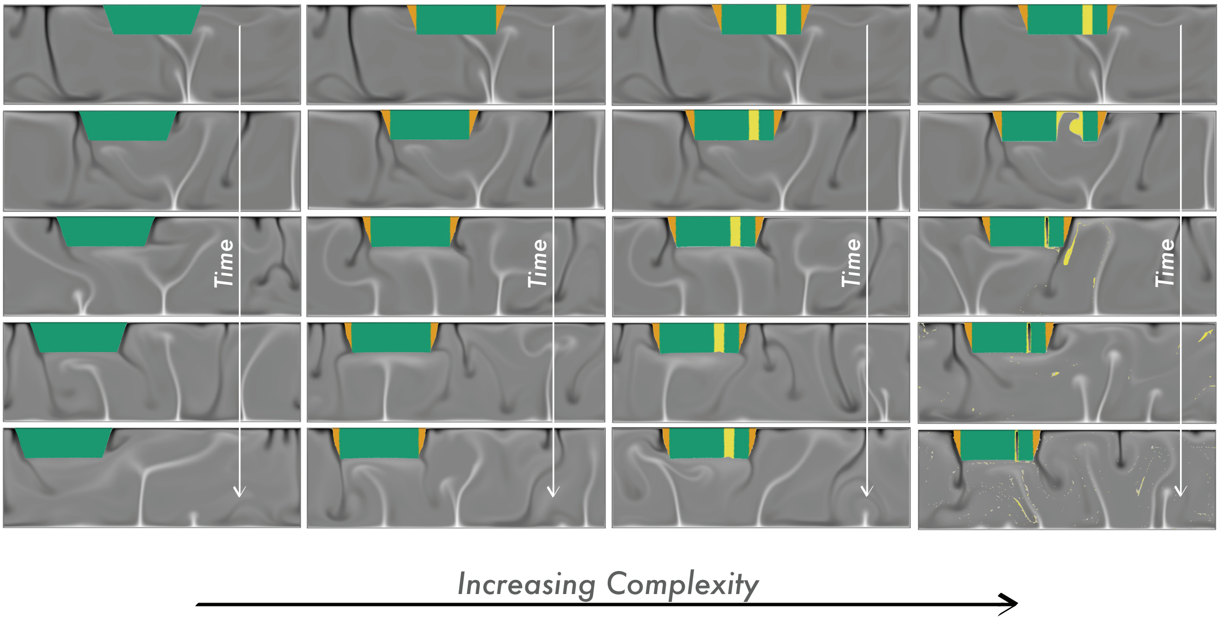

FIGURE 2 Snapshots from a set of geodynamical simulations that model the response of increasingly complex cratonic lithosphere when interacting with the convecting mantle. Specifically, the rheological structure of the cratonic lithosphere changes from uniform (**FAR LEFT**) to heterogeneous viscosity (**FAR RIGHT**). All simulations were ran for several mantle overturns, which is defined as the time it takes for convecting material to travel the entirety of a convective cycle (i.e., cold material at the surface sinking, heating up, and then rising back to the surface). The chemical boundary layer (CBL) of the cratonic lithosphere is green, green and yellow, or green, yellow, and orange depending on the simulation. The convecting mantle is in grayscale with the darkest gray/black regions indicating the coolest regions, which includes the upper thermal boundary layer (TBL; the entire darkest gray region spanning from the surface downward) and convective sublayer (CSL; the darkest gray region proximal to the CBL (green/orange/yellow)), and the lightest gray/white regions indicating the warmest regions. The orange regions in the second through fourth columns represent cratonic lithosphere margins (both on the left and right) with slightly modified and weak rheology. The yellow region in the last two columns represents a pre-existing weak zone with slightly (third column) to extremely (fourth column) modified and weak rheology.

the lower density and higher viscosity associated with a chemical boundary layer produced through high degrees of melt extraction also promote craton stability. In other words, understanding the structure of cratonic lithosphere means understanding first the condition of cratons—mostly undeformed, long-lived regions—from which any subsequent deformation must be explained. Our short summary above demonstrates tremendous potential for complexity within the general vertical structure of cratonic lithosphere. It is from this conceptual grounding that we now turn our attention to what might be gleaned from lateral variations within cratonic lithosphere.

LATERAL VARIATIONS

As mentioned, cratonic lithospheric structure is a result of the cumulative events that the craton experienced during its lifetime. As such, conceptually, one would expect lateral variations at depth within the cratonic lithosphere. Even if a craton remained perfectly undeformed during its history, it is unlikely that it would be laterally homogeneous unless the cratonic lithosphere was formed in a single event (which also seems unlikely, see Lee et al. 2011). During formation, lateral variations in thickness, composition, and/or rheology may be introduced if cratonic lithosphere is thickened through accretion or compression (Cooper and Miller 2014; Pearson et al. 2021). Post-formation, cratonic lithosphere may experience re-fertilization, re-heating, metasomatism, shearing, thinning, and/or slow re-hydration (e.g., Lee et al. 2011). Interpreting the causes of lateral variations within cratonic lithosphere, whether formation or post-formation processes, requires better constraints on the potential longevity of complex lithospheric structures.

The upper crust, and even whole crustal structure, of the continents have been imaged with active source (explosions or other man-made sources) experiments and earthquake-based methods targeting the crust–mantle boundary depth, whereas the lithospheric-scale structure of the deep cratons remains less well known. As the density of seismometers increases with the expansion of temporary passive deployments, geophysicists are increasingly able to sharpen the images of the complexity of the cratonic lithosphere's internal structure. Fischer et al. (2020) and references therein synthesize the community's advancements in imaging the continental lithosphere by documenting how we are learning more about the continental interiors. Recent efforts utilizing different, complementary seismic techniques and datasets, such as various types of tomographic imaging, inferring seismic anisotropy, and analyses of converted and reflected waves, has changed our initial conception that cratons were primarily neutrally buoyant, cold, and seismically fast monoliths. Part of that increased knowledge includes the advent of the discovery and increased recognition of mid-lithospheric discontinuities (MLDs), which may provide important clues about the internal structure of cratonic lithosphere (for a more in-depth review of the potential origins of MLDs, see Fischer et al. 2020).

Lateral complexity is also recognized from mantle xenolith observations. For example, although overall mostly dry, the water content within cratonic peridotites varies both vertically and laterally (Peslier et al. 2017), as does olivine composition (O'Reilly and Griffin 2006). Intriguingly, the textures of xenoliths also change across the cratonic lithosphere with some textures capturing past localized deformation events, such as lithospheric drips (Chin et al. 2021). Much like seismic observations, cratonic xenoliths point to lateral and vertical complexity within cratonic lithosphere as the norm rather than the exception.

There are dynamic consequences to lateral variations. Changes in cratonic lithospheric thickness, or the shape of deep cratonic margins, can affect cratonic stability by channelizing mantle flow against the interior of the craton (Cooper et al. 2021). Thicker cratonic lithosphere can deflect mantle plumes to thinner regions (Sleep et al. 2002). The sharp lateral change in temperature between thick cratonic lithosphere and the surrounding mantle can induce small-scale convective instabilities, called edge-driven convection, that can drive anomalous thermal upwellings and melting events (King and Anderson 1998). Areas of pre-existing weakness within the cratonic lithosphere may catalyze deformation and eventual craton destruction (Liu et al. 2018). Conversely, cratonic lithosphere also has the potential to preserve weak regions within their domain (e.g., Liu et al. 2018; Fu et al. 2022).

Some of these consequences are visualized in the simulations in FIGURE 2, which demonstrate the potential impact of heterogeneity within the cratonic lithosphere. All simulations were run using Underworld2 (Mansour et al. 2020; https://doi.org/10.5281/zenodo.1436039) and full details can be found at this online repository (https://github.com/coopergeodynamics/elementspaper). The first column in FIGURE 2 represents the simplest scenario in which a cratonic lithosphere consisting of a chemical boundary layer (the green region) with a uniform enhanced viscosity and sloped margins on each side is emplaced into the upper thermal boundary layer of the convecting mantle (in grayscale, the upper thermal boundary layer (TBL) is the darkest gray region extending from the surface). In this simulation, as with the rest, the behavior of the cratonic lithosphere happens in response to the dynamics of the convecting mantle. In other words, no lateral compression, extension, or plate forces were imposed. During this simulation, the cratonic lithosphere translates across the surface in response to the mantle dynamics with no discernible deformation. Even for this simple case, we see the development of edge-driven convection within the convective sublayer (CSL) along the right margin of the cratonic lithosphere. As we add progressive complexity to the cratonic lithosphere in the set of simulations by introducing slightly weaker margins (orange regions along the edges of the chemical boundary layer (CBL) in FIG. 2) and/or pre-existing weak zones (yellow regions in the interior of the right-hand side of the CBL in FIG. 2), the behavior changes with the deformation occurring either within the margins or the pre-existing weak zone. In the most extreme case (fourth column), wherein the pre-existing weak zone was prescribed the same rheology as the convecting mantle, the entire cratonic lithosphere split apart along the weak zone (whose material was then reworked into the convecting mantle) and then came back together (with the plate motions likely driven by competing effects of mantle plumes and subduction-like downwellings). By comparison, within the simulation with a pre-existing weak zone (third column), the weakened region (in yellow) experienced some localized thinning, but overall, the entire cratonic lithosphere remained intact. Note that to keep from changing too many parameters at once and allow for ease of comparison among simulations, we only considered rheologically distinct cratonic lithosphere with enhanced viscosity within the chemical boundary layer and neglected compositional buoyancy for this proof-of-concept exercise; however, even the simplest of simulations demonstrate the need to further explore the consequences of lateral heterogeneity within the cratonic lithosphere.

CASE STUDIES AND PROMISING FUTURE WORK

We end with examples of two case studies, one from the North China craton (NCC) and one from the Yilgarn craton of Western Australia. The NCC has been a focus of both seismic imaging, structural, and geochemical studies and has been particularly extensively studied with dedicated, densely spaced seismic arrays, which have allowed beautiful images to be obtained of the lithospheric structure (e.g., Feng et al. 2022). It is a classic example of

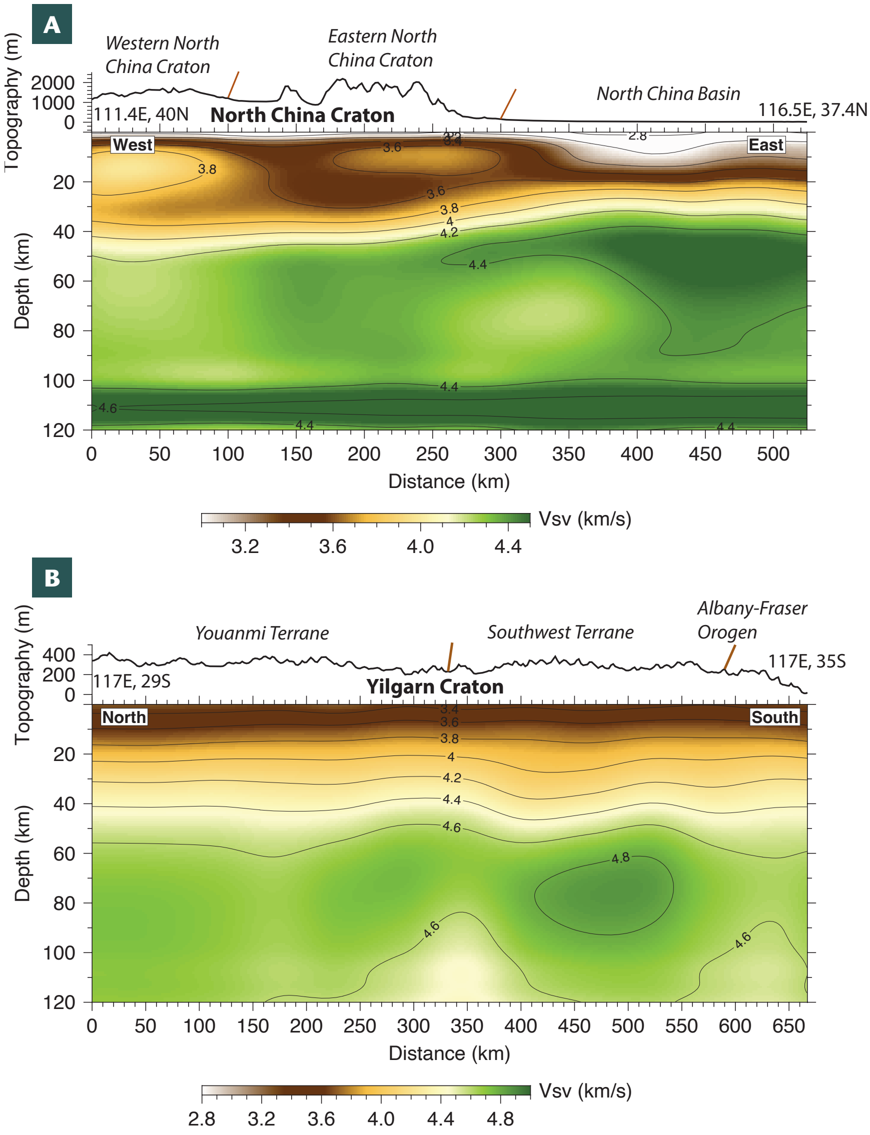

FIGURE 3 (**A**) Cross section of a Rayleigh wave tomography model of the North China craton from Feng et al. (2022) from west (111.43° E, 39.87° N) to east (116.56° E, 37.38° N). (**B**) Cross section through a Rayleigh wave tomography model of the Yilgarn craton of Western Australia from north (117° E, 27° S) to south (117° E, 35° S) (Miller et al. 2023a). The color scale and contours in both panels correspond to vertical shear wave velocity (Vsv). Brown lines mark the terrane boundaries at the surface and are labeled in italics.

cratonic reactivation and destruction. The surface wave model of Feng et al. (2022), based on teleseismic Rayleigh waves and ambient noise cross-correlations, is shown in Figure 3A. The profile taken WNW to ESE from the central part of the craton across to its eastern edge and into the North China Basin illustrates both lateral and horizontal complexity inferred from the velocity structure. The authors of this work identify complex lateral variations in lithospheric thickness and fine-scale structure and variations in seismicity, in both the north–south and east–west directions (Feng et al. 2022).

In comparison to the modified, deformed cratonic lithosphere inferred from the NCC, new results from the more tectonically stable Yilgarn craton of Western Australia similarly show significant complexity, as inferred from surface wave tomography. Figure 3B shows a profile through a new teleseismic Rayleigh wave-based model (Miller et al. 2023a) from a new seismic array in southwestern Western Australia that images the Yilgarn craton (Miller et al. 2023b). The structure of the Yilgarn craton is the product of a sequence of tectonic events, including Mesoarchean crustal formation and Neoarchean cratonization followed by later episodes of rifting (see Miller et al. 2023b). The net result of these events is complex with laterally varying structures that seem to have expressions extending through the entire cratonic lithosphere, which itself is significantly seismically faster and thicker than the NCC (Fig. 3B). These two test cases demonstrate, much like the simulations, the wide range of lateral variations within cratonic lithosphere, either spanning a long history of events leading to and being the result of large-scale deformation (NCC and fourth panel in Fig. 2) or representing localized events that seemingly do not disturb cratonic stability, but are still captured within the rock record (Yilgarn craton and second and third panels in Fig. 2).

In conclusion, the cratonic lithosphere continues to provide opportunities (literally and figuratively) to test constraints on early Earth processes and lithospheric strength, inspire new insight into the perhaps imperfect concepts of stability and longevity, and build multidisciplinary time–space collaborations that couple observations capturing multiple time periods with locations run through geodynamic models that test for physical feasibility. Indeed, if we hope to unlock the secrets trapped in the deep rock record, then we need to work collaboratively, within and across disciplines, and constructively as a community to embrace the complexity within the cratonic lithosphere.

ACKNOWLEDGMENTS

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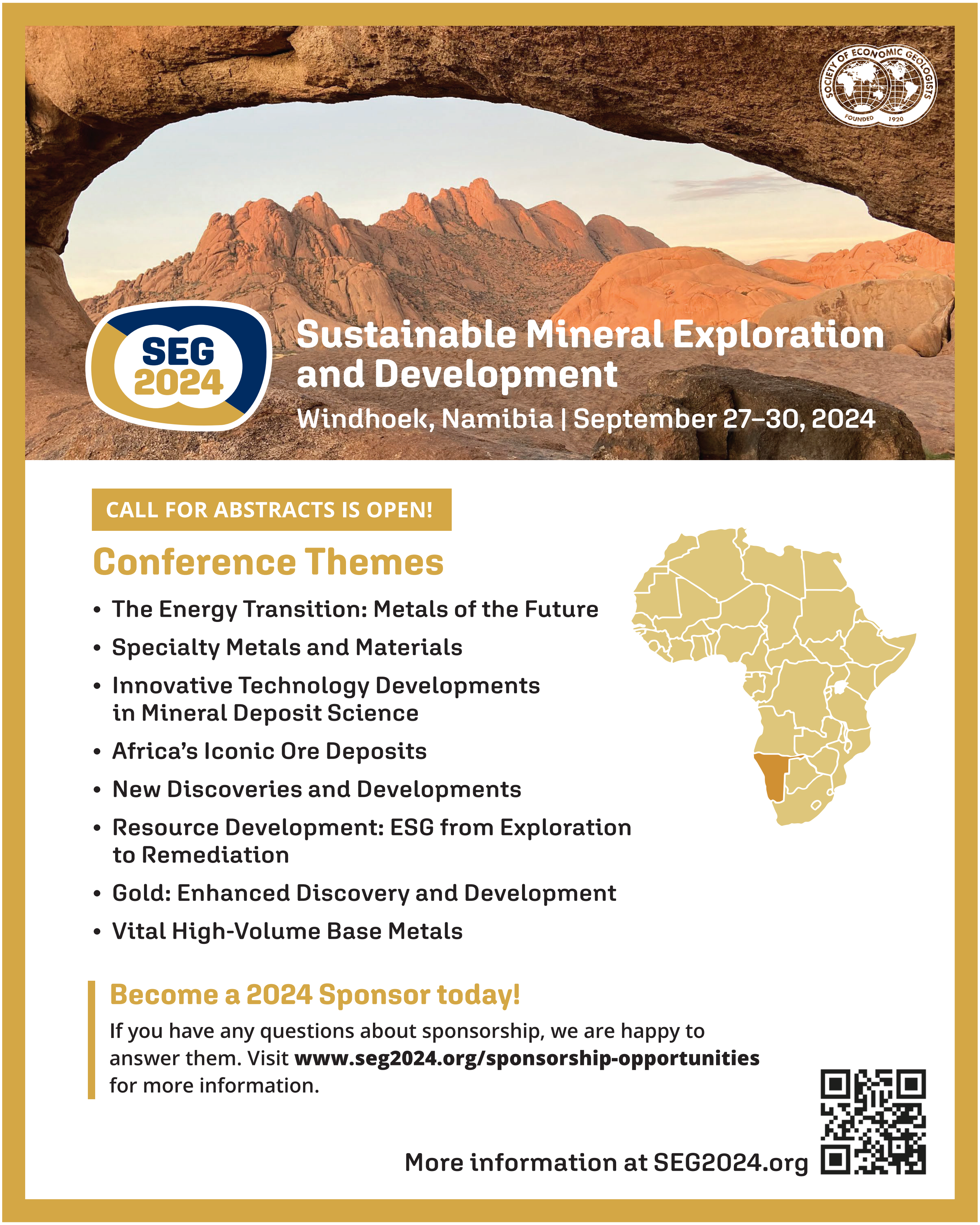

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RESEARCH TOPIC FROM JAMS: ORIGIN AND DYNAMIC PROCESSES OF THE LITHOSPHERE-ASTHENOSPHERE BOUNDARY IN SUBDUCTION ZONE SETTINGS

Yuto Sato*

The lithosphere–asthenosphere boundary (LAB) is located between the rigid lithosphere (the tectonic plate in the framework of plate tectonics) and the ductile asthenosphere, across which the heat and material transport mechanisms change drastically owing to dynamic processes such as conduction, convection, and magma transport. The constant supply of water-rich fluids released from the subducting slab significantly hydrate the LAB in subduction zone settings, affecting its origin and the dynamic processes operating in the LAB. This is because the water in the mantle significantly decreases its viscosity and melting temperature. Previously, our group revealed the petrologic structure across the LAB in subduction zone settings based on careful geothermobarometry of spinel peridotite xenoliths from the Ichinomegata maar on the back-arc side of the Northeast Japan Arc (Sato and Ozawa 2019). Accordingly, the mantle beneath Ichinomegata consists of two distinct layers. The lithospheric mantle (25–40 km) is granular, amphibole-bearing, and subsolidus, whereas the top of the asthenosphere (40–55 km) is porphyroclastic, amphibole-free, and partially molten. Their boundary was interpreted as the petrologic LAB, in which the pressure and temperature conditions coincided with the melting condition of the hydrated mantle. Here, I briefly introduce two papers discussing the origin of the LAB (Sato et al. 2023) and the temporal changes in the thermal state and dynamics of the LAB (Sato and Ozawa 2023).

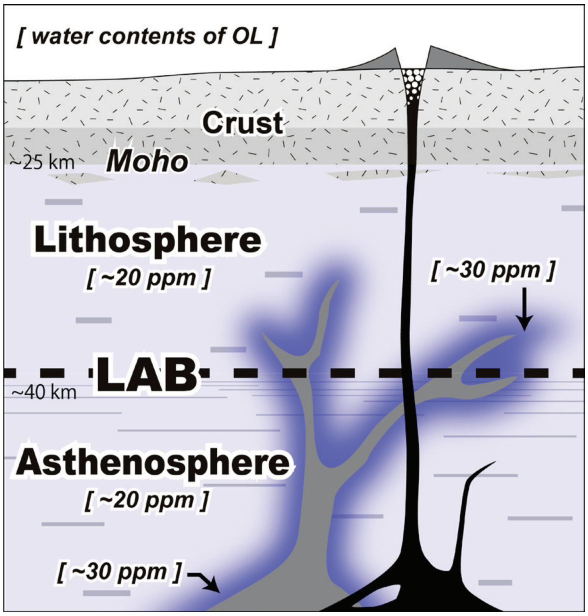

FIGURE 2 A schematic cross-section for the region beneath Ichinomegata, with the proposed distribution of olivine water content in the mantle

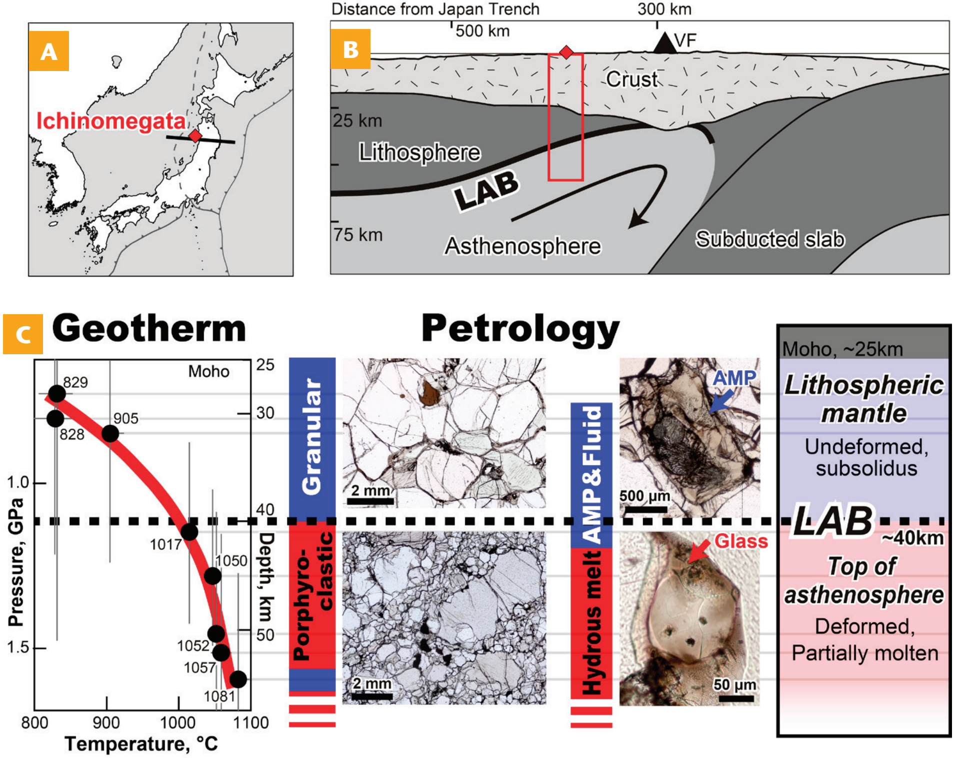

FIGURE 1 (**A**) Location of Ichinomegata maar in Northeast Japan Arc. (**B**) Schematic cross-section along the black line shown in (B). (**C**) Reconstructed thermal and petrologic structures in the mantle beneath Ichinomegata.

Origin of the LAB

Two models for the origin of the LAB have been proposed, which are the 'partial-melting model' to explain the low seismic velocity of the asthenosphere by the presence of melt (Kushiro et al. 1968), and the 'olivine-water model' to explain the low viscosity of the asthenosphere by assuming the presence of water in olivine (Hirth and Kohlstedt 1996). To examine these models, the depth profile of the water content using Ichinomegata xenoliths was reconstructed. However, obtaining the depth profile remains challenging because of the rapid diffusive loss of hydrogen during magma ascent and eruption. This problem was checked by examining the diffusion profiles of water using FTIR mapping and SIMS line analysis for olivine and orthopyroxene.

Extensive analysis of the water content of 17 Ichinomegata xenoliths revealed that olivine and pyroxene exhibited a variety of zoning patterns, from which the timescale of diffusive loss was estimated. The xenoliths from Ichinomegata underwent only limited diffusive water loss (<1 h duration) because of the low temperature of the andesitic host magma and the rapid quenching in the maar deposit. The water content of the mantle is well preserved in the homogeneous core parts of the large olivine and pyroxene grains. The water content of olivine suggests clear correlations with petrogenetic factors, except for those marking anomalously high values, implying hydrous metasomatism by a water-rich

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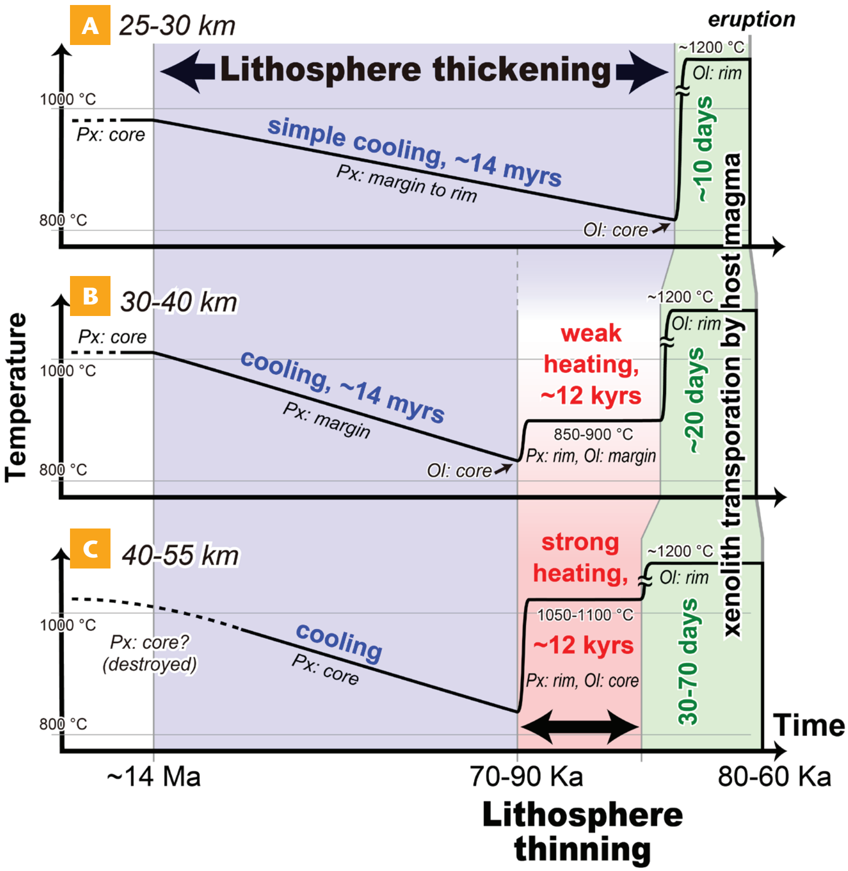

Figure 3 Schematic diagrams showing the overall thermal history of the mantle beneath Ichinomegata (thick solid line) at depths ranging from (**A**) 25–30 km, (**B**), 30–40 km, and (**C**) 40–55 km, deduced from zoning profiles in olivine and pyroxenes. Blue, red, and green backgrounds indicate stages of cooling, heating, and magma transport, respectively.

fluid. By combining the estimated water content of the minerals and depth estimation of the xenolith samples, the depth profile of the water content of the mantle was obtained, including the LAB, down to ~55 km. The results showed that olivine, orthopyroxene, and clinopyroxene in the lithospheric mantle (depth range of 28–38 km) contained 21 ± 2, 302 ± 64, and 616 ± 99 wt. ppm H_2O, respectively, which are similar to those at the top of the asthenosphere (depth range of 39–52 km) that contain 20 ± 2, 258 ± 38, and 561 ± 80 wt. ppm H_2O. In the region that experienced local metasomatism, a higher water content was recorded (30 ± 4, 414 ± 48, and 741 ± 43 wt. ppm H_2O). Accordingly, this result verifies that there is no contrast in the water content across the LAB beneath the Ichinomegata maar. Therefore, the ‘partial-melting model’ for the origin of the LAB is supported rather than the ‘olivine-water model’ for the western Pacific Plate subduction zone.

Dynamic processes operating in the LAB

The thermal history of the Ichinomegata xenolith was decoded from the chemical heterogeneity of the constituent minerals. The timescale of the dynamic processes operating in the LAB is discussed based on the depth variation of the decoded thermal history. Extensive mineral chemical analyses of olivine and pyroxene in nine Ichinomegata xenoliths from a depth range of 28–55 km revealed a wide variation in chemical zoning patterns. There are two types of CaO zoning of olivine in the vicinity of clinopyroxene; four types of chemical zoning in CaO, Al_2O_3, Cr_2O_3, and TiO_2 contents of orthopyroxene; and four types of chemical zoning in CaO, Al_2O_3, Cr_2O_3, and TiO_2 contents of clinopyroxene. A systematic depth-dependent variation in the chemical zoning was reconstructed based on the derivation depths of the xenoliths. The depth variation of the thermal histories of the Ichinomegata xenoliths was decoded by applying diffusion-controlled reaction modelling to reproduce the zoning patterns. The decoded thermal events in the order of occurrence are (1) ~14 million years of cooling via thermal conduction, causing lithosphere thickening up to ~55 km depth, (2) subsequent ~12,000 years of heating from the underlying asthenosphere, resulting in lithosphere thinning up to depths of ~40 km, and (3) 1–68 days of heating during xenolith transport by the host magma. The duration of the lithosphere thickening was consistently explained by the period of the Japan Sea opening. However, the timescale of the lithosphere thinning is too short to be explained by heat conduction through the ~15-km-thick LAB and requires a more effective heat transport mechanism, such as direct magma injection into the LAB or a significant viscosity reduction of the mantle peridotite aided by the pervasive permeable flow of silicate melt.

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To make the meeting as accessible as possible the two-day program will include both in-person and remote talks, lightning talks and poster presentations.

Three exciting fieldtrips are on offer illustrating the mineral heritage of the region: `Parys Mountain' (3-day trip), `Forest of Dean' and `Blaenavon and Big Pit' (day trips).

This meeting precedes the European Mineralogical Conference, in Dublin (18–23 August 2024: www.emc-2024.org). There will be a bonus site visit (free of charge) to the National Collections Centre in Dublin for those who attend both events.

There are reduced registration fees for students and retirees. Information on travel grants can be found on the web site.

Conference organisers:
Jana Horák, Tom Cotterell, Andrew Haycock,
Helen Kerbey, Mike Rumsey & Stuart Mills.
Staff support: Kevin Murphy & Russell Rajendra.

For further information see: https://mm-10.org/

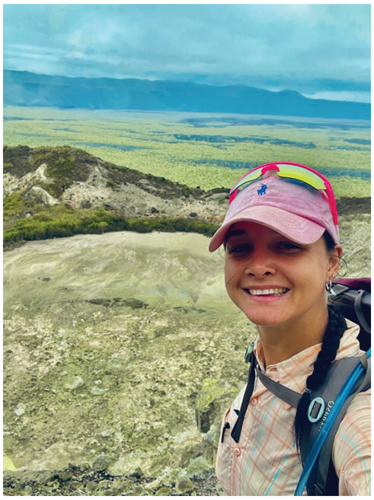
SOCIETY MEMBER, ROGER HARDING, PASSES AWAY

Roger Harding died on January 26th at the age of 85. He completed a PhD at Oxford in the mid-1960s on the igneous intrusions of St. Kilda. He joined the NERC Isotope Geology Unit and in the early 1970s moved to the Petrology Unit in Exhibition Road. He worked on many projects and, by strange coincidence, became the leader of the geological mapping of St. Kilda by Petrology Unit Members. He developed an interest in gemmology under the expert guidance of Alan Jobbins and qualified as a gemmologist. When the Petrology Unit moved to Keyworth in 1985, he transferred to the Natural History Museum along with the Minerals Collection dealing with gemmological matters. After a short time, he moved to The Gemmological Association in Hatton Gardens where he was a tutor, examiner, and editor for the *Journal of Gemmology*. Roger served as Publications Manager for the Mineralogical Society during the early 1990s. On retirement, he moved to the West Country.

FIELD REPORT FROM BURSARY WINNER, LYDIA WHITTAKER

Alcedo Volcano Field Mission, 2023

School of Natural Sciences, Trinity College Dublin, Ireland



At the summit of Alcedo overlooking the caldera.

Thanks to the Mineralogical Society postgraduate student bursary, The Geological Society Research Grants, and The Julian Boldy Bursary, Trinity College Dublin, I was able to participate in a field mission to Alcedo volcano in the Galapagos Islands, accompanied by a team of international researchers. The trip was led by Mike Stock of Trinity College Dublin (Ireland); accompanied by Dennis Geist, professor emeritus at the University of Idaho (USA) and a specialist in the geology of the Galapagos Islands; Marian Holness, a professor at Cambridge University (UK) and a specialist in the processes taking place in magmatic reservoirs; Benjamin Bernard, a member of the Escuela Politécnica Nacional (Ecuador) and specialist in eruptive dynamics; and Jorge Zambrano, a student at the Escuela Politécnica Nacional, researching the rhyolitic eruptions of Alcedo.

The purpose of the expedition was to collect samples and gain insights into the enigmatic rhyolitic eruptions that occurred on this volcano nearly 100,000 years ago. The presence of such high silica content in the Galapagos is exceedingly rare, as typical eruptions in this region produce basalt. Therefore, Alcedo represents a unique natural laboratory where petrological/geochemical techniques can be deployed to directly compare the magmatic processes preceding rhyolitic and basaltic eruptions in a single magmatic system. In the current circumstances, an explosive rhyolitic eruption poses a significant threat to local fauna, tourism, agriculture, fishing, and the resident giant tortoise population. However, the likelihood of such an eruption is very low. Alcedo is an active volcano, but its last eruption, which took place in 1993, involved Hawaiian-type eruptions characterized by basaltic lava flows.

Galapagos tortoises in their natural habitat, overlooking the caldera rim.

(**Left to right**) Dennis, Mike, Marian, Ben, Jorge, and Lydia at the coastline ready for a day of fieldwork.

The trip took place between August 28 and September 4, 2023 and consisted of one week of isolated camping on the volcano at the coastline and along the caldera rim. Fieldwork in the Galapagos is a challenge due to extreme temperatures, terrane, and topography; however, sample collection was a huge success collecting >60 samples of ash and lava, which are currently being analysed at Trinity College Dublin. Alongside the scientific research, the trip was an incredible experience as a postgraduate student. Spending a week immersed in the environment that is the focus of my research alongside internationally renowned experts in the field was an invaluable learning experience. I am incredibly grateful to have had the opportunity to learn from such inspirational scientists in what can only be described as one of the most stunning environments in the world.

This research is part of the project “What triggers Galapagos volcano eruptions? New objectives on Alcedo volcano” funded by Trinity College Dublin (PIEX-IG-23-01) and was conducted under a research permit from the Galapagos National Park (PC-67-23). Logistics were organized by the Charles Darwin Foundation. Immense thanks are extended to all those who enabled the success of this mission.

MINERALOGICAL SOCIETY BURSARIES

As part of its objective to advance knowledge of the science of mineralogy and its applications, the Society awards bursaries to research postgraduate students. These bursaries are intended to allow students to develop, undertake, apply, and communicate research in any area of the mineralogical sciences (including crystallography, geochemistry, petrology, environmental science, and economic geology). By making these awards, the Society also seeks to encourage the development of postgraduate researchers into the next generation of researchers in mineralogy. The President and Council of the Society therefore request applications for bursary awards from students registered for a postgraduate research degree in the disciplines of mineralogy, crystallography, petrology, and geochemistry. Application deadlines and activity cutoff dates are announced at https://www.minersoc.org/postgraduate-bursaries.html.

Geochemical Society

www.geochemsoc.org

GOLDSCHMIDT® 2024 Chicago
18–23 August

GOLDSCHMIDT2024 SPECIAL!

The Geochemical Society (GS) and the European Association of Geochemistry (EAG) look forward to welcoming delegates from all over the world to Goldschmidt2024 (18–23 August, Chicago, Illinois, USA and online) for another fantastic week of geochemistry.

Read on to find out more about some of this year's highlights and visit the website at https://2024.goldschmidt.info/ for all the latest information for in-person and remote delegates.

Plenary Talks

Goldschmidt2024 will feature daily headline talks from five inspirational speakers working across a range of fields of geochemistry:

Corinne Le Quéré, Royal Society Research Professor of Climate Change Science, University of East Anglia (UK). Corinne conducts research on the interactions between climate change and the carbon cycle, including those mediated by marine ecosystems.

Lecture (Monday 11:45 CDT): *Carbon storage by the natural land and ocean reservoirs in a changing climate.*

Jiubin Chen (Gast Lecturer), professor, School of Earth-System Science (SESS), Tianjin University (China). Jiubin's major research interest is the geochemistry of metal isotopes, focusing on methodology development, fractionation mechanisms, and potential applications to various environments.

Lecture (Tuesday 11:45 CDT):
Tracing metal adventures from Earth to life.

Ellen Stofan, Under Secretary for Science and Research, Smithsonian Institution (USA). Ellen's focus is on the Smithsonian's Our Shared Future: Life on a Sustainable Planet initiative and collective research, especially in areas of biodiversity, climate change, global health, sustainable communities, and environmental justice.

Lecture (Wednesday 11:45 CDT):
Space for a Sustainable Planet.

Catherine Chauvel, CNRS Research Director at the Institut de Physique du Globe de Paris (France). Catherine is a high temperature geochemist who combines constrains provided by trace elements and radiogenic isotopes to understand how rocks form.

Lecture (Thursday 11:45 CDT):
Geochemistry and inner Earth.

Christopher Reddy, senior scientist, Department of Marine Chemistry & Geochemistry, Woods Hole Oceanographic Institution (USA). Chris studies how the ocean responds to pollution stemming from shipping accidents, oil spills, ocean dumping, and plastic.

Lecture (Friday 11:45 CDT): *Science Communication in a Crisis.*

A number of in-person and hybrid workshops for those in the early stages of their career will take place throughout the week, including the ever-popular "Meet the Plenary" lunches—a unique chance to meet the plenary speakers and discuss their talks and careers!

Early Career Workshops

Monday lunchtime	Career Paths in Geoscience: Personal Perspectives Meet the Plenary Lunch – Corinne Le Quéré Silly Hats, Serious Business: De-Mystifying the Mad, Mad World of U.S. Political Conventions
Tuesday lunchtime	Meet the Plenary Lunch – Jiubin Chen Proposal Writing Best Practices Silly Hats, Serious Business: De-Mystifying the Mad, Mad World of U.S. Political Conventions
Wednesday lunchtime	Setting up your Geochemistry Laboratory Meet the Plenary Lunch – Ellen Stofan
Thursday lunchtime	Connecting with COP: Student engagement at international climate negotiations Meet the Plenary Lunch – Catherine Chauvel
Friday lunchtime	Meet the Plenary Lunch – Christopher Reddy

To promote engagement from across the geochemistry community and related disciplines, and to ensure an equitable conference for all attendees, the GS and EAG Diversity, Equity, and Inclusion Committees have organized a number of sessions, workshops, and other events during Goldschmidt2024. Please get involved!

Diversity, Equity, and Inclusion Events at Goldschmidt

Monday 19 August	Hidden histories – towards equity, diversity and inclusion in geosciences
Tuesday 20 August	Geohealth, water quality, and engagement with marginalized and environmentally overburdened indigenous communities Goldschmidt Pride Reception
Wednesday 21 August	Developing a diverse geoscientist pipeline
Thursday 22 August	"My career in Geoscience made me an immigrant and polyglot" – Opportunities and barriers for doing research abroad

Social Program

Sunday 18 August	Icebreaker Reception & Opening of Exhibit Hall
Monday 19 August	Early Career Mixer and Chicago Blues Night
Thursday 22 August	Evening at the Field Museum

Awards to be Presented at Goldschmidt2024

The recognition of scientific excellence is one of the core activities of the European Association of Geochemistry, the Geochemical Society, as well as other scientific societies, and we are honored to be presenting the awards below at Goldschmidt2024.

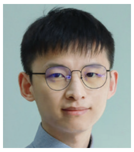
GEOCHEMICAL SOCIETY (GS)

2024 V. M. Goldschmidt Award
Donald E. Canfield (Syddansk Universitet, Denmark)

2024 Endowed Biogeochemistry Lecture
Ronnie Glud (Syddansk Universitet, Denmark)

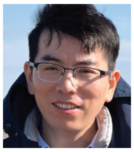
2024 Clair C. Patterson Award
Satoshi Utsunomiya* (Kyushu University, Japan)

2024 Ingerson Lecture
Fang-Zhen Teng (University of Washington, USA)



2024 F.W. Clarke Award
Jihua Hao (University of Science and Technology of China)

EUROPEAN ASSOCIATION OF GEOCHEMISTRY (EAG)



2024 Houtermans Medal
Feifei Zhang (Nanjing University, China)

2024 Epstein Science Innovation Award
Evelyn Füri* (CRPG CNRS Université de Lorraine, France)

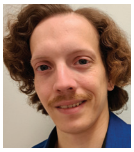
EAG/GS

2024 Gast Lecture
Jiubin Chen (Tianjin University, China)

2024 Robert Berner Lecture
Sarah E. Greene (University of Birmingham, UK)

INTERNATIONAL ASSOCIATION OF GEOANALYSTS

2024 Early Career Researcher Award
Shiqiang Huang (Colorado School of Mines, USA)



2024 Early Career Researcher Award
Birk Haertel (University of Calgary, Canada)

GS/EAG GEOCHEMISTRY FELLOWS

Dereje Ayalew, (Addis Ababa University, Ethiopia)

Jochen Brocks, (Australian National University, Australia)

Peter Cawood (Monash University, Australia)

Kent Condie (New Mexico Institute of Mining and Technology, USA)

Tetsuo Irifune (Ehime University, Japan)

Fabrizio Nestola (University of Padova, Italy)

Christine Putnis (University of Münster, Germany)

Mark Rehkämper (Imperial College London, UK)

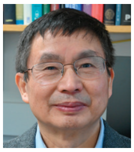
Urs Schaltegger (University of Geneva, Switzerland)

Fang-Zhen Teng (University of Washington, USA)

Jeffrey Vervoort (Washington State University, USA)

Paul Wallace (University of Oregon, USA)

Helen Williams (University of Cambridge, UK)



Youxue Zhang (University of Michigan, USA)

GEOCHEMICAL SOCIETY OF JAPAN

2024 Geochemical Journal Award
Takashi Miyazaki (Agency for Marine-Earth Science and Technology, Japan)

SHEN-SU SUN FOUNDATION

2024 Shen-su Sun Award
Ming Tang (Peking University, China)

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* Medalists are also named Geochemical Fellows by virtue of their medal.

International Association of GeoChemistry

www.iagc-society.org

THE 3rd IAGC INTERNATIONAL CONFERENCE

The **3rd IAGC International Conference** will be held in Cagliari, Italy on 16–21 June, 2025. This meeting will include the 18th Water-Rock Interaction Working Group Meeting (WRI-18), the 15th Applied Isotope Geochemistry Working Group Meeting (AIG-15), Urban Geochemistry sessions, and celebration of the 20th Anniversary of *Elements Magazine*. Visit https://sites.unica.it/wri-18/ to learn more!

IAGC 2024 AWARDS

Harmon Distinguished Service Award

Dr. W. Berry Lyons is a professor and Distinguished University Scholar in the School of Earth Sciences at The Ohio State University, USA. Dr. Lyons and his research group currently conduct research on four specific topics: (1) the biogeochemistry of Antarctic terrestrial/aquatic ecosystems and how they respond to climate change; (2) the impact of urbanization, suburbanization, and agricultural management practices on water quality; (3) the role of hydrologic variations, climate change, and anthropogenic activities on the aquatic biogeochemistry of peatlands; and (4) environmental sustainability research and education. Dr. Lyons is a former director of the Byrd Polar Climate and Research Center, and of the School of Earth Sciences at Ohio State. He has been the lead investigator of the McMurdo Dry Valleys Long Term Ecological Research program. He is also a former F.E. Ingerson Lecturer and a Fulbright Research Scholar at University Galway, Ireland. Dr. Lyons has a long history of service in the Earth sciences, including his engagement in the IAGC as Treasurer since 2008.

IAGC Fellows

Dr. Rosa Cidu is a full professor at the University of Cagliari (Faculty of Sciences), Italy. She teaches geochemistry and hydrogeochemistry courses, and has served as a tutor for several MD and PhD theses. Her relevant academic positions were MD coordinator in geological sciences (2014–2018), PhD coordinator in Earth science (2009–2012), and director of the Department of Chemical and Geological Sciences (2018–2021). As an invited professor, she attended short courses devoted to promoting the potential application of hydrogeochemical methods in environmental issues (Universidad Federal da Bahia, Brazil; Universidad Nacional de Cuyo, Argentina; Universidad Catolica del Norte, Cile; Université Mohammed V Rabat, Morocco; École Polytechnique Federal de Lausanne, Switzerland; Jena University, Germany). She has contributed to organizing international symposia, such as the 10th Water Rock Interaction Conference (WRI-10) in 2001 and the Water in Mining Environments in 2007. Prof. Cidu was an editor of conference proceedings, special issues, and associate editor of *Mine Water and the Environment*, and she serves several international journals as a reviewer. She is member of the societies IAGC, AAG, SOGEI, and SIMP, and is an elected member of the Executive Council of the International Mine Water Association.

Her research activities have been carried out within national and international research programs, devoted to water–rock interaction studies in geothermal prospecting, hydrogeochemical gold prospecting, and the environmental impact of mining on the aquatic system in collaboration with researchers from Europe, USA, Morocco, and South America. She has assessed analytical methods for the determination of trace and ultra-trace elements in different aqueous fractions, also investigating the influence of analytical errors on the interpretation of hydrogeochemical data. Many studies were devoted to the understanding of geochemical processes affecting the mobility and fate of harmful and toxic elements (e.g., REE, Hg, Cd, Pb, As, Sb, U) in river water and groundwater, with special attention to areas affected by active and past mining. Recent attention has been given to environmental issues related to the degradation of water quality compared with background values, and the potential sources of nitrate contamination. She has published several full papers in peer-review journals and books, together with many short papers in conference proceedings.

Dr. Carol Ptacek received a PhD degree (1992) in aqueous geochemistry from the Department of Earth and Environmental Sciences at University of Waterloo in Waterloo, Ontario, Canada. After graduating, she worked as a research scientist at the National Water Research Institute, Environment Canada, in Burlington, Ontario, Canada, where she advanced to Section Head for Groundwater Quality and Remediation in 2004. In 2006, she joined the Department of Earth and Environmental Sciences at the University of Waterloo as a professor of environmental geochemistry and contaminant hydrogeology. She is currently a University Research Chair in Environmental Earth Sciences.

Dr. Ptacek's research focuses on developing and implementing improved management strategies for minimizing contaminant release from mine wastes and industrial sites. Her research program integrates laboratory experimentation, field-based measurements, and utilizes a wide range of analytical techniques, including synchrotron-based spectroscopy and electrospray tandem mass spectroscopy. Highlights of her career include detailed studies to address the long-term release of metal(loids) from mine sites, co-development of the permeable reactive barrier technology for passively removing contaminants in subsurface environments, the use of biochar for remediation of mercury-contaminated sites, and application of emerging contaminants as tracers of solute transport in aquifers and aquatic systems. More than 20 of her co-authored articles appear in the IAGC journal *Applied Geochemistry*.

Vernadsky Medal

Dr. Ramon Aravena is currently an emeritus and adjunct professor in the Department of Earth and Environmental Sciences at the University of Waterloo, Canada. He has dedicated over 35 years of his professional life to advancing the field of geochemistry, particularly in the application of isotope and geochemical techniques in hydrogeology. Prof. Aravena's extensive career in academia has included teaching isotope hydrology and geochemistry courses at the University of Waterloo, as well as teaching courses on isotope hydrology in Latin America through collaborations with the International Atomic Energy Agency in the USA, under the umbrella of the National Ground Water Association, and in Europe through collaboration with European Universities. Prof. Aravena was part of the expert pool of the International Atomic Energy Agency, Vienna, Austria, for their projects worldwide.

Beyond his academic endeavors, Prof. Aravena has made significant contributions to geochemical research. His work has focused on groundwater resources and groundwater contamination stemming from agricultural, urban, mining, and industrial activities, with numerous studies conducted in Latin America, Canada, the United States, and Europe. His expertise in applying isotopic techniques to fingerprint and evaluate the sources and fate of contaminants in groundwater has had a profound impact on our understanding of environmental issues. During his career, he developed research collaboration with international universities including the University of Barcelona (Spain); La Sapienza University, Politecnico of Milan, and University of Campania Luigi Vanvitelli (Italy); University of Sao Paulo (Brazil); University of Neuchatel (Switzerland); University of La Plata (Argentina); and the University of Concepcion, Catholic University, and University La Serena (Chile). Prof. Aravena's publication record is a testament to his dedication to advancing the field. He has authored or co-authored almost 200 refereed publications, more than 70 technical papers, and 11 book chapters. Notably, he played a pioneering role in the development of compound isotope analysis (CSIA) and co-edited the influential book "Environmental Isotopes in Biodegradation and Bioremediation" in 2009. His publication record has resulted in 18,380 citations, an H-index of 78, and an i10-index of 188 (Google Scholar).

In addition to his research and teaching commitments, Prof. Aravena has served as a reviewer for major North American and European funding agencies and esteemed groundwater journals, including *Water Resources Research*, *Ground Water*, *Journal of Hydrology*, *Journal of Contaminant Hydrology*, *Environmental Science & Technology*, *Organic Geochemistry*, and *Geochimica Cosmochimica Acta*. His peer review contributions have helped maintain the rigor and quality of research in the field.

Jin Jingfu Award

Dr. Meret Aeppli is a tenure track assistant professor at EPFL, Switzerland, where she leads the Soil Biogeochemistry Laboratory. Her group aims to elucidate the fundamental processes and mechanisms that govern the biogeochemical cycling of carbon and other elements in soils. To this end, Dr. Aeppli and her group are developing novel tools and concepts to unveil the underlying drivers of element cycling, including electron transfer reactions and energy transformations. Before joining EPFL, Dr. Aeppli was a postdoctoral fellow at Stanford University, USA, from 2019 to 2022 where she investigated biogeochemical controls on carbon turnover in soils and sediments. She holds bachelor's and master's degrees in environmental sciences from ETH Zürich, Switzerland, and obtained her PhD from ETH Zürich in 2019.

Kharaka Award

Dr. Kamel Zouari is a professor at the University of Sfax, Tunisia, and is head of the Laboratory of Radio-Analysis and Environment (LRAE) at ENIS in Tunisia. From 1986–1988, Dr. Zouari was a researcher in the Laboratory of Isotope Hydrology of Paris South-Orsay University, France, where received his PhD (1988). His research focus is on isotope hydrology and water resources. Since 1995, he has worked with the International Atomic Energy Agency in Vienna, Austria, and he has collaborated as an international expert with the Arab Atomic Energy Agency since January 2002. Dr. Zouari has completed more than 150 expert missions with the IAEA to several African and Middle Eastern countries and has acted as the National Coordinator of G@GPS (Groundwater@GlobalPaleoclimate Signals) international project since 2010.

In addition to his involvement with international agencies, Dr. Zouari founded the LRAE multidisciplinary laboratory. LRAE research spans across different specialties involving the application of geochemical tracers in geologic and water resources investigations. The laboratory consists of approximately 45 members: teachers, researchers, engineers, and technicians. It is also the only laboratory in Tunisia that offers isotope analysis of water samples ($^{18}O/^{2}H$, ^{3}H, ^{13}C, and ^{14}C). Dr. Zouari has been a supervisor of numerous PhD theses (30 PhD defended) in isotope hydrology and geochemistry. His group research activities focus on the characterization of surface and groundwater resources in Tunisia to support integrated resources management (IWRM). Their research investigates water quality issues and assesses aquifer vulnerability to natural and human-induced pollution. The research activities results are published in more than 130 articles and scientific paper in peer reviewed journals focusing on groundwater geochemistry, geology, and hydrogeology.

Ebelmen Award

Dr. Yao Du was born in China in 1989 and earned his PhD from the China University of Geosciences (Wuhan) in 2017. He has been actively involved in studying the sources and fate of geogenic nitrogen and phosphorus compounds in groundwater and their impact on lake eutrophication in recent years. He proposed novel genetic models of high ammonium and high phosphorus groundwater, and thus greatly advanced our knowledge about the hydrogeochemical behavior of nitrogen and phosphorus in groundwater systems. He successfully identified the spatial variability and controlling factors of nitrogen and phosphorus loads via groundwater discharge into lakes at different scales and developed quantitative evaluation methods. His work highlighted the critical importance of quantitatively characterizing lacustrine groundwater discharge for protection and restoration of lake ecological environments. He has published 34 papers as the first or corresponding author in international peer-reviewed journals, including eight papers in top journals such as *Environmental Science & Technology*, *Water Research*, and *Water Resources Research*; and three papers in the official journal of the IAGC, *Applied Geochemistry*.

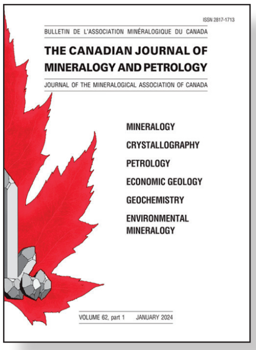
Mineralogical Association of Canada

www.mineralogicalassociation.ca

NEWS FROM *THE CANADIAN JOURNAL OF MINERALOGY AND PETROLOGY* (CJMP)

Highlights

Our January 2024 issue features papers on the *L'Enfer Norite in Québec*, highlighting its possible link to the enigma that remains Proterozoic anorthosite petrogenesis. *Enfer* also means "hell" in French, just to add additional spice to the story. Where else would magmas originate? Other contributions include a study of inclusions in Argentinian corundum, diagenetic carrollite (a Cu–Co sulfide and the main ore mineral of cobalt) from the Central African Copperbelt, gold-bearing sperrylite from Brazil, and unit cell variations in chromite indicator minerals from diamondiferous and non-diamondiferous kimberlites. New minerals appearing here include trebiskyite (the first Ti-decavanadate (TiV_9) mineral, from Montana, kodamaite (an alkali-alkaline earth fluorosilicate-hydrate from Québec), and stanevansite, a hydrous glycolate from Arizona. Ever wanted to rationalize your pyrochlore supergroup stoichiometries, but couldn't? Thanks to Fuat and Vural Yavuz, a Windows-based software is now available.



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BULLETIN DE L'ASSOCIATION MINÉRALOGIQUE DU CANADA

THE CANADIAN JOURNAL OF MINERALOGY AND PETROLOGY

JOURNAL OF THE MINERALOGICAL ASSOCIATION OF CANADA

MINERALOGY
CRYSTALLOGRAPHY
PETROLOGY
ECONOMIC GEOLOGY
GEOCHEMISTRY
ENVIRONMENTAL MINERALOGY

VOLUME 62, part 1 JANUARY 2024

Our recent, most-read publications, according to GeoScienceWorld, include the following:

Growth and Stability of Stratiform Carrollite ($CuCo_2S_4$) in the Tenke-Fungurume Ore District, Central African Copperbelt, by Bjorn Von Der Heyden, Jeffrey Dick, Ryan Rosenfels, Luke Carlton, Kristina Lilova, Alexandra Navrotsky, Tamilarasan Subramani, Brian Woodfield, and Alexis Gibson, in vol. 62 (1).

In second place, for the platinoid-inclined, is the smorgasbord that is the ***Abstracts from the 14th International Platinum Symposium and the Wager & Brown Workshop Technical Session***, featuring many authors, appearing last November (vol. 61 (6), 2023).

Close behind is ***Structural Controls on the Origin and Emplacement of Lithium-Bearing Pegmatites*** by David Silva, Lee Groat, Tânia Martins, and Robert Linnen, also from vol. 61 no. 6.

Our most cited recent paper is ***On the Attributes of Mineral Paragenetic Modes*** from Robert Hazen, Shaunna Morrison, Anirudh Prabhu, Jason Williams, Michael Wong, Sergey Krivovichev, and Marko Bermanec, from vol. 61 (4).

A WARM WELCOME TO OUR NEW CO-EDITOR, DR. GREG SHELLNUTT

"It is with great pleasure that the Mineralogical Association of Canada announces the appointment of Professor Greg Shellnutt, from the National Taiwan Normal University as co-editor of the *Canadian Journal of Mineralogy and Petrology* (*CJMP*). Professor Shellnutt is a very accomplished researcher and has a long history of journal editorship and will be a welcome addition to the *CJMP* team. Professor Shellnutt is replacing Professor Andy McDonald, from Laurentian University, whose term at *CJMP* is ending. Professor McDonald is sincerely thanked for his diligence and hard work throughout his term as co-editor."

Dan Marshall, President

OUR ASSOCIATE EDITORS

As a means of both gratefully acknowledging and promoting the efforts of researchers in the mineralogical and geoscience community who donate their time to the necessary task of facilitating effective peer review, we continue to use this space to feature our Associate Editors (AEs). In this issue, we feature two more of our relatively recent contributors from our expertise-base.

Malte Junge

Dr. Junge is employed at the Mineralogical Museum Munich, Germany, of the Bavarian Natural History Collections. His research focus is on the mineralogy of platinum-group element phases from the prominent mafic-ultramafic igneous rocks, with particular emphasis on the Bushveld Complex of South Africa, where arguably most of them are to be found, as well as the Great Dyke (Zimbabwe). His research includes not only mineral petrogenesis but also ore extraction potential and microanalytical innovations. He is a prominent member of the platinum research community, and has served as an associate editor for *CJMP* since 2022.

Gary Stevens

Gary Stevens is a professor of Earth science at Stellenbosch University in South Africa, where he runs an experimental petrology laboratory, and also serves as the Director of their Central Analytical Facilities. He was previously employed in the Economic Geology Research Unit at the University of the Witwatersrand (Johannesburg), after his PhD studies at the University of Manchester (UK). His main research themes, supported by a very active cohort of graduate students, consist of studies of metamorphism, magmatism and partial melting in the rocks associated with the Barberton greenstone belt, S-type granite petrogenesis and the anatexis of metapelitic/psammitic rocks, and investigations of the behaviour of sulfide minerals and melts during high-temperature processes. He has approximately 8000 citations, an h-index of around 50, and has served as an associate editor of *CJMP* since 2022.

WELCOMING SOME OF OUR NEW MEMBERS OF COUNCIL

The Mineralogical Association of Canada (MAC) is thrilled to introduce two of our newest professionals who will be joining its esteemed council, bringing a wealth of expertise and experience to the forefront of mineralogy to promote and advance its knowledge and allied disciplines.

Councillors (2023–2026)

Tânia Martins
(Manitoba Geological Survey)

Tânia Martins graduated with a geology degree in 2002 from University of Porto, Portugal. After a brief period in consulting, she obtained her PhD in geology in 2009 from the University of Porto, studying Li-Sn-Nb-Ta mineralization in granitic pegmatites. In 2010 and 2011, Tânia worked with Anton Chakhmouradian at the University of Manitoba on the mineralogy of alkaline rocks and carbonatites. Tânia has worked for the Manitoba Geological Survey since November 2011, both in the Mineral Deposits and the Precambrian sections. Currently, she is acting in the position of Chief Geologist, Precambrian Section of the Manitoba Geological Survey. Her research interests are in Li-Cs-Sn-

Nb-Ta mineralization in granitic pegmatites, critical mineral systems, and how these fit in the tectonic evolution of the Precambrian terrains in Manitoba.

Matthew Steele-MacInnis
(University of Alberta)

Matthew is an associate professor of geology at the University of Alberta, whose research focuses on geologic processes that involve fluids, especially formation of mineral deposits. Originally from Newfoundland, he first studied geology at Memorial University, then did a PhD at Virginia Tech, USA (2013), after which he held a Marie Curie postdoctoral fellowship at ETH Zürich, Switzerland (2013–2015). Matthew has been awarded the Hisashi Kuno award from the American Geophysical Union, the Young Scientist Award from the Mineralogical Association of Canada, and the SGA Young Scientist Award from Society for Geology Applied to Mineral Deposits.

We extend our sincerest thanks to departing councillors **Dr. L. Paul Bédard** (Department of Applied Sciences (DSA) at Université du Québec à Chicoutimi), **Dr. Emmanuelle Cecchi** (UQAT – URSTM – IRME), and departing secretary, **Dr. Philippe Belley** (Department of Earth Sciences at Memorial University of Newfoundland).

MAC TRAVEL & RESEARCH GRANT WINNERS

We congratulate Lance Dostie, Amanda Smith, and Avni Patel, each of whom received a 2023 Mineralogical Association of Canada Travel & Research Grant.

Lance Dostie is studying environmental chemistry in his fourth and final year at Trent University, Canada (2023–2024). After two years of research under the supervision of Dr. Ian Power, Lance has gained extensive research experience using various minerals to capture carbon dioxide (CO_2) from the air to mitigate climate change. His focus developed "calcium oxide looping," a technology that uses abundant limestone to source lime from heat. The lime can rapidly capture CO_2 from the atmosphere with the strategies his research employed. He subsequently gave an oral presentation at the American Chemical Society (ACS) conference in March 2023. His work laid vital knowledge on how relative humidity, mineral thickness, and air supply control the ability of lime to capture CO_2 to mitigate climate change. He demonstrated geochemical techniques such as X-ray diffraction, scanning electron microscopy, and carbon coulometry. Overall, Lance's experience allowed him to communicate a new innovative method to mitigate climate change using minerals (lime/limestone), pushing the field to explore this technology for global-scale implementation.

Amanda Smith is a MSc student at Acadia University (Canada) under the supervision of Dr. Sandra Barr. Her research is focusing on Cobequid Highlands, an enigmatic part of Avalonia in the northern Appalachian orogen. A central focus of the project is to better constrain the age(s) of these rocks using U-Pb zircon dating. She used the MAC travel grant to collaborate with experienced geochronologists at the *Senckenberg Naturhistorische Sammlungen, Museum für Mineralogie und Geologie* laboratory located in Dresden, Germany. During her eight-day stay with the institute, Amanda worked closely with Dr. Ulf Linnemann, a recognized expert in U-Pb dating techniques. She learned valuable insights on dating techniques and was trained to use the laboratory's laser ablation and inductively coupled plasma mass spectrometer (LA ICP-MS) to date her samples. After successfully processing her samples using the LA ICP-MS, she was taught the laboratory's data reduction procedure.

Avni Patel is a PhD candidate in the Department of Earth and Atmospheric Sciences at the University of Alberta. She is currently completing her PhD thesis entitled "Amorphous-to-crystalline Ca-Mg carbonate phase transformations in water-limited systems and their effects on Ni partitioning and isotope fractionation" under the supervision of Dr. Sasha Wilson, Dr. Maija Raudsepp, and Dr. Anna Harrison (University of Bern, Switzerland). Her research elucidates the effects of water activity on the (1) rates, (2) pathways, and (3) oxygen isotope signatures of crystallizing amorphous carbonates, as well as the Ni sequestration capacity of amorphous carbonates and their crystalline transformation products. The MAC Travel Grant was used to support her attendance at the 2023 AGU meeting in San Francisco, where she gave an oral presentation entitled "Humidity-driven crystallization of amorphous Ca- and Ca-Mg-carbonate and the effects on ion mobility and isotopic exchange." Her presented research contributes to our understanding of mineral–fluid interactions in the absence of bulk water and the effects of these mineral reactions on the rewriting of isotopic signatures—which may have important implications for the interpretation of paleoproxy data. The MAC Travel Grant allowed her an invaluable opportunity to showcase her research to the wider community and to network with collaborators and future colleagues.

UNDERGRADUATE AWARDS 2023

The Mineralogical Association of Canada Undergraduate Student Awards are given annually to undergraduate students (2nd year of study or higher) at a recognized Canadian university or institute of higher education for excellence in one of the specialties supported by the society: mineralogy, crystallography, geochemistry, petrology, and mineral deposits.

Congratulations to the following students who received this award in 2023:

ISAAC AWRAM, UBC Okanagan
FRANÇOIS-XAVIER BONIN, McGill University
JAMIE BURNETT, Trent University
KATHRYN CHENG, University of Toronto
CAMERON A. COATS, Lakehead University
MADISON A. DECORBY, University of Saskatchewan
FRÉDÉRIQUE BARON, Université Laval
COLLIN GERMANN, University of Regina
IRINA MALAKHOVA, University of Alberta
KRISTINA MIRONOVA, University of Waterloo
SARAH A. REBITT, University of Victoria
ANNIKA M. RICHARDSON, University of Calgary
MONET STREIT, Acadia University
TOBY M. D. BUTT, Memorial University of Newfoundland
JESSICA TOMACIC, Carleton University
TESSA WARKENTINE, University of Manitoba
CHARLOTTE MOTUZAS, University of Western Ontario

Mineralogical Society of America

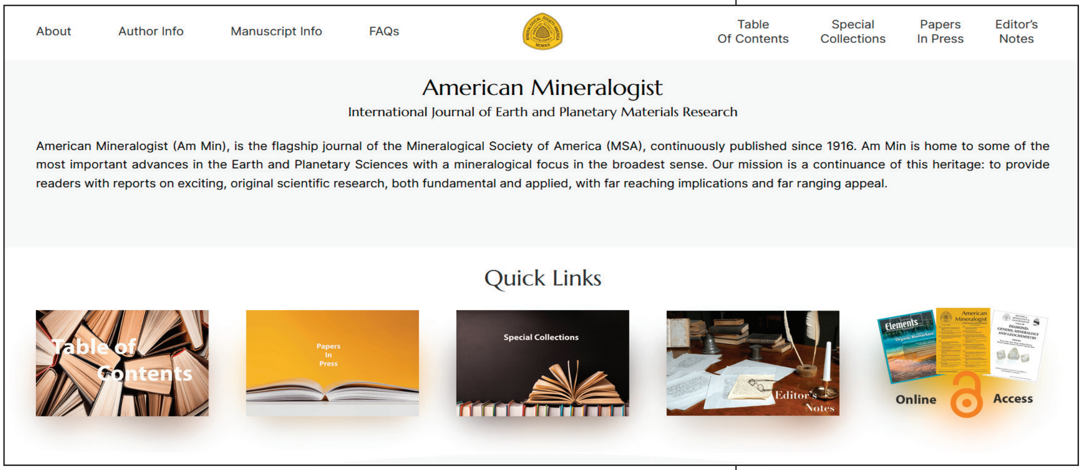
web

www.msaweb.org

PRESIDENT'S LETTER

The MSA-published journal, *American Mineralogist*, is more than 100 years old. The large number of articles that have been published between 1916 and today represent an exceptional archive of mineral sciences research and authors from many countries. MSA is proud to announce that this remarkable publication now has a beautiful new and user-friendly website: https://msaweb.org/MSA/AmMin/.

The current editors, Don Baker (McGill University, Canada) and Hongwu Xu (Los Alamos National Laboratory, USA), will be stepping down at the end of 2024 after serving for six years. MSA is therefore in the process of searching for two new editors. By tradition, one editor has expertise in petrology or geochemistry and the other in mineralogy—recognizing that these terms used to describe research disciplines are very broad and flexible. Ideally, the new editors will be identified in time for a transition period before they start their new positions in January 2025. MSA welcomes expressions of interest from potential new editors. Please contact Ann Benbow in the MSA Business Office for more information (abenbow@minsocam.org).



American Mineralogist

International Journal of Earth and Planetary Materials Research

American Mineralogist (Am Min), is the flagship journal of the Mineralogical Society of America (MSA), continuously published since 1916. Am Min is home to some of the most important advances in the Earth and Planetary Sciences with a mineralogical focus in the broadest sense. Our mission is a continuance of this heritage: to provide readers with reports on exciting, original scientific research, both fundamental and applied, with far reaching implications and far ranging appeal.

A recent member survey produced the unsurprising results that *American Mineralogist* is one of the MSA-based activities that members value the most. The journal is supported by expert staff—Rachel Russell (Managing Editor), Christine Elrod (Assistant Editor), and Kristi Bailey (Editorial Assistant)—as well as a dedicated team of about 70 Associate Editors. Together with MSA administration and a new Publications Committee, the journal is striving to improve aspects that members have identified as concerns and to grapple with major publication-related issues, such as open access and the use of artificial intelligence in research and writing.

I want to take this opportunity to thank all those who contribute to making *American Mineralogist* a premier international journal of the mineral sciences (broadly defined)—editors, staff, authors, and readers.

Donna Whitney
2024 MSA President

NOTES FROM CHANTILLY

- **Renewal Season!** Don't forget to renew your memberships for 2024, as well as subscriptions to MSA's publications. Member dues are: Regular Members and Fellows ($85); Early Career Members ($45); Student Members ($20); Senior Members ($0); Sustaining Members ($135—membership plus a $150 contribution to support MSA's many activities). You can renew via the home page of MSA's website: www.msaweb.org. At that time, we hope that you will also make a contribution to one or more of MSA's funds. These funds support our student research grants, lecture series, websites, education and outreach activities, awards, and much more.

AWARDS NOMINATION 2024 DEADLINE

Last year, MSA implemented a change in the nomination procedure for four awards (Roebling, Dana, MSA, Distinguished Public Service). The main change was to require a pre-nomination in March, in advance of the full nomination deadline of June 1. The motivations for the change were:

- to help committee chairs identify and manage conflicts of interest well in advance of the full nomination deadline; and
- to lower barriers for possible nominators by first requiring only a nominator statement and the nominee's CV (with support letters only required for the full nomination step); ideally, more nominators—representing a wider range of career stages than has typically been the case—would be inspired to submit pre-nominations.

As with any change to a long-standing procedure, there has been a transition period as MSA has worked to advertise and implement the change. The transition has been complicated by the fact that, for various operational reasons, the "old" MSA website has still been accessible, even as the "new" MSA website with the updated information superseded the old. Owing to this confusion, MSA will accept full nominations for the four awards until the usual deadline of June 1 this year. That is, nominations that did not have a pre-nomination this spring will be accepted this year. MSA is very grateful to those who submitted pre-nominations, as this has helped attain the goals of the procedure change.

If you did not submit a pre-nomination and plan to submit a new, full nomination, it would be helpful if you communicated your intent to the committee chair in advance.

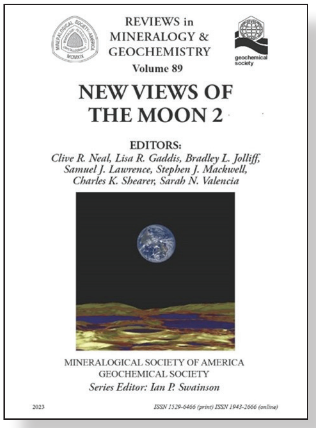
For more information, please check the Awards section of the MSA website at https://msaweb.org/awards-grants/.

MSA FELLOWS NOMINATIONS

It is again the time of the year when MSA is soliciting nominations for MSA Fellowship. Nominations for fellowship can be made by any MSA Fellow or Member by following the instructions at https://msaweb.org/fellowship-in-msa—please follow these instructions carefully so that the committee can evaluate all candidates equally. The committee asks that the nominator will compile the *nomination* (including cover page, which is available at https://msaweb.org/wp-content/uploads/2021/01/Fellowship-Nomination-Cover-Page.pdf); *all letters of support*, and the *supplementary materials* into a ***single electronic file*** before submitting the nomination package. The entire package must then be submitted to Reto Giere, the Chair of the Committee for Nominating Fellows of the Society (giere@sas.upenn.edu) no later than **June 1**.

NEW VIEWS OF THE MOON 2

This new publication of *Reviews in Mineralogy & Geochemistry* Volume 89: *New Views of the Moon 2* sold so quickly that we are reprinting. Volume editors are Clive R. Neal, Lisa R. Gaddis, Bradley L. Jolliff, Samuel J. Lawrence, Stephen J. Mackwell, Charles K. Shearer, and Sarah N. Valencia. The series editor is Ian P. Swainson, and *American Mineralogist* Managing Editor Rachel Russell is responsible for production. The volume is available in both hard copy and online via a subscription to the *Reviews* series. For more information, visit the Publications section of the MSA website: www.msaweb.org. While there, you can also view the list of MSA's other publications. The next *Reviews* volume to be published in 2024 will be Volume 90: *Exoplanets*. This volume will be accompanied by a short course at the Goldschmidt conference in Chicago, IL, USA this summer.



REVIEWS in
MINERALOGY &
GEOCHEMISTRY
Volume 89

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MINERALOGICAL SOCIETY OF AMERICA
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CONTRIBUTIONS

Many members donate to MSA by including a contribution with their annual dues and/or by responding to special appeals. The *MSA Forward* Annual Fund supports MSA's infrastructure. Depending on the wishes of the member, contributions are deposited with the principal of the MSA Endowment, the J. Alexander Speer Outreach Fund, MSA Mineralogy/Petrology Fund, J. B. Thompson Fund, Edward H. Kraus Crystallographic Research Fund, F. Donald Bloss Fund, or the Peter R. Buseck Lecture Fund. The income of these Funds is used to support MSA's research grants in crystallography, mineralogy, and petrology; the MSA Undergraduate Prizes; the Mineralogical Society of America Award; the Distinguished Public Service Award; the Dana Medal; the Roebling Medal; the website; and the Distinguished Lecturer program. If you have not done so previously, please consider contributing at the next opportunity.

DID YOU KNOW?

MSA has a new Communications Committee, chaired by Dr. Andrea Koziol. The Committee's charge is to review MSA's existing communications mechanisms (websites, MSA-Announce, MSA-Talk listserv, social media, etc.) and make suggestions for improvements, additions, and/or enhancements. Already, due to the efforts of this Committee, MSA's social media portfolio now includes LinkedIn, in addition to our other social media outlets.

Sociedad Española de Mineralogía

www.semineral.es

SEM 2025 ANNUAL MEETING IN SEVILLE

The 41st annual meeting of the Spanish Mineralogical Society (SEM) will be held in Seville on January 15–18, 2025. This special event will be co-organized with the Spanish Clays Society (SEA) at the Faculty of Chemistry, University of Seville. The organizing committee, led by Cinta Barba-Brioso and Antonio Romero Baena, comprises members from the University of Seville and University Pablo de Olavide (UPO), Seville.

The meeting will feature a one-day workshop on January 15th, focusing on cultural heritage and chaired by Pilar Ortiz (UPO). The workshop will commence with a plenary lecture and, thereafter, high-relevance international researchers will lead discussions on topics such as monumental stone restoration, historical pigments, aquatic heritage research, and glass-ceramics. During the two-day meeting, renowned researchers will provide plenary conferences followed by four sessions: Mineralogy and Geochemistry, Clays, Crystallography and Material Science, and Petrology and other topics. Each session will feature invited keynote speakers presenting the latest advances in their respective fields, along with oral presentations and poster sessions. Communications in the fields of clays, mineralogy, petrology, crystallography, geochemistry, and education can be submitted.

IMAGE SOURCE: FREETOURSEVILLA.COM.

The lectures from the workshop will be published in volume 16 of "Seminarios SEM", while the scientific contributions will be included in volume 28 of *Macla*, the journal of the Society.

The meeting will conclude with a one-day field trip on Saturday, January 18th, showcasing some geological wonders of Seville province.

We invite you to join us in Seville for this enriching scientific exchange and to explore the vibrant city. For more information and inscriptions, please visit https://gestioneventos.us.es/congreso-sem-sea-2025.

Cinta Barba-Brioso (University of Seville)
Coordinator SEM-SEA 2025

Source: freetoursevilla.com.

The Clay Minerals Society

www.clays.org

THE PRESIDENT'S CORNER

This is my last contribution to the Clay Minerals Society's President's Corner. By the time you read this column, I will have completed my tenure as the president of the CMS. For more than 20 years, I have been a member of the CMS where I felt very comfortable sharing new ideas and gaining insights from the valuable experiences of colleagues, many of whom became friends. I feel very honored and privileged to have served as president of this society and I must thank the members of the CMS for giving me this opportunity. This year as the CMS president has been a humbling experience. Indeed, add my own insights as the president was not the subject. Many people serve CMS as members of the office staff, executive committee, standing committees, ad hoc committees, councillors, representatives, and correspondents, and the volunteer commitments of each of them drive the inner workings of the society.

The geopolitical as well as the climate change context directly and indirectly affect people's lives but also scientific societies. Our society, as a small and dedicated organization, is far from being in a privileged position. In this complex context, we are at a crossroads facing a range of challenges, such as financial health, membership counts, journal quality and production, and adding value to members. We are trying to make positive changes on continuing to encourage and stimulate research in the field of clay science, disseminate research results, exchange innovative ideas, and attract young researchers. To support these goals, the ClayMinar series was inaugurated, the interface platform for annual meetings was created, our presence on social media was strengthened, e-communications were increased, the student and young researcher member status was revised, and our journal publisher was changed. I want to reiterate my thanks to all of the people who consistently donate their time to our society, seeking creative and innovative ways to bring about continual improvements for the benefit of all.

My final task is to introduce Ian Bourg, from the University of Princeton, USA, who will take over as the new CMS president. I wish Ian much success in his presidential duties for this coming year.

I look forward to meeting with you in person in Dublin, Ireland, next year at our 62nd annual meeting organized at the XVIII International Clay Conference (13–18 July 2025).

Sabine Petit, CMS President

CMS PROFESSIONAL AWARD 2024 SPOTLIGHT

Among our four distinguished professional awardees, we highlighted Dr. Prakash Malla in *Elements'* April issue. In this issue, we are delighted to showcase **Dr. Eric Ferrage** (IC2MP, Université de Poitiers – CNRS, France) as Marion L. and Chrystie M. Jackson Mid-Career Clay Scientist, and **Professor Dr. Toshihiro Kogure** (The University of Tokyo, Japan) for the CMS Pioneer in Clay Science Lecture.

Eric Ferrage obtained his PhD from the University of Grenoble (France) in 2004, followed by two postdoctoral positions at the Natural History Museum of London (UK) and the University of Nancy (France). He joined the CNRS in 2007 as a permanent researcher at the Institute of Chemistry and Material Resources (Poitiers, France). Since then, his work has focused on the multiscale analysis of the structural and dynamical properties of fluids in contact with natural phyllosilicates, using experiments (mainly X-ray diffraction) and simulations (molecular and Brownian dynamics) to understand the fate of water and solutes in the environment.

Toshihiro Kogure received his master's degree in mineralogy from the Graduate School of Science at the University of Tokyo, Japan, in 1983. After working as a researcher in a plate glass company, he joined the University of Tokyo in 1996 and obtained his PhD there. He subsequently conducted research and education at the Department of Earth and Planetary Science at the University of Tokyo until 2023. Prof. Kogure currently holds the position of an emeritus professor at the University of Tokyo and continues research involving clay science at the university and several other institutes. He has made significant contributions to the analysis of the microstructure of clay minerals or phyllosilicates, primarily using transmission electron microscopy (TEM), and elucidation of their formation mechanisms. He is particularly well known for his research on the structure of beam-sensitive clay minerals, such as kaolinite, using high-resolution TEM. Additionally, he has conducted research on biomineralization using various electron microscopic techniques. He has also made important contributions to understanding radiocesium contamination in the environment resulting from the Fukushima nuclear accidents in 2011, reporting several significant insights. He has authored over 230 original papers to date. In recognition of his contributions, he received the CMS Jackson Mid-Career Clay Scientist Award in 2010, the George Brown Lecture Award from the Mineralogical Society of Great Britain and Ireland in 2019, as well as several awards from Japanese scientific societies. He was the president of the Clay Science Society of Japan in 2021–2022.

IMPORTANT ANNOUNCEMENT

Join CMS

Join us with new types of membership! Please visit www.clays.org or contact the Business Office at cms@clays.org.

Association Internationale pour l'Étude des Argiles

www.aipea.org

AIPEA CLAY CONFERENCES

As you probably know, our community is on the move: The last meeting of the Euroclay series was successfully organized last July in Bari (Italy) by Saverio Fiore and the Associazione Italiana per lo Studio delle Argille, and the final International Clay Conference will be organized in July next year (18–25 July 2025) in Dublin by Steve Hiller, Kevin Murphy, and the Clay Minerals Group of the Mineralogical Society of the UK and Ireland (https://icc.aipea.org/). From 2027 onward, these two historical conferences will merge to give rise to a new series of conferences simply titled CLAY. This unified series of CLAY conferences will be held every other year, ideally with hosts and locations alternating between ECGA-affiliated societies and National Clay Groups (NCGs) worldwide. The first conference of this new series will be CLAY 2027 organized by the Sociedad Española de Arcillas in Madrid (Spain) in June 2027. As proposals to organize the CLAY 2029 conference will be due before the July 2025 Dublin ICC conference, it is thus time for potential organizers to begin planning and inquiring about possible venues for this future conference. As clay scientists, do not hesitate to attend these different gatherings as they testify to the vivid character of our community.

They are also great opportunities to share your research results, to benefit from the experience of other participants, to discuss and enrich that of others with your own experience and expertise, to create or broaden your network, and to generate new projects.

Bruno Lanson, AIPEA President

AIPEA NETWORK OF EARLY CAREER CLAY SCIENTISTS

In 2021, AIPEA established an Early Career Clay Scientists (ECCS) Committee for scientists within 5 years of completion of their PhD. The creation of the committee triggered the establishment of a network of ECCS, which has been very active since then. The core event to allow early career scientists to meet regularly is the online bi-monthly webinar series, an idea of ECCS Committee member Guanzheng Zhuang. Each webinar is organized by the national clay group representative, comprises one to four talks, and lasts about 1 hour. There are 30–50 connections per event. Since the launch of the event in February 2023, we have had an amazing opportunity to discover research on clay minerals from different parts of the world: from the Korean Clay Science Society, Indian Clay Group, Spanish Clay Society, The Clay Science Society of Japan, Italian Association for the Study of Clays, Croatian Clay Group, and German-Austrian-Swiss Clay Group (DTTG). The next event is planned on May 24 and will be organized by the representatives of the Clay Minerals Society. Indeed, an online event like this series is very relevant for an international network to meet regularly.

The ECCS Committee also organizes workshops for early career researchers during clay conferences. Previously, activities were carried out during the International Clay Conference in Istanbul, Turkey in 2022 and the Euroclay 2023 conference in Bari, Italy. The topics of the workshops were suggested by network members such as "Becoming a supervisor," "Writing a research grant proposal: where to start," "Clay Scientific Societies: interest in becoming a member," and "Meet the editors of the clay science journals." The committee also serves as a contact point to collect and share the information from national clay groups about available grants and other support to early career researchers to attend conferences and to disseminate information about conferences and other announcements. Last but not least, the committee manages the AIPEA Research and travel grants for early career scientists attributed every four years during the International Clay Conference and, starting in 2027, the CLAY conference series.

Liva Dzene, Chair, AIPEA ECCS Network

INTERNATIONAL CLAY CONFERENCES
aipea

XVIII ICC
Dublin, Ireland
13-18 JULY 2025

International Association of Geoanalysts

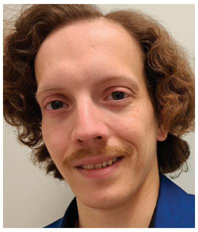
http://geoanalyst.org

WINNERS OF THE IAG EARLY CAREER RESEARCHER AWARD

Our Early Career Researcher Award was launched in 2006 and is made annually for research by a young scientist that closely reflects the goals of our Association. The award aims to promote the careers of scientists who have either developed innovative analytical methods or provided new strategies to improve data quality as applied to the chemical analysis of geological or environmental materials.

The joint winners of the 2024 Award are Shiqiang Huang (Colorado School of Mines, USA) and Birk Härtel (University of Calgary, Canada). They will be presenting their research and receiving their IAG awards at the 2024 Goldschmidt conference to be held in Chicago, USA, 18–23 August.

Shiqiang Huang manages the LA-ICP-MS/MS lab at Colorado School of Mines (CSM), USA, specialising in LA-ICP-MS techniques and their application in economic geology. During his PhD (2019–2022) at CSM, his studies were focused on in-situ Rb-Sr dating of micas and the influence of organic matter on the Re-Os dating of pyrite. After completing his PhD, he has been engaged in the U-Pb dating of zircon, garnet, and cassiterite, plus trace element analysis and mapping of various minerals and glasses. In addition, he is working to improve the U-Pb dating method for wolframite and scheelite, as well as on indicators of magma fertility in the Las Bambas deposit, Peru, which involves extensive LA-ICP-MS measurements.



Birk Härtel is a postdoctoral researcher at the Department of Earth, Energy and Environment at the University of Calgary (Canada). His field of research is method development and data analysis in low-temperature thermochronology. He received his PhD degree from Freiberg University of Mining and Technology (Germany), where he worked on the development of α-radiation-damage-based dating of zircon. He established a new calibration procedure for radiation-damage measurements on zircon with Raman microprobe that takes into account the damage sensitivity of different Raman bands. He also developed new protocols for age calculation and data evaluation for zircon-Raman and other thermochronometers, and suggested a new reference material for (U-Th)/He analysis. Currently, Birk is developing a triple-dating approach to combine zircon-Raman dating with in-situ (U-Th)/He and U-Pb dating by LA-ICP-MS.

For more information about our winners and their publications, please see www.geoanalyst.org/early-career-researcher-award/

IAG LINKEDIN® PAGE

The IAG is now using LinkedIn® to provide regular updates with announcements about IAG initiatives including, but not limited to, conferences, workshops, awards, proficiency testing schemes, reference material developments, and other exciting news from the field of geoanalysis.

Stay updated with our latest news and events by following the IAG on LinkedIn®. To start receiving these updates, simply visit https://www.linkedin.com/company/geoanalyst to visit our LinkedIn® page and click the "Follow" button.

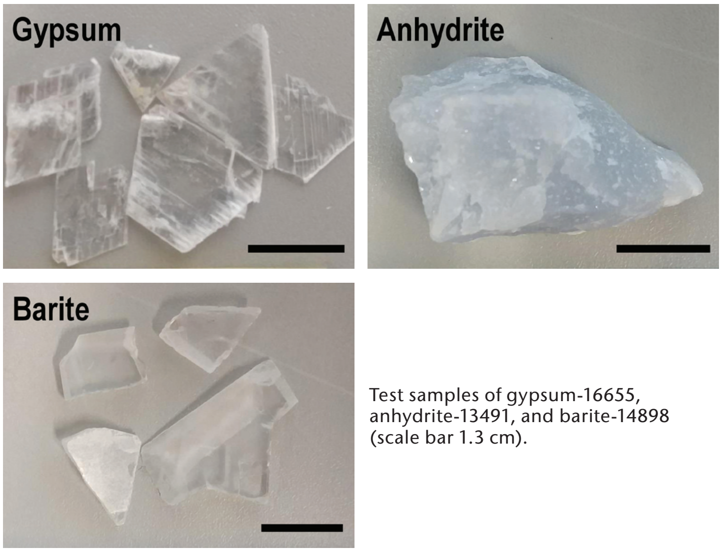
GEOANALYSIS 2024

Please join us at the 12th International Conference on the Analysis of Geological and Environmental Materials in Wuhan, China this September. The China University of Geosciences is hosting the latest in this series of international conferences devoted to developments in analytical geochemistry and their application.

Several IAG bursaries are available to assist students to attend this conference. For more information, please consult https://geoanalysis2024.aconf.org/

NEW SULPHATE REFERENCE MINERALS

The IAG supports an ongoing programme for the characterisation and distribution of high-quality materials targeting the calibration of isotope ratio determinations based on in-situ analytical methods. These include tourmalines characterised for Li, B, and O isotope ratios and apatites for Cl and O isotope ratios.



Test samples of gypsum-16655, anhydrite-13491, and barite-14898 (scale bar 1.3 cm).

Recent additions to our list of mineral reference materials are some sulphate minerals (anhydrite, gypsum, and barite) characterised for $\delta^{18}O$ and $\delta^{34}S$. These can be purchased individually or in sets consisting of either two anhydrites, two gypsums, or three barites. Full details of their characterisation can be found in Li et al. (2023).

In all cases, a single aliquot consists of approximately 100 mg of sub-1.4 mm chips of material. A full list of our reference materials and prices can be found at iageo.com – IAG members qualify for a significant discount (up to 30%).

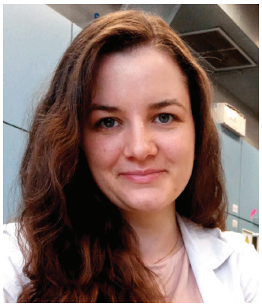
Li B and 12 coauthors (2023) Barite, anhydrite and gypsum reference materials for *in situ* oxygen and sulfur isotope ratio measurements. Geostandards and Geoanalytical Research 48: 179-205, doi: 10.1111/ggr.12533

Mineralogical Society of Poland

www.ptmin.pl

YOUNG SCIENTISTS AWARDED

The Best Master's and Best PhD Thesis Awards are given annually by the Mineralogical Society of Poland and recognize outstanding and original contributions in the area of mineralogy, petrology, and geochemistry. As always, numerous excellent contributions were submitted in 2023 and the jury decided to award two doctoral and two master's dissertations. Congratulations to the winners! We wish them good luck on their scientific paths.



The Award for the Best Doctoral Thesis of 2023 was received by **Karolina Rybka**. The thesis "Hydrotalcite-like adsorbents derived via transformation of selected minerals for the removal of anions from aqueous solutions" was supervised by Jakub Matusik and the research was carried out at the Faculty of Geology, Geophysics and Environmental Protection, AGH University of Krakow. This work was conducted at the border of mineralogy and materials engineering, and aimed to develop a facile and cost-effective method for synthesis of layered double hydroxides (LDH, hydrotalcite-like materials) via transformation of abundant minerals, i.e., magnesite, dolomite, halloysite, and hematite. The obtained LDH materials demonstrated high efficiency in removing anionic pollutants, which shows their potential applicability in the industrial wastewater treatment sector. These materials are an alternative to conventionally obtained LDH from chemical reagents. The use of various methods of structural analysis has revealed similar features and comparable affinity towards anionic pollutants. Currently, Karolina is continuing her research on layered minerals at the Institute of Geological Sciences, Polish Academy of Sciences, with a focus on clay minerals.

The Award for the Best Doctoral Thesis also went to **Tomasz Powolny**, who completed his research at the same institution as Karolina, the Faculty of Geology, Geophysics and Environmental Protection, AGH University of Krakow. His PhD thesis, entitled "Petrogenesis of Permian volcanics from the Intra-Sudetic Basin (Lower Silesia, Poland) and their alteration products," was chiefly aimed at the origin of continental non-marine spilitization of volcanogenic rocks from the Intra-Sudetic, the timing of this process concerning other regional-scale (tectono-magmatic) events recognized in SW Poland, as well as the mobility of trace elements during the formation of spilitic assemblages. His work also deciphered the magma evolution in the study area and put constraints on the relationships between spilitization and the development of coexisting moss and vein-type agate mineralization in amygdaloidal varieties of volcanic rocks. Tomasz is now a post-doctoral researcher at the Faculty of Natural Sciences (University of Silesia in Katowice, Poland), where he deals with dedolomitization processes recognized in the cave system from the Rovte area (central Slovenia). His area of interest also covers chalcedony-forming mechanisms in agate deposits worldwide, as well as the petrology of alkaline rocks from NE Vietnam.

The Best Master's Thesis of 2023 was realized by **Jacek Futrzyński**. The awarded work under the title "Uvarovite from reduced native Fe-bearing paralava, Hatrurim Complex, Israel" was carried out at the Institute of Earth Sciences, University of Silesia under the supervision of Evgeny Galuskin and Rafał Juroszek, and published as an article in *Lithosphere* (Futrzyński et al. 2023). Results of an investigation of a new genetic type of uvarovite, $Ca_3(Cr,Al,Ti^{4+}V^{3+})_2(Si,Al)_3O_{12}$, detected in unusual wollastonite-gehlenite paralava within the Hatrurim Complex in Israel, are presented in the article. This paralava contains nodules and grain aggregates of native Fe. The article presents the results of compositional, structural, and Raman spectroscopic investigations of the uvarovite. Associate minerals are also described, including rare minerals zoharite, djerfischerite, schreibersite, wüstite, tetrataenite, and Fe3N. The crystallization of uvarovite occurs in the narrow interval of oxygen fugacity, a little above the iron-wüstite buffer $fO_2 \geq \Delta IW$. The study published by Futrzyński et al. suggests the finding of "meteoritic" garnet, such as rubinite ($Ca_3Ti^{3+}2Si_3O_{12}$) in super-reduced, phosphide-bearing pirometamorphic rocks of the Hatrurim Complex.

Mateusz Wolszczak was also honored with the award for the Best Master's Thesis. The awarded work, entitled "The influence of variation in maceral composition on micro-organism activity in the copper bearing shale" was carried out at the Institute of Geological Sciences of the University of Wrocław under the guidance of Anna Potysz and Grzegorz Lis. Mateusz's master's thesis delved into the exploration of microbially induced bioleaching as a potential process to extract metals from copper-bearing black shales. The experimental approach involved incubating both autotrophic and heterotrophic bacterial strains, with a focus on quantifying the amounts of metals released into the incubation solution. One of the conclusions reached through the studies indicated that heterotrophic bacteria can effectively utilize rock-contained organic matter as a carbon source, thereby stimulating bioleaching of metals. These groundbreaking conclusions contribute significantly to our understanding of the potential applications of microbially induced bioleaching in metal recovery processes. Mateusz's dedication to advancing our knowledge on bioleaching continues as he pursues his PhD at the University of Wrocław.

Meteoritical Society

http://meteoriticalsociety.org

REPORT OF THE METEORITE NOMENCLATURE COMMITTEE

The Nomenclature Committee (NomCom) continues to receive submissions at an increasing rate each year, so we are happy to report that Earth's supply of meteorites continues to grow. Furthermore, many of the meteorite-collecting efforts that were postponed or paused since the start of the COVID-19 pandemic have since resumed (e.g., ANSMET).

Many individuals are responsible for the success of NomCom, including all the NomCom members, scientists, and engineers that improve our ability to find and detect meteorites, meteorite finders and classifiers, and repository curators. I would like to thank everyone mentioned above for their tireless efforts to ensure that the global inventory of meteorites continues to grow and that meteorites remain a rich, valuable, and accessible scientific resource for studying the Solar System rock record. I also want to acknowledge the positive impacts on the study of meteoritics from the global community of meteorite collectors. Their interests and resources help to drive the demand to find new meteorites, and the scientific community continues to benefit from those efforts.

NomCom is currently composed of nine appointed members: Francis McCubbin (Chair; NASA JSC, USA), Camille Cartier (Université de Lorraine, France), Cyrena Goodrich (Lunar and Planetary Institute, USA), Ansgar Greshake (Museum für Naturkunde, Germany), Juliane Gross (Rutgers University, USA), Katherine Joy (The University of Manchester, UK), Bingkui Miao (Guilin University of Technology, China), Devin Schrader (Deputy Editor, Arizona State University, USA), and Bidong Zhang (UCLA, USA); and three ex-officio NomCom members: Jérôme Gattacceca (*MetBull* Editor; CEREGE, France), Jeff Grossman (Database Editor, NASA, USA), and Guy Consolmagno (MetSoc Vice President; Vatican Observatory, Italy).

The NomCom is a committee of The Meteoritical Society; its purpose is to approve new meteorite names and classifications, and to establish guidelines and make decisions regarding the naming and classification of meteorites. New meteorites, dense collection areas (DCAs), type-specimen repository collections, and revisions are published through the *Meteoritical Bulletin* and the Meteoritical Bulletin Database (MBDB) (https://www.lpi.usra.edu/meteor/).

As of this writing, there are 73,953 approved meteorites in the Meteoritical Bulletin Database, including 15,653 with a full classification description.

Meteorites and Dense Collection Areas: The 2022 entries of the MBDB, totaling 3904 meteorites, have been published in the *Meteorite Bulletin*, No. 111 by Gattacceca et al. (2023). The full write-ups of 1307 non-Antarctic meteorites and supplementary tables can be found online as supporting information and in the MBDB archive. The *MB* 111 includes 11 approved falls as well as 31 new DCAs. *Meteoritical Bulletin* No. 112, containing new meteorites, DCAs, and type-specimen repositories approved in 2023, is in preparation and will be submitted later this year to *Meteoritics & Planetary Science*.

Meteorite naming: remember to send your write-ups for new and provisional names to NomCom at least four weeks before submitting your conference abstract or manuscript to journals to avoid potential issues with naming and classification, which can delay publication. The release of the write-up to the database may be held on request if there is an embargo from publishers.

Finally, please do not hesitate to contact us with questions or concerns about the NomCom, especially with suggestions for improvement (metbulleditor@gmail.com).

Francis McCubbin
Chair of the Nomenclature Committee
NASA Johnson Space Center

REFERENCE

Gattacceca J and 11 coauthors (2023) The Meteoritical Bulletin, No. 111. Meteoritics & Planetary Science 58: 901-904, doi: 10.1111/maps.13995

PAUL PELLAS / GRAHAM RYDER AWARD WINNER

The Pellas-Ryder Award for the best student paper in planetary sciences is jointly sponsored by the Meteoritical Society and the Planetary Geology Division of the Geological Society of America. It is awarded to an undergraduate or graduate student who is first author of the best planetary science paper published in a peer-reviewed scientific journal during the year prior to the award. The award has been given since 2001 and honors the memories of meteoriticist Paul Pellas and lunar scientist Graham Ryder.

Congratulations to the 2024 winner for this highly deserved honor and for leading this impressive study! We also thank everyone who submitted nomination packages and the Pellas-Ryder Award Committee for their work to make this award possible.

12 NEW ENDOWMENT GRANTS AWARDED

The Meteoritical Society Endowment Fund (https://meteoritical.org/grants/general-endowment-fund) supports a variety of activities through grants that advance the goals of the society, with selections made twice a year. The recently selected grant efforts are:

Community Grants – more details on the Meteoritical Society website

Samanta Aravena *(Universidad de Chile, Chile)* – Meteorites: Human Heritage

Nicholas Gessler *(Duke University (retired), USA)* – EL ALI in Contemporary Somali Media (Translated into English)

Richard Greenwood *(The Open University, UK)* – A New Meteorite Gallery at the Open University: A Community Science Outreach Resource

Kuljeet Kaur Marhas *(Physical Research Laboratory, India)* – 4th Symposium on "Meteoroids, Meteors and Meteorites: Messengers from Space" (MetMeSS-2024)

Peng Ni, Bidong Zhang *(UCLA, USA)* – Meteorite Information Digitization and Archiving (MIDiA) at UCLA

Lee Franci White *(The Open University, UK)* – Engaging Local Schools at the European Lunar Symposium (ELS)

Mehmet Yesiltas *(Kirklareli University, Turkey)* – Turkish All-Sky Fireball Network

Research Grants – more details on the Meteoritical Society website

Luke Alesbrook *(University of Kent, UK)* – Impacting Exotic Ices

Mayssa Daldoul *(University Tunis El Manar, Tunisia)* – Mapping Martian Craters

Yeimmy Alexandra Gutierrez Pardo *(Universidade de Brasília, Brazil)* – Genesis of the Mafic Granophyre Impact Melt Rock, Vredefort Impact Structure, South Africa

Sadeeda Marjan *(University of Kerala, India)* – Hydraulic Modelling and CRN Dating of Inlet and Outlet Valleys on Terrestrial and Martian Craters

Ran Zhao *(University of Bayreuth, Germany)* – Meteoroid Impacts

Additionally, one proposal submitted for consideration of a Community Grant was recommended by the Membership Committee to be supported out of the society's operating budget rather than the endowment fund went to **Thomas Burbine** *(Mount Holyoke College, USA)* – Information Booth at AGU.

GIFTS AND GRANTS GUIDELINES

The stated mission of the Meteoritical Society is "*to promote research and education in planetary science with emphasis on studies of meteorites and other extraterrestrial materials that further our understanding of the origin and history of the solar system.*" Besides the Society's publications, the annual scientific meetings, establishing official names for newly found meteorites, and the awards sponsored by the Society, there are other ways by which we work toward furthering our mission. This includes supporting student travel to conferences and workshops, supporting student research, assisting scientists from economically disadvantaged countries, supporting classes or field schools, especially those that bring meteoritics and planetary science to developing countries, compiling oral histories from prominent members of the Society, and supporting outreach to the broader public community on meteoritics and planetary science.

To support these activities, the Society has created an Endowment Fund. The majority of the Endowment consists of the *General Fund* which can support one-time activities that are not part of the normal Society business. The Endowment Fund also has named funds, the *Nier Fund*, the *McKay Fund*, and the *TIM Fund*, which were established for specific purposes. Details about activities supported by all of these Funds can be found under Activities Supported on the society website (https://meteoritical.org).

For those who wish to assist in this mission, donations can be made to the General Fund or to any of the specific Funds (see Ways to Contribute on the society website).

ANNUAL MEETING SCHEDULE

2024	July 28–Aug 2	Brussels, Belgium (EU)
2025	July 14–18	Perth, WA (Australia)
2026	August 9–14	Frankfurt, Germany (EU)
2027	Dates TBD	Flagstaff, Arizona (USA)

RENEW YOUR MEMBERSHIP NOW!

Please don't forget to renew your membership for 2024. Students, this is particularly important if you are interested in applying for one of our student presentation awards, as you must be a member to be eligible. You can renew online at https://meteoritical.org/membership/join.

European Mineralogical Union

www.eurominunion.org

MEDAL FOR RESEARCH EXCELLENCE 2023: JOSÉ ALBERTO PADRÓN-NAVARTA

One of the means by which the European Mineralogical Union (EMU) fosters and encourages research in the mineralogical sciences is to present a silver medal each year. The "**EMU Research Excellence Medal**" is presented to early career scientists (no more than 15 years since completion of PhD) who have made significant contributions to research and who are active in strengthening European scientific links.

The 2023 EMU Research Excellence Medal has been awarded to **Dr. José Alberto Padrón-Navarta** from the Andalusian Earth Science Institute (IACT), Granada (Spain).

Dr. Padrón-Navarta has achieved remarkable success in the fields of mineralogy and petrology, offering groundbreaking insights into the cycle and fate of volatiles through Earth's subduction zones.

Dr. Padrón-Navarta completed his PhD at the University of Granada, Spain. After undertaking postdoctoral research fellowships in Australia and France, he joined the French National Center for Scientific Research (CNRS) at Géosciences Montpellier. In 2021, he returned to IACT (Granada) under the prestigious Ramón y Cajal Fellowship.

Dr. Padrón-Navarta has made outstanding contributions to mineralogy and petrology by providing novel and detailed insights into the cycle and fate of volatiles on planet Earth through subduction zones into the deep mantle. He has integrated methods from several disciplines to discover "invisible" oceans within Earth's deep interior. He has published several landmark papers on the mineralogy, phase relations, experimental petrology, rheology, microstructure, and the geochemical consequences of subducting hydrated mafic-ultramafic lithologies. He played an instrumental role in significant papers on the importance of serpentinite in the cycling of water, sulfur, and carbon, and in the thermodynamic modelling of chromite alteration.

Dr. Padrón-Navarta published a pioneering experimental and thermodynamic study on the critical role of Tschermak's solubility in antigorite, related to the stability of serpentinites. His research also encompasses the mechanisms and thermodynamic modelling of hydrogen in nominally anhydrous minerals (NAMs) and their role in recycling water in the deep Earth. In this emerging field, he has made essential contributions on site-specific hydrogen diffusion rates and hydrogen incorporation in forsterite.

Dr. Padrón-Navarta has been invited as a keynote speaker to many prestigious international meetings (e.g., American Geoscience Union, European Geosciences Union, Goldschmidt, International Geological Conference) and has convened many sessions on the cycling of volatiles and NAMs (e.g. EGU meetings, Goldschmidt, IMA). He has established collaborations with leading researchers and institutions in these fields in Europe and worldwide. He is the recipient of prestigious European research funds, such as Marie Curie and ERC Consolidator (2022) grants, reflecting the significance, excellence, and European embeddedness of his research and achievements. He leads the IACT high-pressure experimental research group, equipped with FTIR facilities to track oxygen, water, or hydroxyls and assess volatile recycling at subduction zones.

Dr. Padrón-Navarta's research achievements are game-changers in mineralogy and petrology, providing fundamental contributions to our understanding of volatile cycles at subduction zones. This makes him a highly deserving recipient of the 2023 Research Excellence Medal of the European Mineralogical Union.

GEOSCIENCES IN GERMAN SCHOOLS

For the first time, DVGeo was represented at the federal congress of the German Association for the Promotion of STEM teaching, *MINT* teaching in German, i.e., teaching of science, technology, engineering, and mathematics, see https://MNU.de/. The aim of DVGeo is to anchor geosciences more deeply in the school curricula in Germany.

The Geosciences Olympiad, the Earth Learning Ideas exercise concepts, different modules of the MiLeKo mineralogical teaching kit, and information material from German GeoParks were presented at the DVGeo exhibition stand. The offer was completed by a lecture and workshop given by Sylke Hlawatsch (DGGV) as well as workshops offered by Carolin Otte (DMG) and Martin Meschede (DGGV). Alexandra Mauerberger (DGG), spokeswoman of the “Geosciences in Schools” group, says: “Our presence at the MNU has once again shown that we are dealing with a multitude of challenges. The response also showed how important our offer is for teachers and students.”

Geosciences at school are promoted by Sylke Hlawatsch (DGGV), Klaus-D. Grevel (DMG), Tamara Fahry-Seelig (DVGeo), Mathias Faller (geowindow.de), and Thora Schubert (Bundesgesellschaft für Endlagerung, BGE). PHOTO: DVGEO.

Tamara Fahry-Seelig (Berlin)

DMG SECTION MEETING 2024

Applied Mineralogy and Crystallography

The sections for crystallography and applied mineralogy of the German Mineralogical Society conducted their yearly workshop from the 6th to 8th of March 2024 in Bad Windsheim, Bavaria. Nineteen participants from universities (Frankfurt, Bremen, Halle, Augsburg, Jena, Munich), research institutes (Fraunhofer Institute for Chemical Technologies, ITEL – German Lithium Institute, Helmholtz Centre of Materials and Energy, Max Planck Institute for Coal Research), and of the Mineralogical State Collection Munich gave 16 talks on topics such as energy materials, circular economy, biomineralisation, and storage minerals. The young scientists used the opportunity for networking with each other and with experienced colleagues and to discuss questions of their ongoing research. The use of mineralogical methods, from X-ray diffraction via spectroscopy and electron microscopy to density functional theory, and the interactions between materials and their environment connected a variety of different topics, ranging from the synthesis of materials for energy transition via characterisation of mineral wastes and by-products to the storage of pharmaceuticals in zeolites.

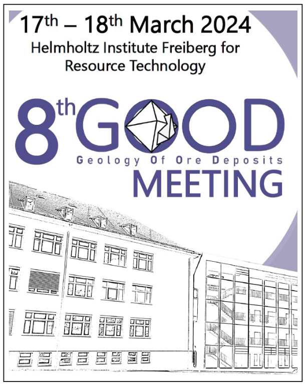
2024 Crystallography / Applied Mineralogy section meeting. Group photo in front of Hotel Späth in Bad Windsheim, Germany.

Besides the scientific exchange and socialising, the future of mineralogy as bridge between Earth and materials sciences was the dominant topic of the meeting. In this context, the emc2024 in Dublin was promoted and several participants of the meeting confirmed their participation in this event as well. Suggestions for mineralogical sessions will also be made for the annual meeting in Göttingen (2025). A possible joint meeting with the German Crystallographical Society or associations from materials sciences was discussed. Finally, for the next section meeting taking place from the 26th to 28th of March 2025 in Bad Windsheim, it was decided to switch the language to English to address a broader group of scientists—please, mark your calendars accordingly!

Daniel Vollprecht (Augsburg)

8th GOOD MEETING

Geology of Ore Deposits



On the 17th and 18th of March 2024, the 8th Geology of Ore Deposits (GOOD) meeting took place at the Helmholtz Institute Freiberg for Resource Technology. After a hiatus of about two years, we were very happy that the meeting received such good resonance: almost 40 participants travelled to Freiberg from Austria, Switzerland, Belgium, and different universities and research institutes across Germany. We enjoyed one evening of socialising over a BBQ and beers to break the ice, followed by a whole day filled with exciting talks and poster presentations on ore deposits, economic geology, geometallurgy, and archaeometallurgy. Some of the participants then embarked on the Kupferschiefer field trip of the DMG’s working group on mineral resources, which took place from the 19th to 21st of March and visited former mining and current exploration projects across Thuringia, Saxony-Anhalt, and Brandenburg.

Happy participants of the 8th GOOD Meeting in the entrance hall of the Helmholtz Institute Freiberg. PHOTO: TINA PEREIRA, HZDR.

The meeting was a great success and we would like to thank all the participants for their excellent posters and presentations! We are also grateful for the support we received from the DMG and DGGV in sponsoring student attendance, and helping us to spread the news. At the moment, we are actually still looking for someone to host the meeting next year (get in touch!), and are excited to hopefully see everyone again soon. Stay tuned.

Marie Guilcher, **Max Frenzel**, **Jan Cerny**,
and **Axel Renno** (Freiberg)

DMG SHORT COURSES IN SUMMER/FALL 2024

The DMG will support several short courses in summer/fall. All courses will be aimed primarily at advanced-level undergraduate and graduate students but, as always, are open to more senior researchers as well. Nonlocal student members of DMG will be eligible for travel support to the amount of € 100. Further information can be found at https://www.dmg-home.org/aktuelles/doktorandenkurse/. Please mark your calendars:

In-situ Analysis of Isotopes and Trace Elements by Femtosecond Laser Ablation ICP-MS, Institute for Mineralogy, Leibniz University Hannover, Ingo Horn, Marina Lazarov, Martin Oeser, Stefan Weyer, September 16–20, 2024 (s.weyer@mineralogie.uni-hannover.de)

Application of Diffusion Studies to the Determination of Timescales in Geochemistry and Petrology, Institute for Geology, Mineralogy and Geophysics, Ruhr University Bochum, Sumit Chakraborty, Ralf Dohmen, October 21–25, 2024 (sumit.chakraborty@rub.de)

TRIPLE POINT • *Cont'd from page 151*

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Société Française de Minéralogie et de Cristallographie

www.sfmc-fr.org

EXPERIMENTAL MINERALOGY, PETROLOGY, AND GEOCHEMISTRY XIX MEETING

Dear colleagues,

We are delighted to announce that the next Experimental Mineralogy, Petrology, and Geochemistry meeting, EMPG XIX, will take place at Orléans, France, on 16–19 June 2025.

The International Symposium on **Experimental Mineralogy, Petrology and Geochemistry** brings together researchers from all fields of experimental geosciences with a focus on material science and numerical modelling. The meeting offers a unique opportunity for research presentations and discussion on experimental work.

1 September 2024	Abstract Submission, Grant, and Student Helper Applications Open
1 January 2025	Grant Application Deadline
1 January 2025	Abstract Submission Deadline
1 January 2025	Early Registration Deadline
16–19 June 2025	EMPG 2025

More information about submission, registration, and accompanying events will soon be available. Please regularly check our website: https://empg2025.sciencesconf.org/

Yours faithfully,

Fabrice Gaillard, on behalf of the organisers

Working in the metal-free cosmochemistry laboratories at the Max Planck Institute for Solar System Research

When it comes to finding the smallest differences in the isotopic composition of meteorites and rocks from the Earth, Moon, and Mars, special metal-free clean rooms and laboratories are required. For this reason, the German special equipment manufacturer MK Versuchsanlagen und Laborbedarf e.K. has installed completely metal-free, chemically resistant laboratories at the Max Planck Institute for Solar System Research in Goettingen (Germany). The fact that the entire laboratory could be realized in a container solution on the roof of the Max Planck Institute for Solar System Research within a very short time was ideal for the conditions on site.

Preparation of samples without contamination

Here, the Cosmochemistry working group of the Planetary Sciences Department conducts research into the formation and development of the Solar System and the physical and chemical processes during the accretion and differentiation of asteroids and terrestrial planets. The isotopic compositions of meteorites and rocks from the Earth, Moon, and Mars used in the study are determined by using state-of-the-art methods of multi-collector plasma and thermionic mass spectrometry.

All samples are prepared and chemically processed in modern metal-free clean room laboratories under contamination-free conditions. Working in a metal-free environment is essential, as the smallest impurities from microscopic dust particles of rock or corroding metals would fundamentally distort the research results. A metaphorical comparison: it is like spreading a drop of paint evenly over several Olympic-sized swimming pools.

A metal-free clean room differs significantly from conventional laboratories and clean rooms that are made of stainless steel. Even the vapours of the highly concentrated acids would attack metal. The resulting metal particles would enter the room air and could render samples unusable.

Some exemplary activities of the scientists in Goettingen are:

1. Purification of mineral acids (HCl, HNO_3, HF) by distillation: Teflon distillation units are used in a special laboratory fume hood (workstation acid distillation) for the purification of mineral acids.

The MK Mobile Lab on the roof of the Max Planck Institute for Solar System Research in Goettingen, Germany. *Photos (4): MK Versuchsanlagen*

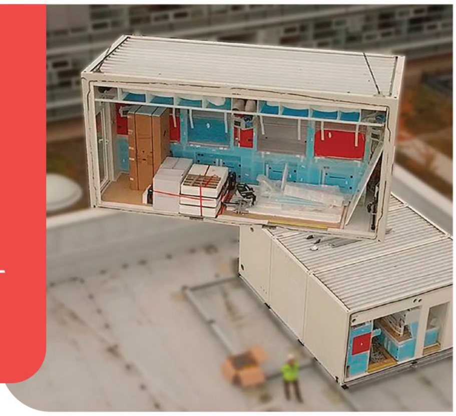
2. Cleaning of materials (e.g., teflon cup, pipette tips, centrifuge tubes, chromatography columns) in fume hoods.
3. Insertion of samples into the laboratory via a material airlock.
4. Weighing the samples using two scales in the weighing room of the metal-free container laboratory.
5. Digestion and evaporation of meteorite and rock samples in laminar flow workstations.
6. Element separation in the metal-free laminar flow workstations using ion exchange chromatography.
7. Evaporation of the purified sample solution in the evaporation system in preparation for mass spectrometry.
8. Transfer of the final sample solutions from the metal-free laboratory to the mass spectrometry room via a material airlock for the measurement of their isotopic composition.

In addition to such mobile container solutions, the German company MK Versuchsanlagen and its U.S. subsidiary MK Metalfree Corp. also offer metal-free cleanrooms and laboratories as room-in-room solutions in new or old buildings.
Further information: www.mk-versuchsanlagen.de

Kontakt:
German headqaurter
MK Versuchsanlagen und Laborbedarf e.K.
Stueckweg 10
35325 Muecke
Germany

The weighing room.

Special laminar flow fume hoods for acid distillation and sample preparation.



2024

June 3–6 **61st Clay Minerals Society Meeting**, Honolulu, HI, USA. Web page: www.clays.org/2024-meeting/.

June 23–27 **American Conference on Neutron Scattering (ACNS 2024)**, Knoxville, TN, USA. Web page: ceramics.org/event/american-conference-on-neutron-scattering-acns-2024/.

June 23–28 **Gordon Research Conference: Geochemistry of Ore Deposits for a Low Carbon Society**, Newry, ME, USA. Web page: www.grc.org/geochemistry-of-mineral-deposits-conference/2024/.

June 23–28 **Asia Oceania Geosciences Society (AOGS) 21st Annual Meeting**, Gangwon-do, South Korea. Web page: www.asiaoceania.org/aogs2024/public.asp?page=home.asp.

July 7–12 **74th American Crystallographic Association Annual Meeting**, Denver, CO, USA. Web page: https://www.acameeting24.com.

July 8–12 **12th International Kimberlite Conference**, Yellowknife, Canada. Web page: https://12ikc.ca.

July 8–12 **Eighth International Conference on Mars Polar Science and Exploration**, Whitehorse, Yukon, Canada. Web page: www.hou.usra.edu/meetings/marspolar2024/.

July 14–18 **International Congress on Ceramics**, Montréal, QC, Canada. Web page: ceramics.org/event/international-congress-on-ceramics/.

July 14–18 **Gordon Research Conference: Research at High Pressure: Exploring Matter Beyond Equilibrium**, Holderness, NH, USA. Web page: www.grc.org/research-at-high-pressure-conference/2024/.

July 15–19 **Tenth Annual Earth Educators' Rendezvous**, Philadelphia, PA, USA. Web page: serc.carleton.edu/earth_rendezvous/2024/index.html.

July 22–25 **Tenth International Conference on Mars**, Pasadena, CA, USA and virtual. Web page: www.hou.usra.edu/meetings/tenthmars2024/.

July 28–August 1 **Microscopy & Microanalysis 2024**, Cleveland, OH, USA. Web page: mmconference.microscopy.org/.

July 28–August 2 **87th Annual Meeting of the Meteoritical Society**, Brussels, Belgium. Web page: metsoc2024.brussels/.

August 4–9 **Gordon Research Conference: Capturing Timescales of Rock Deformation**, Lewiston, ME, USA. Web page: www.grc.org/rock-deformation-conference/2024/.

August 5–9 **3rd International Training School "Empirical and Ab Initio Thermodynamic Models of Minerals and Melts"**, Athens, Greece. Web page: sites.google.com/view/3rdmeltsgr.

August 7–8 **4th Annual Workshop on "Resilient Supply of Critical Minerals"**, Rolla, MO, USA. Web page: sites.mst.edu/criticalmineralsworkshop/.

August 12–13 **Museums & Mineralogy 10**, Cardiff, Wales. Web page: mm-10.org/.

August 17–18 **RiMG (Reviews in Mineralogy and Geochemistry) short course: Exoplanets: Compositions, Mineralogy, Evolution**, Chicago, IL, USA. Web page: conf.goldschmidt.info/goldschmidt/2024/meetingapp.cgi/Session/6035.

August 18–22 **American Chemical Society Fall Meeting**, Denver, CO, USA. Web page: www.acs.org/meetings/acs-meetings/fall.html

August 18–23 **European Mineralogical Conference**, Dublin, Ireland. Web page: emc-2024.org/.

August 18–25 **2024 Goldschmidt Conference**, Chicago, IL, USA. Web page: 2024.goldschmidt.info

August 25–31 **37th International Geological Congress (IGC)**, Busan, Republic of Korea. Web page: www.igc2024korea.org/.

August 26–30 **European Crystallographic Meeting (ECM-24)**, Padova, Italy. Web page: www.ecm34.org/.

August 30–September 2 **18th European Powder Diffraction Conference (EPDIC18)**, Padova, Italy. Web page: epdic18.org/.

September 3–6 **Granulites & Granulites 2024**, Verbania, Italy. Web page: granulites2024.sfmc-fr.org/.

September 12–14 **2024 Annual Meeting of the Japan Society of Mineralogical Sciences**, Nagoya University, Japan. Web page: confit.atlas.jp/guide/event/jams2024/top

September 15–19 **12th International Conference on the Analysis of Geological and Environmental Materials, Geoanalysis 2024**, Wuhan, China. Web page: geoanalysis2024.aconf.org.

September 16–20 **13th International Conference on Acid Rock Drainage (ICARD 2024)**, Halifax, NS, Canada. Web page: icard2024.cim.org/.

September 22–25 **Geological Society of America National Meeting**, Anaheim, CA, USA. Web page: community.geosociety.org/gsa2024/home.

September 23–25 **SerpentineDays**, Granada, Spain. Web page: serpentinedays.org/serpentine-days-2024-granada/.

September 30–October 4 **7th Orogenic Lherzolite Meeting**, Oviedo, Spain. Web page: lherzolite2024.github.io/.

October 6–10 **ACerS 126th Annual Meeting with Materials Science and Technology 2024**, Pittsburgh, PA, USA. Web page: ceramics.org/event/acers-126th-annual-meeting-with-materials-science-and-technology-2024/.

October 14–18 **30th International Applied Geochemistry Symposium (IAGS)**, Adelaide, SA, Australia. Web page: iags2024.com.au/.

October 17–20 **29th Meeting of the Petrology Group of the Mineralogical Society of Poland**, Bobrovec, Slovakia. Web page: ptmin24.webnode.sk/.

October 20–24 **Ross International Symposium: Geochemistry for Sustainable Development, SIPS 2024**, Crete, Greece. Web page: www.flogen.org/sips2024/.

November 1–4 **44th New Mexico Mineral Symposium**, Socorro, NM, USA. Web page: geoinfo.nmt.edu/museum/nmms/home.cfml#.

November 8–9 **Swiss Geoscience Meeting (SGM 2024)**, Basel, Switzerland. Web page: geoscience-meeting.ch/

November 25–28 **International Conference on Clays in Natural and Engineered Barriers for Radioactive Waste Confinement (Clay Conference) 2024**, Hannover, Germany. Web page: clayconference2024.de/.

December 1–6 **MRS Fall Meeting**, Boston, MA, USA. Web page: www.mrs.org/meetings-events/fall-meetings-exhibits/2024-mrs-fall-meeting.

December 9–13 **American Geophysical Union Fall Meeting**, Washington DC, USA. Web page: https://www.agu.org/annual-meeting.

2025

January 26–31 **49th International Conference and Expo on Advanced Ceramics and Composites (ICACC2025)**, Daytona Beach, FL, USA. Web page: ceramics.org/event/49th-international-conference-and-expo-on-advanced-ceramics-and-composites-icacc2025/.

March 23–27 **American Chemical Society Spring Meeting**, San Diego, CA, USA. Web page: forthcoming.

June 19–23 **Penrose 2025: Eclogites in space and time—bridging the micro to planetary scales**, Rohnert Park, CA, USA. Web page: www.geosociety.org/GSA/Events/Penrose_Conferences/GSA/penrose/current.aspx.

June 27–July 4 **ECROFI 2025 - European Current Research On Fluid and Melt Inclusions – Dedicated to Jacques Touret**, Torino, Italy. Web page: forthcoming.

July 6–11 **Goldschmidt Conference**, Prague, Czech Republic. Web page: forthcoming.

July 13–18 **AIPEA International Clay Conference**, Dublin, Ireland. Web page: icc.aipea.org/.

July 14–18 **88th Annual Meeting of the Meteoritical Society**, Perth, Australia. Web page: forthcoming.

July 16–21 **Third IAGC International Conference (IAGC-3)**, Cagliari, Italy. Web page: sites.unica.it/wri-18/.

July 18–23 **75th American Crystallographic Association Annual Meeting**, Lombard, IL, USA. Web page: forthcoming.

July 20–25 **Materials Challenges in Alternative & Renewable Energy 2025 (MCARE 2025) combined with the 6th Annual Energy Harvesting Society Meeting (EHS 2025)**, Bellevue, WA, USA. Web page: ceramics.org/event/materials-challenges-in-alternative-renewable-energy-2023/.

August 17–21 **American Chemical Society Fall Meeting**, Washington DC, USA. Web page: forthcoming.

September 19–23 **Penrose 2025: Eclogites in space and time—bridging the micro to planetary scales**, Rohnert Park, CA, USA. Web page: geosociety.org/GSA/Events/Penrose_Conferences/GSA/penrose/current.aspx.

September 22–25 **Geological Society of America Annual Meeting**, San Antonio, TX, USA. Web page: forthcoming.

October 19–22 **Geological Society of American Annual Meeting**, San Antonio, TX, USA. Web page: forthcoming.

November 7–9 **45th New Mexico Mineral Symposium**, Socorro, NM, USA. Web page: forthcoming

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March 22–26 **American Chemical Society Spring Meeting**, Atlanta, GA, USA. Web page: forthcoming.

June 22–24 **7th International Workshop on Mechanisms and Modelling of Waste/Cement Interactions**, Bern, Switzerland, Web page: www.empa.ch/cement2026.

August 11–16 **27th Congress and General Assembly of the International Union of Crystallography (IUCr)**, Calgary, Canada. Web page: www.iucr2026.org.

August 30–September 2 **16th Quadrennial IAGOD Symposium**, Porto, Portugal. Web page: iagod.org/.

October 11–14 **Geological Society of America Annual Meeting**, Denver, CO, USA. Web page: forthcoming.

November 6–8 **46th New Mexico Mineral Symposium**, Socorro, NM, USA. Web page: forthcoming.

The meetings convened by the societies participating in *Elements* are highlighted in yellow. This meetings calendar was compiled by Andrea Koziol.

ELEMENTS' ONLINE EVENTS CALENDAR

www.elementsmagazine.org/events

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