Noble Gas Thermochronology

MARISSA M. TREMBLAY, EMILY H.G. COOPERDOCK, and PETER K. ZEITLER, Guest Editors

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Sedimentary Provenance
Faults, Fluids, and Heat
Deep-Time Exhumation Histories
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Noble Gas Thermochronology

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Marissa M. Tremblay and William S. Cassata

Lazed and Diffused: Untangling Noble Gas Thermochronometry Data for Exhumation Rates
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The Clay Minerals Society (CMS) began as the Clay Mineralogists’ Committee of the US National Academy of Sciences – National Research Council in 1952. In 1962, the CMS was incorporated with the primary objective of stimulating research and disseminating information relating to all aspects of clay science and technology. The society holds annual meetings, workshops, and field trips, and publishes the Clay Minerals and the CMS Workshop Lecture Series. Membership benefits include reduced registration fees to the annual meeting, discounts on the CMS Workshop Lectures, and eligibility to become an ordinary member. Day-to-day administration of the society is handled by an executive committee, with officers in charge of each of the society’s subcommittees. Website: www.claymin.org Contact: cms@claymin.org

The Sociedad Española de Mineralogía (SEM) is an international organization for mineralogists and related disciplines. Founded in 1975 to promote research in mineralogy, petrology, and geochemistry, the SEM organizes annual conferences and field trips, invites lecturers, and publishes the journal, Semillas. Membership benefits include subscriptions to the Sociedad Española de Mineralogía and the International Society of Applied Geochemistry. Website: www.sem.org Contact: office@sem.org Society News Editor: John Carranza (jmcarranza@gmail.com)

The Geological Society (GS) is a learned society founded in 1807 for the advancement of knowledge of the Earth through the study of geology and its relationship to other disciplines. The society organizes annual meetings, international conferences, and symposia, publishes the Journal of Geology, Geological Society Special Publications, and reviews. Membership benefits include subscriptions to the Journal of Geology, reduced registration fees, and a discount on the society’s annual meeting. Website: www.ggb.org.uk Contact: membership@ggb.org.uk Society News Editor: Toreh Brazil (toreh.brazil@ucl.ac.uk)

The Polish Towarzystwo Mineralogiczne (Mineralogical Society of Poland; MTMP) was founded in 1969, draws together professionals and amateurs interested in mineralogy, crystallography, petrology, geochemistry, and economic geology. The society promotes links between mineralogical science and education and technology through annual conferences, field trips, invited lectures, and publishing. Membership benefits include subscriptions to Mineralogie and Elements. Website: www.ptmmin.pl Contact: ptmin@ptmmin.pl Society News Editor: Zbigniew Sawłowicz (zbigniew.sawlowicz@uj.edu.pl)

PARTICIPATING SOCIETIES

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 list of honorary fellows is reflected in the list of honorary fellows, which include M. v. Laue, G. v. Tschermak, F. C. W. Correns, H. W. Strunz, to name a few. The society coorganizes the DMG major awards and the gap with other communities such as materials science, solid state chemistry, physics, and environmental sciences. The society especially tries to support young researchers, e.g., to attend conferences and short courses. Membership benefits include the European Journal of Mineralogy, Elements, and GCA. Website: www.dmgs.org Contact: post@dmgs-home.org Society News Editor: Klaus-Dieter Grevel (klaus-dieter.grevel@rub.de)

The Società Italiana di Mineralogia e Petrologia (SIM; Italian Society of Mineralogy and Petrology, SIM) was founded in 1929 as a national body representing all researchers dealing with mineralogy and related disciplines. Membership benefits include receiving the European Journal of Mineralogy, Elements, and GCA, and reduced registration fees for SIM meetings and short courses. Membership benefits include the European Journal of Mineralogy, Elements, and GCA. Website: www.socominpet.it Contact: segreteria@socominpet.it Society News Editor: Costanza Bonadiman (bdc@uni.it)

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The Japanese Association of Mineralogical Sciences (JAMS) was established in 2007 by merging the International Mineralogical Association’s Commission on Ore Deposits (IAGOD) and the Japanese Association of Mineralogists, Petrologists, and Economic Geologists, which was established in 1928. JAMS covers the wide field of mineral sciences, geochemistry, and geology. Membership benefits include receiving the Journal of the Japanese Association of Mineralogists, Petrologists, and Economic Geologists (JAMES) and the Japan Association of Mineralogical Sciences (JAMS) and the Japan Association of Mineralogical Sciences (JAMS). Website: www.jams.or.jp Contact: miyazaki@jams.or.jp Society Editor: Atsuko Koizumi (koizumi@geol.tusukuba.ac.jp)

The International Association on the Genesis of Ore Deposits (IAGOD) was established in 1963 to promote international cooperation and increase knowledge in the field of the genesis of ore deposits and is affiliated with the International Union of Geological Sciences (IUGS). The society organizes biennial symposia and cosponsored sessions at the International Geosciences & Biennial Meetings. The IAGOD working groups and commissions promote ore deposits research and sponsor international speaker series. Membership includes reduced fees for our meetings, subscriptions to our flagship journal Ore Geology Reviews and other publications, and a subscription to Elements. Website: www.iagod.org Contact: http://iagod.org/node/87 Society News Editor: Simon Jowitt (simon.jowitt@uni.edu)

The Swiss Society of Mineralogy and Petrology was founded in 1948 as an international society from academia and industry and jammed to remote promote knowledge, in the fields of mineralogy, petrology, and geochemistry and to disseminate it. It is an umbrella organization for the many subdisciplines jointly with the national geological and palaeontological societies. Website: bern.gge.ch Contact: bern.gge.ch/Society News Editor: Tomislav Vennemann (torsten.vennemann@uni.ch)
A DATE FOR ODYSSEUS

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Jon Blundy

Time is a big deal for us geologists. Rates of Earth processes range from those operating at the one-week (isotope exchange in sea water) to the one billion year scale (uranium decay to dating rocks), as well as new developments in mass spectrometry. Lord Rutherford would be most impressed.

Time is not the unique province of the geologist. Historians, archaeologists and anthropologists also rely on chronometers to reconstruct a younger, but no less important, swath of Earth history. To both radiometric tools (e.g., radio-carbon dating of organic matter) and diffusive tools (e.g., water diffusion in obsidian) these scholars add written and verbal testimony. Often Bayesian statistical methods are used to bring these different approaches into conformity, but cases remain where the written testimony is not entirely reliable and geological chronometers are not entirely suitable. This is an exciting interdisciplinary frontier for both Earth sciences and archaeology, and one destined to stir up controversy and debate.

As I write this editorial on the Ionian Greek island of Ithaca, I am reminded of a particular opportunity at this new frontier. Ithaca is widely held to have been the home of Odysseus, the Greek king whose exploits are documented in fantastic detail in the epic poems of Homer. After ten long years fighting the Trojans and a further ten action-packed years getting lost on the way home, Odysseus was eventually reunited with his patient bride, Penelope. It is one of the more celebrated homcomings in literature. But did it really take place on Ithaca?

There are several inconsistencies in Homer’s description of Ithaca. Unlike today’s rugged island, Odysseus’ Ithaca is flat and the westernmost of the Ionian islands: “lies low, furthest from the mind-numbingly slow (mantle convection) to the catastrophically fast (volcanic eruptions) with everything in between. Geologists move effortlessly from units of seconds to Mega years in a way that often confounds scientists in other disciplines; no geologist is unaware of humanities’ fleetingly brief tenure of the planet in the grand scheme of things.

Not surprisingly, devising ways of measuring time is a central plank of the Earth sciences. Most so-called chronometers fall broadly into two categories: those involving radioactive decay and those involving diffusion. The former clock ticks relentlessly at a rate dependent only on the abundance of the parent isotope undergoing decay – a classic first-order process. The latter clock ticks sporadically at a rate governed by the gradient in chemical potential and the prevailing temperature – a second-order process.

The original concept of applying radioactive decay to dating rocks is attributed to Ernest (Lord) Rutherford who proposed, in the early 1900s, that the concentration of helium (a proxy for alpha particles) in uranium-bearing materials could be used to estimate time. Over the subsequent century or so, many variants of the radiometric clock have been devised, exploiting our ever-increasing ability to measure different isotopes using mass spectrometers. Diffusion chronometry has had a slightly less steady trajectory, although its roots may be traced to Joseph Fourier’s seminal work on conduction heat flow (also a diffusive process) published in 1822. The challenge in applying diffusion chronometry has been to know both diffusion coefficients (less tractable and more variable than radioactive decay constants) and temperature, which is rarely constant throughout any geological process. Here, complex numerical modelling, as well as analytical sophistication, is required.

This issue of Elements elegantly draws together these two ways of telling (the geological) time. To exploit the radiometric chronometer, radiogenic helium is measured in rocks and minerals: the diffusive clock is exploited by measuring the spatial distribution of helium, either by high-resolution microbeam analysis or by progressive heating of the sample, and monitoring the resultant stepwise helium release. The result is a cutting-edge time piece that is applicable over a very wide time range and to problems that do not always lend themselves to one or other chronometer used in isolation. Examples in this issue include landscape evolution (page 311), fault movement (page 319), and extra-terrestrial processes (page 331). To this lay reader, the potential is considerable and is set to be enhanced by new generations of numerical models applied to large datasets, as well

Cont’d on page 296

Odysseus returns to Penelope. © The Trustees of the British Museum CC BY-NC-SA 4.0.
ABOVE THIS ISSUE

Noble gases are uniquely stable and resistant to forming bonds. It is their stability and non-reactive nature which drives their practical uses. Our most common encounters with noble gases are probably with colorful helium-filled balloons or with the ever-present glow of cities from neon lights. As scientists, we have many other applications for noble gases, such as refrigerants for analytical equipment, inert atmospheres for storage of reaction-sensitive materials, ionizing gases in Geiger counters, and as gas- and excimer lasers.

Marissa Tremblay, Emily Cooperdock, and Peter Zeitler, guest editors of this issue of *Elements*, introduce us to another application of noble gases: thermochronology. In addition to editing the six thematic articles on the utility of noble gas thermochronology to fundamental geological questions (e.g., What are the rates of exhumation? How does a fault zone evolve?), these guest editors also wrote this issue’s Toolkit, which introduces the different methods used to extract, isolate, and measure the concentration of noble gases (and their isotopes) derived from natural materials. We hope you enjoy reading about this fascinating topic!

CONTRIBUTE TO ELEMENTS’ FEATURE COLUMNS

*Elements* regularly publishes short, 1- to 2-page, feature columns in addition to its thematic content and society news items. The different types of feature columns are summarized below. You are welcome to submit your ideas for future feature columns to Jodi Rosso (jrosso.elements@gmail.com) or to the individuals mentioned below.

**Triple Point** raises issues of broad interest. This feature has explored different aspects of our science (e.g., teaching, publishing, historical aspects), our societies, funding, science policy, and political issues that impact us. Contact Jodi Rosso (jrosso.elements@gmail.com).

**People in the News** highlights the accomplishments of members of our communities, awards they have received, or exciting new projects in which they are engaged. We rely on members to bring to our attention the relevant people. Contact Jodi Rosso (jrosso.elements@gmail.com).

**Mineralogy Matters** highlights where mineralogy (broadly defined) is of fundamental importance to understanding an issue or a problem in topic areas that can range from Earth resources to the global environment. Contact Jodi Rosso (jrosso.elements@gmail.com).

**Elements’ Toolkit** presents new technological developments of interest to our readers. Articles focus on instrumental techniques, analytical and compositional methods, as well as on laboratory design. Contact Jodi Rosso (jrosso.elements@gmail.com).

**Meeting Calendar** is a list of workshops, short courses, and conferences that are of interest to the mineralogy–geochemistry–petrology community. Contact Andrea Kozioł (akozio@udayton.edu) to add your meeting to the list.

**CosmoElements** keeps us in touch with exciting discoveries in cosmochemistry by providing short articles, which can be used in the classroom, or reports on space missions that carry geochemical and mineralogical instruments. Contact Cari Corrigan (corrigan@si.edu).

**Life in Science** focuses on ways to make all stages of your career as a geoscientist (as student, professional, or retiree) easier and more satisfying. Contact Penny King (penny.king@anu.edu.au).

**Teaching Mineralogy, Geochemistry, and Petrology** presents ideas and tools for effective teaching and the resources that are available to instructors. With recent demand for online instructional tools, such a column is more important than ever! Contact Jodi Rosso (jrosso.elements@gmail.com).

**GEOCHRONOLOGY**

has a lot going for it in terms of geography, but beyond the wrong name there’s another catch. Paliki is connected to the rest of Kefalonia by a thin strip of land, up to 180 m above sea-level. This at first insuperable problem has been explained by a group of geologists and archaeologists, known as the Odysseus Unbound Foundation, to be the result of a giant landslip filling a narrow seaway sometime between Odysseus’ homecoming and the present day. Such landslides are not uncommon in tectonically active regions. And Kefalonia straddles a plate boundary.

Resolving the hypothesis that Odysseus returned to modern-day Paliki rather than modern-day Ithaca is crying out for a suitable chronometer. Dating faulted surfaces and landslide deposits is no easy matter. The Odysseus Unbound Foundation is no doubt exploring possible dating methods as I write. I rather hope they might read this issue of *Elements* to see just what insights thermochronology can offer. This is just one of a number of exciting interdisciplinary opportunities in this rapidly evolving field.

**Jon Blundy**, Principal Editor

1 Read more at www.geolsoc.org.uk/Geoscientist/Archive/May-2018/Ithaca-the-story-continues
From our inventory of over 200,000 specimens, we can supply your research specimen needs with reliably identified samples from worldwide localities, drawing on old, historic pieces as well as recently discovered exotic species. We and our predecessor companies have been serving the research and museum communities since 1950. Inquiries by email recommended.

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IAG Young Scientist Award 2021
The International Association of Geoanalysts (IAG) sponsors an annual award for research by a young scientist that closely reflects the goals of our Association.

The award promotes the careers of young scientists who have either developed new analytical methods and strategies to improve data quality or characterised reference materials relevant to the field of geoanalysis.

Eligibility is limited to scientists who are currently pursuing a higher degree in a field related to geoanalysis or who have completed their university education within the past three years.

The candidate must be nominated by a senior scientist from the geosciences community.

The award is based upon first-authored peer-reviewed papers published in an international journal.

The award consists of an 18-month free membership of the IAG and a cash prize of $1000 US. The awardee will be expected to present their work at the 2021 Goldschmidt conference in Lyon, France where the award ceremony takes place. The registration fee for this conference will be paid as part of this award.

Submission requirements, further details and the nomination form can be downloaded from the IAG website: http://www.geoanalyst.org/awards/

Nominations must be received by 31 October 2020
SAILING THE SEA OF OPEN ACCESS: CELESTIAL NAVIGATION OR DEAD RECKONING?1

Kevin P. Murphy2 and Aaron B. Johnson3

INTRODUCTION/HISTORICAL BACKGROUND

In 2013, *Elements* published an article by Speer et al. entitled “Open Access: A Current Perspective”. The present article is intended to provide an update on the subject and to discuss how the open access landscape has changed since then.

The notion of open access (OA) began to gain traction in the mid–late 1990s (Laakso et al. 2011). The Bethesda Statement (2003) followed a year later with the definition of ‘open access’ as: “free, irrevocable, worldwide, perpetual right of access to, and a license to copy, use, distribute, transmit, and display the work publicly and to make and distribute derivative works, in any digital medium for any responsible purpose, subject to proper attribution of authorship.”

As pointed out by Speer et al. (2013), the main drivers towards OA publication were the ever-increasing subscription costs of journals and the concomitant static or shrinking library budgets. The argument was that research funders were paying for the research to be done, and then paying again to be able to read the results of that research. There was also a sense that the publishing behemoths were controlling an increasing proportion of the market and that, by changing the financial model, this control would cease to exist.

In 2018, cOAlition S, a consortium of principally European Union–based research funders, issued their so-called ‘Plan S’. Plan S “requires scientists and researchers who benefit from state-funded research organisations and institutions to publish their work in open repositories or in journals that are available to all by 2021.” In 2020, the debate surrounding this goal is ongoing.

The White House (Obama administration) Office of Science and Technology Policy (OSTP) (2013) directed federal agencies which had budgets in excess of $100 million per year in research and development spending (e.g., Department of Energy, National Science Foundation, National Institutes of Health) to develop plans to make the published results of federally funded research freely available to the public within 0–24 months of publication, based on the topical discipline and depending on the national agency. At present (Trump administration), a revision of that policy is being considered. The sense is that the 12-month embargo will be removed and that research (as described above) will have to be made publicly available immediately after publication, though with a period of transition: a time range from 0 to 36 months is being considered.

In 2013, there were two primary kinds of OA publishing:

**Gold OA**: authors or their funders pay an author publication charge (APC) to cover the costs of publication of a paper in an OA or hybrid journal (i.e., one that mixes traditional subscription with OA).

**Green OA**: the author has typically not paid an APC but, after a certain embargo period, the published paper can be made available via a freely accessible, author-managed webpage or institutional repository.

There are also more recently introduced terms related to OA. “Platinum OA” for which journals don’t charge any APCs and fund the journal in another way, such as through a university or research organization. “Diamond OA” for which journals do not charge any APCs either, but the work is often done on a voluntary or ‘in-kind’ basis, so there is no need for payment.

WHAT HAS BEEN THE IMPACT OF OPEN ACCESS OVER THE PAST SEVEN YEARS?

Because of the way in which OA was funded over the past seven years, the traditional subscription model has continued to exist, with a minority of OA funding made available to publish works in OA or hybrid journals. This financial status is not sustainable. It requires more money than was available previously.

The number of full OA journals has burgeoned. In March 2020, the Directory of Open Access Journals (DOAJ) – https://doaj.org listed 14,348 journals which have published >4.7 million articles between them. In 2003, DOAJ was launched with just 300 journals.

According to Piwowar et al. (2019), 31% of all articles were available in 2019 as OA, and 52% of views were to OA articles. Those authors estimated that by 2025, 44% of all articles will be available as OA, with 70% of all views to OA articles (Fig. 1). This is clearly an increasing trend.

**Predatory Journals**

With the very large number of OA journals has come a number of so-called predatory journals. These are journals which publish papers without appropriate (or any) peer review, or without checks in terms of plagiarism or ethical matters. (See the now-defunct Beall’s List of predatory publishers at https://bealllist.net/) These journals take up scarce resources and sow doubt and confusion in the literature.

1 A full-length open access version of this article is available from at https://doi.org/10.2138/gselements.16.5.298

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**Figure 1**

Percentages of access types: (Left) current; (Below) projected. Reproduced from Piwowar et al. (2019).
WHAT IS NEW IN 2020?

Plan S and rumblings from OSTP in 2018/2019 have encouraged publishers to move more quickly than had previously been the case. There are many challenges with Plan S, including the points outlined in the American Chemical Society’s statement, published in February 2019 (prior to some revision by cOAlition S):

- Hybrid journals provide a clear path to achieving full and immediate open access—yet are considered ‘non-compliant’ by Plan S.
- Restricting Plan S authors to a current small sub-set of established OA journals risks stifling scientific collaboration.
- Clarity around transformative agreements is lacking.
- A one-size-fits-all approach to article publishing charges (APCs) is problematic.
- The proposed timetable is impractical.

Not all publishers will have the same complaints. Some may be prepared to abide by the “reasonable level” APC being proposed by cOAlition S. An updated set of Plan S conditions was released in April 2020 (see below).

- What about authors who are not supported by a cOAlition S funder?
- What about authors who do research without financial support?

On 8 April 2020, cOAlition S announced updates to its criteria for transformative journals. Authors supported by cOAlition S funders must publish in journals which meet Plan S requirements. The changes are as follows:

- “The threshold when a journal must flip to full Open Access has moved from 50% to 75% and we have removed the commitment to ‘flip’ to OA by December 2024. In making these changes, however, we have stressed that publishers must explicitly state their commitment to transition to full Open Access and that our support for this model (in terms of paying for publishing services in subscription journals) will cease at the end of 2024...”
- “[Reduce] the annual growth target for the proportion of content which must be published in Open Access from 8% to at least 5% in absolute terms and at least 15% in relative terms, year-on-year.”
- In July 2020, cOAlition S announced a ‘Rights Retention Strategy’, and all research published by those authors in receipt of financial support from cOAlition S funders will be subject to it. The intellectual rights to work published will no longer belong to the author or to the publisher but rather to the public. Though many authors are keen to promote their work as widely as possible (and many willingly sign CC BY licenses to publish, which allows unlimited sharing, copying and even translation of the work, even to the extent that others may benefit financially from it), others may resent the imposition of this license upon them by funders and removal of the option to choose how their work is used by others (Anderson 2020).

In a move which may well be related to the latest cOAlition S pronouncement, the European Research Council (ERC) has withdrawn its support for Plan S.

IMPACT OF OPEN ACCESS ON STAKEHOLDERS

On Publishers

Publishers have been required to turn on its head the financial model used in journal publishing for centuries. In the past 20 years, the ability of publishers to carry out their function has been threatened by the demands/implications of OA. Publishers are scrambling to survive.

On Authors

Throughout the twists and turns in the 20 years of the OA saga, some authors have, arguably, been least engaged in OA. This silent majority of authors, no matter their sympathies and desires to propel OA change, default to the path of least resistance in publishing through traditional subscription journals.

On Funders

Funders (governments, national scientific agencies [e.g., NERC in the UK, or NSF in the USA], or charitable agencies such as the Wellcome Trust, Bill and Melinda Gates Foundation) would like to see all published research made available to all, free of charge. But how do we achieve that without killing the messenger, i.e., the publishers/societies?

On Science

Open access in a digital world fosters dissemination of knowledge and scientists’ collective ability to collaborate and accelerate the pace of research and to problem solve. Open access content is, on average, downloaded ten times more than that which is behind a paywall. According to Piwowar (2018), OA articles are cited, on average, 18% more than non-OA articles.

On Readers

We will, ultimately, arrive at a situation where any reader anywhere will be able to access almost any piece of published content they wish. But will readers be able to rely on what they read? Can the system maintain review and production quality? Can we avoid the “predator pitfall” mentioned above? Will we, the general public, benefit from being able to access all of this content? Maybe.

On Learned Societies

Open access ‘tipping points’ are causing change throughout scholarly communities. The present authors (representing learned societies) join others in trying to document and to plan amidst a changing landscape. Some societies have taken the view that society OA journal publishing should be an extension of the society’s mission, via Diamond Open Access (Harington 2017). Others with existing subscription portfolios are embracing OA while not discarding the historic role of societies and their journals’ place in championing science. While the future may be open, they rally their members: “we keep in mind and advocate for the traditional strengths of our peer reviewed publication system: institutional support for publishing, editorial decisions made by practicing scientists, and placing scientific rigor over financial exigencies” (Piston 2019).

Learned society publishers are a subset of the publisher group. Many small learned society publishers are less well-resourced in terms of their abilities to respond to and deal with the implications of a drive towards full OA publication. How do we adjust our modus operandi to allow us to continue to operate and to ensure a fair share of the library budget pie?

Can small publishers survive in the world of ‘Read and Publish’/‘Publish and Read’ deal-making? Will there be space outside of those deals in which they can continue to exist if they cannot make such deals (Harington, 2017)?
commercial/not-for-profit publishing partners and journals which are published independently. We have journals which range from purely subscription-based to hybrid (with 0–10% OA content) to journals which are 100% OA. Other than those journals which are already fully OA, only those with commercial or other partners view themselves as being on a path to mostly or fully OA. It is clear that all society publishers would wish their content to be available to as wide an audience as possible. Societies which can afford Platinum OA welcome the move, as do those which have already transitioned to OA and are glad of the support for this kind of publication. Some (most) of the publishers still involved in hybrid publishing do not appear, as yet, to be considering more OA-rich solutions. Within the context of the survey carried out, none of the Elements publishers who responded sees the current OA ‘heave’ as an existential threat.

**CASE STUDY**

In 2019, the University of California, which has 10 constituent universities, cancelled its ‘big-deal’ subscription with Elsevier.

Researchers at the University of California publish, on average, 50,000 journal papers per year. The library budget is $40M. Before ‘Read and Publish’ deals existed, a further $10M per year was spent on APCs. Under the terms of the ‘Read and Publish’ deal, the University of California asked authors to make the decision about where to publish (offering them much-sought academic freedom) and will support APC fees. Because authors are also asked to help with APCs where possible, they will be partly responsible for finding the best APCs. In April 2019, the University of California entered into its first OA ‘Read and Publish’ agreement with Cambridge University Press.

**WHAT IS THE FUTURE?**

The version of OA which has been in vogue since 2013 has not led to the bulk of content being available to all because there is not enough money out there in the world of libraries to pay for subscriptions and open access (at the same time). The temporary answer – pre-publication and Green OA – has not worked either.

The numbers of OA papers published (and attendant revenue) are increasing, whether in hybrid or Gold OA journals.

**Transformative Deal**

One viable solution, which could work, is that which transforms subscription money into OA money (to put it very simply). In Plan S terminology, deals based on this solution are referred to as “transformative”. Forward-looking, mostly larger publishers, have been quick to negotiate with libraries and consortia (e.g., the University of California) to come up with deals which do that. The deals vary from one publisher to the next, but, for the most part, allow authors to publish OA papers in those journals without additional cost to them or the institution.

From a university press publisher’s perspective, Cambridge University Press has transformative deals in place with 28 entities (Cambridge Core: https://www.cambridge.org/core/services/open-access-policies/read-and-publish-agreements.)

At a national level, the German government has put in place ‘Projekt Deal (2020)’, for which the stated objectives are immediate OA publication of all new research articles by authors from German institutions, permanent full-text access to the publisher’s complete journal portfolio, and fair and reasonable pricing for such services articulated with a simple and future-oriented model based on the number of articles published.

So, moves and negotiations at all levels. But the following questions remain:

- Is ‘Read and Publish’/’Publish and Read’ likely to instigate the aforementioned tipping point?
- Will a significant proportion of the international subscription budget remain as money allocated to subscriptions?
- Will it be possible for one- or two-journal publishers to respond adequately, i.e., negotiate ‘read and publish’-style deals with subscribers?
- Will libraries want to negotiate with small society publishers?
- What about institutions which cannot afford either subscriptions or APCs? They will benefit from the OA secured by other institutions, but local authors will have to find journals which do not require APCs (i.e., their content will be behind a paywall).
- What of libraries at institutions that do a lot of teaching but little or no publishing? Why would they continue to pay subscriptions if, as more institutions sign up, a greater proportion of content becomes OA?

**WHO IS RESPONSIBLE FOR WHAT?**

Some funders, such as those in cOAlition S, have gotten off the fence and forced publishers into action. What about other funders?

Many institutions are keen to change the ancient paradigm (subscription-based existence) and to move past the hybrid-journal idea. Neither solution is working, and, in many institutions, readers are left without access to key content because of budget and other restrictions. Key participants have taken a brave step. Will others follow?

Publishers are more cautious. Those with greater resources and larger teams of staff are better placed to move with the changing landscape. Smaller publishers will wait until the picture becomes clearer. Will there still be time to secure some of those precious library resources if we do reach that OA tipping point? There is an irony here: the move to OA to reduce the impact of the very large commercial publishers has had the opposite effect. Society publishers which have joined forces with commercial or not-for-profit partners are, perhaps, the most likely to be ready when the tipping point (between subscription-based and OA publishing) is reached, if it is reached.

Readers have always been very resourceful. They obtain a copy of the content they need by asking the author for it, by paying to download it, or by obtaining it from a site where it is hosted illegally. Everything on the internet is free isn’t it?

And, finally, authors have a significant responsibility here. What is it you would like? Does “the right to publish your work in a good-quality journal with high peer-review standards, decent review times and good access to an appropriate audience (best assured by Open Access)” sound right? If, as an author, you struggle to meet all of the criteria above, at a price you and your institute can afford, then perhaps consider changing your publishing habits.

**SUMMARY**

The view of the present authors is that we are reaching critical mass in terms of OA. No longer will the majority be able to continue to rely on the traditional subscription funding model with OA simply a bit-part player. Open access will certainly be a significant part of the future. Both cOAlition S and the OSTP have made significant moves, but they have not been backed by some of the other major powers in the world of science publishing. All eyes are on China: to date, it has broadly supported OA movements such as Plan S, but it has not yet made any firm commitment. And the future may yet depend on moves by visionaries, publishers and libraries who might see a different future.
Alexis K. Ault applies low-temperature thermochronology to resolve cryptic thermal signatures of Earth processes in the rock record. She integrates Fe-oxide (U–Th)/He thermochronology with multiscale microscopy and geochemical data to decode the fingerprint of earthquakes and slow slip events in exhumed fault systems. She received her BA in geology and political science at Wellesley College (Massachusetts, USA), her MSc at University of New Mexico (USA), her PhD at the University of Colorado, Boulder (USA), and completed a National Science Foundation postdoctoral fellowship at the University of Arizona (USA). Alexis’ appointment to associate professor in the Department of Geosciences at Utah State University (USA) marks the culmination of her professional and personal journey among the Four Corners states. She finds inspiration while pedaling her mountain bike in the desert.

William S. Cassata is a research scientist at Lawrence Livermore National Laboratory (California, USA) where he leads a noble gas mass spectrometry laboratory. He received a PhD in Earth and planetary science from the University of California at Berkeley (USA) in 2012 and a BS in geology and geophysics from the University of Wisconsin at Madison (USA) in 2007. He investigates the chemical and isotopic evolution of Mars’ atmosphere, the geologic histories of the Moon and Mars, and the origin and evolution of volatiles in the solar system.

Emily H. G. Cooperdock earned her BA (Earth sciences) from Columbia University (New York, USA) and her PhD from the University of Texas at Austin (USA). She was a postdoctoral fellow at Woods Hole Oceanographic Institution (Massachusetts, USA) before starting her current position as an assistant professor at the University of Southern California (USA) where she directs the USCHelium laboratory. Her research focuses on method development and applications of (U–Th)/He thermochronology, with a special focus on tectonic plate boundaries, fluid–rock interactions, and metamorphic processes.

Rebecca M. Flowers is a geochronologist at the University of Colorado, Boulder (USA), where she directs the Thermochronology Research and Instrumentation Laboratory. Her research combines thermochronology, geochronology, and geochemical observations to address problems that include the erosion history of the Great Unconformity, the missing sedimentary record of continental interiors, the topographic evolution of the western U.S. and southern African Plateau, and the impact history of the Moon. Her group’s research also focuses on developing and refining (U–Th)/He thermochronometers.

Matthew Fox is a NERC Independent Research Fellow and a lecturer at University College London (UK) who works on landscape evolution and geodynamics. He received his primary degree from the University of Oxford (UK) (2008) before moving to Switzerland to explore the Alps and to earn his PhD from ETH Zurich (2013). After that, he worked as a postdoctoral research fellow at the University of California, Berkeley (USA) and at the Berkeley Geochronology Center investigating the incision of the Grand Canyon and the landscape evolution of the Antarctic Peninsula. At the London Geochronology Centre, he collects new thermochronometric data and writes numerical models to help interpret them. These data, as well as other geochemical approaches, help us understanding how Earth’s dynamic surface has been (and is being) shaped by tectonics and erosion.

Cécile Gautheron is a professor of geochemistry and mineralogy at the Paris-Saclay University (France). Her research aims to quantify the geodynamic evolution of Earth’s continental crust via the determination of weathering and exhumation timings and rates. In order to quantify these phenomena, she applies and develops dating tools, such as (U–Th)/4He and (U–Th)/21Ne thermochronometers/chronometers, and attempts to understand their theoretical behaviour. She uses multi-disciplinary approaches to study rare gas diffusion processes in minerals, from the atomic to macroscopic scales and from seconds to geological timescales.

Kalin T. McDannell applies noble gas (40Ar/39Ar and U–Th/He) and fission-track thermochronology to understand large-scale tectonic and geomorphic problems over long timescales, including the evolution of cratons, mountain belt erosion, and sedimentary basin development. He also conducts experimental mineral diffusion studies and is interested in advancing thermochronology analytical methods and data interpretation. He earned his BS in geology from the Indiana University of Pennsylvania (USA) as a first-generation student and a Ronald E. McNair Scholar, his MS in geology from West Virginia University (USA), and his PhD in Earth and environmental science from Lehigh University (Pennsylvania, USA). He was a postdoctoral fellow at the Geological Survey of Canada (Calgary) prior to joining Dartmouth College (New Hampshire, USA) as a research associate.

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David L. Shuster is a professor of isotope geochemistry in the Department of Earth and Planetary Science at the University of California, Berkeley (USA) where he directs the Surface Process Geochimistry Research Group and the Noble Gas Thermochronometry Laboratory at the Berkeley Geochronology Center. His research interests include noble gas isotope geochemistry, thermochronometry, and cosmogenic nuclide observations applied to problems involving alpine glacial erosion, chemical weathering, lunar impacts and magnetism, and the thermal evolution of Martian meteorites. He is currently a return-sample science specialist on NASA’s Mars 2020 mission who will use the Perseverance rover to (remotely) collect and return Mars surface samples to Earth for future analyses.
Daniel F. Stockli is the Chevron (Gulf) Centennial Professor in Geological Sciences at the Jackson School of Geosciences of the University of Texas at Austin (USA). He received his diploma from ETH Zurich (Switzerland), his PhD from Stanford University (California, USA), and is currently the Director of the Texas UTChron Geo- and Thermochronology Laboratory. His research combines tectonics, petrology, and stratigraphy with geo- and thermochronometry to investigate the timing and thermal evolution of mountain belts, continental rifts, and rifted margins. He has been engaged in the development and application of new geo- and thermochronometric dating techniques, integrating these with trace-element signatures and applying them to tectonic and detrital provenance studies.

Marissa M. Tremblay uses noble gas thermochronology to study the physical and chemical processes that shape the surfaces of Earth and other planetary bodies. She also conducts experimental research on the kinetics of noble gas diffusion in minerals. Marissa earned her BA from Barnard College (New York, USA) and her PhD from the University of California, Berkeley (USA). She held a Royal Society Newton International Fellowship at the Scottish Universities Environmental Research Centre (UK) prior to joining Purdue University (Indiana, USA) as an assistant professor in 2019. Marissa is the recipient of the 2018 Charles and Nancy Naeser Prize (International Standing Committee on Thermochronology) and of the 2020 Doris M. Curtis Outstanding Woman in Science Award (Geological Society of America).

Peter K. Zeitler is a professor of Earth and environmental sciences at Lehigh University (Pennsylvania, USA). His research interests include the development and application of techniques in geochronology, the geodynamics of coupled surface and tectonic processes, the origin of mountains, and the geologic evolution of Asia. He earned his BA, MS, and PhD degrees (the latter in 1983) from Dartmouth College (New Hampshire, USA). He then spent five years as a research fellow in isotope geochemistry at the Research School of Earth Sciences at the Australian National University. In 2013, Zeitler was named a Fellow of the America Geophysical Union; in 2014 he became the Chair of the International Standing Committee on Thermochronology (ISCT); and in 2016 he was awarded ISCT’s Dodson Prize in thermochronology.

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Noble Gases Deliver Cool Dates from Hot Rocks

Cécile Gautheron¹ and Peter K. Zeitler²

INTRODUCTION

Temperature matters to geologists. Heat transfer within our dynamic planet drives deformation of the lithosphere and the development of topography, which, in turn, drives erosion and other surface processes (Fig. 1). Changing temperature alters rock properties, controlling crustal behavior during deformation. And processes such as erosion, sedimentation, magmatism, and fluid flow can interact and modify temperatures in the crust. At plate boundaries and within continental interiors, growth and erosion of high mountains and plateaus divert atmospheric circulation, leading to feedbacks that integrate the solid Earth with surface processes, leaving behind a record of rocks with diagnostic temperature histories.

Using temperature-sensitive dating methods applied to a variety of minerals, we can measure such temperature changes, which can then be used to understand the timing and magnitude of geodynamic processes and the role of the solid Earth within the Earth system. Those dating methods, which most commonly rely on the accumulation of the radiogenic gasses \(^{4}\text{He}\) or \(^{40}\text{Ar}\) and are balanced by gas loss via temperature-activated diffusion, form part of the subdiscipline known as thermochronology. Also, in this subdiscipline, but not covered in this issue, is fission track thermochronology, which relies on the accumulation and temperature-activated annealing of damage ‘tracks’ produced by \(^{238}\text{U}\) fission. By combining our understanding of diffusion behavior in minerals with models of noble gas accumulation and loss, we can infer thermal histories from measured ages. In terrestrial applications, the temperature sensitivity of noble gas thermochronology spans conditions from the middle- to upper crust, ideal for studying tectonics, geomorphology, basin analysis, and more. The other articles in this issue provide specific examples of how this approach can help to solve exciting and important geological problems on Earth and beyond.

Excellent reviews of the origins and underpinnings of thermochronology already exist (McDougall and Harrison 1999; Reiners et al. 2005, 2018; Ault et al. 2019). Here, we highlight thermochronology’s fundamental principles and how knowledge about noble gas diffusion behavior provides an opportunity to learn about the evolving Earth.

HISTORY

The field of geochronology was developed in the early 20th century. But it became increasingly obvious that mineral ages measured using different methods often disagreed and were younger than geological constraints. In the 1960s, workers reached the key conclusion that apparent unreliability was actually a useful consequence of a sample’s temperature history. This set the stage for Martin Dodson introduced the concept of closure temperature (Dodson 1973), which changed the course of geochronology by showing how to use diffusion theory to quantify mineral-age interpretation. It became the expectation (rather than a surprise) that different minerals from a single rock should give different ages. Dodson’s work encouraged subsequent generations of geochemists to apply diffusion theory to age data.

Mark Harrison (currently at the University of California, Los Angeles, USA) catalyzed the use of noble gas thermochronology for terrestrial applications in a series of papers that exploited the new \(^{40}\text{Ar}/^{39}\text{Ar}\) method, showing how quantitative, diffusion-based analysis of argon mineral ages could be applied to settings such as orogens, basins, and intrusive contacts (MacDougall and Harrison 1999). The previously dismissed U-Th/He method was resurrected by Zeitler et al. (1987), and there was a series of papers by Ken Farley’s group at the California Institute of Technology (USA) (e.g., Farley 2000), all of which led to the development of dating approaches suited to low-temperature processes (<250°C). The \(^{40}\text{Ar}/^{39}\text{Ar}\) and \(^{3}\text{He}/^{4}\text{He}\) step-heating

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Credit: Greg Balco

Metal packet containing a thermochronology sample in the ultrahigh vacuum laser microfurnace at the Berkeley Geochronology Center (California, USA). The packet is heated with a diode laser to the point of glowing.
Although the decay rates for $^{40}$K and $^{40}$Ar; decay of $^{238}$U, $^{235}$U, $^{232}$Th, and $^{147}$Sm to alpha particles that become $^4$He atoms; nucleogenic interaction of alpha particles with crystal atoms to produce $^{20,21,22}$Ne (and even $^{84}$Kr); and radiogenic production of $^{129,131,135}$Xe by spontaneous fission of $^{239}$U and radioactive decay of iodine. We will focus on methods involving He and Ar (Fig. 2). Although the decay rates for $^{40}$K and the $^4$He parent isotopes are not high, noble gases are easy to precisely measure across timescales from thousands to billions of years. Moreover, the U and Th decay chains release 6 to 8 helium nuclei in the form of alpha particles (only one alpha particle is produced during Sm decay), amplifying $^4$He production rates. Finally, argon and helium are highly incompatible elements and have low solubility in minerals, so very little is incorporated at the time of mineral formation.

The main difference in how K–Ar and U–Th/He measurements are handled is mostly methodological. First, because Earth’s atmosphere is ~1% argon, it is necessary to correct for $^{40}$Ar contamination, usually by measuring stable $^{36}$Ar and using the atmospheric $^{40}$Ar/$^{36}$Ar ratio. In contrast, because of its low atmospheric concentration, correction for initial $^4$He is unnecessary. Second, during decay, $^{40}$Ar and $^4$He atoms travel some distance before stopping. For argon, this short distance can be neglected; but for helium, the distance varies from 5 µm to 30 µm (Fig. 2), requiring an alpha-ejection correction for decays that happen close to grain margins. Finally, another practical difference between Ar and He chronometers is that K occurs at percent levels in commonly used minerals such as feldspars, micas, and amphiboles, whereas U and Th occur at ppm levels in accessory phases such as apatite, zircon, and titanite.

**Loss by Diffusion**

Being chemically inert and present in small amounts, noble gases in minerals act as ideal tracer diffusants. Atoms diffuse between neighboring sites with close diffusion jump distances following a 3-D random walk within the host crystal structure. The differences in diffusion rate for noble gases in minerals are linked to atomic size and the energy required to jump between sites (Farley 2000). Diffusion jump distances lie close to the size of the unit cell, which means that to escape from a small grain using a random walk, a noble gas atom follows a path several meters in length! This implies that diffusing atoms visit large fractions of each grain’s volume, guaranteeing interaction with imperfections in the crystal lattice. Whereas individual diffusing atoms take random walks, the ensemble diffusion of many atoms emerges as a smooth profile that leaves a grain with high interior concentrations that decrease towards the zero-concentration boundary at its edge (Fig. 2).

However, just knowing about diffusion mechanisms is not enough. For thermochronology, we need to know how diffusion rates depend on temperature, and we need to know several other factors specific to the mineral grain in which we measure the noble gases. Diffusion in a crystal lattice typically obeys an exponential temperature dependence described by the Arrhenius equation: diffusion kinetics for each noble gas in each mineral grain are characterized by an activation energy $E_a$ and a diffusivity at infinite temperature $D_0$. The diffusion dimension must also be known—in some cases this is the actual grain size (noted as $a$ or $r$); in others, it is a smaller domain defined by crystallographic structures (Fig. 2).

How do we know the real diffusion parameters? Our knowledge is based on a fairly limited database of laboratory diffusion experiments, although for a few thermochronometers, kinetic information can be obtained as part of the analysis process. Diffusion experiments can be performed using natural $^4$He or $^{40}$Ar, or better, using uniformly
distributed $^{3}He$ or $^{39}Ar$ created from proton spallation or fast-neutron reactions with the sample’s constituent atoms (McDougall and Harrison 1999; Shuster and Farley 2004). Using these artificial isotope profiles as a reference, progressive step-heating analysis can reveal the internal distribution of $^{4}He$ or $^{40}Ar$ and, thus, information about a sample’s specific kinetics (Fig. 2). An obvious issue is that kinetic experiments occur over laboratory timescales that are a billion times shorter than geologic applications. Therefore, an important supplement to our kinetic calibrations for various thermochronometers comes from numerous comparative studies where the performance of different systems can be compared with one another in geologic settings having well-understood temperature histories.

Compared to idealized “perfect crystals”, diffusion behavior in real samples—as shown by ab initio calculations (e.g., Djimbi et al. 2015) and laboratory experiments—is complicated by imperfections that are the result of chemical substitutions, strain-induced defects, radiation damage, or voids in the structure (including fluid inclusions). Noble gas diffusion can be accelerated if the imperfection content is high enough to provide many fast paths, but, more commonly, at lower levels, damage will slow diffusion due to trapping or obstruction of diffusion pathways. For example, diffusion experiments show how different natural apatite crystals from the same sample can be characterized by different diffusion behaviors and that He within some apatite crystals can occur in different sites, such as within the crystal lattice, defects, damage zones, and/or voids (McDannell et al. 2018) (Fig. 3).

**Figure 2** A comparison between the diffusion behavior of $^{4}He$, $^{3}He$ and $^{40}Ar$, $^{39}Ar$ in a single crystal and in a multicrystal complex. Symbols: $D =$ diffusion coefficient; $a$ and $r$ refer to the diffusion domain sizes (grain radius or half-width depending on diffusion geometry); $eU =$ effective uranium content. $R_0 =$ reference apparent radius consistent with the gas release from the smallest diffusion domains. (A left) Diffusion behavior of $^{4}He$ and $^{40}Ar$ in a single crystal (single diffusion domain) illustrated with the yellow to green to blue color. Transect line marked A–A’ relates to data in graphs to right. (A top right) $^{4}He$, $^{3}He$ and $^{40}Ar$, $^{39}Ar$ concentration variation along the A–A’ transect though the single crystal. As $^{4}He$ and $^{39}Ar$ are artificially produced within the crystal by laboratory experiments, the concentration is homogeneously distributed, contrary to $^{4}He$ and $^{39}Ar$ concentration. (A middle right) Evolution of the $\ln(D/a^2)$ value as a function of the inverse of the temperature ($T$) based on the degassed fraction of $^{3}He$ and $^{4}He$ from the single crystal.

**Net Retention Behavior**

Dodson (1973) set out the mathematics needed to describe the balance between radiogenic production and diffusional loss. For cooling systems, this leads to the concept of closure temperature ($T_c$), which gives the temperature of the system at the time given by the measured age (Fig. 4). This insight provided a quantitative framework for thermochronology: under the right conditions, a sample’s differing ages can be interpreted as a series of time–temperature points along its thermal history. Thus, above $T_c$ noble gases produced by decay will be completely lost by diffusion, while below $T_c$ those gases will be fully retained. During cooling at temperatures close to $T_c$ only some noble gas atoms will be retained.

Closure temperature depends on a specific sample’s diffusion dimension and cooling rate, as well as its individual kinetics (Fig. 4). As a practical matter, it is worth knowing that in comparing different systems, people often cite a single value for $T_c$, which is referenced to a slow cooling rate of $10^\text{°C/My}$ and a “typical” grain size. If a rock undergoes a pulse of reheating after cooling, the noble gas atoms accumulated in the crystal can be partially or totally lost, and this will “reset” the system. This can happen for a wide range of time and temperature combinations. It is important to realize that closure temperature cannot be equated to an “opening” temperature.

Closure temperature is a crucial concept, but many geological processes involve more than just cooling at a constant rate—in general, a thermochronometer age could be the outcome of myriad variations of thermal history. For
thermal histories where a rock spends many millions of years teetering at near-constant temperatures where argon or helium are partially retained, if there are major changes in cooling rate, or if reheating and partial resetting come into play, the concept of simple closure temperature does not apply, even if the measured age still represents a net measure of the sample’s complex history. As we discuss below, this is why modeling is an important aspect of thermochronological analysis.

Thermochronometers

Numerous systems are now available for use in geological applications. Figure 4 compares these thermochronometers and their temperature ranges.

Helium

Most U-Th/He thermochronology uses the accessory minerals apatite and zircon, which are common in many rock types. This system can address the low temperatures of 40–120 °C (by apatite) and <100–200 °C (by zircon). Titanite and rutile have seen some use, and successful dates have also been obtained on fluorite, goethite, hematite, manganite and spinel. But, for all these systems, more diffusion data are needed. In many cases, single grains are analyzed for total U, Th, Sm, and He concentrations, yielding a single age. In some cases, 4He/3He analysis is used for apatite. Though more time-intensive, this approach allows stepwise heating to measure sample-specific diffusion kinetics and learn more about the sample’s thermal history (Fig. 2).

For apatite, zircon, and titanite, the diffusion domain is the dated grain itself. Radiation damage strongly impacts on He diffusion, leading to a broad spread of temperature sensitivity (Fig. 4) and, often, a correlation between U-Th/He age and effective uranium (eU), or the concentration of U and Th weighted for their alpha productivity (e.g., Fig. 2). For polycrystalline phases such as hematite, variable retentivity is controlled by the range in diffusion dimensions (Figs. 2 and 4) (Cooperdock and Ault 2020 this issue).

Argon

The minerals most commonly used for argon-based thermochronology are K-feldspar, biotite, the white micas, and the amphiboles (Fig. 4). Essentially all analyses use the 40Ar/39Ar variant of the K–Ar method, a form of neutron activation analysis for K that allows age information to be determined directly from 40Ar/39Ar data through the use of suitable age standards (Fig. 2). Step-heating analysis can reveal 40Ar concentration gradients and can also use 39Ar loss to obtain sample-specific kinetic data. Together, these data can be inverted for thermal histories (see below). In practice, the observed instability of ferromagnesian hydrous phases under vacuum means that step-heating results from biotite and amphibole do not yield useful kinetic data. As a result, step heating is most fruitful when used with feldspars and white micas. These latter phases have been shown to be stable, or at least metastable, during heating. Because feldspars remain stable during vacuum heating, considerable effort has gone into the development of K-feldspar 40Ar/39Ar thermochronology based on the multi-diffusion domain (MDD) model (Lovera et al. 1991). This posits that intragrain features reduce diffusion dimensions to be much smaller than the physical grain size. Figure 4 shows how MDD behavior alters and extends thermal sensitivity and how the thermal history can be obtained by inverse models. Although most MDD analyses have been on K-feldspars, muscovite appears to show MDD behavior as well. Plagioclase holds some promise, but data interpretation is more complicated because of much lower K contents and complex zoning.

Potential Complications

Argon- and helium-based thermochronometers can be impacted by a variety of phenomena. Zoning of U-Th in some minerals will complicate alpha-ejection correction, and U-Th or K zoning will alter He or Ar diffusion processes. Samples need to be fresh, unaltered, pure phases in which diffusion was the main transport mechanism. Despite great interest in the thermal history of shear zones, this is a challenging geochemical environment: there can be extensive flow of fluids containing 40Ar and 4He, and dynamic recrystallization can lead to the development of crystallographic defects. Metamorphic and hydrothermal fluids can also paint thin layers of U-rich phases around grains, leading to implantation of excess 4He that can be significant for low-U phases. Also, fluid inclusions and partitioning into retentive sites can cause minerals to incorporate nonradiogenic “excess” 40Ar or 4He. Such problems are not widespread, but care must be taken to anticipate and, if possible, avoid them.
WHAT DO AGES MEAN?

Significance of a Measured Thermochronometer Age

A single age from any one thermochronometer has no unique thermal or geological significance. Both the ages that record thermal history and the thermal histories created by geological processes depend on diffusion (since heat flow in the lithosphere is largely controlled by diffusive heat conduction), and nonuniqueness is inherent in diffusive processes. Context is required for even qualitative interpretation of data, usually involving dates from other systems as well as geological information and constraints. If you collaborate with a thermochronologist and they initially ask you what ages you expect, they are not being lazy. They are asking about necessary context. Could there have been reheating? Can nearby unconformities constrain that? What cooling histories are permitted from the tectonic setting?

Two steps are required to take full advantage of thermochronological data: 1) extracting thermal histories from measurements; 2) understanding what those thermal histories might say about geology.

First Step: Thermal-History Modeling

It’s usually safe to say a rock was once hot and now it’s not, but truly quantitative interpretation of noble gas data requires thermal-history modeling to extract time-temperature histories (as distinct from thermal modeling to predict temperature distributions in geological settings). Given information about sample kinetics and grain size, diffusion models can assess which thermal histories explain measured ages. Forward “what-if” modeling (using trial thermal histories to predict ages) can be a useful first step in examining scenarios. But because of the wide range of possible solutions, this approach is insufficient to explore the full set of solutions. Far better are inverse models that determine the set of thermal histories most consistent with observed ages and geological constraints. Such models can jointly invert mineral-age data as well as $^{40}$Ar/$^{39}$Ar and $^{3}$He release spectra. Those models can also include the impact of accumulated radiation damage on He diffusion kinetics in zircon and apatite such that separate grains from a single sample can be inverted jointly for a segment of thermal history. Codes are available that incorporate most thermochronometers, and they use different approaches that range from simple Monte Carlo searches to efficient learning algorithms. Fox and Shuster (2020 this issue) discuss this approach in more detail.

Second Step: Thermal and Geodynamic Modeling

Determining the nature, timing, and rates of geological processes remains the ultimate rationale for developing thermochronological methods. No single model can handle the complete range of complexity and scale across which these processes occur, but inverse thermokinematic models exist which use key controlling tectonic or geodynamic parameters to explore combinations consistent with the measured thermal evolution (e.g., Braun 2003). This can be done as an independent step, or, ideally, directly combined with thermal-history modeling to create a single integrated inverse model.

HOW CAN AGES BE USED?

Thermochronology has been applied to a wide range of geological environments, driven by creativity about where thermally sensitive tools might be brought to bear and by continuing progress in developing and understanding mineral systems. Examples of this diversity include studies of landscape evolution using natural coal fires (Riihimaki et al. 2009), assessing fault-zone processes or determining the timing of ore deposition (Cooperdock and Ault 2020 this issue), measuring thermal histories for meteorites (Tremblay and Cassata 2020 this issue), and examining thermal histories of various environments in pre-Phanerozoic deep time (McDannell and Flowers 2020 this issue).

Mainstream applications of thermochronology have focused on studies of mountain belts and basins (FIGS. 1A AND B), including the detrital minerals that link source to sink (FIG. 1B). Basin sediments contain detrital thermochronometers that provide an indirect record of orogenic evolution, and basins themselves can be targets for thermal-history study (Stockli and Naiman 2020 this issue). Because basins host important energy and mineral resources, detailed knowledge of their low-temperature thermal history is important for understanding diagenesis and hydrocarbon maturation. Mountainous regions, whether compressional or extensional in origin, offer rock exposures that record the geodynamic processes responsible for deformation and that have responded to it, and they have received a large amount of attention over decades (FIGS. 1A AND 1C).

Here, we give just one brief example of an application to an orogen. Other articles in this issue explore at length many of the other applications.

**FIGURE 4** The evolution of closure temperature ($T_c$) with time for a range of rock-forming or common accessory minerals used as U–Th/He thermochronometers (apatite, zircon, titanite, hematite, rutile) or $^{40}$Ar/$^{39}$Ar thermochronometers (feldspar, biotite, muscovite, hornblende), arranged from lower to higher temperature. (INSET UPPER LEFT) Graph of the temperature at which 50% of the radiogenic He or Ar being produced is retained in the crystal ($T_c$) for a monotonic cooling path. The $T_c$ values correspond to a 10°C/My cooling rate and a 100 µm grain size. (INSET LOWER RIGHT) Graph of the temperature at which 50% of the radiogenic He or Ar being produced is retained in the crystal ($T_c$) for a monotonic cooling path. The $T_c$ values correspond to a 10°C/My cooling rate and a 100 µm grain size. For minerals such as apatite, zircon, and titanite, radiation damage alters the He and Ar diffusion within the crystal, causing $T_c$ to increase and then decrease again as damage concentration increases and diffusion then inhibits the transition to a more rapid percolation (LD to HD). For samples with multiple diffusion domains (e.g., hematite, feldspar, muscovite), a bulk grain will have a range of $T_c$ values due to the range of different diffusion-domain sizes (LS to SS). The example of hematite presents the $T_c$ value evolution from 100 µm to 1 nm grain size and intermediate value.
Fig. 5

Example of thermochronology applied to tectonic-scale landscape evolution in southern Tibet. MDD = multidiffusion domain. (A) Observed age–elevation data and predictions from a thermokinematic model that includes landscape evolution. The data are shown by open circles, squares and hexagons; modeled results are filled circles, squares and hexagons, color-coded to match the thermal histories shown in panel (B). (B) Thermokinematic models for landscape evolution: a forward model of a simple constant-cooling scenario (straight line decreasing from left to right) and thermal histories for the best-fit inverse model of low- and high-elevation samples. The linear history covers the relevant age and temperature ranges but cannot fit the observed age–elevation relationships, which require a more complex thermal history. The independent $^{40}\text{Ar} / ^{39}\text{Ar}$ MDD K-feldspar and $^{4}\text{He} / ^{3}\text{He}$ apatite inversions (not included in the thermokinematic inversion) agree well with the best-fit model results. After Tremblay et al. (2015).

The study by Tremblay et al. (2015) on southeastern Tibet showcases how integrating multiple thermochronometers, elevation-based sampling, and thermokinematic modeling can reveal just how dynamic and nonintuitive landscape evolution can be across the roof of the world (Fig. 5). Samples taken over 1,100 meters of relief recorded over 300°C of thermal history spanning 60 Ma. The data document a complex thermal history that includes very rapid cooling between about 17 Ma and 11 Ma, and, of greater interest, almost a total lack of erosional exhumation since then. The best explanation for these data is that deformation shifted into the bordering Himalayan ranges to Tibet’s south (Tremblay et al. 2015), causing a reduction in orographic precipitation within Tibet and a significant reorganization of southern Tibet’s drainage network. Modeling of alternative scenarios for these data also shows clearly the constraining power and great sensitivity that thermochronology can have (Fig. 5).

FUTURE DIRECTIONS

Thermochronology has a bright future, thanks to both methodological and technological developments. These are leading to new discoveries that expand the range of timescales, temperatures, and processes that we can study, allowing us to ask ever-broader Earth-science questions.

There has been particular interest in developing lower-temperature systems to expand the reach of thermochronology towards shallower environmental conditions, including the study of fluid flow and diagenesis. Exploiting He and Ar diffusion behavior in new minerals such as clays, iron oxides, and hydroxides is promising, as is the $^{40}\text{Ar} / ^{39}\text{Ar}$ dating of illites and the U–Th/He dating of hematite that crystallizes within fault zones. Interest is also growing in hybrid low-temperature methods that exploit the diffusion of cosmogenic nuclides, chiefly $^{21}\text{Ne}$ and $^{3}\text{He}$.

The accuracy and precision of thermochronometric measurements are currently limited by our kinetic data and our limited knowledge of detailed diffusion mechanisms. Progress will come from further development of ab initio calculations to understand 3-D diffusion behavior not only for perfect crystals but also those with different chemistries and classes of imperfections. There will be new experimental studies on real samples that document the impact of various types of imperfections on He diffusion. It is becoming clear that each dated mineral grain represents a unique system with unique diffusion kinetics, meaning that we should expect a range of retentivity for each thermochronometer (Fig. 4). While this might provide the insights needed to explain and manage the excess age dispersion sometimes seen in data sets (Zeitler et al. 2017), cost-effective technical advances are needed to acquire more kinetic data, ideally for all samples. Finally, improvement in inverse codes for thermal-history modeling, integrating more thermochronometers as well as tools for assessing the full uncertainty in thermal histories, would be of great help in getting the most out of the data.

Promising technological innovations are also on the horizon. These include new methods for directly assessing diffusion systematics and for screening samples (Idleman et al. 2018), and new technologies such as laser ablation with higher spatial resolution to directly sample diffusion gradients (Danišk et al. 2017). Finally, because studies often require large sample numbers to constrain complex thermal structures created by topography and tectonics, it will pay to develop cost-effective and rapid analytical methods that can lead to a synoptic thermochronology that addresses larger geographic regions or greater detrital datasets.

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Advances in detrital noble gas thermochronometry by $^{40}\text{Ar}/^{39}\text{Ar}$ and (U–Th)/He dating are improving the resolution of sedimentary provenance reconstructions and are providing new insights into the evolution of Earth’s surface. Detrital thermochronometry has the ability to quantify tectonic unroofing or erosion, temporal and dynamic connections between sediment source and sink, sediment lag-times and transfer rates, the timing of deposition, and postdepositional burial heating. Hence, this technique has the unique ability to use the detrital record in sedimentary basins to reconstruct Earth’s dynamic long-term landscape evolution and how basins are coupled to their hinterlands.

**Keywords**: thermochronology, detrital, provenance, source-to-sink, lag times, basin evolution

**INTRODUCTION**

The Earth’s surface has been modified through the interplay between lithospheric, hydrologic, and atmospheric processes throughout geological time. These dynamic interactions have been archived in depositional records preserved in the sedimentary basins of the world. These archives of eroded material from continents and mountain belts provide an invaluable, long-term record of tectonism and erosion in the hinterland—a record that is often no longer accessible in the bedrock of the source region due to progressive tectonic or metamorphic overprinting or subsequent erosion.

Whereas petrographic studies have long been used to unravel sedimentary provenance and, thus, hinterland tectonics and erosion, single-grain detrital isotopic techniques are increasingly being used as a potent tool for reconstructing hinterland tectonics, past drainage systems, landscapes, linkages between sediment sources and depositional sinks, and hydrocarbon reservoir characterizations. This revolution is largely attributable to technological and analytical advances, in particular zircon U–Pb laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS), making data more affordable and more readily available in large numbers (e.g., Gehrels 2014). However, interpretations based on zircon U–Pb crystallization ages can be hampered by nondiagnostic source signatures and sediment recycling, preventing discrimination between different source terranes. Thus, although these traditional provenance tools can shed light on the evolution of drainage basins, low-temperature thermochronometers can deliver quantitative insights into the dynamic and thermal evolution related to tectonic unroofing or erosional denudation of different portions of the source area (e.g., Ehlers and Farley 2003; Reiners and Ehlers 2005). Hence, detrital thermochronometry affords the unique ability to constrain the history of source regions in terms of both the timing and rates of exhumation or erosion.

Detrital thermochronometry has been applied on very different spatial scales, ranging from individual drainages to elucidate geomorphic or erosional processes, to regional drainage systems to reconstruct source-to-sink linkages and tectonic processes in the hinterland, to continental-scale reconstructions of drainage system evolution or mantle-driven dynamic topography. Detrital thermochronometry, based on either noble gas or fission track measurements produced by radiogenic alpha particles, has mainly been used to decode cooling histories recorded by the K-bearing rock-forming minerals and U–Th-bearing accessory minerals that are common detrital phases in modern and ancient siliciclastic sedimentary deposits (e.g., Bernet and Spiegel 2004; Hodges et al. 2005). Although fission track techniques have low-precision single-grain ages compared to $^{40}\text{Ar}/^{39}\text{Ar}$ and (U–Th)/He dating, interpretations are never based on an age of a single grain but always on grain populations, age peaks, or weighted averages of a number of grains. This can shed light on the exhumational history of different portions of the source area or to reveal abrupt changes in the source area. These are characterized by nominal closure temperatures for certain minerals: $\sim350°C$ for muscovite and $\sim350–180°C$ for K-feldspar $^{40}\text{Ar}/^{39}\text{Ar}$; $\sim250°C$ for zircon and $\sim100°C$ for apatite fission track; $\sim180°C$ for zircon and $\sim60°C$ for apatite (U–Th)/He (e.g., Reiners 2009). See Gautheron and Zeitler (2020 this issue) for further discussion of this concept. These different moderate- to low-temperature sensitivity windows can make them either excellent detrital recorders of tectonic and erosional signals in the source area or make them sensitive to postdepositional burial heating and resetting. Overall, improved and novel noble gas thermochronometric methods and their applications, integrated with innovative new conceptual and numerical models, provide an improved quantitative understanding of timing, rates, and spatial patterns of long-term landscape evolution, erosion budgets, and tectonic and geodynamic processes.

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DETRITAL THERMOCHRONOMETRY

The sedimentary records of basins have long been linked to the erosion of mountain belts: these records document hinterland erosion and tectonic activity and quiescence. At the same time, bedrock thermochronometry has become a routine approach to recover thermal histories of mountain belts and, thus, to quantify their short- and long-term tectonic, exhumational, and erosional unroofing histories (Figs. 1 and 2). Detrital thermochronometric methods combine these two approaches and have been applied to sedimentary archives in order to reconstruct erosional and tectonic processes in large-scale orogenic systems (e.g., Bernet and Spiegel 2004; Malusà and Fitzgerald 2019). Early studies focused mainly on giant orogenic systems, such as the Himalayas and their associated foreland basin and large-scale depocenters of the Indus and Bengal Rivers, in light of high to ultrahigh exhumation rates (>5 km/My) in the orogenic hinterland and the substantial associated sedimentary archives (Najman 2006). These early studies relied mainly on detrital 40Ar/39Ar thermochronometry, because this could be accomplished by high-precision, single-grain 40Ar/39Ar dating of detrital muscovite and K-feldspar and the fact that exhumation rates and magnitudes were sufficient to reset 40Ar/39Ar ages in the source terranes. Practically, this methodology also benefited from the possibility of 40Ar/39Ar dating large numbers of individual detrital grains by laser, yielding statistically robust datasets. However, the cost and speed of analysis (notably the need for neutron irradiations) represents an impediment for detrital 40Ar/39Ar dating. Furthermore, the relatively high closure temperatures of 40Ar/39Ar minerals (>300 °C) limits their thermal sensitivity to upper-crustal processes in the source area.

Detrital thermochronometry of refractory accessory phases, such as zircon, titanite, or apatite, by (U–Th)/He dating has experienced dramatic growth over the last decade. Many of these detrital low-temperature thermochronometers leverage their <200 °C closure temperatures to reveal upper-crustal (<6 km) tectonic activity and erosion in sediment source areas. Besides refining provenance, detrital thermochronometry is able to recover source terrane exhumation rates by using the concept of lag-time, which is a measure of the temporal difference between cooling age of the detrital mineral grain in the source region and the depositional age of the sedimentary host rock (Figs. 1 and 2). Whereas application of apatite fission track dating in detrital studies has been hampered by both postdepositional burial resetting and low single-grain precision, thus relying on multi-grain pooled ages, detrital fission track dating of zircon has been more widely applied in mega-orogenic source-to-sink studies (e.g., Carter et al. 2019). Most detrital zircon fission-track provenance studies exploit zircon’s low closure temperature (~250 °C) to provide insights into source area denudation and temporal variations in exhumation rates in the Himalayas and North American Cordillera (Cerveny et al. 1988; Garver and Brandon 1994). Increasingly, these studies couple zircon fission track dating with U–Pb dating of the same crystal to refine provenance identification and to identify volcanic grains (U–Pb age = low-temperature thermochronometric age) (Fig. 2). This double-dating approach can provide more detailed insight into the cooling history of specific hinterland terranes (e.g., Carter and Moss 1999). However, the applicability of zircon fission track dating has been limited by analytical complexities (e.g., etching), single-grain precision, and uncertainties in thermal sensitivity due to lack of a robust track annealing model (Malusà and Fitzgerald 2019).

The higher precision of single-grain (U–Th)/He dating of accessory phases overcomes some of the limitations of detrital fission track dating. In particular, zircon (U–Th)/He dating, with a single-grain age precision (~8%) and a nominal closure temperature of ~180 °C, has become widely utilized for revealing upper-crustal exhumation histories and tectonic activity in source terranes (e.g., Rahl et al. 2003; Reiners 2005). Importantly, zircon is also very conducive to U–Pb–He double dating of the same detrital grain, enabling more differentiated and sophisticated provenance interpretations by linking source area crystallization ages with source area exhumation histories (e.g., Reiners et al. 2005; Thomson et al. 2017; Carter 2019). Detrital apatite (U–Th)/He dating can also be a powerful tool in modern geomorphic and active tectonic studies, given its low to very low thermal sensitivity window (e.g., Stock et al. 2006). Limitations in this technique arise due to the need for intact, inclusion-free apatite and apatite’s propensity for undergoing mechanical abrasion during transport and postdepositional burial (partial) resetting.

**FIGURE 1** Diagram illustrating the partial path from cooling, exhumation, erosion, transport, deposition, and burial in an extensional source-to-sink system. Detrital thermochronometric ages and their lag time (tL) can be used as a measure of the rate of exhumation in a source area by estimating the time difference between cooling through a closure isotherm (TC) at time tC and erosion at the surface (TS) at time tS and depositional age (tD) at temperature (TD), assuming a negligible transport time (e.g., Ruiz et al. 2004). For obtaining accurate lag time estimates it is essential to exclude volcanic zircons (tV), identified as having identical crystallization and cooling ages (tC, U–Pb = He) (e.g., Saylor et al. 2012).
EARTH’S DYNAMIC PAST IN A GRAIN OF SAND

Detrital thermochronometry has become more versatile and sophisticated through an expanded analytical repertoir, innovative conceptual approaches, and numerical modeling, making it more applicable to a wider spectrum of tectonic and geomorphic environments. The obtained data can constrain the timing and rates of hinterland erosion and tectonic unroofing, or determine the maximum depositional ages and presence of first-cycle volcanic zircons, as illustrated in the following sections.

Improved Sedimentary Provenance

Zircon U–Pb geochronology has exploded as a sedimentary provenance tool over the past decade with the advent of LA-ICP-MS analysis, data now being available in staggering quantity. Detrital zircon U–Pb provenance studies, based on source crystallization ages, have worked exceedingly well in geological settings with highly variable crustal formation ages, such as North and South America, and in the Himalayas. However, as shown by modern river studies, this is often not the case, due to either monotonous source signatures or significant recycling of older sedimentary strata.

Double dating by U–Pb and (U–Th)/He can differentiate between different sources with the same or similar zircon U–Pb age signatures (Fig. 2). For example, in the Paleogene foreland basin of the southern Pyrenees, Thomson et al. (2019) showed that identical Variscan U–Pb ages from the foreland and the orogenic wedge can readily be differentiated by (U–Th)/He double dating. Whereas Variscan zircons from the foreland are characterized by Permian He ages, Variscan zircons from the Pyrenees yielded early Paleogene He cooling ages, which reflect rapid tectonic exhumation of the fold-and-thrust belt (Fig. 3). Similarly, Xu et al. (2018) showed that U–Pb and He double dating of Miocene strata in the northern Gulf of Mexico is able to differentiate detrital zircons that have a nondiagnostic, invariant, late Mesoproterozoic (Grenvillian) age by leveraging their cooling ages, thereby improving sediment provenance reconstructions on the basis of otherwise nondiagnostic zircons.

Hinterland Dynamic Past

In addition to refining sedimentary provenance, detrital thermochronometry potentially makes lag time calculations possible, the aim being to quantify hinterland bedrock exhumation rates from the detrital signature. Lag time, as defined above, is a measure of the time elapsed between a mineral grain’s passage through its closure isotherm to its surface exposure, erosion, and deposition (e.g., Ruiz et al. 2004; Saylor et al. 2012). Hence, assuming negligible transport and recycling duration, minimum lag times reflect the rapidity of source terrane exhumation rates and give a measure of the dynamic evolution of the hinterland (Fig. 1). Whereas short lag times reflect rapid unroofing, long lag times are indicative of slow exhumation or long-term intermediate storage. The temporal evolution and variation in hinterland exhumation rates can be assessed by comparing lag time estimates from different stratigraphic horizons. A temporal decrease in lag time can be interpreted as an increase in source terrane exhumation rate, but an increase in lag time might signal either a decrease in exhumation rate or a change in sediment source (e.g., Saylor et al. 2012).

Detailed zircon (U–Th)/He and apatite fission track analyses from the northern Alpine Molasse foreland basin in central Switzerland illustrate the insights that can be gleaned from high-resolution lag-time reconstructions (Fig. 4). The Swiss Molasse basin is characterized by two major shallowing-upward Oligo-Miocene sedimentary sequences, divided by a marine transgression in the early Miocene (Schlüegger et al. 1997). It has been suggested that thrusting and erosion...
might have waned during the transgression; however, thermochronometric lag times tell a different story. Lag times are uniformly ~5–10 My during deposition of the Lower Freshwater Molasse, but decrease abruptly to ~0 My at the transgressive base of the Upper Freshwater Molasse at ~19 Ma, signaling a major phase of accelerated exhumation of the fold-and-thrust belt, possibly due to either out-of-sequence thrusting or syn-orogenic hinterland extension. Lag times again increase to ~10 My at ~12 Ma, interpreted as a decrease in shortening in the Helvetic thrust belt, the onset of shortening in the Jura Mountains, and the Molasse basin becoming a piggy-back basin. Hence, high-resolution lag time studies have great potential to elucidate tectonic and erosional evolution of an orogenic hinterland (Fig. 4).

Recently, Malusà and Fitzgerald (2020) explored some of the assumptions and limitations of quantitative lag time interpretations. They pointed out that for reliable lag-time quantification, ages need to reflect mineral closure ages resulting from a simple cooling history (no partial resetting), source terrane isotherms should be in steady-state resulting from a simple cooling history (no partial resetting), source terrane isotherms should be in steady-state quantification, ages need to reflect mineral closure ages resulting from a simple cooling history (no partial resetting), source terrane isotherms should be in steady-state through time, and sediment transport time from source to sink should be negligible. Importantly, for reliable lag

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**Figure 3** Case study from the southern Pyrenean foreland basin demonstrating the power of U–Pb and He double-dating in differentiating sediment inputs to the South Pyrenean Foredeep from the foreland (from the south) and orogenic hinterland (from the north) in time and space, despite there being a nondiagnostic zircon U–Pb signature. Whereas Cretaceous strata (Santonian, Garumnian) are dominated by Permo-Triassic cooling ages, the onset of the Pyrenean provenance is marked by an abrupt shift to Paleocene–Eocene cooling ages, which are derived from exhuming the Pyrenean fold-and-thrust belt. Stratigraphic divisions: Corça A and B Formations, Ametella Formation, (all Eocene in age), Baronia Formation (Eocene–Paleocene in age), Garumnian = an informal local European term for uppermost Maastrichtian (Late Cretaceous) to lowermost Paleogene strata in the Pyrenees; Santonian = middle Late Cretaceous. Modified after Thomson et al. (2019).

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**Figure 4** Application of temporal variations in thermochronometric lag times in the Cenozoic Northern Alpine Foreland basin in central Switzerland. These data show how the detrital record can record the dynamic tectonic evolution of the orogenic hinterland. There is a rapid decrease in lag time ($t_L$) that is temporally coincident with the Burdigalian transgression (roughly 20 Ma) in the foredeep, signaling the onset of rapid Early Miocene thrust belt exhumation, while a Middle Miocene increase in lag time signals the onset of shortening in the Jura Mountains (mainly in France and Switzerland) and of the Molasse Basin becoming a piggy-back basin. The blue swaths is the envelope of the youngest zircon He ages. The diagonal lines are contours of constant lag times ($t_L = 0, 10, 20$, and $30$ My). Abbreviations: UFM = Upper Freshwater Molasse (Miocene); UMM = Upper Marine Molasse (Miocene); LFM = Lower Freshwater Molasse (Miocene). Data from Miller (2012).
time estimates, it is critical to exclude first-cycle volcanic grains because they do not track the exhumation path from closure to erosion. This is best accomplished by U–Pb–He double-dating and the exclusion of volcanic grains with identical crystallization and cooling ages (Saylor et al. 2012).

Short- and Long-term Landscape Evolution

Detrital geo- and thermochronometry are potent tools for reconstructing past drainages and landscapes or continental paleogeographies, and for elucidating their long-term erosional and landscape evolution. Detrital zircon U–Pb dating has been the principal workhorse for these reconstructions, but detrital thermochronometry has both refined these reconstructions and, more importantly, provided unique quantitative insights into the dynamic evolution of continents.

Detrital thermochronometry is not limited in its application to large-scale, deep-time reconstructions: studies have also used detrital thermochronometric data to track geomorphic processes, such as the locus of erosion within a catchment or the nature and efficiency of erosive agents (e.g., glaciers). This approach is most effective if the distribution of bedrock thermochronometric ages within a drainage are spatially variable and well-defined. The technique can, therefore, pinpoint where sediment came from and allow one to attribute detrital ages to a specific portion or elevation within a drainage.

Stock and others (2006) utilized apatite (U–Th)/He to investigate glacial, fluvial, and hillslope erosion processes in the Sierra Nevada (USA). By using statistical comparison of observed and predicted age distributions, based on catchment hypsometry, they were able to point to the locations of sediment generation and storage in mountain-scale catchments. Ruhl and Hodges (2005) used detrital muscovite 40Ar/39Ar ages to make a similar comparison of catchment erosion in the Nepal Himalayas. These authors reconstructed catchment-averaged erosion rates to evaluate spatial uniformity or heterogeneity of erosion, and explored possible transience in erosional processes and departure of those processes from steady-state over a million-year timescale. Finally, detrital thermochronometry from modern catchments has proven useful in mapping late Cenozoic exhumation patterns in large, inaccessible regions, such as the ice-covered mountains of Alaska (Lease et al. 2016).

Stratigraphic Age Constraints

Dating by U–Pb of first-cycle detrital volcanic zircons has been extensively used to determine depositional ages in strata that lack biostratigraphic age constraints (Dickinson and Gehrels 2009). Although this methodology has been shown to work well in tectonic basins adjacent to magmatic and tectonic exhumation magnitudes and rates, and, thus, quantify the dynamic evolution of sedimentary source terranes with considerable temporal and spatial resolution. Furthermore, geo- and thermochronometric double dating (e.g., U–Pb–He double dating) can provide more accurate sedimentary provenance information. This approach allows for a better characterization of sediment contributions from volcanic, first-cycle basement, or recycled sedimentary input into source-to-sink systems on the basis of both lag time and age differences between crystalli-
Detrital thermochronometry has been applied to a range of tectonic environments, from orogenic systems to continental rifts. High-octane orogenic systems and fold-and-thrust belts, such as the Himalayas or Andes, have long been the playground for detrital provenance and thermochronometry studies, purely because the thermochronometric signals, like the mountains themselves, are big. Analytical advances have dramatically improved our ability to resolve the timing and rates of hinterland exhumation, making it now possible to tie detrital fluxes and depositional records to specific thrust sheets, and to provide a detailed record of the dynamic past of an orogen. In extensional rifts and continental margins, bedrock thermochronometry has been a compelling technique to elucidate the temporal and exhumation histories, while isotopic provenance studies have focused on large-scale source provenance reconstructions, basin fill history, and reservoir characterizations.

D detrital zircon He cooling ages provided crucial new chronostratigraphic constraints, allowing for stratigraphic differentiation and correlation and links to stratigraphic packages and tectonic events that have affected the region over several hundred million years. Abbreviations: E = Early; Fm. = Formation; L = Late. Data from Pujol (2011).

Looking to the future, as detrital noble gas thermochronometry and its combination with U–Pb double dating is experiencing rapid growth, more time- and cost-effective data acquisition is needed: the development of detrital laser (U–Th)/He dating should provide this boost (e.g., Horne et al. 2016). In addition, improved recovery of thermal information from single detrital grains would also be desirable. This has been potentially possible, though rarely utilized, in the case of single-grain detrital 40Ar/39Ar step-heating; it should also be feasible in the case of 4He/3He thermochronometry (e.g., Shuster and Farley 2005). To date, no detrital 4He/3He thermochronometric studies have been attempted. However, statistically more robust large
sample size studies and single-grain thermal history recovery in the future will also require better integration of numerical modeling, such as coupled thermo-mechanical, landscape, and geodynamic modeling, to warrant the increased analytical effort.

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Iron Oxide (U–Th)/He Thermochronology: New Perspectives on Faults, Fluids, and Heat

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Fault zones record the dynamic motion of Earth’s crust and are sites of heat exchange, fluid–rock interaction, and mineralization. Episodic or long-lived fluid flow, frictional heating, and/or deformation can induce open-system chemical behavior and make dating fault zone processes challenging. Iron oxides are common in a variety of geologic settings, including faults and fractures, and can grow at surface- to magmatic temperatures. Recently, iron oxide (U–Th)/He thermochronology, coupled with microtextural and trace element analyses, has enabled new avenues of research into the timing and nature of fluid–rock interactions and deformation. These constraints are important for understanding fault zone evolution in space and time.

Keywords: iron oxide, thermochronology, faults, heat, fluid–rock interaction, hydrothermal mineralization

INTRODUCTION

Faults are dynamic environments that can be active over temporal and spatial scales that span several orders of magnitude. Deformation along faults occurs by creep, microseismicity, and/or mega-earthquakes (e.g., Scholz 2002). Faults also serve as pathways for fluids (e.g., Sibson 1981). Textural and geochemical transformations of fault materials are associated with these diverse processes and depend on the mineralogy and rheology of the lithologies present (i.e., continental crust, oceanic crust, or mantle), the ambient conditions (i.e., depth, geothermal gradient), fluid composition, and strain rate. Reconstructing the deformation and fluid–rock interaction histories of these systems is central to understanding fault zone evolution, earthquake mechanics, and how Earth material properties change through time.

Minerals used for more conventional thermochronological applications, such as apatite and zircon, can track cooling of rocks from fault-related processes, such as exhumation. Most applications quantify variations in exhumation rates that are broadly linked to fault activity over million-year timescales and require kilometer-scale offsets. Recently, (U–Th)/He thermochronology of zircon and apatite entailed within, or adjacent to, fault zones has been used to decipher the timing of shear heating and thermal fluid flow (e.g., Maino et al. 2015; Louis et al. 2019). Minerals that grow on fault surfaces, on the other hand, can directly record changes in temperature, geochemistry, and strain rate during deformation.

Iron (Fe) is the fourth most abundant element on Earth and iron oxides (i.e., hematite, magnetite, goethite) are common in many geologic environments, from Earth’s surface to deep magmatic systems (e.g., Cornell and Schwertmann 2003) (Fig. 1). Hematite (Fe₂O₃), goethite (FeOOH), and magnetite (Fe₃O₄) often grow as microcrystalline aggregates, concretions (hematite, goethite), or up to centimeter-sized single crystals (magnetite, hematite), depending on conditions at the time of mineralization. The ubiquity of Fe oxides makes them attractive targets for constraining the timing of diverse geologic processes. In this contribution, we highlight Fe oxides in fault zones and fractures; however, we note that hematite and goethite also precipitate from oxidizing fluids as diagenetic cements, hydrothermal deposits, and deep weathering horizons (e.g., laterites) (Fig. 1). Magnetite can form as a primary mineral in igneous rocks or as an alteration product in metamorphic and hydrothermal systems (Fig. 1).

Figure 1: Simplified block diagram showing geologically diverse occurrences of hematite (hexagons), magnetite (diamonds), and goethite (ovals) in continental and marine settings.
Iron oxides are suitable for (U-Th)/He thermochronology because they incorporate measurable U and Th, negligible initial He, and are generally He-retentive on geologic timescales at near-surface temperatures (e.g., Strutt 1909; Bahr et al. 1994; Farley and Flowers 2012). Early applications of hematite and magnetite (U-Th)/He dating focused on high-temperature hydrothermal systems and igneous rocks, respectively (e.g., Fanale and Kulp 1962; Wernicke and Lippolt 1997; Blackburn et al. 2007). These studies demonstrated that Fe oxide (U-Th)/He thermochronology can constrain simple thermal histories, such as mineralization or volcanic eruption ages.

Analytical advances and improved understanding of He diffusion kinetics has enabled research using Fe oxide (U-Th)/He thermochronology to document more complicated thermal histories and diverse processes, such as exhumation, diageneis, and soil development (Shuster et al. 2005; Evenson et al. 2014; Reiners et al. 2014). The low-temperature sensitivity of Fe oxide (U-Th)/He thermochronometers, coupled with their occurrence in faults, provides the unique opportunity to investigate the thermal and deformation histories of fault systems. Here, we review the Fe oxide (U-Th)/He systematics that make this analytical tool distinct from other noble gas thermochronometers. We highlight methodological advances and complementary data that have improved our ability to accurately interpret Fe oxide (U-Th)/He dates. We then illustrate how hematite and magnetite (U-Th)/He thermochronology can be applied to document fluid-rock interactions, mineralization, and deformation on faults.

**IRON OXIDE (U–TH)/HE TEMPERATURE SENSITIVITY**

British physicist Robert John Strutt (1875–1947) measured the first hematite U–He date in 1909 and concluded that the lower-than-expected age was the result of He loss from the mineral. Subsequent step-heating 4He diffusion experiments revealed that specular and botryoidal hematite have relatively low closure temperatures between ~100°C and 300°C (e.g., Bahr et al. 1994). The magnetite (U-Th)/He system has a reported closure temperature of ~250 ± 50°C, based on a diffusion experiment using internal fragments from a single igneous magnetite crystal (Blackburn et al. 2007). These hematite and magnetite closure temperatures are calculated using a 10°C/My cooling rate and the assumption that the He diffusion domain is the entire grain. However, this assumption may lead to incorrect interpretations in samples composed of different grain sizes or subdomains. For example, aliquots of hematite (or goethite) analyzed for (U–Th)/He dating are commonly aggregates of individual tiny crystals that may record a range of closure temperatures within a single sample (Farley and Flowers 2012; Evenson et al. 2014).

Our understanding of He diffusion in minerals was advanced by the ability to generate a spatially uniform distribution of 3He by proton bombardment. By incrementally heating an aliquot of sample and measuring the synthesized 3He that degasses, we can determine a He Arhenius relationship (the relationship between the diffusion coefficient and temperature) (see Gautheron and Zeitler 2020 this issue) that characterizes the diffusion domain(s) and diffusion kinetics of He for that aliquot of sample (e.g., Farley and Flowers 2012; Farley 2018). Moreover, by measuring the naturally occurring 4He that degasses at the same time as 3He, we can use the measured 3He/4He ratio to constrain the spatial distribution of 4He in a single grain or aggregate (e.g., Shuster and Farley 2005). Information about the spatial distribution of 4He can be used to place tighter constraints on the geologic thermal histories of samples than is possible from a bulk 4He measurement and a (U-Th)/He date alone.

Atom-scale diffusion calculations and 4He/3He diffusion experiments indicate that polycrystalline hematite exhibits polydomain He diffusion, or simultaneous He loss from individual crystallites in the aggregate (Farley and Flowers 2012; Evenson et al. 2014; Farley and McKeon 2015; Balout et al. 2017). New single-crystal 4He/3He and bulk (U-Th)/He data from different-sized crystals confirm that each hematite grain in an aggregate constitutes a diffusion domain (Farley 2018; Jensen et al. 2018). Hematite 4He/3He diffusion experiments refine the closure temperature to ~50–250°C, given a range of typical grains sizes (0.01–1,000 µm) and assuming a 10°C/My cooling rate, thereby confirming the strong dependence of closure temperature on grain (domain) size (Farley and Flowers 2012; Evenson et al. 2014; Farley 2018).

Iron oxide 4He/3He data have also enabled researchers to interpret increasingly complex geologic histories. For example, 4He/3He thermochronology of hydrothermal hematite has been applied to reconstruct the long-term burial and erosion history of the eastern Grand Canyon (Arizona, USA) (Farley and Flowers 2012), the rapid exhumation and evolution of the Buckskin–Rawhide detachment system of Arizona (USA) (Evenson et al. 2014), past fluid movement in the vicinity of the Moab Fault in Utah (USA) (Garcia et al. 2018), and the mineralization history of banded iron formations (Farley and McKeon 2015).

**IRON OXIDE GROWTH, COOLING, AND HE LOSS IN FAULTS AND FRACTURES**

Iron oxide (U-Th)/He thermochronology can document a variety of fault-related processes, such as fluid flow and mineralization, tectonic exhumation, or thermal resetting from frictional heating or hydrothermal processes (Fig. 2A). These diverse interpretations are, in part, possible because Fe oxides in fault rocks are secondary minerals. Thus, they can form above or below their closure temperature, making them distinct from other minerals traditionally used for (U-Th)/He thermochronology. Apatite and zircon, for example, crystallize in igneous or metamorphic systems well above their respective closure temperatures and, thus, yield (U-Th)/He dates that record subsequent cooling through their closure temperatures. In this section, we will explore the implications of variable formation temperatures and subsequent thermal histories that induce He loss on the interpretation of Fe oxide (U-Th)/He thermochronology data.

Iron oxide (U-Th)/He data patterns and interpretations depend on a sample’s specific closure temperature, formation conditions, and the postformation thermal history (Fig. 2B). For example, if an Fe oxide crystallizes and remains at temperatures below its closure temperature, such as in some upper crustal faults or hydrothermal systems, then the associated (U-Th)/He date will record the time of mineral growth (i.e., mineralization, formation age) (Fig. 2B) (Moser et al. 2017; Garcia et al. 2018; Jensen et al. 2018; Cooperdock et al. 2020). Alternatively, if an Fe oxide experiences or forms at temperatures higher than its closure temperature, then the (U-Th)/He date captures subsequent cooling due to tectonic or erosional exhumation (Fig. 2B) (Calzolari et al. 2018). Furthermore, a sample may contain multiple Fe oxide generations that, depending on the aliquot-specific closure temperature, will reflect formation and/or cooling (Cooperdock and Stockli 2016).
Fault and fracture systems host thermal, chemical, mechanical, and/or fluid-mediated processes that may cause open-system behavior (i.e., He loss and/or parent isotope gain or loss) (Fig. 2B) that also must be considered. For example, friction-generated heat during fault slip may induce He loss from hematite on fault surfaces by thermally activated volume diffusion or recrystallization (Fig. 3) (Ault et al. 2015; McDermott et al. 2017; Calzolari et al. 2020). Hydrothermal fluids present in a fault zone may also cause He loss from hematite (U–Th)/He dates can represent either a formation age, a cooling age, or thermal resetting, depending on the ambient temperature at which the hematite formed relative to $T_c$, and also the post-formation thermal and deformation history. Symbols: $t$ = time; $T$ = temperature; $T_c$ = closure temperature.

### STRATEGIES FOR DATA INTERPRETATION

The fact that Fe oxides can grow above or below their closure temperature and experience He loss and/or parent isotope gain presents unique challenges for interpreting Fe oxide (U–Th)/He thermochronology data, but also opportunities for achieving deeper insight into fault zone processes. How do you know if an Fe oxide (U–Th)/He date reflects mineralization, exhumation, or a superimposed thermal process such as frictional heating (Fig. 2)? Is there geological significance to scattered dates from aliquots of a single sample or from across multiple samples? Addressing these questions requires: (1) knowing aliquot-specific closure temperature estimates; (2) providing detailed Fe oxide textural analysis and aliquot characterization; (3) determining the mineralization temperature and/or background thermal conditions that the Fe oxide experienced.

Estimating an aliquot-specific closure temperature involves knowledge of the aliquot’s grain size distribution. Micron to submicron hematite platelets or particles commonly observed on fault surfaces and in some fault veins are below the resolution of a petrographic microscope and require field-emission scanning electron microscopy (SEM) for imaging (e.g., Ault et al. 2016). Magnetite grain sizes, however, can typically be measured using an optical microscope (Cooperdock and Stockli 2016) (Fig. 4). The range of potential aliquot closure temperatures is inferred from the grain size distribution, the assumption that the plate half-width or grain radius is the diffusion domain length-scale, and the application of available diffusion kinetics (Blackburn et al. 2007; Farley 2018). Aliquots with variable grain sizes or an evolving grain size distribution with deformation may experience variable He loss, which will lead to intrasample data scatter over their thermal history (Fig. 5).

Textural, grain quality, and chemical characterization are also critical to addressing these questions. Scanning electron microscopy, energy-dispersive X-ray spectroscopy, X-ray computed tomography (micro-CT), and electron microprobe analyses are used to characterize aliquot quality and chemistry. For example, these methods can reveal the presence and abundance of non–iron oxide phases introduced during or after Fe oxide mineralization from fluid circulation, or via mechanical mixing during deformation. These phases may be U-bearing and/or have a

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**Figure 2** (A) Schematic cross-section showing potential processes recorded by hematite (hexagons) and magnetite (diamonds) (U–Th)/He thermochronology in fault and fracture systems. (B) Potential processes and their interpretations in terms of Fe oxide (U–Th)/He thermochronology data from fault zones. Simplified cross-sections show a polycrystalline Fe oxide aliquot, with a hypothetical associated 120 °C closure temperature ($T_c$). Iron oxide (U–Th)/He dates can represent either a formation age, a cooling age, or thermal resetting, depending on the ambient temperature at which the hematite formed relative to $T_c$, and also the post-formation thermal and deformation history. Symbols: $t$ = time; $T$ = temperature; $T_c$ = closure temperature.

**Figure 3** The temperature and time, from seconds (s) to millions of years (My), that are required to reset (i.e., induce 90% He loss) the (U–Th)/He systems in magnetite, hematite, and apatite, taking into account grain sizes as denoted in legend. Shaded boxes highlight thermal resetting conditions for frictional (i.e., earthquake) and fluid-mediated heating. Modified from Ault et al. (2015, 2016).
demonstrates different He retentivity compared with Fe oxide, and, thus, contribute to Fe oxide (U-Th)/He data scatter (e.g., Evenson et al. 2014). Alternatively, U that is added to existing Fe oxides by subsequent fluid interaction may be revealed by a negative relationship between Fe oxide (U-Th)/He date and Th/U ratio within a sample (Reiners et al. 2014). In addition, the shape of these individual micro- to nanoscale crystals can yield key insights into the (de)formation and related thermal processes from fault slip. Textures can be linked to Fe oxide (U-Th)/He data patterns within individual samples and/or across multiple samples in a larger dataset to infer complex thermal histories (Fig. 4) (McDermott et al. 2017; Moser et al. 2017).

Hydrothermal or igneous magnetite can be rife with inclusions, fractures, or intergrowths, all of which have the potential to introduce excess He, modify the He diffusion kinetics, and otherwise complicate data interpretation (Cooperdock and Stockli 2016). Iron oxides cannot be screened for internal inclusions or fractures using transmitted light. Reflected light microscopy or SEM imaging can provide a 2-D view of a grain, but this requires a thin section and polishing away part of the crystal. In contrast, micro-CT provides a nondestructive, 3-D view through an entire mineral grain at micron-scale resolution, and can identify inclusions of other minerals, fluid inclusions, or fractures (Fig. 4). This technology does not heat or alter the sample during preparation or scanning, so that the same grains screened by micro-CT can be used for subsequent (U-Th)/He analysis (e.g., Cooperdock and Stockli 2016).

Together with image analysis, fault rock data interpretation is augmented by independent thermometry and constraints on the postmineralization ambient thermal history. Mineralization temperature estimates can be made by Ti-in-quartz thermometry of cooccurring phases, fluid inclusion microthermometry of hematite and/or coprecipitated calcite or quartz, and stable or clumped isotope analysis of coeval carbonates (Jensen et al. 2018; Cooperdock et al. 2020). Thermal history constraints from apatite or zircon (U-Th)/He or fission track thermochronology of nearby undeformed rocks are compared with Fe oxide (U-Th)/He dates and corresponding closure temperature estimates. Thus, aliquot-specific closure temperature estimates, microtextural observations and aliquot screening, and information on the ambient thermal history, collectively provide context for interpreting Fe oxide (U-Th)/He dates as recording mineralization or some other postmineralization thermal process.

**BREAKTHROUGHS IN APPLICATIONS TO FAULT SYSTEMS**

Advances in our understanding of He diffusion in Fe oxides, coupled with textural analysis, have enabled emerging applications of Fe oxide (U-Th)/He thermochronology that sit at the intersection of deformation and fluid–rock interaction processes within fault zones. Here, we highlight novel Fe oxide thermochronology data interpretations in fault systems over a spectrum of conditions from low-temperature mineralization to high-temperature thermal resetting.

**Mineralization Events in Fault and Fracture Systems**

Fault and fracture zones enhance fluid–rock interactions, which can form new minerals by direct replacement or by precipitation from fluids. Hematite (U-Th)/He studies have focused on the timing of mineralization in hydrothermal systems (Wernicke and Lippolt 1997; Farley and Flowers 2012). For example, Jensen et al. (2018) extracted individual crystals from specular hematite veins associated with basement-hosted, fault-controlled sandstone injectites in the Colorado Front Range (USA). Hematite (U-Th)/He dates exhibit a positive relationship with hematite plate thickness, and the oldest Cryogenian dates are interpreted as recording a minimum formation age. In this study, coeval sand injection and hematite mineralization may reflect fluid circulation during extensional tectonics.

Cooperdock and Stockli (2016) applied (U-Th)/He thermochronology to date magnetite in serpentinite, which is a fluid-altered mantle rock. Magnetite grains were sampled from a kilometer-scale shear zone within an exhumed subduction complex on Syros (Greece). A combination of textural and geochemical analyses reveals two magnetite populations that record distinct fault-related events based on variations in grain size, (U-Th)/He date, trace element chemistry, and field context. A millimeter- to centimeter-diameter grain size population enriched in Mg, V, Ti, and Al, which were mobilized via hot (400°C) subduction-related fluids, yield middle Miocene (U-Th)/He dates consistent with cooling through the magnetite closure temperature during tectonic exhumation (Fig. 5). A second, submillimeter-diameter grain population, found exclusively within a localized slip surface defined by talc, are depleted in Mg, V, Ti, and Al and yield ~3 Ma magnetite (U-Th)/He dates, significantly younger than ~10 Ma zircon (U-Th)/He dates from the same regional shear zone. Due to their grain size, the ~3 Ma magnetite grains should have a higher closure temperature than the zircon (U-Th)/He system, and, therefore, these magnetite (U-Th)/He dates are interpreted as mineralization below the magnetite closure temperature along a Pliocene-age fault surface (Fig. 5). Trace element–depleted rims on the...
large magnetite grains located on the slip surface provide further evidence for two growth events in this fault zone. This study demonstrates that magnetite (U–Th)/He can be used both as a thermochronometer and to date mineralization within fault zones, and it highlights the ability of serpentinites to episodically grow new magnetite in the presence of repeated fluid pulses.

**Thermal Resetting in Fault Zones**

Fault zones host a variety of thermal processes from coseismic friction-generated heat during an earthquake to fluid-mediated heat advection. Progressive deformation and strain localization create thin (millimeter-scale) slip surfaces in fault zones. During fault slip, the rate of heat generation can outpace heat dissipation, leaving a thermal and textural fingerprint on fault surface minerals such as hematite. For example, a network of hematite “fault mirrors”, or high-gloss, light-reflective thin slip surfaces, in the exhumed, seismogenic Wasatch Fault damage zone (Utah) preserve textural and thermochronometric evidence for transient, elevated temperatures during microearthquakes (Ault et al. 2015; McDermott et al. 2017). Plio-Pleistocene hematite (U–Th)/He dates from fault mirrors are associated with polygonal hematite crystals, a high-temperature texture reflecting annealing and/or grain growth. These textures and hematite (U–Th)/He dates, when compared with host-rockapatite (U–Th)/He data, are best explained by flash heating (T > 1,000°C) at rough patches (i.e., asperities) on the slip surface causing He loss by diffusion and/or recrystallization (McDermott et al. 2017).

Laboratory deformation experiments on hematite at earthquake slip rates confirm that hematite (U–Th)/He thermochronology can serve as a fault slip paleotemperature proxy (Calzolari et al. 2020). Experimentally generated fault surfaces develop fault mirror–like patches comprising sintered nanoparticles similar to some natural fault surfaces (Figs. 6A, 6B). Comparison of hematite (U–Th)/He dates from undeformed and deformed hematite reveal that fault mirror zones exhibit >70% He loss during seismic slip in the laboratory (Fig. 6C). The magnitude of He loss is consistent with asperity flash heating to temperatures >900°C that occurs during fault slip (Calzolari et al. 2020). These examples reveal how hematite (U–Th)/He thermochronology can be used to identify earthquakes in the rock record.

Minerals precipitated in or trapped within faults can also be thermally reset by fluids (e.g., Ault et al. 2016; Louis et al. 2019). For example, hematite (U–Th)/He dates from fault-related fissures exposed in Devonian and Carboniferous rocks on the Gower Peninsula (Wales) are ~141–120 Ma and overlap with ~131 Ma detrital apatite fission track (AFT) data from sediments infilling the fissures (Ault et al. 2016). Burial history reconstructions are inconsistent with both hematite (U–Th)/He and AFT dates reflecting cooling due to erosion alone. Early Cretaceous thermal fluid circulation, coeval with North Atlantic rifting, may have reset the hematite (U–Th)/He and AFT systems or, alternatively, new hematite was precipitated from those thermal fluids. This highlights how high-permeability faults and fractures can serve as conduits for fluid and heat transfer, even long after these structures originally formed.

**CONCLUSIONS**

Recent analytical and data interpretation advances in Fe oxide (U–Th)/He thermochronology enable application of this tool to constrain the timing of a variety of geologic processes: in particular, those in fault zones. The range of temperature sensitivities that can occur within a single sample, due to grain size variations, allows for reconstruction of a broader swath of a sample’s, and, thus, a fault’s,
history. The fact that Fe oxides can mineralize or lose He below their He closure temperatures provides an opportunity to investigate thermal histories of both high- and low-temperature processes in fault systems. This also means that Fe oxide (U-Th)/He thermochronology should be viewed and approached differently from more traditional thermochronometers. In fact, Fe oxide (U-Th)/He data is more powerful when combined with them.

Although there has been much progress over the past decade, opportunities exist for growth and new research directions. Iron oxide 4He/3He thermochronology will provide additional insight into He diffusion and how the kinetics might vary for different grain morphologies, crystal structures, and chemistries. Further developments that link Fe oxide (U-Th)/He thermochronology with microstructures, chemistry, and thermometry will allow us to better understand the significance of (U-Th)/He dates in fault systems and other environments. Iron oxide (U-Th)/He and 4He/3He thermochronology can be coupled with other direct dating techniques, including 40Ar/39Ar dating of clay gouge (e.g., Fitz-Diaz and van der Pluijm 2013) or U-Pb dating of syntectonic calcite (e.g., Nuriel et al. 2017), to document kinematics and rates of fault slip in heterogeneous fault rocks.

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Vestiges of the Ancient: Deep-Time Noble Gas Thermochronology

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INTRODUCTION

“Deep time” is fundamental to geology and sets it apart from other physical sciences. The vastness of geologic time is both profound and almost incomprehensible when one considers that the human perception of time is only a few decades. The concept of deep time was first explored by James Hutton in his Theory of the Earth where he concluded: “The result, therefore, of our present enquiry is, that we find no vestige of a beginning, — no prospect of an end” (Hutton 1788). This famously describes Hutton’s observations at Siccar Point (Scotland) where ~370 Ma sandstones directly overlie ~440 Ma greywacke rocks. A key question that comes to mind is: what happened during the intervening ~70 My? Preserved, in situ, rocks define the geologic record. However, this archive is dominated by gaps (or unconformities) that represent “missing” time, which makes determining the dates and rates of Earth’s surface evolution challenging, particularly as the timescale increases.

Noble gas thermochronology can decipher this missing record by constraining the thermal histories of rocks. Most rocks form at elevated temperatures and depths in the Earth: they cool if exhumed to the surface through erosion or fault motion, and heat back up if buried to greater depths. The worn bedrock may retain part of this history due to the unique temperature sensitivity of different minerals and radiogenic methods, even when overlying rocks have been removed by erosion. Although noble gas thermochronology has been used primarily to constrain the Cenozoic evolution of active tectonic settings, it is applied increasingly to continental interiors of low topographic relief comprised of ancient rocks usually 1,000–3,000 Ma in age (referred to as “cratons”, from the Greek kratos meaning “strength”). Many of these cratonic regions are deeply eroded and lack Phanerozoic sedimentary cover, leaving few rocks behind to yield information about their history following initial craton growth and stabilization.

“Deep-time thermochronology” refers to the application of mid- and low-temperature (<350°C) thermochronology to decipher thermal histories over hundreds of millions of years to billion year intervals (McDannell et al. 2014). Thermochronologic studies of ancient rocks were first conducted primarily with high-to-medium temperature (U–Th)/He datasets has improved (e.g., Guenthner et al. 2010). Deep-time (U–Th)/He studies have evolved from a few initial applications (e.g., Lorencak et al. 2004; Flowers et al. 2006) to more systematic studies, as the ability to interpret complex (U–Th)/He datasets has improved (e.g., Guenthner et al. 2017). We can now assemble nearly continuous histories spanning hundreds of degrees Celsius and more than one billion years of time by using a multisystem approach (McDannell et al. 2019). Although the customary view has been that the ancient cores of continents were “geologically boring” for hundreds of millions of years—passively eroded by rivers, wind, and glaciers—thermochronologic studies increasingly suggest that they contain intriguing records of a long and circuitous journey to becoming “flat.” Some cratonic localities underwent late Proterozoic erosion, contributing to the formation of the Great Unconformity, a large gap in the rock record spanning 100 to >1,000 Ma that may have ties with tectonic and environmental change (e.g., DeLucia et al. 2018; McDannell et al. 2018). Other cratons show evidence of being affected by later burial and erosion episodes, possibly driven by deeper mantle dynamic processes (e.g., Flowers et al. 2012).

In this article, we discuss the theory and advances in noble gas thermochronology that make deep-time studies possible, and provide two examples of the power of combining multiple noble gas systems to retrieve deep-time thermal histories. New opportunities now exist to quantify the tempo and magnitude of long-term erosion rates,
better understand the longevity of landscapes, and gain new insights into the links between continental interior burial and erosion histories, tectonics, mantle dynamics, and other Earth processes in deep time.

**DEEP-TIME NOBLE GAS THERMOCRONOLOGIC METHODS**

The broad temperature sensitivity ranges of K-feldspar \(^{40}\)Ar/\(^{39}\)Ar and He diffusional loss in zircon, titanite, and apatite (U–Th)/He thermochronometers can be exploited in powerful ways to decipher thermal histories in deep time. Dating by the K-feldspar multidiffusion domain (MDD) \(^{40}\)Ar/\(^{39}\)Ar technique (Lovera et al. 1991) is advantageous because the analyst can acquire age information and (effective) size parameters for an individual sample. This is achieved by exploiting complex Ar degassing behavior due to discrete grain size differences (diffusion domains) within K-feldspars during a laboratory heating experiment (also see Gautheron and Zeitler 2020 this issue). To illustrate K-feldspar MDD behavior, one can imagine two spheres of different size filled with gas, such as argon (Fig. 1A). During heating, even though both spheres degas simultaneously, the smallest sphere will exhaust its gas first, while the larger one will still retain Ar (Harrison and Lovera 2014). The progressive diffusive exhaustion of domains is manifest in the Arrhenius relationship as linear arrays with apparent “step-overs” at points where smaller domains become depleted in Ar during a laboratory heating experiment (see Fig. 1A).

Variability in He diffusion kinetics among crystals of the same mineral from the same sample can be exploited to decipher continuous thermal histories over tens to hundreds of degrees Celsius in a manner somewhat analogous to the K-feldspar MDD behavior described above. Radiation damage (e.g., Shuster et al. 2006), grain size (e.g., Reiners and Farley 2001), and U–Th zonation (e.g., Farley et al. 2011) can all influence He diffusion kinetics, and consequently cause (U–Th)/He dates to vary in a mineral suite. In essence, due to these effects, individual crystals act as separate thermochronometers. Radiation damage generally contributes the most to kinetic variability, either impeding or enhancing He diffusion, depending on the amount of crystalline damage, itself a function of U–Th decay and damage accumulation at lower temperatures and on damage repair and annealing at higher temperatures (Shuster et al. 2006; Guenthner et al. 2013; Baughman et al. 2017). A suite of crystals from the same rock with varying effective U (eU, i.e., concentrations of U and Th weighted for their alpha productivity) and a shared thermal history will have different damage accumulation rates and can evolve to have temperature sensitivities that vary between ~110°C and 60°C in apatite and ~220°C and 0°C in zircon and titanite. Overall date–eU trends are more meaningful than any individual date. Generally, a longer interval of damage accumulation produces greater divergence in temperature sensitivity across a mineral suite. This may manifest as positive (apatite, zircon) and/or negative (zircon, titanite) correlations between date and eU for time-temperature (t–T) histories characterized by protracted cooling or reheating and partial He loss (Fig. 1B, C). Such histories typify those of cratonic regions. Radiation damage accumulation and annealing models for apatite (RDAAM) and zircon (ZRDAAAM) He diffusion enable the thermal history significance of (U–Th)/He data patterns to be interpreted quantitatively (Flowers et al. 2009; Gautheron et al. 2009; Guenthner et al. 2013). Refinement of these models is an important focus of ongoing study. If the causes of kinetic variability are sufficiently understood, the large variation that commonly characterizes cratonic (U–Th)/He datasets can be inverted to deconvolve thermal histories in deep time.

**DECIPHERING CONTINUOUS DEEP-TIME THERMAL HISTORIES**

*Forward Modeling of Complex Cratonic Thermal Histories*

The complex t–T paths that are common in continental interiors can generate broad distributions of thermochronologic dates (Fig. 1). Figure 1B depicts multiple simplified thermal history scenarios.
inverse thermal history modeling for problems in deep time

The typical goal in thermochronologic studies is to determine the range of viable t–t paths that can explain the data in order to test a geologic hypothesis about the dataset. This is generally accomplished using inverse thermal history modeling. Unlike the forward modeling approach in figure 1 where thermal histories are used to predict expected thermochronometer data, in inverse mode the data are used to find thermal histories that predict the observed data. A range of t–t paths generally satisfies a k-feldspar MDD age spectrum or a single (U–Th)/He date. For example, t–t paths 3 and 4 (fig. 1b) generate indistinguishable k-feldspar age spectra (fig. 1c) due to the inherent MDD assumption of similar activation energy for all diffusion domains, which makes their relative response to temperature changes the same and prevents discrimination between cooling-only and reheating histories (McDannell et al. 2019). However, the use of multiple thermochronometers with different diffusion kinetics and overlapping temperature sensitivities, such as K-feldspar and zircon (U–Th)/He, and apatite (U–Th)/He, can dramatically narrow the number of t–t paths that can simultaneously honor all of the data. Ambiguity in t–t path interpretation can be further reduced by forcing all tested paths through t–t boxes that represent key geologic constraints on the thermal history, such as the sample’s emplacement depth, stratigraphic estimates of burial magnitude, and the unconformable relationships that pin when the rock was at the surface during its history.

The number of permissible t–t paths that can explain thermochronologic datasets increases dramatically deeper in time. Consequently, for deep-time studies, it is critical not only to combine multiple chronometers and geologic constraints in the inversions, but also to carefully consider the chosen modeling approach. Common thermal history models employ either random Monte Carlo (MC) or more complex learning algorithms and Bayesian statistical frameworks (see Fox and Shuster 2020 this issue). Taking advantage of multiple modeling strategies in an exploratory fashion can aid in understanding the information contained in datasets. For example, the outcomes of a purely MC t–t search can be relatively simple to represent and understand, but MC modeling can also be inefficient, making it difficult to find suitable solutions for long-timescale problems and large, precise datasets, while requiring user-specified explicit assumptions to delineate the model space. In contrast, the complexity of t–t solutions is inferred from the data in the Bayesian approach, and statistical resampling of the model ensemble can provide confidence intervals around solutions. However, simpler solutions are generally preferred over more complex ones, which may be less appropriate in deep time. Thermal histories generated for this article were modeled using the Arvert program (e.g., McDannell et al. 2019), which utilizes the controlled random search algorithm, a type of optimization method that starts with a randomly generated pool of MC t–t histories that are then iteratively recombined to create new histories, retaining better-fitting solutions in
Figure 3  Inverse thermal history model sensitivity tests using the controlled random search algorithm in the Arvert 4.1 program [free software used to invert $^{40}$Ar/$^{39}$Ar age spectra] applied to the synthetic multidiffusion domain (MDD) data and (U–Th)/He data generated in Figure 2 (from t–T path 1). (A) Model results for zircon and apatite (U–Th)/He data. (B) Model results for synthetic MDD argon data plus the zircon and apatite (U–Th)/He data. In both (A) and (B), the shaded yellow region denotes the synthetic MDD argon data plus the zircon and apatite (U–Th)/He data. In both (A) and (B), the bright yellow region denotes the synthetic MDD argon data plus the zircon and apatite (U–Th)/He data. In both (A) and (B), the gray dotted line is the “true” t–T history that the controlled random search algorithm is attempting to recover. Light gray envelopes are the entire pool of 150 final model solutions (boundaries are not solutions); the dotted gray line is the average path from the entire pool; 10 solid blue lines are the top 10 best-fit model paths; the solid red line is the overall best-fit model path. Adding MDD data to the (U–Th)/He data in panel (B) improves recovery of the true history and increases the similarity between the pool average and best-fit solution. (C) Plot of date versus effective U (eU) showing the true (black) and predicted (blue and red) zircon (U–Th)/He (diamonds) and apatite (U–Th)/He (circles) dates for the two models (note differences in eU x-axes). The “true” zircon and apatite dates are assumed to have 10% and 5% analytical uncertainties (2σ), respectively. Most individual errors are smaller than symbols; symbol size differences are for visual clarity only. Abbreviations: MDD = multidiffusion domain, ZHe = zircon (U–Th)/He, AHe = apatite (U–Th)/He.

CASE STUDIES INTEGRATING MULTIDIFFUSION DOMAIN AND MULTIMINERAL (U–TH)/HE DATA

Although it is increasingly common to decipher cratonic thermal histories from K-feldspar $^{40}$Ar/$^{39}$Ar or zircon (U–Th)/He and apatite (U–Th)/He data, we are aware of few studies that simultaneously simulate all of these data types (McDannell et al. 2019). Here, we provide two examples of comprehensively integrating such results with geologic observations to invert for continuous deep-time thermal histories in the Canadian Shield and the Kaapvaal craton of southern Africa.

East Lake Athabasca Region, Canadian Shield

The East Lake Athabasca region is an exposure of granulite-facies rocks located in the interior of the Canadian Shield. A multichronometer U–Pb and $^{40}$Ar/$^{39}$Ar dataset documented multistage unroofing of these lower crustal rocks to the surface by ~1,700–1,650 Ma, when sedimentary units of the Athabasca Basin were deposited unconformably on top of the exhumed basement (Rayner et al. 2003). Here, we use Arvert to simulate K-feldspar MDD data with a “flat” age spectrum (i.e., signifying rapid cooling) (Fig. 4A LEFT) (McDannell et al. 2018), zircon (U–Th)/He dates of ~1,400–1,300 Ma (Flowers et al. 2006), and Phanerozoic apatite (U–Th)/He dates with an eU correlation (Flowers 2009) (Fig. 4A INSET). We allow two reheating events, one of which can occur any time during the early portion of the history, while the other is loosely required to occur after 450 Ma, which is the age of regionally deposited Orдовician carbonates. Proterozoic reheating is allowed but the timing/magnitude is not explicitly enforced in the model, while the latter event is required by geology (see McDannell and Flowers 2020 for model details). The thermal history model result (Fig. 4A RIGHT) is consistent with initial rapid 1,700 Ma cooling and exhumation, burial heating to ~100–125 °C by ~800 Ma, cooling to surface conditions by the early Paleozoic, and later Phanerozoic burial heating. Neoproterozoic reheating may be due to burial by sediments derived from the Grenville (~1,300–1,000 Ma) mountain belt.
Ancient Gneiss Complex, Kaapvaal Craton, Southern Africa

Our second example is from the Archean Ancient Gneiss Complex (AGC) of the eastern Kaapvaal craton. Biotite $^{40}\text{Ar} / ^{39}\text{Ar}$ data record cooling to $<300{\text{°C}}$ by $\sim3\ 000$ Ma (Layer et al. 1992). In the broader region, $1\,400$–$1\,300$ Ma volcanic rocks and $\sim300$ Ma sedimentary rocks unconformably overlie the basement, requiring basement exposure at these times. The Karoo Supergroup buried the craton from $300$ to $1\,833$ Ma, followed by basement re-exhumation to the surface. Here, we use Arvert to simulate new K-feldspar MDD step-heat data, which range from $\sim1\,930$ to $1\,000$ Ma (Fig. 4B LEFT), together with Cretaceous zircon (U–Th)/He and apatite (U–Th)/He dates (Fig. 4B INSET) (Baughman and Flowers 2020), and we apply the geologic constraints outlined above (McDannell and Flowers 2020). We allow two reheating events, one any time during the early portion of the history, and the other after $300$ Ma. The Arvert results are similar to the $t$–$T$ history published in Baughman and Flowers (2020) based on (U–Th)/He data alone (Fig. 4B RIGHT), but the addition of K-feldspar MDD data and use of the controlled random search algorithm narrows the envelope of $t$–$T$ paths during initial Mesoproterozoic cooling and later Neoproterozoic heating (Fig. 4B RIGHT). Uncertainty in the detailed timing of Neoproterozoic cooling remains because of the “gap” in thermochronometric constraints between the K-feldspar MDD data (blue shading) and the (U–Th)/He data (green shading) due to subsequent Karoo burial and thermal resetting of the zircon (U–Th)/He system. Future work on a titanite (U–Th)/He radiation damage model may refine the timing of Neoproterozoic cooling. This thermal history was interpreted to record initial basement cooling and exhumation by $\sim1\,400$–$1\,200$ Ma, Mesoproterozoic burial reheating by sediments shed from the Namaqua–Natal orogenic belt during Rodinia supercontinent assembly, Neoproterozoic re-exhumation, and later burial by and erosion of the Mesozoic Karoo Basin (Baughman and Flowers 2020).

Broad Implications

Our two case studies illustrate several key points. First, integration of the multiple noble gas datasets with geologic information allows us to reconstruct continuous deep-time thermal histories that link relatively high temperature ($>350{\text{°C}}$) and low temperature ($<100{\text{°C}}$) systems and thereby constrain the transit of rocks from midcrustal levels to the surface. Second, the ancient thermochronologic dates and geologic evidence for initial basement exhumation to near-surface conditions in the Proterozoic are consistent with the first-order thermal stability (i.e., lack of pervasive tectonic activity) of these two regions for $>1\,000$ Ma. Finally, despite this antiquity, the results require that both regions underwent one or more later episodes of burial and erosion prior to final basement exhumation to the surface. Both results indicate more substantial phases of burial and erosion in Proterozoic and Phanerozoic time than implied by the conventional view of cratonic “stability.”

LOOKING FORWARD: OPPORTUNITIES AND CHALLENGES IN DEEP-TIME THERMOCRONOLOGY

Over the last 15 years, advances in understanding of noble gas diffusion kinetics and improvements in inverse thermal history simulation techniques have transformed the field of noble gas thermochronology and enabled its more routine application to decipher $t$–$T$ paths in deep time. During the next 15 years, we anticipate that three critical foci of ongoing research will continue to improve our ability to deconvolve high-resolution thermal histories over hundreds of millions of years to billion-year intervals.

First, there is great opportunity to refine existing, and to develop new, noble gas kinetic models. Calibrating He diffusion kinetic models requires quantifying how He diffusion is modified as a function of both damage accumulation and annealing. Continuing work is aimed at improving the zircon and apatite He kinetic models and understanding differences between alpha damage and fission-track annealing kinetics (e.g., Ginster et al. ...
Second, some noble gas datasets are characterized by variability that is not fully understood. An important community research focus is determining the causes of this variability, which in some cases takes the form of uninterpretable K-feldspar MDD $^{40}\text{Ar}/^{39}\text{Ar}$ spectra, and in other cases as age scatter in $(U$–$Th)/He$ datasets. For example, kinetic variability among grains dated by $(U$–$Th)/He$ may be caused not only by radiation damage but also by grain size, parent isotope zonation, chemistry, crystal lattice defects, and possibly other yet-to-be-identified factors (see Gautheron and Zeitler 2020 this issue). If the contributors to kinetic variability are sufficiently well understood, then these parameters can be exploited to extract additional thermal history information from a dataset.


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Noble Gas Thermochronology of Extraterrestrial Materials

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INTRODUCTION
Extraterrestrial materials come to us in two forms: meteorites that have fallen to Earth, and, much rarer, rocks and soils collected on other bodies by astronauts or robotic missions and returned to Earth. The chemical and physical properties of these materials archive how different parts of the Solar System have evolved through time, and are especially critical for constraining models of early Solar System workings that predate the rock record on Earth. Noble gas thermochronology, in particular, has improved our understanding of thermal processes that affect extraterrestrial materials.

One of the most dramatic of these thermal processes, which has also arguably garnered the greatest attention, is impact events on planetary surfaces (Fig. 1). Impacts produce heating of the target rocks that can last for as little as a fraction of a second but raise temperatures up to several thousand degrees. These conditions are extreme compared to the thermal histories commonly studied using noble gas thermochronology on Earth (e.g., Gautheron and Zeitler 2020 this issue). Nonetheless, noble gas thermochronology can reveal the timing, duration, and temperatures associated with impact heating (e.g., Turner et al. 1966, 1973; Gilmour and Filtness 2019). This is important not only for developing and validating models of how the flux of impactors has varied through time but also for contextualizing the other physical and chemical changes that rocks have undergone during impacts (e.g., brecciation, melting).

Beyond impacts, a number of other important processes that affect the thermal evolution of planetary materials can be studied using noble gas thermochronology. Such processes include, but are not limited to, parent body accretion (e.g., Trieloff et al. 2003; Henke et al. 2012), intrusive magmatism, contact metamorphism and alteration of crustal rocks (e.g., Claydon et al. 2015; Lindsay et al. 2015; Jourdan et al. 2020), and past planetary body surface environments (e.g., Weiss et al. 2002) (Fig. 1). In the case of meteorites, we can also use noble gas thermochronology to learn about the thermal effects of space transit and atmospheric entry as these samples made their journey to Earth (Fig. 1) (Min and Reiners 2007). Although these processes occur over a range of timescales (subseconds to billions of years) and temperatures (subzero to thousands of degrees Celsius), a variety of common minerals (e.g., plagioclase and phosphates) that host radiogenic and cosmogenic noble gases have different thermal sensitivities (i.e., closure temperatures) (see Gautheron and Zeitler 2020) that span most, if not all, of this time-temperature range. In cases where multiple
noble gas thermochronometers are present in one meteorite or returned sample, or where we can combine noble gas thermochronology with other chronometers, it is possible to reconstruct billions of years of history, as will be shown below. Finally, in addition to directly informing our understanding of planetary processes, noble gas thermochronology has also been an essential tool for demonstrating the fidelity of other archives in extraterrestrial materials that are sensitive to thermal disturbance, such as records of ancient planetary magnetic fields (e.g., Garrick-Bethel et al. 2017).

In this article, we provide historical context for the application of noble gas thermochronology to planetary materials. This is followed by an overview of several recent applications of noble gas thermochronology that have improved our understanding of how the Moon, Mars, and other planetary bodies, including Earth, have evolved. This is by no means a review of all aspects of noble gas cosmochemistry or planetary geochronology. Rather, this article is intended to provide intriguing examples of what we can learn about processes occurring on terrestrial bodies, specifically from applications of noble gas thermochronology. More comprehensive reviews, particularly focused on the 40Ar/39Ar system, can be found elsewhere (e.g., Bogard 2011).

**SPACE AGE BEGINNINGS**

Although measurements using the (U–Th)/He, K–Ar, and I–Xe chronometers occurred earlier, the development of modern noble gas thermochronology arguably began in the mid- to late-1960s, when the 40Ar/39Ar method became possible (Merrihue and Turner 1966). As discussed in Gautheron and Zeitler (2020 this issue), the 40Ar/39Ar method allows for incremental degassing experiments that have two specific advantages for thermochronology. First, they reveal the spatial distribution of radiogenic 40Ar in minerals, which is a function of the sample’s thermal history. Second, they can be used to quantify the kinetics of argon diffusion via the 39Ar introduced by neutron irradiation. Collectively, this information can be used to constrain a sample’s thermal history (for additional details, see McDougall and Harrison 1999).

One of the first applications of 40Ar/39Ar thermochronology was to L-type (low iron) ordinary chondrite meteorites (Turner et al. 1966). Earlier (U–Th)/He dates obtained from L-chondrites and other types of meteorites were often substantially younger than K–Ar ages from the same sample (e.g., Kirsten et al. 1963). This discordance was generally attributed to greater thermally driven loss of radiogenic (e.g., Kirsten et al. 1963). This discordance was generally substantially younger than K–Ar ages from the same sample (Turner et al. 1966). Earlier (U–Th)/He dates obtained was to L-type (low iron) ordinary chondrite meteorites elsewhere (e.g., Bogard 2011).

Since the beginnings of noble gas thermochronology more than 50 years ago, a large body of research has emerged that utilizes 40Ar/39Ar and other noble gas thermochronometers to generate quantitative constraints on the thermal histories of planetary materials. Research over the last 20 years, in particular, has built on advances in noble gas thermochronology from terrestrial applications, especially with respect to understanding factors that affect noble gas diffusion kinetics such as the presence of multiple diffusion domains and radiation damage (e.g., McDougall and Harrison 1999; Gautheron and Zeitler 2020 this issue, and references therein). Below, we highlight several examples where such recent advances have been applied to study events that occurred on the Moon, Mars, and other planetary bodies.

**ASTEROIDAL PARENT BODY METAMORPHIC AND MAGMATIC EVOLUTION**

Constraints on asteroidal parent body sizes, structures, and metamorphic histories have informed models of the Solar System’s evolution. Meteorites from asteroids provide information about the sources of volatiles on terrestrial planets; the growth of geomagnetic dynamos on small bodies; and the effects of differentiation, magmatism, and parent–body disruption on petrologic, chemical, and isotopic characteristics. The way in which we interpret meteorite data is fundamentally tied to the inferred thermal history of a sample.

Noble gas thermochronology has been instrumental in constraining the thermal histories of asteroidal parent bodies and informing theories about asteroidal parent body characteristics (e.g., Trieloff et al. 2003; Bogard 2011). Perhaps the most well-studied example to consider is the cooling history of the H-chondrite (high iron) parent body. Many H-chondrites yield a trend of decreasing ages for chronometers with decreasing closure temperatures, including 40Ar/39Ar chronometry in feldspar (Fig. 2) (see Henke et al. 2012 for a review). Additionally, ages obtained from each radioisotopic system are inversely correlated with meteorite metamorphic grade (i.e., 40Ar/39Ar ages obtained from H4 chondrites are older than those obtained from more thermally metamorphosed H5 chondrites—the higher the H number, the greater the defined degree of metamorphism) (Fig. 2A).
These observations were taken by some as evidence for a simple H-chondrite parent body thermal history, commonly referred to as the onion-shell model (e.g., Tielhoff et al. 2003) (Fig. 2B). In this model, internal heating driven primarily by the decay of short-lived radioisotopes such as $^{26}$Al causes metamorphic temperatures to increase and cooling rates to decrease with distance from the parent body surface. In this framework, and assuming instantaneous accretion, Henke et al. (2012) calculated a radius for the H-chondrite parent body of 123 km. Recent paleomagnetic data from H-chondrites, however, have been used to argue that the parent body possessed an internally driven geomagnetic dynamo associated with a differentiated core (Fig. 2C) (Bryson et al. 2019). Paired with H-chondrite thermochronometric data (Fig. 2A), this suggests that the H-chondrites may be derived from different depths within a late-accreted crust that surrounded a differentiated interior (Fig. 2C), rather than from the central parts of an undifferentiated parent body (Fig. 2B) (Bryson et al. 2019). Using an incremental accretion model constrained by these thermochronometric data, Bryson et al. (2019) suggested that the radius of the H-chondrite parent body may have been ~170 km or larger, substantially bigger than typically inferred from the onion-shell model (Henke et al. 2012).

Although the thermochronology data described above can be interpreted in the context of accretion and secular cooling of the H-chondrite parent body, observations of the I–Xe system (Crowther et al. 2016) and elemental exchange reactions (e.g., Ganguly et al. 2013) in H-chondrite minerals indicate a more complex thermal history. These observations do not conform to the simple, instantaneous accretion onion-shell model, but instead suggest that impacts played an important role in redistributing heat and material during the first tens of millions of years after the H-chondrite parent body had accreted. Additional support for complex, impact-related processes affecting the thermal evolution of chondritic meteorites comes from I–Xe dating of LL-chondrites (those with low total iron and low metal), which provides evidence that processing of regolith (unconsolidated surface material covering bedrock) may be responsible for petrologic variations (Gilmour and Filtness 2019). Collectively, these examples demonstrate that noble gas thermochronology has played a pivotal role in shaping and reshaping our understanding of the origins of chondritic meteorites.

In addition to recording thermal conditions during the accretion process in chondritic meteorites, noble gas thermochronology has been used to reconstruct the postcrystallization metamorphic evolution of achondritic crusts from parent bodies that have definitively experienced differentiation. For example, Jourdan et al. (2020) studied a suite of eucrites—a type of meteorite thought to have originated from the large, differentiated asteroid Vesta. Application of $^{40}$Ar/$^{39}$Ar thermochronology to extrusive eucrites, combined with Pb–Pb data, suggest that these samples cooled slowly at a rate of ~17°C/My at 10–15 km depth in the crust from 4,555 Ma to 4,515 Ma. Jourdan et al. (2020) interpreted this slow cooling of extrusive rocks, which are otherwise expected to have cooled rapidly, as support for the hypothesis that large-scale crustal metamorphism associated with burial beneath thick lava piles occurred while volcanic activity on the eucrite parent body was still active (Yamaguchi et al. 1996). Similar protracted crustal metamorphism has been inferred for other achondritic parent bodies, such as the parent body of GRA 06128/06129 [an achondrite found at Graves Nunataks, Antarctica], based on I–Xe and Ar–Ar analyses compared to higher-temperature chronometers (Claydon et al. 2015; Lindsay et al. 2015).

**Figure 2** (A) Summary of radioisotope ages obtained from H4, H5 and H6 chondrites [where H = high iron; the number refers to a defined degree of increasing metamorphism], which exhibit an expected trend of decreasing ages from high-temperature chronometers (Hf–W, Pb–Pb, and U–Pb) to $^{40}$Ar/$^{39}$Ar in feldspar. Likewise, there is a general trend of increasing ages with decreasing metamorphic grade (H6 to H4). These trends indicate that H-chondrites originating from greater depths cooled more slowly. The age of calcium-aluminum inclusion (CAI) formation, which is the earliest recorded process in the Solar System, is shown for reference. Age summary as compiled by Henke et al. (2012). (B) A model of an undifferentiated H-chondrite parent body, derived from the thermal information in Figure 2A. (C) As for Figure 2B but for a differentiated parent body. Whether the H-chondrite parent body was differentiated has implications for parent body size, accretion rate, and heat sources. Locations for H chondrites as follows: Guareña (H6, Spain); Kernouve (H6, France); Richardton (H5, North Dakota, USA); Allegan (H5, Michigan, USA); Nadiabondi (H5, Burkina Faso); Forest Vale (H4, New South Wales, Australia); Saint Marguerite (H4, France).
**PLANETARY MAGNETISM**

As already mentioned for H-chondrites, much recent noble gas thermochronology applied to planetary materials has been motivated by a desire to understand the origins of ancient magnetic fields recorded in these materials. When rocks cool from high temperatures, magnetic minerals encode information about the strength of the magnetic field in which the rock cools. This information can be accessed via laboratory magnetism experiments and used to infer whether the planetary body from which the sample came had a magnetic field. However, the minerals that record the ancient magnetic fields do not encode information about when their magnetic remanence was acquired. Whereas processes such as igneous crystallization can record primary magnetic signatures, including magnetic fields generated by a core dynamo, impact events can also raise rock temperatures and generate temporary magnetic fields that later reset this signature. Determining the thermal histories of planetary materials, therefore, provides critical context for interpreting the magnetic remanence these materials contain.

As an illustration, we highlight the Apollo 17 lunar sample 76535, an intrusive igneous rock (troctolite). This sample records a magnetic field intensity that is comparable to the present-day strength of the Earth’s magnetic field (Garrick-Bethell et al. 2017). Measurements of 40Ar/39Ar on whole-rock fragments of troctolite 76535 reveal an undisturbed plateau age of ~4,250 Ma. When paired with diffusion kinetics from the 39Ar measurements, these data require that the sample experienced temperatures no hotter than 400°C since ~4,250 Ma. Cosmogenic argon and neon observations in troctolite 76535 further indicate that this rock only experienced heating due to solar irradiation since that time (Garrick-Bethell et al. 2017). These thermal history constraints from noble gas thermochronology provide compelling evidence that the magnetic record of troctolite 76535 dates to 4,250 Ma rather than an overprint by a later impact event and that the Moon had a strong magnetic field generated by a core dynamo at ~4,250 Ma or earlier. Paired thermochronology and magnetic studies on other lunar rocks reveal that the Moon’s magnetic field began to decline in strength after ~3,500 Ma; however, a weak field persisted for much longer, possibly as late as 1,000 Ma (Tikoo et al. 2017).

**IMPAC T S**

The I–Xe, 40Ar/39Ar, and (U–Th)/He systems can be used to quantify the timing, duration, and temperatures experienced due to impact events. Such studies are important because they document the conditions during impact events that occurred sometime after initial crystallization or impact melting. This can not only be used to assess the fidelity of observations like paleomagnetism, as discussed above, but is also critical for creating a more complete picture of a planetary body’s impact history.

The history of impacts that can be inferred from noble gas thermochronology of a single sample is nicely demonstrated by Kelly et al. (2018). They obtained zircon (U–Th)/He ages from Apollo 14 lunar sample 14311, a polymict impact-melt breccia that displays a strong, negative correlation between age and effective uranium concentration (eU), which is a weighted measure of the U and Th concentration in each zircon (white circles, Fig. 3). At least two impact-related heating events are necessary to explain this age pattern: one at ~3,950 Ma, which is corroborated by ages from the higher-temperature U–Pb chronometer applied to zircons formed by impact melting; and one much more recently at ~110 Ma (Fig. 3) (Kelly et al. 2018). If Kelly et al. (2018) only had the zircons with relatively low eU and old (U–Th)/He ages (Fig. 3), they would not have been able to detect the presence of a second thermal disturbance after 3,950 Ma. It is the presence of reset zircon (U–Th)/He ages at relatively high eU (>100 ppm) that requires this second impact event. Only the zircons with relatively high eU are reset because these zircons have greater amounts of radiation damage from U and Th decay. This causes helium to diffuse at a much higher rate during episodes of heating than from zircons with relatively low damage.

Furthermore, the relationship between age and eU observed in these zircons allowed Kelly et al. (2018) to constrain the likely timing of the second heating event as well as possible peak temperatures and durations of the cooling that followed each impact event. For example, if breccia 14311 took 2,000 years to cool following the second impact event at ~110 Ma, the reset zircon (U–Th)/He ages at relatively high eU require that peak temperatures during this event were between ~250°C and 300°C (green lines) reproduce the observed age–eU pattern. Data and models from Kelly et al. (2018).
Noble Gas Thermochronology and the Late Heavy Bombardment

We would be remiss to describe the ability of noble gas thermochronometers to record information about impact events without discussing the central role of noble gas thermochronology in hypotheses about the early impact history of the Solar System. Since the first samples were returned from the Moon in 1969, hundreds of $^{40}$Ar/$^{39}$Ar datasets have been collected on material from Apollo and Luna samples, as well as from meteorites we can now identify as having originated from the Moon (e.g., Norman et al. 2006). By and large, these datasets have been interpreted as providing geochronologic, rather than thermochronologic, information: age plateaus, whether observed over an entire degassing experiment or only a portion of it, represent the time of crystallization or melting (e.g., Fig. 4). The preponderance of full and partial plateau ages between 3,800 Ma and 4,000 Ma has been interpreted as supporting the hypothesis that there was a spike in the flux of impactors to the inner Solar System at that time (e.g., Norman et al. 2006). In this hypothesis, known as the Late Heavy Bombardment, the spike in impact events caused large-scale resurfacing of the Moon, generating the vast majority of impact melt rocks at that time. This interpretation of lunar $^{40}$Ar/$^{39}$Ar datasets has been bolstered by a preponderance of similar $^{40}$Ar/$^{39}$Ar ages in asteroidal meteorite samples (e.g., Marchi et al. 2013). However, this interpretive approach of lunar and asteroidal $^{40}$Ar/$^{39}$Ar datasets has recently come under fire (Boehnke and Harrison 2016). Many of the datasets used to support this hypothesis exhibit evidence for $^{40}$Ar loss due to later reheating (e.g., Fig. 4) that is often not quantified. Later reheating could mean that an $^{40}$Ar/$^{39}$Ar age inferred from a partial plateau is significantly younger than a sample’s primary crystallization or initial melting age. Boehnke and Harrison (2016) use this logic, together with noble gas diffusion modeling, to suggest that the peak in plateau ages at ~3,900 Ma could be an artifact caused by most lunar samples (1) first crystallizing between 4,000 and 4,500 Ma, and (2) then experiencing multiple reheating episodes due to later impact events. If this interpretation is correct, it has significant implications for the bombardment history of all inner Solar System bodies, including Earth.

SURFACE PALEOTEMPERATURES

In addition to high-temperature events such as impacts, noble gas thermochronology has also been used to study low-temperature phenomena on planetary bodies. Whereas on Earth there is a thick atmosphere that plays an essential role in modulating surface temperatures and making our planet habitable, other planetary bodies in our Solar System either lack an atmosphere completely or have atmospheres that are orders of magnitude thinner than the Earth’s, such as those of the Moon and Mars. A consequence of an extremely thin to nonexistent atmosphere is that the surfaces of other planetary bodies experience extreme diurnal and seasonal temperature variations. For example, ground temperatures on Mars today often exceed 0°C during the day and plummet to below –150°C during the night. Similarly low temperatures occur during the lunar night, but temperatures soar above 100°C during the lunar day. When experienced by rocks at or near the surface of a planetary body for durations of over tens to hundreds of millions of years, the relatively high temperatures that can occur during diurnal cycles, including cycles experienced by meteoroids during space transit, can be sufficient to cause diffusive loss of noble gases.

A number of systems have been demonstrated to be sensitive to lunar surface temperatures, including argon in lunar glasses and feldspars (e.g., Turner 1973), neon in feldspars (Garrick-Bethell et al. 2017), and helium in zircon (Kelly et al. 2018). For example, solar heating during the several-million-year surface residence of Apollo 14 impact-melt breccia sample 14311 is insufficient to explain the observed zircon (U-Th)/He age pattern, but does make shorter durations or lower temperatures permissible for the second impact event that this sample experienced (Kelly et al. 2018). However, all of the examples from the Moon record relatively recent surface conditions over the last several hundred million years when we know that lunar surface conditions were similar to those of today.

A compelling example of where surface temperature changes were anticipated comes from ALH84001, a Martian meteorite originally found in the Allan Hills of Antarctica in 1984. Constraining surface conditions on Mars in the distant past is of particular importance because there was most likely liquid water on the Martian surface early in its history. The ALH84001 meteorite is unique among Martian meteorites in that it is a coarse-grained orthopyroxenite that also contains a significant amount of carbonate, which attests to its near-surface residence. It is also one of the oldest Martian meteorites, with an $^{40}$Ar/$^{39}$Ar age of ~4,160 Ma (Cassata et al. 2010). Therefore, it is a prime candidate for assessing what surface conditions were like early in Mars’ history.
Thermochronologic datasets have been generated for ALH84001 from 40Ar/39Ar in maskelynite, which is a K-rich glass generated during impact events and pyroxene (Weiss et al. 2002; Cassata et al. 2010), as well as (U-Th)/He in phosphates (Min and Reiners 2007). Argon and helium diffusion at low temperatures for maskelynite and phosphates, respectively, constrain near-surface conditions on Mars over the ~4,160 Ma history of ALH84001, as well as conditions during the last ~12 My after it was ejected from Mars (Cassata et al. 2010; Min and Reiners 2007). The observed ages and diffusion kinetics for both argon and helium in ALH84001 require that this meteorite spent most of its ~4,160 My history at temperatures of ~60 °C to ~70 °C (Weiss et al. 2002; Min and Reiners 2007). The surface temperature today, which prevent liquid water from persisting. However, these temperatures could be consistent with liquid water on ancient Mars if ALH84001 resided more than ~100 m below the surface for most of its history, escaping the diurnal and seasonal temperature variations that occurred at shallower depths.

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**FUTURE APPLICATIONS**

The application of noble gas thermochronology to materials from the Moon, Mars, and different asteroid meteorite classes has provided important insights into planetary processes spanning orders of magnitude in temperature and duration, some of which we have highlighted here. As we continue to collect and identify meteorites from Antarctica and hot deserts, and as the world’s space agencies pursue in situ thermochronometry as well as sample return missions to bodies such as Mars and asteroids, there will be ample opportunity to advance our understanding of planetary science by applying noble gas thermochronology to extraterrestrial materials.

**ACKNOWLEDGMENTS**

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**FOR FURTHER READING**

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Thermochronometric data can record the thermal history of rocks as they cool from high temperatures at depth to lower temperatures at the surface. This provides a unique perspective on the tectonic processes that form topography and the erosional processes that destroy it. However, quantitatively interpreting such data is a challenge because multiple models can do an equally good job at reproducing the data. In this article, we describe how inverse modeling can be used to improve quantitative interpretations of noble gas thermochronometric data on a variety of scales, ranging from mountain belts to individual mineral grains.

**KEYWORDS:** thermochronology, inverse methods, laser ablation, exhumation

**INTRODUCTION**

Recent advances in our ability to infer the timings and rates of kilometre-scale topographic changes using noble gas thermochronology have improved our understanding of geomorphic and tectonic processes. These datasets can quantify cooling associated with erosion in the geologic past but require the use of models to help with the interpretation. Forward numerical models of how landscapes erode and rocks exhume have been used to understand the significance of thermochronometric data. In this sense, a set of parameters describing landscape evolution and tectonics are used to predict thermochronometric data. The focus of this article, in contrast, is to review applications of inverse models, which can be applied to noble gas thermochronometric data to determine thermal and exhumation histories. This article will highlight how noble gas thermochronology methods have been used to provide insight into exhumation rates, while also revealing some of its limitations.

Thermochronology methods are sensitive to the thermal histories of rocks over time intervals ranging from thousands of years to hundreds of millions of years, and are, therefore, useful for measuring rates of exhumation, which is the motion of rocks relative to Earth’s surface. The well-known decay rates of radioactive nuclides, along with the temperature-dependent diffusion of daughter products, provide the basis of radiogenic nuclide thermochronology (Gautheron and Zeitler 2020 this issue). For example, at relatively high temperatures (~400–300°C), radiogenic 40Ar produced by the decay of 40K begins to be retained in micas. A range of crystallographic shapes and sizes (or sub-grain domains) can help retain 40Ar, each local factor effectively having different temperature sensitivities, thereby, constraining a continuous thermal history between 400°C and 300°C (Harrison and Lovera 2014). At lower temperatures (~70°C), radiogenic 4He produced along the U and Th decay series begins to be retained in apatite crystals. Because the temperatures that a rock experiences generally increase with depth, the temperature and time constraints provided by thermochronologic data can be converted to a history of its exhumation rate.

In order to resolve exhumation rate histories accurately, additional information is required. For example, multiple samples recovered from near to each other but from different elevations can, under the assumption of a relatively constant thermal structure of the crust, provide constraints on different durations of exhumation from the same depth with respect to sea level (Wagner et al. 1979). This can be visualized by plotting an age–elevation relationship, with the slope of the line providing an estimate of the past exhumation rate (Fig. 1). Alternatively, multiple ages from the same rock sample can be obtained using different thermochronometric systems (e.g., different mineral or decay schemes) sensitive to different temperatures, thereby constraining exhumation rates from different depths.

Here, we highlight the importance and limitations of different inverse methods that have been designed to extract information from thermochronometric data. We begin by describing methods that have been used to extract time–temperature information from thermochronometric data with a focus on thermal-history models. In many cases, however, exhumation rates are required for geological interpretations and, therefore, we highlight work that has attempted to infer exhumation rates across mountain belts from thermochronometric data using thermokinematic models, and highlight some of the associated complications with these approaches. In the last section, we take a closer look at inverse modeling developments applied to data treatment across single crystals. In particular, we highlight how combining laser ablation data with diffusion models of helium from individual crystals of apatite represents an important advance.
Topography, exhumation and isotherms

Figure 1 (A) Illustration showing the thermal structure below topography and the upward paths that rocks take from depth (arrows). Topography perturbs the thermal structure of the crust, and the samples from the deepest parts of the illustrated valley may be sensitive to the evolution of topography. The exhumation is here controlled by surface processes and spatially variable rock uplift rates which reflect regional tilting and normal faulting (left of scene). (B) The cooling histories (black curves) of two closely spaced samples from different elevations are almost parallel. As a first-order approximation, apatite fission track (AFT) ages record the time since a rock cooled below ~110 °C, whereas apatite (U–Th)/He (AHe) ages record when the rock cooled below 70 °C. Because elevation differences can be related to temperature differences, different samples constrain cooling over slightly different time intervals. (C) The simplest model used to link ages in terms of exhumation rate is a linear age–elevation relationship (AER). This model assumes that the closure isotherms are flat and stationary and that the model parameters are the exhumation rate (slope of the AER) and the closure depth (AER intercept). This model requires that samples be linked in space: how the samples link will influence the inferred exhumation rate(s). In reality, the relationship between age and elevation may be nonlinear due to such factors as the advection of heat, perturbation of isotherms by topography, topographic change, and changes in exhumation rate.

Thermal-History Models

A thermochronometric date doesn’t necessarily reflect a single event: it reflects the integrated thermal history experienced by the sample. The goal of thermal-history modeling is to recover time–temperature information from dates and other thermochronometric data. In many cases, recovering time–temperature information from thermochronometric data is a highly non-linear problem, in that a small change in model parameters can lead to a large change in model predictions. For example, consider a case where a rock is exhumed to the surface rapidly at 100 Ma and is then buried until it is re-exhumed very recently. If the model parameter describing temperature during this burial phase is increased from 0 °C to 30 °C then there will be no significant change in the predicted apatite (U-Th)/He age. This is because the apatite (U-Th)/He system is not sensitive to these very low temperatures. However, as the temperature during burial continues to increase, there will, at some stage, be rapid changes in the model predicted apatite (U-Th)/He ages due to the non-linear dependence of He diffusivity on temperature. It is this non-linear temperature sensitivity that makes thermochronometry possible. It is also the property that leads to challenges in data interpretation.

To extract information from this non-linear problem, non-linear inverse methods are used. Typically, these are based on generating many random time–temperature paths. Non-linear methods often require solving the forward model many, many times, which can be computationally very expensive. In contrast, linear inverse methods are based on computationally efficient matrix inversions, but often require making limiting simplifications – we will return to these types of methods later. For non-linear methods, random time–temperature paths can be used in a range of mathematical models to predict a range of data, such as fission track ages and length distributions (Ketcham et al. 2007), or noble gas–based thermochronometric ages and diffusion data. The models have the ability to characterize the changing efficiency of noble gas diffusion as crystal defects, and in particular radiation damage, accrue and anneal in the lattice structure of minerals (Flowers et al. 2009; Gautheron et al. 2009). The models can also account for samples that possess a range of crystallographic shapes and sizes (Harrison and Lovera 2014; McDannell and Flowers 2020 this issue). In order to describe a time–temperature path, some sort of parameterization is required, and for this discussion we will use a very simple parameterization in which a series of time–temperature points are linked by straight lines. The locations of the time–temperature points are our model parameters. These parameters are said to occupy the “parameter space”. We aim to explore this space but must avoid getting lost in the process.

Thousands of candidate time–temperature paths are typically generated to find the best parameters (time–temperature points) describing time–temperature paths that predict the thermochronometric data. If paths are generated purely randomly, there is a good chance that the inversion algorithm will spend a large amount of time exploring time–temperature paths that do a poor job of predicting the observed thermochronometric data. One technique commonly used to speed up the search process is to use some form of prior knowledge, such as independent geologic constraints. For example, the formation age of the rock can be used as an indication of when to start the time–temperature paths in geological time such that parameters older than this do not need to be tested. Another example is to force paths through a surface temperature condition at a time when there is a geologically constrained unconformity, meaning that high temperatures don’t need to be tested during this time period.

A second technique is to guide the search based on what has previously been successful. If a time–temperature path does a very good job at reproducing the data, then a new path can be generated that is very similar to this promising path. Part of the parameter space that produces a small misfit between the observed and predicted data is referred to as a minimum, and mapping out these minima is a goal of inversions. However, if all the paths that are generated are too similar, the algorithm may become trapped in a local minimum. It is, therefore, important that a search-based algorithm has the ability to explore parameter space to find a global minimum without getting trapped in a local minimum. These techniques – random versus guided searches of parameter space – have advantages and disadvantages. Nevertheless, both approaches have been shown to provide similar results.
Incorporating more data + Model Assumptions = Improved Resolution

Figure 2: A demonstration of how incorporating more data can improve the resolution of an inverse model. (A) An apatite (U-Th)/He (AHe) age is interpreted with a simple model that randomly generates time–temperature (t–T) paths that fit the data (red lines). All the paths go through a point constrained by the closure temperature ($T_c$) and age. However, the red lines are not necessarily similar to the true cooling history (black line). (B) An apatite fission track (AFT) age interpreted as was done for 2A. (C) The two ages in Figures 2A and 2B combined, which requires making the assumption that the analyzed crystals share the same thermal history. This leads to increased resolution.

The two most commonly used pieces of software designed to extract thermal history information from single samples using these two different approaches are HeFtY (Ketcham 2005) and QTQt (Gallagher 2012). HeFtY uses a purely random path generation procedure that can be guided by user-defined constraint boxes. This means that a time–temperature path is generated that must pass through these areas of parameter space. The ability of the path to predict the thermochronometric data is defined by asking whether it passes a statistical hypothesis using a goodness-of-fit test based on a “p-value”. The purely random model has the benefit that it explores a range of model parameters. The QTQt software uses a reversible jump Markov Chain Monte Carlo algorithm to generate paths that are similar to the best models. By exploring parameter space around promising models, the algorithm can converge to a solution more quickly. In addition, QTQt’s algorithm provides a means to choose how many time–temperature points are required based on the quality of the data.

As mentioned earlier, in order to gain more robust time–temperature information, additional thermochronometric data are required, either from different systems or different elevations. The QTQt software has the capability to model samples from different elevations within a vertical transect. In this case, a thermal model is required to link the data. The thermal model employed by QTQt is a simple geothermal gradient that does not account for heat transport but that does provide the link between samples. Figure 2 highlights how incorporating additional data can help constrain different, but overlapping, portions of the same thermal history. In some cases, however, a more sophisticated thermal model is used that can account for the effects of topography on the thermal structure of the crust, or the physics of heat flow. In the next section, we describe some of the recent developments in approaches to using thermochronometric data to learn about geodynamic processes, such as exhumation rates.

GEODYNAMICS FROM THERMOKINEMATIC MODELS

Thermokinematic models provide a framework to use thermochronometric data not just to extract thermal histories but to directly constrain geodynamics by linking thermal histories to physical processes. Thermokinematic models used to interpret thermochronometry data have evolved, both as the questions asked of the data have evolved and as weaknesses in existing models have been identified. For example, the potential problem by which topography leads to incorrect interpretations of age–elevation relationships (e.g., Manktlewlow and Grasemann 1994) has been embraced, and thermochronometry is now used to measure evolving topography (e.g., House et al. 1998). Today, thermokinematic models solve the heat transfer equation based on user-defined kinematics and accounting for complex initial conditions, transient advection of heat, fluid flow, and tectonic and geomorphic processes (Braun et al. 2012). In this way, a specific rock in a model can be tracked through time along its user-defined kinematic path to the surface. The temperature experienced along that path is recorded, and the resulting time–temperature path can be used to predict thermochronometric data. These thermokinematic models can be coupled to a non-linear inversion algorithm to find a best set of model parameters. Unlike in thermal-history models, where the model parameters are typically time–temperature points, model parameters in thermokinematic models may define the slip rate on a fault, the timings of topographic change or the thermal properties of rocks. The finite element
code Pecube (Braun et al. 2012) is the most commonly used thermokinematic model. It uses state-of-the-art age models to predict thermochronometric data and to guide a non-linear algorithm.

A compelling example of thermokinematic modelling using Pecube comes from Michael et al. (2018), who investigated the impact of Pleistocene glaciation on exhumation rates across the Olympic Mountains (Washington State, USA). Here, exhumation is driven by accretionary processes as the Juan de Fuca plate subducts beneath the North American plate, resulting in predictable kinematics that can be approximated with an elliptical-shaped spatial pattern of exhumation rates that decrease from the centre of the ellipse outwards. This ellipse is designed to approximate the spatial patterns of crustal accretion and rock uplift within a critically tapered orogenic wedge (Brandon et al. 1998). In this scenario, exhumation rates would increase towards the centre of the ellipse. This pattern can be incorporated into a 3-D thermokinematic model (Pecube) (Braun et al. 2012) and used to predict the observed apatite (U-Th)/He and zircon (U-Th)/He data from the Olympic Mountains. By finding predicted data that match observed data, the location and size of the ellipse and the gradient in exhumation rates within the ellipse can be determined (Fig. 3). In addition, temporal changes in exhumation rate can be parameterized and resolved. Michael et al. (2018) found that the data can be explained by an ellipse-shaped exhumation pattern which increases from ~0.25 km/My at the edge of the ellipse to 0.9 km/My at its centre. In addition, they showed that Pliocene–Pleistocene alpine glaciation in the Olympic Mountains likely led to a 50%–150% increase in exhumation rates in the past 2–3 My. This study highlights that if the underlying kinematics of exhumation cannot be inferred and parameterized, the parameters defining the ellipse and changes in rates through time can be explored. In some cases, however, this is not possible because the underlying kinematics of exhumation cannot be parameterized with a simple elliptical geometry. This may be because exhumation varies over a large area, it may be overly complex and computationally expensive, or the underlying spatial pattern of exhumation is unknown.

When the underlying exhumation function cannot be parameterized with less than about 20 model parameters, linear inverse methods are often required (Fox et al. 2014a). In this approach a simple thermokinematic model is used to estimate the closure isotherm for each age in a dataset, taking into account transient geotherms, perturbations of the isotherms by topography, and thermochronometer and cooling rate–dependent closure temperatures (Dodson 1973). For each age in the dataset, the distance to the closure isotherm can be written as the integral of the exhumation rate between today and the thermochronometric age. This integral formulation can be written as a linear system of equations that can be efficiently rearranged to find the unknown exhumation rate parameters. Samples are linked in space so that samples close together share the same exhumation rate history. This linking enables the ages to resolve temporal changes in rate, because ages are forced to share similar exhumation rate histories with different ages that constrain overlapping portions of time. One disadvantage of spatially linking samples in this way is that spatial and temporal patterns in exhumation rates might be smearing out: for example, across faults or other boundaries that have disparate exhumation rate histories (Fox et al. 2014; Schildgen et al. 2018).

Thermal-history and thermokinematic models have been used to test all sorts of geodynamic and geomorphic hypotheses, but measuring small amounts of recent erosion remains a challenge. In turn, key hypotheses, such as whether Pliocene–Pleistocene alpine glaciation can lead to enhanced erosion rates remain debated (e.g., Herman et al. 2013; Willenbring and Jerolmack 2016; Michael et al. 2018; Schildgen et al. 2018). In the next section, we describe 4He/3He thermochronometry in apatite, how it allows us to constrain the crucial shallow exhumation history, and how recent numerical modeling developments on grain-scale datasets have helped to provide better resolved, quantitative thermal histories.

**GRAIN-SCALE INVERSE MODELS**

Inverse models can also use grain-scale data to improve the interpretation of thermochronometric data. To highlight a recent example where this has been done, we focus on two aspects of inverse modeling applied to 4He/3He datasets. In 4He/3He thermochronometry, a crystal of apatite is sequentially heated and the gas that is released during each heating step is measured isotopically using a noble gas mass spectrometer (Shuster and Farley 2004). Because the gas is extracted by diffusion, the gas from the first
degassing steps is released primarily from the outermost parts of the apatite crystal. The next heating step releases gas from within slightly deeper parts of the crystal and so on, until all the gas is released. To improve the quality of the data and obtain sample-specific diffusion data, two isotopes of helium are measured: \(^{4}\)He, the naturally occurring daughter product of radioactive decay, and \(^{3}\)He, which is produced via nuclear reactions caused by proton irradiation of the sample prior to analysis. The \(^{4}\)He signal contains information about the thermal history of the sample, which must be extracted using inverse methods, and the spatial distribution of the parent isotopes. The \(^{3}\)He signal is spatially uniform and contains information about diffusion kinetics.

The data from \(^{4}\)He/\(^{3}\)He measurements can be visualized on a ratio evolution diagram, where the cumulative fraction of \(^{4}\)He released (\(R_{step}/R_{bulk}\)) is plotted on the x-axis, and the \(^{4}\)He/\(^{3}\)He ratio of each step normalized by the bulk \(^{4}\)He/\(^{3}\)He ratio (\(S_{F^{3}}\)) is plotted on the y-axis. We can predict what \(^{4}\)He/\(^{3}\)He values are permissible in a ratio evolution diagram based on what we know about the spatial distribution of \(^{4}\)He in an ‘ideal’ apatite crystal (i.e., close to spherical and with a uniform composition) for any given thermal history. However, we sometimes observe values that are outside of this permissible range (e.g., Fig. 4A).

The cause of unexpected results may be due to several factors: the analyzed crystals may be poorly approximated as spheres; the spatial distribution of \(^{4}\)He may be strongly influenced by variations in parent isotope concentration within the crystal (e.g., chemical zoning); intra-crystal radiation damage may lead to spatial variations in the diffusion kinetics within the analyzed crystal (Ault and Flowers 2012). This last factor would lead to zones throughout the crystal that are more retentive of helium due to radiation damage and so hold on to their helium until the final degassing steps.

Fox et al. (2014b) explored different sources of unexpected diffusion behaviour using a very unusual result from the Appalachian Mountains (USA). In this geologic setting, the exhumation times have been slow for the last 200 million years, allowing radiation damage to accumulate. The importance of chemical zonation on the (U–Th)/He system had been previously established for these samples by looking at the effect of abrading the crystals (McKeon et al. 2014). Abrading effectively removed the outer portion of the crystal, which had a different uranium and thorium concentration (or effective uranium, \([eU] = [U] + 0.24[Th]\), which accounts for the relative alpha particle productivity of U and Th) (Gastil et al. 1967; Flowers et al. 2009) to the central part of the crystal. The ages obtained from these abraded crystals were used to extract a thermal history, whereas the ages from the unabraded crystals remained unexplainable. By using \(^{4}\)He/\(^{3}\)He thermochronometry, the \(^{4}\)He being released from different parts of the crystal can be observed directly without the need for abrasion (Fox et al. 2014b). During the first steps, the ratio of \(^{4}\)He to \(^{3}\)He is much lower than the bulk ratio (Fig. 4). These low values persist until almost half the total amount of \(^{4}\)He is released, telling us that almost half of the crystal had released its gas. Then the ratio of \(^{4}\)He to \(^{3}\)He dramatically increases to almost three times the bulk ratio. This indicates that almost all of the \(^{4}\)He is coming from a relatively small, central portion of the crystal.

The next step was to quantify the spatial distribution of the \(^{4}\)He-producing uranium and thorium using laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS). In this method, a laser spot with a diameter of about 20 microns is fired at a polished section of the apatite crystal, which ablates small volumes of the crystal into a mass spectrometer (Farley et al. 2011). This highlighted that there was indeed a zone within the central part of the crystal with a higher \([eU]\). Therefore, a 3-D model of the crystal was built accounting for spatial variability in \(^{4}\)He production and intra-crystal radiation damage. Fox et al. (2014b) found that both of these factors are required to explain the observed \(^{4}\)He/\(^{3}\)He data (Fig. 4). These data have prompted the development of efficient 3-D crystal models and corresponding inverse methods, which are now suitable to tackle other geological problems and help resolve recent cooling of a sample to low-temperatures.

In a related study, Fox et al. (2017) found that even with the LA-ICP-MS maps and 3-D crystal models, \(^{4}\)He/\(^{3}\)He datasets of apatites from Yosemite Valley (California, USA) were still impossible to explain, even using thermal history modeling that accounted for these complexities. This is because the crystals were releasing too much \(^{4}\)He during the initial degassing steps, suggesting that zoning effects were important. It was only when the resolution of the elemental maps used to quantify zonation were improved, that thermal-history models were able to predict the data. It was possible to improve the resolution of these elemental maps using linear inverse methods by exploiting the fact that thermal-history models were able to predict the data. It was possible to improve the resolution of these elemental maps using linear inverse methods by exploiting the fact that thermal-history models were able to predict the data.

The importance of chemical zonation on the (U–Th)/He system had been previously established for these samples by looking at the effect of abrading the crystals (McKeon et al. 2014). Abrading effectively removed the outer portion of the crystal, which had a different uranium and thorium concentration (or effective uranium, \([eU] = [U] + 0.24[Th]\), which accounts for the relative alpha particle productivity of U and Th) (Gastil et al. 1967; Flowers et al. 2009) to the central part of the crystal. The ages obtained from these abraded crystals were used to extract a thermal history, whereas the ages from the unabraded crystals remained unexplainable. By using \(^{4}\)He/\(^{3}\)He thermochronometry, the \(^{4}\)He being released from different parts of the crystal can be observed directly without the need for abrasion (Fox et al. 2014b). During the first steps, the ratio of \(^{4}\)He to \(^{3}\)He is much lower than the bulk ratio (Fig. 4). These low values persist until almost half the total amount of \(^{4}\)He is released, telling us that almost half of the crystal had released its gas. Then the ratio of \(^{4}\)He to \(^{3}\)He dramatically increases to almost three times the bulk ratio. This indicates that almost all of the \(^{4}\)He is coming from a relatively small, central portion of the crystal.

The next step was to quantify the spatial distribution of the \(^{4}\)He-producing uranium and thorium using laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS). In this method, a laser spot with a diameter of about 20 microns is fired at a polished section of the apatite crystal, which ablates small volumes of the crystal into a mass spectrometer (Farley et al. 2011). This highlighted that there was indeed a zone within the central part of the crystal with a higher \([eU]\). Therefore, a 3-D model of the crystal was built accounting for spatial variability in \(^{4}\)He production and intra-crystal radiation damage. Fox et al. (2014b) found that both of these factors are required to explain the observed \(^{4}\)He/\(^{3}\)He data (Fig. 4). These data have prompted the development of efficient 3-D crystal models and corresponding inverse methods, which are now suitable to tackle other geological problems and help resolve recent cooling of a sample to low-temperatures.
that laser ablation spots overlap and, thus, that the same spatial location on a crystal section will be sampled by multiple spots. In this scenario, multiple spots that measure the same part of the crystal may have different concentration values, smoothing zonation information (e.g., Ganguly et al. 1988). Deconvolving this information results in finding an elemental map that has single values at each spot location and yet still gives the average values measured spot values. Deconvolving, therefore, increases the resolution of the map. In fact, the resolution depends on the degree to which the spots overlap, not their size (Fig. 4B). Here, overlapping spots with diameters of 20 microns have been used to resolve concentrations over a narrow zone only ~5 microns wide. In turn, this inverse method is able to resolve finer-scale differences in parent isotope concentrations than is possible by simply interpolating between the measured values at the centres of the spots (e.g., Farley et al. 2011) and does not require the use of analytical instruments that are capable of operating with smaller spot sizes. Some degree of smoothing and blurring does occur, as shown by the comparison with the true zonation imposed to produce the synthetic data (Fig. 4B), but this can be further minimized by collecting more overlapping spots. This is an example of where inverse methods have been applied to extract more information from a single crystal which can then be incorporated into thermal-history and thermokinematic models. As a result, the method allows us to now infer geodynamic processes operating across entire mountain ranges.

**SUMMARY**

Analytical and numerical modeling methods in noble gas thermochronology have complemented one another, enabling geoscientists to tackle geological problems from fresh perspectives. On the one hand, new analytical methods have been developed, and numerical methods have had to catch up to interpret these new datasets. On the other hand, numerical methods have opened up new possibilities that have led to new types of datasets being developed. These exciting developments will continue to deepen our understanding of Earth's dynamic surface.

**ACKNOWLEDGMENTS**

We would like to thank Sam Johnstone and Kendra Murray for very helpful revisions, and thank Emily Cooperdock, Marissa Tremblay, and Peter Zeitler for handling the manuscript. MF is supported by NERC (NE/N015479/1).

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Willenbring JK, Jerolmack DJ (2016) The null hypothesis: globally steady rates of erosion, weathering fluxes and shelf sediment accumulation during Late Cenozoic mountain uplift and glaciation. Terra Nova 28: 11-18
The articles in this issue show how applications of noble gas thermochronology can help answer fundamental questions about Earth and planetary processes. Here, we discuss how noble gas measurements are actually made. We review the different methods used to extract and isolate noble gases from natural materials and to measure those gas concentrations and isotopic compositions using mass spectrometry.

**NOBLE GAS EXTRACTION AND ISOLATION**

To extract gases from rocks and minerals in the laboratory, we often take advantage of the same properties that make them useful for thermochronology: they diffuse with an exponential dependence on temperature, and they are highly incompatible elements. Heating rocks and minerals to high temperatures in an ultrahigh vacuum (<10^{-9} torr) liberates noble gases, either by diffusion in stable phases or though melting. In the early days, this heating was usually by radiofrequency induction, but labs turned to double-vacuum resistance furnaces that isolate the sample vacuum from the vacuum surrounding the heating element, reducing exposure of the sample to gases sourced from heated metal. Today, heating and extraction with a laser is also very common. Laser heating typically adds a lower background signal than furnaces because lasers heat a smaller volume, and they have become cheaper and easier to work with. Lasers can either couple directly with rocks and minerals to achieve heating or can heat samples indirectly by coupling with metal packets holding sample material (e.g., House et al. 2000; see title image in Gautheron and Zeitler 2020 this issue). An advantage of both furnace and indirect laser heating is that they can be used to control sample temperatures accurately and precisely, which is necessary for quantifying the kinetics of noble gas diffusion. However, conducting such measurements can be technically challenging and does require care in experimental design. A less frequently used way to extract noble gases is laser ablation, whereby the surface of a sample is removed (ablated) with a high-energy, short-wavelength laser pulse (e.g., Boyce et al. 2006). This approach can be used to extract noble gases from a targeted subregion of a mineral or rock, but is often challenging because, in most minerals, small ablated volumes release proportionately small amounts of noble gases.

These extraction methods liberate not only noble gases but also other gases and other easily volatilized elements that can be a nuisance during noble gas measurement, introducing mass interferences or altering sensitivity through gas scattering or changes in sample ionization. We typically “clean” the extracted gas prior to measurement on a mass spectrometer using reactive-metal getter pumps and sometimes cold traps that separate gas species based on their adsorption properties and freezing temperatures. By the same principle, cold traps can also be used to separate different noble gas elements from one another, allowing for multiple noble gases to be measured in sequence from the same aliquot of gas.

**NOBLE GAS MEASUREMENT**

Having extracted clean gas, we can then analyze its composition using a mass spectrometer. There are three essential parts of a mass spectrometer: an ion source, a mass analyzer, and detectors.

**Ionization**

All noble gas ion sources operate by using electron impact to strip an electron from a noble gas atom. In this process, electrons are generated from a hot metal filament, then accelerated by an electric field, which creates a stream of electrons that travels from the filament, across the ionizing chamber and into an electron trap. The filament emission and trap current are closely controlled using feedback in order to create an extremely stable beam. Such sources cleverly use a pair of magnets to cause this electron beam to spiral, greatly increasing the electrons’ path length and, hence, their chance of intersecting noble gas atoms. Intersected atoms are stripped of one or more of their electrons, generating a positively charged noble gas ion. A number of charged metal plates are then used to collimate and focus the ions and accelerate them into the mass analyzer across a potential of several kilovolts. Measurement parameters, such as peak shape and mass-spectrometer sensitivity, will vary as a function of the voltages on these different plates as well as on the energy of the electrons emitted from the source filament (e.g., Mabry et al. 2012).

A major difference between analyses for noble gases compared to other gas species is that their small, finite sample sizes means measurement must be done in a static vacuum: all the gas is let into the mass spectrometer at once while the machine is isolated from the ion and the turbomolecular pumps that maintain its ultrahigh vacuum. Once introduced, the noble gas atoms in the mass spectrometer will be continuously ‘consumed’ by ionization, then implanted into the detectors, flight tube, or ion source itself. As a result, the strength of the observed ion beam will decrease as a function of time for large beams, but could even increase for small beams if previously embedded sample gas is liberated from surfaces. Because each individual beam changes in intensity during analysis, the beam intensity must be quantified. To do this, we typically extrapolate the trend in measured ion-beam intensity to “time zero,” the time when the gas first entered the mass spectrometer.

**Mass-to-Charge Ratio Separation**

Once noble gases are ionized, we use a mass analyzer to separate different noble gas isotopes from one another. Two different types of mass analyzer are commonly used in noble gas mass spectrometry: magnetic sectors, and quadrupoles (Fig. 1). In a magnetic sector, ions are accelerated into a magnetic field generated by a strong electromagnet that has the shape of a “sector” of a circle (Fig. 1A). The ions enter the magnetic field nearly perpendicular to magnetic field lines, which deflect them into circular paths. Heavier ions take a wider path, segregating ions with different mass-to-charge ratios into separated ion beams as they exit the magnetic field (Fig. 1A). In a machine with a single detector, it is then possible to measure the ion beam for each mass by precisely shifting the magnetic field.

In contrast to a magnetic sector, a quadrupole consists of four cylindrical metal rods arranged in a rectangle (Fig. 1B). One pair of diagonally opposite rods is kept at one voltage, while the other pair is held at the opposite voltage. A combination of radiofrequency (RF) and direct current (DC) voltages are applied to each pair of rods to generate a two-dimensional, hyperbola-shaped electric field. The field only allows ions with a narrow range of mass-to-charge ratio to travel down the...
center to a collector so that one particular ion species is selected at a time; others are directed to collide with the rods (Fig. 1B). Different ions can be selected by changing the RF and DC voltages on the rods.

Compared to magnetic sectors, quadrupoles generally operate faster and have a much smaller volume. They are also much less expensive. However, quadrupoles typically have lower mass resolution than magnetic sectors and only allow transmission of one isotope at a time. Because of these differences, magnetic sectors are usually preferred for measurements of low-abundance noble gases and/or where measurement precision is a critically limiting factor. Most measurements for $^{4}$He/$^{3}$He and $^{40}$Ar/$^{39}$Ar thermochronology have been done using a magnetic-sector instrument, whereas $^{4}$He abundance measurements for conventional (U–Th)/He analyses by isotope dilution can be carried out with a quadrupole.

**Detection**

There are two types of detectors typically used for noble gas analyses: Faraday cups, and electron multipliers. Faraday cups place a conductive metal target in a circuit that converts a current to a voltage. The current, caused by ions hitting the detector and generating a small net charge, is measured across a very stable and high-value resistor (typically $10^{11}-10^{13}$ Ω) in an amplifier. In electron multipliers, the ion beam impacts a primary metal surface and generates secondary electrons, which are then accelerated across a potential difference into either a series of metal surfaces that have increasing electric potentials or into a continuous curved surface with an increasing electric potential, so generating increasingly larger electron showers as they impact each surface. Faraday cups have stable, linear relationships between ion-beam intensity and measured voltage over a wide range of ion beam intensities, but they have intrinsic noise that makes it difficult to measure small ion beams precisely. Conversely, while electron multipliers lack the stability, linearity, and ion-beam range of Faraday cups, they can be used to measure smaller ion beams because they can have very low intrinsic noise. The recent introduction of capacitive amplifiers and $10^{13}$ Ω resistors for Faraday systems reduces their electronic noise substantially and increases their sensitivity, such that much smaller ion beams can be measured on Faraday cups, which is a potentially big advantage for noble gas thermochronology. What has also become quite common is to outfit sector instruments with multicolonlector arrays laid out to collect multiple beams at once, thereby shortening analysis times and increasing measurement precision.

For $^{40}$Ar/$^{39}$Ar thermochronology, this is effectively the end of the measurement process. But for (U–Th)/He and $^{4}$He/$^{3}$He thermochronology, the buck doesn’t stop there. We must also measure the abundance of $^{4}$He parent isotopes U and Th (and sometimes Sm), which typically requires wet chemistry followed by measurements with inductively coupled plasma mass spectrometry (ICP-MS).

This Toolkit provides an overview of how we go from noble gas atoms trapped inside a mineral to a measurement that can be used for thermochronology, but our description of this measurement process is by no means exhaustive. In detail, there are a number of phenomena that happen to noble gas atoms during the measurement process—such as mass discrimination and isobaric interference—that we must account for in order to accurately calculate isotope ratios or calibrate abundances from the raw measurements we get at the end of this process. The interested reader should see Burnard et al. (2013) for a more detailed review of these phenomena and how we can account for them.

**ACKNOWLEDGMENTS**

We thank Ryan Ickert, Sam Boone, and an anonymous reviewer for their feedback.

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**Figure 1** (A) Schematic depiction of a magnetic sector mass analyzer separating ions of naturally occurring isotopes of argon with masses 36, 38, and 40. (B) Schematic depiction of a quadrupole mass analyzer separating atoms of helium isotopes with masses 3 and 4.
The recipient of the 2019 Research Excellence Award of the European Mineralogical Union is Dr Nadège Hilairet from the Université de Lille (France). She received the award for her outstanding contributions to understanding rock deformation and rheology, as well as for her international collaborative research.

Below are two statements by medalist Dr Nadège Hilairet on her works and passions.

**My best scientific achievements**

My research interests relate to understanding how/when mineralogy affects the dynamics of subduction zones, from long (convection) to shorter (earthquakes) timescales. I carried out some of the first in situ studies on controlled deformation of hydrous phases under high pressure and temperature. These studies used synchrotron radiation to characterize mechanical and microstructural behaviour of the minerals or rocks as they were deforming. I have also worked on phase transformations within subduction zones and their associated relationships with deformation. I joined my expertise of in situ deformation studies with the expertise of colleagues from the École normale supérieure in Paris (France) in acoustic emissions recording. Together, we designed a unique experimental setup to reveal new possible connections between deep earthquakes, phase transitions in olivine, and the mineralogical reactions that occur in subduction zones under high pressure.

**Why I work as a scientist**

I was very fortunate to have met the right people at the right time, from supervisors, to colleagues and students, and have learned a lot from them. Aside from that, I became a geoscientist because it is a very interdisciplinary field, which also involves chemistry, physics, and material science. As a student, I was drawn to petrology by the beauty of rocks, and I became convinced this was the right path for me the day I saw muscovite under a polarizing microscope. During my PhD and postdoc, I spent days and nights at the synchrotron looking at rocks transforming and deforming under the effects of pressure and temperature. This led to my realization that experiments could help you understand rocks and their behaviour in nature. In my day-to-day research, I am driven by the instant at which the pieces of the puzzle assemble to form a meaningful reality. I now hope I can transfer this interest in high-pressure experiments and mineral deformation to students and young people.

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MAC 2020 AWARDS

The Mineralogical Association of Canada (MAC) is pleased to announce its award winners for 2020.

Peacock Medal to Dr. Simon Jackson

The Peacock Medal is the highest award bestowed by the Mineralogical Association of Canada and recognizes the long-term research efforts and contributions of an individual to the Earth sciences within the Canadian context. This medal is awarded to a scientist who has made outstanding contributions to the mineral sciences in Canada.

This year’s awardee is Dr. Simon E. Jackson, a crustal lithogeochemist and research scientist with the Geological Survey of Canada (Ottawa) who works in the survey’s Analytical Chemistry section.

Dr. Jackson’s nomination was presented by a team of high-calibre research scientists, which speaks volumes of the high regard they hold him in. His nomination reads as follows:

Citation: Simon Jackson is a scientific pioneer who has been at the forefront of mineralogical and geochemical research for his entire career, beginning with his seminal work on the development of laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) in the early 1990s. Simon has led many of the major developments in LA-ICP-MS techniques that have revolutionized the quantitative micro-analysis of minerals. This includes the development of new laser ablation systems, the first robust software for data processing (LAMTRACE), methods for quantitative calibration and uncertainty of LA-ICP-MS datasets, high-resolution trace-element mapping, and the development of geologic reference materials through international collaboration. These advances have helped transform the trace-element analysis of minerals at the micron scale, within a spatial context, and have led to significant new applications in diverse fields, including mineralogy, metallurgy, geochronology, environmental geochemistry, archaeology and ore system science. His impact on these diverse research fields has often gone beyond analytical method development and analysis, making him a sought-after collaborator across government and academic research.

Many of Simon's earliest papers now represent seminal contributions in the field. For example, the calibration strategies for converting LA-ICP-MS signals to fully quantitative element concentrations developed by Simon and colleagues have endured rigorous scientific testing over the last several decades and remain the method of choice for fully quantitative micro-analysis. His 1992 paper in The Canadian Mineralogist (v30, pp1049–1064) describing some of these innovative procedures was immediately recognized as ground-breaking; it justifiably received the 1993 Hawley Medal. Simon has also made important contributions to the development of micro-analytical standards – which form the foundation of all applied in situ analytical studies – and his research has been integral in the development of LA-ICP-MS analysis of zircon for U-Pb geochronology. His 2004 paper in Chemical Geology (v211, pp47–69) has garnered over 3,000 citations and was one of the first to document and compare the precision and accuracy of LA-ICP-MS measurements for U-Pb ages of various zircon reference materials – a task of interest by numerous research teams today.

Simon is also a mentor for many young students and early career researchers through his positions in academia and government. To those that know him, these personal connections have had a lasting impact on their careers by instilling a sense of scientific experimentation and rigor. It is this combination of research quality and magnanimous personality that have contributed to Simon’s recognition as a leader across the Canadian and international research community, the sum of which makes him the pre-eminent choice for the 2020 Peacock Medal.

Hawley Medal Winners

The Hawley Medal is awarded to the best paper published in The Canadian Mineralogist. In 2019, this award went to Drs. Elliot A. Wehrle and Andrew M. McDonald (Harquail School of Earth Sciences, Laurentian University) for the following paper:


This contribution combines cathodoluminescence (CL) data and trace-element chemistry in quartz (including a novel application of the Ti-in-quartz geothermometer) to elucidate the conditions of formation relating to offset dikes in the Sudbury area. These dykes also serve as important exploration targets for Ni–Cu–platinum group element (PGE) sulfide mineralization at Sudbury. Although the contemporaneous timing of both the offset dikes and the main mass of the Sudbury Intrusive Complex is supported by their similarities in trace-element geochemistry, individual dikes possess unique characteristics that suggest differences in their respective parageneses. A combination of qualitative CL images and electron probe micro-analysis trace-element data suggests that the CL response of quartz may potentially be used not only as a tool for recognizing textures that are not apparent or resolvable by other techniques but also as an indirect proxy for Ti concentration in quartz. The authors have demonstrated that the combination of CL imaging and Ti analysis of quartz has the potential to serve as a robust indicator of not just the conditions of formation and subsequent crystallization processes that impacted the Sudbury offset dikes but also of the broader formational processes that operated in the Sudbury Basin.

Elliot A. Wehrle is a graduate student of the University of Windsor (Canada), supervised by Dr. Iain Samson. His current MSc project focuses on Archean gold mineralization in the Wawa Gold Corridor (Ontario, Canada). Elliot completed his BSc at Laurentian University (Canada) under the supervision of Prof. Andrew M. McDonald, who supervised both his NSERC Undergraduate Student Research Award (USRA) (during which the research for this project was undertaken) and his undergraduate thesis. Mr. Werhle graduated at the top of his class (grade point average of 9.67, Dean’s Honour Roll for four years) and has already received numerous accolades: the NSERC USRA (in the second year of his program); the David Beilitz Award for the best undergraduate thesis presentation; a Society of Economic Geologists (SEG) Undergraduate Scholarship; a Student Industry Economic Workshop (S-IMEW) award; and a SEG field trip attendee (Gold Deposits in the Birimian of Ghana, West Africa); a Geological Association of Canada–Mineralogical Association of Canada (GAC–MAC) Earth Sciences Award; and an Ontario Graduate and an SEG scholarship in 2019. Mr. Wehrle has balanced his academic achievements with practical experience, including summer work terms with Canadian Malarctic (Kirkland Lake, Ontario) and Red Pine Exploration (at Wawa). As an undergraduate, Mr. Wehrle also penned a paper on gahnite and its exploration implications, based on research stemming from his undergraduate thesis. He has presented two papers at a national conference (at the “Resources for Future Generations” conference in Vancouver, in June 2018), both of which received very high accolades and significant attention. Mr. Werhle is an outstanding young scientist with a keen interest in using mineralogy to elucidate processes involved in the formation and evolution of ore deposits.
Andrew M. McDonald is an applied mineralogist in the Department of Earth Sciences at Laurentian University (Canada). His background is firmly planted in the crystal chemistry of minerals and the geological processes they reveal, applying these to solve geologically relevant problems, specifically problems on the high field-strength elements (Ti, Zr, Nb) and platinum-group and sulfide (magmatic ore deposit) mineralogy. He obtained a BSc (Hons.) from the University of Toronto (1987) and graduate degrees from Carleton University (MSc in 1989; PhD in 1992). He joined the faculty at Laurentian in 1992 and currently holds the rank of full professor; he is also the Director of the Microanalytical Centre there. He volunteers his time with the International Centre for Diffraction Data, is the Canadian member of the IMA Commission on Ore Mineralogy (COM), was a former associate editor of the American Mineralogist (2010–2013), served as the Vice-Chair of COM (2010–2013), along serving on the former IMA Commission on the Classification of Minerals (1996–2002). Within the MAC framework, he has served as secretary (2000–2006), president of the society (2016–2018) and past-president (2018–). He has also served two terms as an associate editor of The Canadian Mineralogist (2006–2009; 2020–), was a guest editor for the special issue entitled “The Mineralogy and Beneficiation of PGM–Cu–Ni Ores” (v49, pt6), was a member of the Hawley Medal Committee (2012), organized with Prof. Jim Nicolls (University of Calgary) a highly successful workshop entitled the Berry Summer School on Optical Mineralogy, and was vice-chair for the Sudbury 1999 GAC–MAC meeting. This is his third Hawley Medal: he and his team had been previously awarded in both 2015 and 2018.

Young Scientist Award to Prof. Chris Yakymchuk

The MAC Young Scientist Award recognizes research excellence by a young scientist under the age of 40 who has made a significant international research contribution and a very promising start to a scientific career.

The 2020 Young Scientist Award, which includes a medal, goes to Prof. Chris Yakymchuk, a dynamic, young researcher in Department of Earth and Environmental Science at the University of Waterloo (Canada) whose research interests broadly lie in understanding the tectonic history of mountain belts.

Citation: Chris Yakymchuk is an extraordinary young researcher. He is a true all-around geologist with a broad range of expertise in petrology and tectonics. He has become an internationally recognized leader in the area of accessory mineral petrochronology. Through his novel thermodynamic modelling, his research has provided (a) innovative predictive models to link metamorphic ages derived from accessory minerals to specific parts of P–T paths in high-temperature metamorphic settings; (b) the first quantitative framework in which to interpret trace-element concentrations in accessory mineral chromonometers, including Th/U ratios of metamorphic zircon in aluminous rocks, which is a commonly used but poorly understood ratio for differentiating between igneous and metamorphic zircons. His interdisciplinary approach to tectonics research – combining theoretical, experimental, analytical and field-based studies – positions him as a future leader in this area. More recently, he has applied his knowledge in petrology, phase mineral geochronology and tectonics to mineral deposit studies.

Teaching award. Prof. Yakymchuk is a prolific and high-impact researcher. He has contributed to 36 papers and currently has an additional eight submitted for review. His papers have been well-cited: one of his papers from 2014 received over a hundred citations, and three of his papers on accessory minerals have each had over 50 citations (Google Scholar). He has a h-index of 14. These are remarkable achievements for an early career scientist just five years after finishing his PhD.

Prof. Yakymchuck’s research is diverse, but includes several themes espoused by the MAC: the behaviour of open systems that have undergone high-grade metamorphism, fluids in the deep crust and the U–Pb geochronology of accessory minerals, all being firmly rooted in sound field studies. The MAC is incredibly proud to be able to recognize Prof. Yakymchuck’s research excellence and to support him as his career develops.

MAC AWARDS – CALL FOR NOMINATIONS

Peacock Medal

The Peacock Medal is awarded to a scientist who has made outstanding contributions to the mineralogical sciences in Canada. There is no restriction regarding nationality or residency. The medal recognizes the breadth and universality of the awardee’s contributions to mineralogy, applied mineralogy, petrology, crystallography, geochemistry, or the study of mineral deposits.

Young Scientist Award

The Young Scientist Award is given to a scientist who has made a significant international research contribution during the early part of their scientific career. The scientist will have received his/her PhD not more than 15 years before the award. He or she must be a Canadian working anywhere in the world or be a scientist of any nationality working in Canada. The research areas include mineralogy, crystallography, petrology, geochemistry, mineral deposits or related fields of study.

Leonard G. Berry Medal

The Leonard G. Berry Medal is awarded annually for distinguished service to the association. The award recognizes significant service to the MAC in one or more areas that may include leadership or long-term service in an elected or appointed office or as important contribution(s) that has enhanced the mineral sciences in Canada or that has broadened the Canadian mineralogical perspective. The medal is named after Leonard G. Berry (1914–1982), a founding member of MAC, editor for 25 years of The Canadian Mineralogist and its predecessor journal, and the first winner of MAC’s Past-Presidents’ (now Peacock) Medal.

Nominations for the 2021 medals and award are to be submitted to Andrew M. McDonald (Harquail School of Earth Sciences, Laurentian University, Sudbury, ON P3E 2C6, Canada); E-mail: amcdonald@laurentian.ca.

Please submit your nominations by 31 December 2020. Check our website, www.mineralogicalassociation.ca, for additional details.

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The University of Western Ontario in London, Ontario (Canada)
You are cordially invited to attend the 84th Annual Meeting of the Meteoritical Society to be held 14–21 August 2021 in Chicago (Illinois, USA). Please mark your calendars. We are planning for an in-person meeting but are prepared to hold the meeting online should the situation with the COVID-19 pandemic require it. The Meteoritical Society (Met Soc) 2021 meeting is being organized by planetary scientists at the Field Museum of Natural History and the University of Chicago. The Field Museum is the birthplace of the Meteoritical Society, which was founded there in 1933 as the Society for Research on Meteorites. Chicago has a long history of pioneering work in meteoritics, cosmochemistry, and planetary science, and several of its scientific institutions are still active in these fields.

The 2021 Met Soc meeting will feature special sessions on asteroid sample-return missions Hayabusa2 and OSIRIS-REx. More details about the meeting program and events will be provided later. The meeting venue will be downtown at the Hilton Chicago on 720 South Michigan Avenue, with views overlooking Grant Park, Lake Michigan, and the museum campus. The venue is within walking distance to most major attractions. Chicago is a top tourist destination in the USA. Please mark your calendars. We are planning for an in-person meeting. The meeting venue will be downtown at the Hilton Chicago on 720 South Michigan Avenue, with views overlooking Grant Park, Lake Michigan, and the museum campus. The venue is within walking distance to most major attractions. Chicago is a top tourist destination in the USA. You are cordially invited to attend the 84th Annual Meeting of the Meteoritical Society to be held 14–21 August 2021 in Chicago (Illinois, USA). Please mark your calendars. We are planning for an in-person meeting but are prepared to hold the meeting online should the situation with the COVID-19 pandemic require it. The Meteoritical Society (Met Soc) 2021 meeting is being organized by planetary scientists at the Field Museum of Natural History and the University of Chicago. The Field Museum is the birthplace of the Meteoritical Society, which was founded there in 1933 as the Society for Research on Meteorites. Chicago has a long history of pioneering work in meteoritics, cosmochemistry, and planetary science, and several of its scientific institutions are still active in these fields.

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We have COVID-19 precautions for an in-person meeting. The event organizers will do whatever is possible to minimize the risk for attendees of exposure to the SARS-CoV-2 virus. The hotel has already started implementing special cleaning procedures to minimize pathogen exposure to guests. The City of Chicago has reopened cautiously and has implemented comprehensive guidelines to reduce the spread of COVID-19. The organizers will work with city and hotel officials to provide the safest and most enjoyable meeting possible. The event organizers and the Council of the Meteoritical Society will decide if an in-person meeting can be held when we get closer to the meeting. Information will be provided on our meeting website: https://www.metsoc2021-chicago.com.

The meeting, be it in-person or virtual, will be an excellent venue to present and discuss your research and learn about the state-of-the-art in our fields. We encourage you to reserve the dates of 14–21 August 2021 in your calendar today, and we hope to welcome you to Chicago in the summer of 2021.

Philipp R. Heck (e-mail: prheck@fieldmuseum.org)

2020 GOLDSCHMIDT MEETING AWARDS

With the postponement of the Annual Meeting of the Meteoritical Society in Glasgow (UK) due to COVID-19, no student travel awards were made this year. Instead, the Met Soc chose to assist students and postdocs who were interested in attending the Goldschmidt2020 Virtual Meeting. Those who registered for Goldschmidt2020 and were selected will have their 2021 Meteoritical Society membership dues paid for by an award from the Meteoritical Society’s Endowment Committee. The society’s travel awards will resume for the 2021 Meteoritical Society meeting in Chicago, assuming that meeting takes place in person. Travel grant awardees are as follows:

- Kana Amano (Tohoku University, Japan)
- Brendan Chapman (Arizona State University, USA)
- Yankun Di (Australian National University)
- Emilie Dunham (University of California, Los Angeles, USA)
- Hideyuki Hayashi (University of Tokyo, Japan)
- Zilang Jin (Arizona State University)
- Tanya Kizovsky (University of Toronto, Canada)
- Linnea McCann (Arizona State University)
- Souma Ray (Arizona State University)
- Quinn Shollenberger (University of California, Los Angeles)
- Sherry Singerling (US Naval Research Laboratory, Washington DC, USA)
- Amanda Stadermann (University of Arizona, USA)
- Zachary Torrano (Arizona State University)
- Krysten Villalon (University of Chicago)
- Craig Walton (University of Cambridge, UK)
- Zoe Wilbur (University of Arizona)

In Memoriam: Richard (Dick) Pugh (1940–2020)

Our colleague, friend, and long-time member of the Meteoritical Society, Richard (Dick) Pugh passed away 15 June 2020 from complications associated with liver failure. His passing was peaceful and at home.

In 2003, Dick helped establish the Cascadia Meteorite Laboratory at Portland State University together with myself and Dr. Melinda Hutson. He also helped establish an endowment for meteorite curation at the university for a collection that now numbers over 1,300 different meteorites. In 2011, Dick received the Service Award from the Meteoritical Society for his excellent efforts in outreach and informal education. Throughout his career, Dick contributed to the recognition of seven new meteorite finds in Oregon, Idaho, Nevada, and Texas (all USA), and one new fall from Trapeang Ronoas (Cambodia). Dick was active in informal education right through last year when his health began to deteriorate. Dick was, in many ways, the heart of the Cascadia Meteorite Lab. His enthusiasm for meteorites was infectious, his world both that of the researcher and teachable layperson. He will be missed, but memories of him will live on and inspire.

This website at the Cascadia Meteorite Laboratory, Portland State University, has more information on Dick’s many contributions: http://meteorites.pdx.edu/Pugh-tribute.html.

Alex Ruzicka, Portland State University
ABRAHAM GOTTLOB WERNER MEDAL IN GOLD TO EKKEHART TILLMANNS

With the Abraham Gottlob Werner Medal in Gold, the German Mineralogical Society (DMG) honors outstanding efforts in advancing the mineralogical sciences. This year, the DMG honors Prof. Dr. Ekkehart Tillmanns (University of Vienna, Austria) in appreciation of his outstanding merits. Prof. Tillmanns’ career has been characterized by exchanging scientific ideas in the fields of mineralogy and crystallography. He served as a co-editor for the journals Mineralogy & Petrology and Zeitschrift für Kristallographie, as well as associate and chief editor of the European Journal of Mineralogy. For many years, he was member of the advisory board of Physics and Chemistry of Minerals. Being a member of several national and international mineralogical societies, he actively helped shape their development. Within the DMG, he was member of the advisory board and was a representative of the crystallography working group; in the Austrian Mineralogical Society he served as a board member and became an honorary member. For the board of the International Mineralogical Association (IMA), he was first a councillor before serving as president of this worldwide society, including the responsibility of organizing the IMA meeting in Budapest (2010). Besides his services to the scientific community, he was an outstanding scientist, publishing more than 185 scientific papers. In his contributions, he focused on the crystal chemistry of minerals and inorganic compounds and their physico-chemical characterization. The work of Ekkehart Tillmanns has been honored several times over his career. Highlights are the 1998 Distinguished Grantee Award of the International Centre for Diffraction Data, the 2002 Erwin Schrödinger Award of the Austrian Academy of Sciences, his election as a foreign member of the Russian Academy of Natural Sciences (Moscow) in 1999, as well as his election as a member of the Deutsche Akademie der Naturforscher Leopoldina – National Academy of Sciences (Halle/Saale) in 2000. With the Abraham Gottlob Werner Medal in Gold, the German Mineralogical Society honors Ekkehart Tillmanns as an internationally renowned mineralogist and crystallographer.

Peter Paufler, Dresden

CALL FOR AWARD NOMINATIONS

Please consider nominating a colleague for one of the Meteoritical Society’s awards.

Nominations should be sent to Secretary Munir Humayun (metsocsec@gmail.com) by January 15 (January 31 for the Service Award and the Paul Pellas–Graham Ryder Award). For more information and details on how to submit a nomination for any of these awards, please see the latest Meteoritical Society Newsletter at the society’s website or e-mail the secretary.

The society gives a number awards each year. The Leonard Medal honors outstanding contributions to the science of meteoritics and closely allied fields. The Barringer Medal and Award recognizes outstanding work in the field of impact cratering and/or work that has led to a better understanding of impact phenomena. The Nier Prize recognizes outstanding research in meteoritics and closely allied fields by a young scientist. The Service Award honors members who have advanced the goals of the Meteoritical Society to promote research and education in meteoritics and planetary science in ways other than by conducting scientific research. The Paul Pellas–Graham Ryder Award is given for the best student paper in planetary science and is awarded jointly by the Meteoritical Society and the Planetary Geology Division of the Geological Society of America. The newest society award, the Elmar Jessberger Award, recognizes a mid-career female scientist in the field of isotope cosmochemistry.

EUROPEAN JOURNAL OF MINERALOGY

In the first seven months of 2020, the European Journal of Mineralogy (EJM) published 32 articles in 425 pages. All EJM papers are full open access, giving you the opportunity to freely enjoy reading them. Until the end of 2020, as part of the promotion of the EJM’s new open access format, we will continue to offer a very attractive discount with an article processing charge (APC) at €50 per page (€40 for members).

A New Series

We are pleased to announce the launching of a new series of special issues under the general title “Probing the Earth”.

The production of first two special issues in the series are now underway:

PROBING THE EARTH: REVIEWS OF OH GROUPS IN ANHYDROUS AND HYDROUS MINERALS

Submissions open until 31 January 2021.

EDITORS: Patrick Cordier, Etienne Balan, István Kovács, and Roland Stalder.

Provisional article titles already scheduled include:

- Influence of water on the transport properties of olivine, wadsleyite, and ringwoodite
- OH in quartz
- OH in orthopyroxene
- OH point defects in olivine
- Hydrogen-bonding topology of hydroxide perovskites

PROBING THE EARTH: EXPERIMENTS AND MINERAL PHYSICS AT MANTLE DEPTHS

Submissions open until 30 June 2021.

EDITORS: Elisabetta Rampone, Patrizia Fumagalli, Stephan Klemme, Monika Koch-Müller, Didier Laporte, and Max Wilke.

More information on these special issues is provided on the web-page of the journal at https://www.european-journal-of-mineralogy.net/.

We look forward to receiving your exciting papers, either for the EJM itself or as part of the new Probing the Earth series.
John A. Hansuld, a founding member of the Association of Applied Geochemists (AAG) (originally named the Association of Exploration Geochemists, AEG), died at the age of 88 on 26 November 2019. John played a key role in establishing the AEG/AAG. Stimulated by the well-attended International Geological Exploration Symposium (IGES) of the late 1960s, John and fellow geochemists – including Alan Coope, Herb Hawkes and Eoin Cameron – recognised the need for a professional organization of exploration geochemists and, thus, the AEG was formed in 1970. John became President of the AEG in 1971. In a remarkably short time, the AEG had taken over responsibility for the IGES series (the 4th took place in London, UK, in 1972) and John had negotiated with Elsevier the launch of the association’s flagship journal (Journal of Geological Exploration) which would be published from 1972 onwards. In the following years, John focused on the role of business editor. The early association newsletters (later to become EXPLORE) make for very interesting reading and can be found at https://www.appliedgeochemists.org/explore-newsletter/explore-issues. Recognition of John’s numerous important contributions to the AEG are shown by the Distinguished Service Award of the association presented to him in 1982 and the Past-President’s Medal in 1999.

Ontario-born, John earned his Bsc (Hons) in geology from McMaster University (Canada) in 1954, followed in 1956 by an MSc from the University of British Columbia (Canada) where his work focused on the factors influencing the rate of leaching from ore at the Britannia Mines (British Columbia) copper sulfide deposit. While having a beer on a train to a Prospectors and Developers Association of Canada (PDAC) convention, John was recruited to do a PhD at McGill University in Montreal (Canada). That chance meeting led to a blossoming of his fascination for geochemistry, specifically into the mobility of metals (especially Mo) in the surficial environment using Eh–pH phase equilibrium diagrams. He essentially establishing this technique in predictive geochemical studies.

After obtaining his PhD in 1961, John joined Amax Inc. and, in 1962, he was promoted to Chief Geochemist at their headquarters in Denver (Colorado, USA), followed by a further promotion to Manager of Exploration Research. In 1967, John returned to Toronto where he was responsible for managing exploration in Eastern Canada; the following year, supported by Amax, he obtained a Professional Master’s Degree (akin to an MBA) from Harvard Business School. In 1973, John was further promoted to Canadian Exploration Manager and, by the late 1970s, Amax Exploration (Canada) was one of the largest groups in the country, with 91 active projects. In 1978, he became Vice-President of Amax with responsibility for the worldwide exploration budget. In 1983, John persuaded Amax to spin out its Canadian operations into a new company – Canamax Resources – of which he became President and CEO. The spin-out raised $30 million in its initial public offering, a major achievement as the financing introduced ‘flow through’ shares, already used by the oil and gas industry, to the mining sector. This tremendous boost to financing mineral exploration, especially for junior companies, led to the positioning of Canada as a global leader in the mining industry. John was dubbed “The father of flow through” and was named “Mining Man of the Year” by the Northern Miner in 1988 and “Developer of the Year” by the PDAC in 1989.

John left Amax in 1989 to take on executive and directorship positions with various mining companies. He was President of the PDAC in the period 1993–1996 when, again, his leadership had a major impact through his strategic plan to revitalise and expand the organization beyond its North American focus to an international one that had extensive influence. In 2012, John was inducted into the Canadian Mining Hall of Fame (https://www.mininghalloffame.ca/john-a-hansuld), and it was at the ceremony that the presenters demonstrated to all present the full breadth of his accomplishments, as a geochemist, entrepreneur, mine-finder, financial investor, and leader. John remained active in the mining community up to the age of 85.

John and his wife of 64 years, Jane, travelled the world extensively. He was very much a family man. Jane, their three children, six grandchildren and two great-grandchildren were his priority and his delight.

John Hansuld was a trailblazer and leader in the exploration and mining industry. The AAG benefited greatly from his talents.

Gwendy E.M. Hall

RECENT ARTICLES PUBLISHED IN EXPLORE

The following article is for an article written by C.U. Ibe, S.C. Obiora and T.C. Davies (all from the Department of Geography, University of Nigeria) in issue 185 (December 2019) of the EXPLORE newsletter.

“Petrological and Geochemical Study of the Precambrian Basement Complex Rocks in Katchuan Irruan Areas, Southeast of Ogoja, Southern Eastern Nigeria”

This study shows that Katchuan Irruan and its adjoining areas in southeastern Nigeria are underlain by Precambrian Basement Complex rocks, namely: migmatitic banded gneiss, garnet mica schists and granitoids.

The gneisses show positive anomalies in Rb, K, La and Sm and strong negative anomalies in Th, Ta, Nb, Sr, Ti, Tm, Yb, Zr and Y, with an overall enrichment of the large ion lithophile elements (LILEs) and a depletion of the high field-strength elements (HFSEs). This confirms their protoliths as sedimentary. There is a dominance of shale in the protoliths of the garnet mica schist unit, whereas greywackes, iron shale, iron sand and arkose originally formed the migmatitic banded gneiss unit. Both major element data and trace element ratios (i.e., Th/Sc, Th/U) indicate that the protoliths had an average upper crustal composition. Detritus from a mixed source is indicated for the two units, with clastic material resulting mainly from both andesitic and felsic/recycled detritus. The overall data consistently suggest a continental island arc and/or active margin setting as the probable geodynamic setting for the deposition of the sedimentary precursors of these units. Geochemical data also indicate that the granitic rocks are generally shoshonitic, alkali-calcic to calcic, f erroan and peraluminous. They are enriched in both LILEs and HFSEs. Their trace elements and rare earth element (REE) patterns are similar, indicating that they are co-genetic. They are slightly to strongly light REE-enriched ([La/Yb]N = 3.04 to 228.44) and have pronounced negative Eu anomalies (Eu/Eu* = 0.23–0.71). Their overall geochemical features indicate that they were most likely derived from partial melting of crustal materials in an orogenic (post-collisional) tectonic setting. They are, therefore, related to other Pan-African granites, which were emplaced during the Pan-African orogenic event.

This article was prepared for the EXPLORE newsletter as a requirement for receiving analytical support in 2016 for the MSc research of the senior author under the Association of Applied Geochemists Student Support Initiative (https://www.appliedgeochemists.org/students/student-support-initiative).
THE PRESIDENT'S CORNER

In my previous President’s Corner, I discussed the impact that the current COVID-19 pandemic has had on the organization of scientific meetings. Meetings are one of the most important tools scientific societies have to encourage the advancement of science, to promote research, and to increase and diffuse knowledge. The COVID-19 pandemic had an impact on these three goals not only by significantly increasing the difficulty in organizing conferences and meetings but in the more pervasive way of hampering our everyday activities: worldwide, laboratories are running at a reduced pace, projects are being delayed, and teaching the next semester is now clouded with many unknowns. Scientific societies are, thus, facing new challenges, and they will have to reinvent themselves by adapting, developing, and diversifying their activities to fulfill their objectives. Some of the issues that our scientific communities face are obviously beyond our capacity of action: lockdown and the often-severe travel restrictions for foreign students and collaborators between countries, or even within a single country. On the other hand, the present situation could be a great opportunity for learned societies to be creative in developing new ways to fulfill their goals. In particular, this can be through the development of electronic communication, webinars, on-line courses, and, more generally, having on-line activities, which are minimally impacted by the pandemic. Such on-line communication is now widely available worldwide. Letting their audience know about their activities should remain part of a society’s communication line, but this communication should also contribute more actively to the increase and diffusion of knowledge.

Tremendous efforts have been developed by devoted university teachers to keep their classes going. Societies can probably try to capitalize on these to organize and propose a series of classes, tutorials, and practicals that would benefit the geological community in its broadest sense.

Bruno Lanson (bruno.lanson@univ-grenoble-alpes.fr)
President, The Clay Minerals Society

2020 CMS PROFESSIONAL AWARD RECIPIENT SPOTLIGHT

Prof. Eduardo Ruiz-Hitzky received the 2020 Marilyn and Sturges W. Bailey Distinguished Member Award. At the 2020 CMS meeting, Prof. Ruiz-Hitzky will present a plenary talk titled, “Clay-Based Bionanocomposites For Health And Environmental Applications”.

Eduardo Ruiz-Hitzky is Ad Honorem Research Professor at the Materials Science Institute of Madrid (ICMM), which is part of the National Research Council of Spain (CSIC). He is the founder and first director of several departments at this institution, including the New Architectures in Materials Chemistry Department which he created in 2010.

Prof. Ruiz-Hitzky earned his primary degree in chemistry at the Universidad Complutense, Madrid (Spain) in 1970; his Docteur en Sciences at the Université Catholique de Louvain (Belgium) in 1974, supervised by Professor José J. Fripiat; and his PhD in chemistry at the Universidad Complutense, Madrid, in 1979, supervised by Professor José M. Serratosa. In 1976, he was a postdoctoral fellow at the University of Kiel (Germany), supervised by Professor G. Lagaly.1

Prof. Ruiz-Hitzky dedicated his research life to the study of clays, clay minerals, and related solids. He is the most cited scientist on sepiolite. He has supervised around 20 PhD theses; has authored more than 300 publications, including in high impact journals such as Nature; and filed around 20 patents, some of which were transferred to industry. His publications have received more than 10,000 citations (h-index > 50).

Prof. Ruiz-Hitzky served as President of the Spanish Clay Society (SEA) and has been General Chair for several international conferences, including the CMS(USA)–CSSJ(Japan)–SEA(Spain) Trilateral Meeting on Clays, which was held in Madrid and Sevilla in 2010. He was Invited Professor at the Université de Paris-Sud (Orsay) in 1987 and at the Collège de France, Paris, in 2011; Senior Fellow at the National Laboratory of Nanotechnology, Campinas (Brazil) in 2015; Invited Professor at Waseda University, Tokyo (Japan) in 2012 and 2014; and was Invited Lecturer at the Massachusetts Institute of Technology in Cambridge (USA) in 2017.

Prof. Ruiz-Hitzky is an Honorary Member of the SEA (2019). He has also received awards from the Académie Royale de Belgique (Brussels) in 1976, the Ministry of Sugar (Havana, Cuba) in 1995, and the National Academy of Sciences (Havana) in 2008 and 2017. He was awarded the Bude Medal by the Collège de France (Paris) in 2011 and the AIPAE Medal (at a meeting in Tokyo, Japan) in 2005.

STUDENT RESEARCH SPOTLIGHT

Congratulations to Adrian Broz (University of Oregon, USA) for winning a 2020 CMS Student Research Grant!

Adrian’s research is focused on the influence of clay mineralogy on the preservation of organic matter in Mars-analog paleosols. This research examines the abundance and types of organic compounds preserved over geologic timescales in phyllosilicate-rich surface paleoenvironments from eastern Oregon and Australia with the goal of prioritizing locations for biosignature investigations on the surface of Mars.

ADDITIONAL RESEARCH AND TRAVEL GRANT AWARDS FOR 2020

In the August issue of Elements, we listed the 2020 CMS research and travel grant recipients. Additional funding became available when the 2020 CMS annual meeting went virtual. This provided more support for research and travel grants.

Recipients of additional 2020 CMS Research Grants are Huseyn Demir (University of Georgia, USA); Rachel Havranek (University of Colorado, USA); Julia McIntosh (Southern Methodist University, Texas, USA); Mohammad Sasar (Purdue University, Indiana, USA); Kelly Tingle (University of California–Santa Barbara, USA); and Chaoqun Zhang (Chinese Academy of Sciences, China).

Recipients of additional 2020 CMS Travel Grants, to be used to pay for CMS meeting registration, are Saba Akbar (Texas A&M University, USA); Huseyn Demir (University of Georgia, USA); Ahmad Khan, (Texas A&M University); Paulina Maziarz (AGH University of Science and Technology, Poland); Jackson Nikoh (Chinese Academy of Sciences); and Ahmed Radwan (Sohag University, Egypt).

1 His three supervisors (J.J. Fripiat, J.M. Serratosa and G. Lagaly) have also each been recognized with a Marilyn and Sturges W. Bailey Distinguished Member Award.
REFLECTION FROM THE SOCIETY’S GENERAL SECRETARY

We live in unconventional times. Not only have our lives changed to accommodate COVID-19, but there is also a powerful movement demanding that we reflect on troubling historical aspects of our national heritage, in particular the links between our subject and colonialism. Museums and universities are looking afresh at their collections, including mineral collections. What does ‘ownership’ mean, and what does that say about colonialism and the ethics under which specimens were acquired? The science may stay the same, but the context has changed. Whilst we cannot rewrite the past, we can represent it more fully and from more than one perspective. This is a valid process. But more important are the actions of society today and the impact we have now. One of the MinSoc’s special interest groups, the Volcanic and Magmatic Studies Group, has devised three webinars to inform discussion that will underpin the co-creation of positive actions to address racial inequality in scientific research. The first of these is available at https://youtu.be/tjulJcVndqY: it is fascinating and engaging. Other presentations will include examples of poor attitudes taken by early researchers in the Caribbean and Latin America toward the indigenous peoples (Dr Jasmin Scarlett and Dr Lisa Seville); examples of historic practice in the overseas work of the British Geological Survey, in contrast to modern-day inclusive practices (Dr Kathryn Goodenough); questioning how we build equal partnerships (Dr Mattieu Kervyn); documenting the evolution from token involvement to meaningful collaborative research partnerships with nationals (Prof. Richie Robertson). (The second webinar is available at youtu.be/0DBXW9dM0gJ.) All these webinar themes will question responsible practice and will be more widely applicable than to scientific research only.

METAMORPHIC STUDIES GROUP MEETING

Video recordings of several oral presentations delivered during this year’s Virtual Metamorphic Studies Group Research in Progress meeting are now available from the Mineralogical Society’s (MinSoc’s) website:

- **Introduction by Chair of the Metamorphic Studies Group, Catherine Mottram**
- **Presentation of the Barrow Award to Clare Warren**

- **“Dating Metamorphism and Other Stories: Travels through PTI Space”**, Clare Warren
- **“Pre-Orogenic Upper Crustal Softening by Lower Greenschist Facies Metamorphic Reactions in Crystalline Basement Units (Example of Central Pyrenees)”**, Laura Airaghi, Nicolas Bellahsen, Benoît Dubacq, David Chew, Claudio Rosenberg, Emilie Janots, Maxime Waldner and Valérie Magnin
- **“Metamorphism on the Moon Recorded by the Granulite Suite”**, J.F. Pernet-Fisher and K.H. Joy
- **“Quantitative Automated Mineralogy to Constrain Metamorphic Processes using ZEISS Mineralogic”**, Richard J.M. Taylor
- **“Reaction Affinity Patterns in Rocks with Porphyroblasts”**, C.T. (Tom) Foster Jr

NEW MEMBERS OF THE MINSOC COUNCIL FOR 2021

The following, all based on the UK, will join as members of council, starting in 2021:

- **Nia Gray-Wannell** (Hutton Institute, Aberdeen)
- **Mike Rumsey** (Natural History Museum, London)
- **Richard Taylor** (Zeiss Microscopy)
- **Public Relations Officer: James Byrne** (University of Bristol)

Welcome all, and thank you for your service to the society.

RECENT CONTENT IN CLAY MINERALS (MARCH 2020)

(go to https://www.cambridge.org/core/journals/clay-minerals/latest-issue)

- **“Clay minerals in drilling fluids: functions and challenges”**, Jun Rui Zhang, Meng Dan Xu, Georgios E. Christidis, Chun Hui Zhou
- **“Smectitic clays enriched with ferric ions for the rapid removal of anionic dyes in aqueous media”**, Itamar A. Rodrigues, Juan C. Villalba, Maria J. Santos, Fábio L. Melquiades, Fauze J. Anaïssi
- **“Regeneration of spent bleaching clay by ultrasonic irradiation and its application in methylene blue adsorption”**, Xiaooyu Liang, Chao Yang, Xintai Su, Xiaogang Xue
- **“Hydrotalcites with heterogeneous anion distributions: a first approach to producing new materials to be used as vehicles for the successive delivery of compounds”**, Franchescoli D. Velázquez-Herrera, Geolar Fetter
- **“The influence of binders for the pelletization of fly ash zeolites on sulfur dioxide sorption properties”**, Natalia Czumaa, Rafal Panek, Pawel Baran, Katarzyna Zarebska
- **“Use of palygorskite as a viscosity enhancer in salted water-based muds: effect of concentration of palygorskite and salt”**, Vanessa Cristina Santanna, Samara Leandro Silva, Rhaul Phillipy Silva, Tereza Neuma Castro Dantas
“A novel method for solving the impact of clay on concrete workability: dimensional design and mechanism analysis”, Xiao Liu, Qian Xu, Xiaoyu Ma, Yunsheng Zheng, Lei Lu, Xiabing Bai

“Refinement of waste phosphogypsum from Prahovo, Serbia: characterization and assessment of application in civil engineering”, Josip I. Išek, Lazar M. Kaluderović, Nikola S. Vuković, Maja Milošević, Ivana Vukašinović, Zorica P. Tomić,

“Mineralogical and hydraulic characteristics of mudstone in the Tamusu candidate area in northwest China for high-level radioactive waste geological disposal”, Long Xiang, Xiaodong Liu, Pinghui Liu, Xingtian Jiang, Chaocheng Dai

“Polygenic chamosite from a hydrothermalized oolitic ironstone (Saint-Aubin-des-Châteaux, Armorican Massif, France): crystal chemistry, visible-near-infrared spectroscopy (red variety) and geochemical significance”, Yves Moëlo, Emmanuel Fritsch, Eric Glouagne, Olivier Rouer

“Thermal degradation kinetics of sepiolite”, Yüksel Sarıkaya, Muşerref Önal, Abdullah Devrim Pekdemir

RECENT CONTENT IN MINERALOGICAL MAGAZINE (JUNE 2020)

“Processes of metastable-mineral formation in oxidation zones and mine waste”, Juraj Majzlan

“Nomenclature of the magnetoplumbite group”, Dan Holtstam, Ulf Hålenius

“Langhofite, Pb2(OH)[WO4(OH)]2, a new mineral from Långban, Sweden”, Dan Holtstam, Fernando Câmara, Andreas Karlsson

“Biagoniite, Tl2SbS2, from the Hemlo deposit, Marathon, Ontario, Canada: occurrence and crystal structure”, Luca Bindi, Yves Moëlo

“Texture and composition of magnetite in the Duotoushan deposit, NW China: implications for ore genesis of Fe–Cu deposits”, Xia Hu, Huayong Chen, Xiaowen Huang, Weifeng Zhang

“The walentaite group and the description of a new member, alcantarillaite, from the Alcantarilla mine, Belalcázar, Córdoba, Andalusia, Spain”, Ian E. Grey, Rupert Hochleitner, Christian Alcus, Anna Vymazalová, Federica Zaccarini, Giorgio Garuti, František Laufek, Daniela Mauro, Chris J. Stanley, Cristian Biagioni

“Progress in the knowledge of ‘ruby silvers’: New structural and chemical data of pyrostilpnite, Ag5SbS4”, Cristian Biagioni, Federica Zaccarini, Philippe Roth, Luca BINDI

“Bowlesite, PtSnS, a new platinum group mineral (PGM) from the Merensky Reef of the Bushveld Complex, South Africa”, Anna Vymazalová, Federica Zaccarini, Giorgio Garuti, František Laufek, Daniela Mauro, Chris J. Stanley, Cristian Biagioni

“Cuyaite, Ca2Mn3+As3+14O24Cl, a new mineral with an arsenite framework from near Cuya, Camarones Valley, Chile”, Anthony R. Kampf, Stuart J. Mills, Barbara Nash, Maurizio Dini, Arturo A. Molina Donoso

“IMA Commission on New Minerals, Nomenclature and Classification (CNMNC) Newsletter 55”, Ritsuro Miyawaki, Frédéric Hatert, Marco Pasero, Stuart J. Mills

BOOK REVIEW

Mont Saint-Hilaire: History, Geology, Mineralogy by L. Horvath, R. A. Gault, E. Pfenninger-Horvath and G. Poirier

BREAKING NEWS

NEW TOPICS IN MINERALOGY 1

Diffusion in Minerals, Rocks and Melts: Potential and Pitfalls

NEW DATE(s): Afternoons (BST) of 26–27 November 2020

ONLINE VIA ZOOM: Registration needed, Free of Charge

ORGANIZER: B.W.D. Yardley, President, Mineralogical Society of Great Britain & Ireland

This meeting, intended to be the first of a new series, will review recent work in diffusion modelling and its application to a range of geological problems. How good (or not) can models be? What are the limits of what can be stated from our models? What are the pitfalls? It is intended to appeal to those interested in applying diffusion modelling to problems of rates, timing and thermal history in a wide range of mineralogical contexts.

The meeting will be led by a series of invited speakers who will address the fundamentals of diffusion theory and its application to modelling geological processes, and provide examples of state-of-the-art research on diffusions in various contexts. Details at https://www.minersoc.org/diffusion.html

OBITUARIES

Peter R. Simpson
Michael Forrest, John E. W. Bowles

Ole Valdemar Petersen
Ole Johnsen, Robert A. Gault, Joel D. Grice, William D. Birch
RENEW YOUR MEMBERSHIP FOR 2021
Geochemical Society members can renew quickly and securely on the GS website: www.geochemsoc.org. Renew by 31 December 2020 to save $5 off the regular dues and enjoy uninterrupted access to Elements, Geochemical News, and registration discounts to Goldschmidt2021 and to other conferences. Members also have access to the online member directory (available by signing into your profile on the website). You can also choose a two-year membership option to save time and money. If you prefer to renew by mail, please visit the website to download a form to send with your payment.

A reduced professional rate of $15 is now available to scientists from countries classified by the World Bank as having low-income or lower-middle-income economies. If dues are paid before 31 December, then the rate is only $10. Visit geochemsoc.org/membership/join to learn more about which countries qualify. Students from qualifying countries may apply for free memberships through the Introductory Student Membership Program.

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<tr>
<th>2021 Dues Rates</th>
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<th>Regular</th>
<th>2-Year Membership (before Dec. 31 / Jan. 1 or later)</th>
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<td>Professional: High- and Upper-Middle-Income Economies</td>
<td>$35</td>
<td>$40</td>
<td>$70 / $75</td>
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<tr>
<td>Professional: Low- and Lower-Middle-Income Economies</td>
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<td>$15</td>
<td>$20 / $25</td>
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<td>Student</td>
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NOMINATE A COLLEAGUE FOR A GS AWARD BY 31 OCTOBER
There is still time to nominate an outstanding colleague for one of the society’s 2021 awards and special lectures. Information about the Goldschmidt, Clarke, Hayes, Patterson, and Treibs awards can be found at www.geochemsoc.org/awards. Details regarding the Geochemistry Fellows, jointly awarded by European Association of Geochemistry (EAG) and GS, are also available on the GS website. The requirements have been changed this year to reduce the number of supporting letters, so nominations take less time to assemble.

We are also seeking nominations for special lectures to be presented at next year’s Goldschmidt Conference. These include the Robert Berner, Endowed Biogeochemistry, and Earl Ingersoll lectures. Lecture nominations require only a single nomination letter—no additional letters of support are needed. The society seeks a broad diversity for its awards, and to achieve this goal we need high-quality nominations from all parts of the geochemical community. Nominations must be received by 31 October 2020; the winners will be announced February 2021.

OFFICER ELECTIONS
The annual election for the society’s board of directors will take place in November and all GS members are encouraged to participate. You will receive an e-mail in early November with instructions for voting. Information about the candidates is available on the GS website—please take a few minutes to review them and vote.

DIVERSITY, EQUITY, AND INCLUSION
Following the online town hall meeting on Black Lives Matter in June 2020, a clear takeaway was the need for more action to confront discrimination within the geochemistry community and institutions. The society is working on several diversity, equity, and inclusion (DEI) initiatives to address this need.

To lead the efforts, a new DEI committee was formed under the leadership of GS board member Magali Ader (IPGP, France). The committee is planning a second town hall meeting to continue the community dialogue begun in the first event. A subgroup is also working on using the society’s social media platforms to promote awareness of DEI issues and highlight the work of scientists from underrepresented backgrounds.

The Geochemical Society and the European Association of Geochemistry have also recently discussed how to improve the diversity of our awards. One action taken so far is changing the nomination requirements for the Geochemistry Fellows honor. In addition to consideration of major discoveries and impactful papers, the selection criteria now include “contributions that create a dynamic environment essential for scientific progress.” Advancing ethics, inclusiveness, and social justice in science is one such contribution.

The Goldschmidt Conference is the societies’ largest program and an important venue for promoting DEI. For the last few years, the early career grant program has been targeted toward scientists in low-income countries and scientists from minority groups, both of whom are traditionally underrepresented at the meeting. The GS was awarded a three-year grant from the National Science Foundation specifically to provide funding for underrepresented groups. These include African Americans, Hispanics, Native Americans, and Pacific Islanders. It also includes students from non-PhD granting institutions and first-generation college students. The GS is providing matching funds for the NSF award.

The societies are encouraging diversity throughout the conference, beginning with the theme chairs and session conveners. Here, the community has a role to play. When proposing a session, people are encouraged to consider early career and minority scientists for convener roles. When sessions are accepted, conveners should consider inviting keynote speakers from diverse backgrounds, as well.

All of these are volunteer-led efforts and we welcome feedback and participation from anyone who is interested. Visit www.geochemsoc.org/DEI to learn more.

MICRO-VOLUNTEER OPPORTUNITY: GS SOCIAL MEDIA TEAM
We are looking for volunteers to contribute content for the GS Facebook, Instagram, and Twitter accounts. Posts may feature fieldwork images, your favorite rock or mineral, a historical moment in geochemistry, an introduction to your work, or just a quote that inspires you. Share your stories or images with our 4,000+ followers and help us communicate the importance of our science. Each volunteer is asked to contribute 2–3 posts per month, so the time commitment is only about an hour.

A focus is giving a voice to scientists from diverse backgrounds, so we particularly welcome contributions that highlight people of color, scientists from developing countries, members of the LGBTQ+ community, and people with different physical abilities. Get in touch at www.geochemsoc.org/socialmedia.
EAG MEMBERSHIP: JOIN NOW OR RENEW FOR 2021

As we near the end of 2020, now is a good time to renew your membership of the European Association of Geochemistry (EAG). Membership renewal for 2021 opens on 15 October 2020. New members who join the EAG after this date will also receive a full year’s membership for 2021. Visit http://eag.eu.com/membership for more information and sign in to the new EAG membership platform to join or renew!

Benefits of Membership

Conferences Member rates to attend the Goldschmidt Conference • Member rates to attend conferences and events organised by the Mineralogical Society of Great Britain and Ireland, by the International Association of GeoChemistry, by the International Society for Environmental Biogeochemistry, by the Society for Geology Applied to Mineral Deposits, by the European Association of Geoscientists & Engineers, and by the International Association of Volcanology and Chemistry of the Earth’s Interior.

Publications Print issues of Geochemical Perspectives • Print and online issues of Elements magazine • Member rates to purchase print publications of the Mineralogical Society of Great Britain and Ireland, the Società Geologica Italiana, the Società Italiana di Mineralogia e Petrologia and the Association Française pour l’Etude du Quaternaire. Member rates to publish open access articles in Mineralogical Magazine and Clay Minerals.

Early Career Scientist Support Sponsorship of students to attend workshops and conferences in Europe • Ambassador Program, which provides support for early career scientists based in Europe to attend conferences outside Europe • Sponsorship of member-led workshops and conferences.

Information and Networking Job postings and conference/online events calendars • Monthly newsletters • EAG Blog, Twitter, Facebook and YouTube • Members’ forum.

2021 Membership Rates

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IMPORTANT DATES

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<tr>
<td>15 October 2020</td>
<td>Call for sessions and workshops closes.</td>
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<td>15 December 2020</td>
<td>Abstract submission and registration opens.</td>
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<td>1 February 2021</td>
<td>Grant application deadline.</td>
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<td>12 February 2021</td>
<td>Abstract submission deadline.</td>
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PRESIDENT’S LETTER

MSA: Dedicated to Diversity, Equity, and Inclusion

The geosciences are among the least diverse of the sciences, and the mineralogy and petrology community is no exception. Yet a diverse workforce is important in addressing many of the grand challenges facing humanity. Locating natural resources, understanding geohazards, remediating environmental degradation, and addressing climate change are just some of the problems that require mineralogy and petrology expertise. The best solutions to these problems will come from a creative mineralogy/petrology community with a full range of interests, experiences, backgrounds, and perspectives.

Professional societies such as the MSA have a special role to play in fostering a diverse community. They set the expectations for their members. For example, MSA’s mission statement says, “MSA depends on the involvement of all individuals who are concerned with the health and direction of the field of mineralogy. MSA supports and champions efforts by individuals and organizations to foster a climate of inclusion, diversity, and acceptance in the sciences and in the wider public.”

It is incumbent on the MSA to ensure these are not empty words. We have an obligation to build an inclusive community of our members, no matter what their career stage, color, gender, and orientation. We must examine our organization, determine what is needed, and take tangible actions to promote and exemplify a professional society that welcomes a diverse membership, promotes responsible practice of mineralogy and petrology, and serves all of humanity with our science.

To that end, I have convened a task force to recommend actions that MSA should take to be more inclusive as a society and to increase the diversity in our discipline. I am truly grateful to the MSA members who responded to the invitation on MSA-Talk and our social media channels and who volunteered to serve on this task force. The members are Tyler Spano and Mark Ghiorso (co-chairs), Don Baker, Ken Brown, Astrid Holzhied, Liz Johnson, Brian Lejeune, Cam Macris, Brittani McNamee, and Zeb Page. They are already at work, sharing experiences and expertise and brainstorming ideas. The task force is considering a variety of possible actions, including recommending best practices for selecting fellows and medalists, a more proactive process for nominating committee members and officers, how to diversify practices for selecting fellows and medalists, a more proactive process for selecting fellows and medalists, a more proactive process for selecting fellows and medalists, a more proactive process for selecting fellows and medalists, a more proactive process for selecting fellows and medalists, a more proactive process for selecting fellows and medalists, a more proactive process for selecting fellows and medalists, a more proactive process for selecting fellows and medalists, a more proactive process for selecting fellows and medalists, a more proactive process for selecting fellows and medalists, a more proactive process for selecting fellows and medalists, a more proactive process for selecting fellows and medalists.

The ShutDownSTEM movement [organized in part by the American Association for the Advancement of Science] declares, “It is not enough to say that you stand in solidarity. We need you to be accountable. We need your actions.” The MSA commits to making a difference and being part of the solution.

Carol Frost
2020 MSA President
Earlier this year, a number of subscribers to MSA-Talk contributed resources and suggestions for teaching mineralogy and petrology courses online. These suggestions have been (and are being) collected and organized and are available on the MSA’s website: see http://www.minsocam.org/msa/Teaching_Resources.html and http://www.minsocam.org/msa/Teaching_Suggestions.html.

The resources include videos, animations, images, models, textbooks, databases, thin section scans, quizzes, Mineralogy4Kids, and much more. The MSA extends its deep thanks to all of those in the community who contributed (and continue to contribute) to these helpful resources and teaching ideas.

ANNUAL MEETING

The Annual Meeting of MSA members will be held virtually via Zoom at 3:00 PM Eastern Time on Saturday, 24 October 2020. The meeting will include presentations by MSA President Carol Frost, Secretary Kimberly Tait, and Treasurer Thomas Duffy. Details for how to register will be sent to all MSA members prior to the meeting.

DID YOU KNOW?

The MSA has a variety of open access publications on its website available at www.minsocam.org/msa/openaccess_publications/. These include the Guide to Thin Section Microscopy; Teaching Mineralogy; Reviews in Mineralogy and Geochemistry Volumes 75 (Carbon in Earth) and 80 (Pore-Scale Geochemical Processes); American Mineralogist from 1916–1999; the Handbook of Mineralogy; and a number of other monographs and special papers.

JAPAN ASSOCIATION OF MINERALOGICAL SCIENCES Awardees

The Japan Association of Mineralogical Sciences (JAMS) is proud to announce the recipients of its 2020 society awards. The Japan Association of Mineralogical Sciences Award is presented to a maximum of two scientists in any one year for exceptional contributions to mineralogical and related sciences. The Manjiro Watanabe Award—named in honor of Professor Manjiro Watanabe, a famous Japanese mineralogist, and founded by his bequest—is awarded every year to one scientist who has significantly contributed to mineralogical and related sciences over his or her career. The Sakurai Medal—named in honor of Dr. Kin-ichi Sakurai, who discovered many new minerals—is awarded to a scientist who has made a lasting contribution to the study of new minerals.

Japan Association of Mineralogical Sciences Award to Takuo Okuchi

Takuo Okuchi is an associate professor at the Institute for Planetary Materials, Okayama University (Japan). By the time news of his award has been published he will have been promoted to professor at the Institute for Integrated Radiation and Nuclear Science, Kyoto University (Japan). Prof. Okuchi revealed how hydrogen was incorporated into the molten metallic core of the Earth: essentially, due to an iron–water reaction that occurred during the accretion phase of the early solar system. This was his PhD research at Tokyo Institute of Technology, and, since then, he had been continuously aiming and working to understand hydrogen’s behavior inside Earth and other planets. He has developed several novel experimental methods for solving these topics. For example, at Nagoya University (Japan) and Geophysical Laboratory (USA) he developed an ultrahigh-pressure high-resolution nuclear magnetic resonance (NMR) spectroscopy method using diamond anvil cells; another example is how, at Okayama University together with his PhD student Purevjav Narangoo, he structurally analysed deep-Earth hydrous minerals using time-of-flight Laue single crystal neutron diffraction. With other high-pressure mineralogists, he also contributed to the development of experimental techniques for in situ high-pressure neutron powder diffraction measurements at the Japan Proton Accelerator Research Complex (J-PARC).

In addition, he has been working on laser-driven shock compression experiments of planetary materials, including dense water, minerals, and extremely compressed magmas. He has played a central role in developing a community of researchers in this field within the region of Japan and east Asia. Laser shock is a very effective way to study planetary shock processes and for analyzing extreme states of matter. Thus, developing a community around this technique and forging links with those who study the mineralogy of meteorites is an important goal for Prof. Okuchi: it helps activate research into planetary materials and advances our understanding of solar system evolution. To this day, Prof. Okuchi continues his cutting-edge research into Earth and planetary minerals.

Japan Association of Mineralogical Sciences Award to Kazuki Komatsu

Kazuki Komatsu is an associate professor at the Geochemical Research Center, Graduate School of Science, University of Tokyo (Japan). He started studying the high-temperature and high-pressure behavior of hydrous minerals (e.g., muscovite, topaz-OH, δ-AlOOH) at the mineralogy group in Tohoku University together with his PhD student Purevjav Narangoo, he structurally analysed deep-Earth hydrous minerals using time-of-flight Laue single crystal neutron diffraction. With other high-pressure mineralogists, he also contributed to the development of experimental techniques for in situ high-pressure neutron powder diffraction measurements at the Japan Proton Accelerator Research Complex (J-PARC).

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University (Japan), significantly contributing to the systematic understanding of the role of hydrogen bonds to phase transitions and the structural changes in hydrous minerals under high pressure. After receiving his PhD in 2006, he was a visiting scientist at the Centre for Science at Extreme Conditions at the University of Edinburgh (UK), where he more rigorously studied hydrogen-bonded materials. His focus was on ice polymorphs, which he studied using high-pressure neutron diffraction techniques. In 2009, he obtained a position at the University of Tokyo and joined a project to construct a high-pressure beamline (currently called ‘PLANET’) at the Materials and Life Science Experimental Facility (MLF) in J-PARC, Ibaraki (Japan). Kazuki Komatsu developed a high-pressure and low- to high-temperature device called the ‘Mito-system’, which can operate at pressures up to 15 GPa and temperatures from 35 K up to 400 K. By using the Mito system, he has made important progress on questions concerning the phase transition mechanism of ice polymorphs. For example, ice I₅, a cubic polymorph of ice first found in 1945, and it has been synthesized by many different routes. However, all such ice included at least some stacking disorder. Kazuki Komatsu found a way to synthesize ice I₅ without any stacking disorder. He also investigated the phase transition between ice VII and ice VIII and advocated a scenario that quantitatively explains many anomalies found in ice VII at around 10 GPa. He recently developed a new high-pressure device using nano-polycrystalline diamond that could be useful for neutron diffraction studies. With it, he managed to obtain the neutron diffraction patterns of ice VII up to 82 GPa, where it might transform to ice X.

**Manjiro Watanabe Award to Hidehiko Shimazaki**

**Hidehiko Shimazaki** received his doctor of science degree in 1968 from the University of Tokyo. His doctoral research, supervised by Prof. Takeo Watanabe, was on the Taguchi skarn-type deposits of the Abukuma Region (northern Honshu). After becoming an assistant professor at the University of Tokyo, he worked as a postdoctoral fellow in Montreal and Saskatoon (both in Canada) for three years, engaged in experimental research with Canadian geologists on liquid immiscibility in magmatic systems. Returning to the University of Tokyo, his research focused on the origin of skarn-type deposits in Japan, Korea, and China. He recognized the occurrence of a new iron-bearing calc-silicate mineral and found it to have a bastutite structure with a composition of Ca₂Fe₅Si₆O₁₈. The mineral was later named ferro-bastutite. Dr. Shimazaki established that this skarn mineral forms under relatively low temperatures in skarnization compared to igneous activity. When skarnization occurs in limestone-bearing sedimentary formations, characteristic skarns occur along the boundary between the limestone and the associated clastic sedimentary rocks. They are usually epidote skarns or plagioclase–hedenbergite skarns. Dr. Shimazaki concluded that the epidote skarns formed under relatively oxidizing conditions, the plagioclase–hedenbergite skarns under reducing conditions. Based on such observations, he could recognize oxidation conditions in skarn formations and so establish a correlation between the oxidation conditions of skarns and the magnetite- and ilmenite-series of their associated granitic rocks. Several new minerals, like tsumoite (BiTe) were found by him from mineral deposits in Japan and China. Dr. Shimazaki has held several positions on geoscience committees and has dedicated almost his whole career to mineralogy and mineral resource science.

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**Sakurai Medal to Takahiro Kuribayashi**

The Sakurai Medal has been awarded to Takahiro Kuribayashi, an associate professor at the Department of Earth Science, Graduate School of Science, Tohoku University, Sendai (Japan), for his discovery of hitachiite (IMA 2018-027). Dr. Kuribayashi has contributed significantly both to field-based mineralogy and descriptive mineralogy through his investigation of new minerals using single-crystal X-ray diffraction.

He and his coworkers discovered a new Pb–Bi–Te–S compound to the tetradyminite mineral group (see 9th edition of the Strunz mineral classification system). This group is of interest as such materials are topological insulators and superconductors. This compound was later named hitachiite after the place where it was discovered: the Hitachi Mine in the Ibaraki Prefecture (Japan). The Hitachi deposit is classified as a volcanic massive sulfide deposit whose age of formation, including the hitachiite, is the oldest in Japan. The empirical chemical formula is determined based on 15 atoms per formula unit, is (Pb₁₇.₅Fe₀.₂₅)₂₄₅₂(Bi₂.₀₀Sb₀.₀₃)₂₇.ₒ₂Te₂.₀₄(S₅.₇₈S₀.₁₁)₆S₅.₅₆, ideally Pb₂Bi₂Te₅S₆. The crystal structure of hitachiite was determined using synchrotron radiation and is based on an ABC-type stacking of 15 layers (five Pb, two Bi, two Te, and six S layers) along the [001] direction, each layer ideally containing only one kind of atom. The stacking sequence is described as Te–Bi–S–Pb–S–Pb–S–Pb–S–Pb–S–Bi–Te. The structure of hitachiite should help clarify the classification of minerals along the Bi₂(Te, S)₃–Pb(Te, S) join in the system Pb–Bi–(Te, S), which comprises the tetradyminite group and its archetype minerals.

Dr. Kuribayashi also used his skills at structural and crystallographic analyses with X-ray diffraction to help characterize tanohataite (IMA 2007-019) and bosoite (IMA 2014-023).

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**JOURNAL OF MINERALOGICAL AND PETROLOGICAL SCIENCES**

Vol. 115, No. 4, August 2020

**Original Articles**

- **Attenuated total reflection infrared (ATR–IR) spectroscopy of antigorite, chrysotile, and lizardite** – Ilona SAKAGUCHI, Yui KOUKETSU, Katsuyoshi MICHIBAYASHI, Simon R. WALLIS.
- **Geochemistry and magmatic zircon U–Pb dating of amphibolite blocks in the Omi serpentinite mélangé, north central Japan: possible subduction of the Cambrian oceanic crust** – Yuji ICHIYAMA, Takahito KOSHIIBA, Hisatoshi ITO, Akihiro TAMURA.
- **Plagioclase–hosted melt inclusions as indicators of inhibited rhyolitic melt beneath a mafic volcano: a case study of the Izu–Omuroyama monogenetic volcano, Japan** – Risako HATADA, Hideni ISHIBASHI, Yukiko SUWA, Yusuke SUZUKI, Natsumi HOKANASHI, Atsushi YASUDA.
- **Assimilation and fractional crystallization of Sanukitik high-Mg andesite–derived magmas, Kyushu Island, southwest Japan: An example of the Cretaceous Shaku–dake diorite body** – Katsuyoshi MICHIBAYASHI, Simon R. WALLIS.
- **Color Cathodoluminescence and minor element zonation of forsterite in Mukundpura chondrite** – Shivani BALIYAN, Dwijesh RAY.
- **Geochronology and tectonic implications of the Urgamal eclogite, Western Mongolia** – Kosuke NAEUMURA, Choiordanjamts ERDENEJARGAL, Terbishlinkhen O. JAVKHLAN, Takenori KATO, Takao HIRAJIMA.
NEWS ON CONFERENCES AND FIELD TRIPS ON CLAY MINERALS AROUND THE WORLD

4th Asian Clay Conference in Thailand
The international clay community, with the Association Internationale pour l’Étude des Argiles (AIPEA) as its umbrella organization, has had to search for ways to operate during the pandemic caused by the SARS-CoV-2 virus (COVID-19). National and regional clay meetings organized by clay societies across the globe in 2020 (https://aipea.org/conferences/) have had to adapt to the global risk assessment made by the World Health Organization of the COVID-19 pandemic.

We are pleased to report a positive outcome: the first virtual/online/remote international clay science meeting, the 4th Asian Clay Conference (Thailand) organized by the Asian Clay Groups and chaired by Prof. Dr Makoto Ogawa. The so-termed 4ACC was held 7–10 June 2020 and was attended by over 200 scientists from across the globe. The plenary lecture on nanomedicine and the role of clays was given by Jin-Ho Choy; session themes ranged from clays in the Earth sciences to their role in the environment, but also covered aspects of health, engineering, and materials science. Keynote lectures were given by Jocelyne Brendlé, Josef Breu, Takeo Ebina, Hendrik Heinz, Kazuyuki Kuroda, Akira Ono, Vanessa Prevot, Atsushi Takahara, and Chun Hui Zhou. Conference papers are currently being prepared for publication in the journals Clays and Clay Minerals, Clay Science, Clay Minerals, and Nanomaterials.

Field Excursions in Kurdistan (Iraq)
In the Kurdistan region of Iraq, clays are being researched at the Chemistry Department of the University of Sulaimani, as well as at Salahaddin University, Koya University, Raparin University and the University of Duhok. Clays in this geologically complex area at the boundary between the Arabian and Eurasian plates have been used for millennia as architectural, medicinal and industrial materials. Today, the saponite deposits in the Tagaran and Topkhana regions and the widely found smectite-rich bentonites have the potential for wastewater treatment. Some clay deposits in Miocene sediments have strong potential for ceramic use. Recent work headed up by professors Dier Shwan, Bakhtyar K. Aziz, Irfan Omar Mousa Yara and Karukh Ali Babakr have revealed the distribution and composition of a wide array of clay mineral types in the Kurdistan region. There is much potential for international collaboration. The photographs from field excursions reveal some of the beauty in researching clays in Kurdistan.

Clay’18 Symposium and ICC 2021 Conference in Turkey
The Clay Science Society of Turkey elected a new Executive Committee at the 18th National Clay Symposium (Clay’18), which was held 25–28 September 2019 in Kocaeli (Turkey). The Clay Science Society of Turkey – along with the Clay Minerals Society (CMS) – are the co-organizers of the 17th International Clay Conference (ICC 2021), which is due to be held 12–16 July 2021 in Istanbul. Istanbul is the most populous city in Turkey and is its economic, cultural and historic centre. Located in the centre of the old world, this exotic city is famous for its historical monuments and scenic views. It is the only city in the world spread over two continents, Asia and Europe, separated by the narrow Bosphorus Strait. The conference venue will be the Istanbul Hilton Maslak Hotel, located within walking distance of the Istanbul Technical University Campus and only a metro ride from downtown. The thematic title for ICC 2021 is “New Interfaces: Bridging Continents and Cultures with Clays”. The organizing committee is headed by Asuman Günal Türkmenoğlu, Selahattin Kadir and Paul Schroeder. More information is available at: www.icc.aipea.org. On behalf of their national clay groups, the organizing committee enthusiastically invites all clay scientists to participate in the 17th ICC Istanbul 2021. We look forward seeing you in Istanbul.

More news on conferences and field trips on clay minerals around the world is available at www.aipea.org

Peter Ryan and Reiner Dohrmann
**SIMP HONORARY FELLOWSHIP FOR 2019**

We are pleased to announce that the SIMP Honorary Fellowship for 2019 has been awarded to **Dr Mark Welch**. Mark is a mineralogical crystallographer at the Natural History Museum in London (UK). His main research interests over the past 30 years relate to quantifying the states of long- and short-range atomic order (including H behaviour) and structural phase transitions in geologically important hydrous minerals. The geological context for most of his research is the mineralogy of “cold” subduction zones and the deep continental crust. Many of his studies have involved experiments on hydrous minerals at high pressure and high temperature. He has used a wide range of techniques, including X-ray diffraction, neutron diffraction, synchrotron radiation, vibrational spectroscopy (both infrared and Raman) and nuclear magnetic resonance spectroscopy. He has many long-standing collaborations with colleagues in Italy over the past 25 years and continues to develop new research links between the UK and Italy.

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**“LUIGI TARTUFARI” AWARDS**

Congratulations to **Diego Perugini**, Professor of Petrology at the University of Perugia (Italy) for being awarded the 2020 “Prof. Luigi Tartufari” International Prize from the Accademia Nazionale dei Lincei. The prize is awarded to outstanding geoscientists. Diego’s main research interests are modelling the mobility of chemical elements in compositionally heterogeneous magmatic systems and investigating the fluid dynamics of magma chambers, including the geodynamic implications of magmatic activities in several areas around the Mediterranean. The prize was awarded by the President of Italy, Sergio Mattarella, at the Accademia Nazionale dei Lincei in Rome.

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**SIMP COMMUNICATION COMMITTEE**

We are pleased to announce a new SIMP communication committee whose board (all from Italy) is composed by Matteo Alvaro (University of Pavia); Alessandra Montanini (University of Parma); Sabrina Nazzareni (University of Perugia); Giulia Consuena (University of Bologna); Luca Samuele Capizzi (University La Sapienza Roma); Francesca Miozzi (University of Milano); Marta Morana (University of Pavia); Mara Murri (University of Milano Bicocca); and Alessandro Pisello (University of Perugia).

Through SIMP’s social media, the committee disseminates news of the scientific activities of SIMP’s members and promotes society initiatives such as the #SIMPaper, #ThinsectionThursday and #Field/LabWorkFriday! Please see the following:

- Facebook: SIMP – Società Italiana di Mineralogia e Petrologia
- Instagram: https://www.instagram.com/soc_min_pet/
- Twitter: https://twitter.com/soc_min_pet

**Sabrina Nazzareni** (University of Perugia)
Member of SIMP Council
Between 1969 and 1972, Apollo mission astronauts explored the lunar surface, collecting geologic materials and returning them to Earth for careful study. After consideration of many lines of evidence, one of the many major results of studying the Apollo rocks is the broad scientific consensus that the Moon formed from the debris of a giant impact of a large body with the proto-Earth (e.g., Stevenson 1987). This left the Moon depleted in highly volatile elements such as hydrogen, relative to Earth. So it was thought.

In situ analytical techniques have advanced significantly since the Apollo era. This now allows scientists to measure the composition of the Apollo rocks far more precisely, which has been done in relation to element abundance, isotopic composition, and speciation of the highly volatile elements of carbon, hydrogen, sulfur, and chlorine. Furthermore, these measurements are now routinely performed at the spatial scale of a few microns, which is necessary for measuring the phases found in the Apollo materials that are likely to contain these volatile elements. The phases in question are the volcanic glass beads found in lunar soils and regolith samples; glassy melt inclusions trapped in the olivines and pyroxenes that comprise the glass beads and the igneous rocks; and volatile-bearing accessory mineral phases, such as apatite [Ca₅(PO₄)₃(OH, F, Cl)]. Through advanced in situ measurements, it has become apparent that these phases contain higher concentrations of carbon, hydrogen, sulfur, and chlorine than previously thought, and, in some cases, perhaps in concentrations similar to those observed in materials from Earth (e.g., Saal et al. 2008; Wetzel et al. 2015; Boyce et al. 2010). This observation has led to a significant revival of interest in examining models for the giant impact hypothesis for the formation of the Moon.

One particularly puzzling aspect of the volatile chemistry of the Apollo lunar rocks is the observation of hundreds to thousands of parts per million of sulfur dissolved in the phosphate mineral apatite (Boyce et al. 2010). Rocks from Earth, where apatite is common, are sufficiently oxidized to contain sulfur dissolved as sulfate (SO₄²⁻), where the oxidation state of sulfur is S⁶⁺. When apatite crystallizes from such a magma, oxidized to contain sulfur dissolved as sulfate (SO₄²⁻, where the oxidation state of sulfur is S⁶⁺), apatite [Ca₅(PO₄)₃(OH, F, Cl)] substitutions in the apatite mineral structure for the phosphate anionic group in a charge coupled substitution with SiO₄⁴⁻ or Na⁺ (Fleet et al. 2005); see Equations 1 and 2 below:

\[
\begin{align*}
\text{Equation 1:} & \quad \text{Ca}^{2+} + \text{PO}_4^{3-} = \text{SO}_4^{2-} + \text{Na}^+ \\
\text{Equation 2:} & \quad 2 \text{PO}_4^{3-} = \text{SO}_4^{2-} + \text{SiO}_4^{4-}
\end{align*}
\]

However, the Apollo lunar rocks are much more reduced than rocks from Earth—apparent in thin section from the presence of iron metal and other phases—and should contain sulfur dissolved as sulfide (S²⁻), which was not known to partition into natural apatite the way it does in Earth’s apatites. Why then, does lunar apatite contain so much sulfur? This question had been difficult to answer, in part because the lunar apatites are very small: they are on the order of 1–20 μm (rarely 100s μm) in longest dimension (Fig. 1). The hundreds to thousands of parts per million sulfur discovered in these apatites is much higher than expected, yet it is still below the detection limit of many available analytical techniques.

Synchrotron-source sulfur X-ray absorption near-edge spectroscopy (S-XANES) can readily distinguish between the K-alpha peak shapes of electronic transitions in sulfide from those peaks in sulfate (Fig. 2). At beamlines of sufficiently brilliant light sources, such as that of the GSECARS (GeoSoilEnviro Center for Advanced Radiation Sources) beamline 13IDE at the Advanced Photon Source at the Argonne National Laboratory (Illinois, USA), this can be done at ~5 μm spatial scales on samples with ~w100 parts per million sulfur present as sulfate or sulfide,
or as a mixture of the two. This cutting-edge analytical technique is ideally suited to answering the question, “Why is there sulfur dissolved in lunar apatite?”

To answer this question, two Apollo-era lunar rocks were examined—Apollo 11 rock sample 10044, a high-Ti ~3.7 billion-year-old basalt; Apollo 12 rock sample 12039, a ~3.2 billion-year-old low-Ti basalt. Both are slightly vesiculated and contain pyroxene, plagioclase, and ilmenite phenocrysts. Apatite occurs as an accessory phase in both samples, sometimes in contact with a glassy groundmass (known as a “mesostasis”), which also contains sulfide blebs, iron metal, and a variety of phases that indicates crystallization under very reducing conditions. When the oxidation state of sulfur in the apatite was measured using S-XANES, the answer was immediately obvious—the sulfur was present in the apatite as sulfide (Fig. 3) (Brounce et al. 2019). Sulfur in the glassy groundmass was also present as sulfide. Both observations confirmed that lunar rocks are very reduced, consistent with the presence of Fe metal in the same rocks. This is exciting, because it is the first measurement of a natural sulfide-bearing apatite, and confirms recent hypotheses about sulfide substitution into apatite made on the basis of ab initio computations and experimental work (Kim et al. 2017; Konecke et al. 2017a). Those hypotheses suggest that, if possible, sulfide substitutes for OH−, Cl−, and/or F− on the column site of the apatite mineral structure. The discovery of sulfide-bearing apatite suggests that the stoichiometry of the column site in apatites from sufficiently reduced systems should be S6+ + OH− + F− + Cl− = 1, and that the presence of sulfate in the apatite will impact studies seeking to estimate the water content of a magma from measurements of OH− in apatite.

Upon closer examination of the lunar rocks, another surprising observation was made. In addition to the sulfide present in the glassy groundmass and apatite grains, there was sulfate present in the cracks and pits of the polished thin section surface (Fig. 1) (Brounce et al. 2019). And this sulfate is heterogeneously distributed; not every crack or pit has sulfate, suggesting that it is not from the epoxy that the Apollo collection curators had used to make the thin section. This sulfur is not thought to be dissolved in mineral structures but precipitated on top of them within the cracks as a secondary mineral phase. It is not known whether this secondary sulfur was precipitated in the rock on the lunar surface (revealing important details of hydrothermal or space weathering processes, e.g., Konecke et al. 2017b) or whether it was precipitated in the rock once it had been brought back to the relatively hydrous, oxidizing conditions of Earth’s surface, so presenting important implications for how we store, process, and protect planetary samples in our laboratories (all of the pristine Apollo samples are currently curated under dry gaseous N2).

To test between a lunar and a terrestrial origin for the secondary sulfur in Apollo-era thin sections, we will measure the oxidation state of sulfur in rocks from the Apollo 17 mission as part of the NASA Apollo Next Generation Sample Analysis (NASA ANGSA) program under Project Investigator Jessica Barnes (assistant professor, University of Arizona, USA). Some of these rocks were frozen a few weeks after their return to Earth and kept that way until now, in anticipation of then-unimagined innovations in analytical techniques and with foresight for answering the question, “What effect does Earth’s relatively warm surface temperatures have on the lunar rocks?” In celebration of the 50th anniversary of the landing on the Moon by the Apollo 11 mission, the NASA ANGSA teams will apply cutting-edge analytical techniques, including synchrotron S-XANES, to these specially frozen rocks to learn about lunar processes and to best prepare for future sample-return missions. Our team will determine the extent to which Earth’s relatively warm surface temperatures have altered the volatile composition of the Apollo rocks (concentrations, isotopes, and speciation) and make specific recommendations for the curation teams of future sample-return missions.

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Konecke BA, Fiege A, Simon AC, Holtz F (2017b) Cryptic metamatism during late-stage lunar magmatism implicated by sulfur in apatite. Geology 45: 739-742


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International response to COVID-19 has resulted in scientific meetings to be canceled and/or postponed. Check meeting web pages for ongoing updates.

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**October 26–30** Virtual Geological Society of America National Meeting, Montreal, Canada. Web page: community.geosociety.org/gsa2020/home

**November 9–13** Astrobiology 2020, Vrededorp Dome, South Africa. Web page: astrobiology.uji.ac.za

**November 9–13** 36th International Geological Congress, Delhi, India. Web page: www.36igc.org

**November 9–13** RESCHEDULED to August 16–21, 2021

**November 16–20** Introduction to Secondary Ion Mass Spectrometry in the Earth Sciences, Potsdam, Germany. Web page: sim.sgf.potsdam.de/short-course/

**November 29–December 4** Virtual MRS Fall Meeting, Boston, MA, USA. Web page: www.mrs.org/fall2020


**December 1–17** Virtual 2020 AGU Fall Meeting, San Francisco, CA, USA. Web page: www.agu.org/fall-meeting

**2021**


**January 24–29** Virtual AGU Fall Meeting, Boston, MA, USA. Web page: www.agu.org/fall-meeting

**February 8–12** Virtual 45th International Conference and Expo on Advanced Ceramics and Composites (ICACC2021). Web page: ceramics.org/event/45th-international-conference-and-expo-on-advanced-ceramics-and-composites

**February 15–19** IAVCEI 2021 Scientific Assembly, Rotorua, New Zealand. Web page: confer.eventsair.com/iavcei2021/

**February 28–March 3** EMPG-XVII, 17th International Symposium on Experimental Mineralogy, Petrology and Geochemistry, Potsdam, Germany. Web page: www.17empg2020.de/

**March 15–19** Virtual 52nd Lunar and Planetary Science Conference, The Woodlands, TX, USA. Web page: www.hou.usra.edu/meetings/lpsc2021/

**March 21–25** Spring ACS National Meeting & Exposition, San Antonio, TX, USA. Web page: www.acs.org/


**April 19–23** MRS Spring Meeting & Exhibit, Seattle, WA, USA. Web page: www.mrs.org/spring2021

**May 9–14** ABSICON 2021, Atlanta, GA, USA. Web page: www.agu.org/abscicon/

**May 11–15** Chapman Conference: Distributed Volcanism and Distributed Volcanic Hazards, Flagstaff AZ, USA. Web page: www.agu.org/Chapmans-Distributed-Volcanism


**May 23–26** Aapg 2021 Annual Convention & Exhibition, Denver, CO, USA. Web page: www.aapg.org/events/aapg-conferences/ace/details/articleid/56336/aapg-2021-annual-convention-exhibition

**June 6–11** International Symposium on Quartz (QUARTZ2021), Tønsberg, Norway. Web page: www.nhm.uio.no/english/research/events/conferences/quartz2020/

**June 9–11** 2nd International Conference on Contaminated Sediments, Bern, Switzerland. Web page: www.oescher.unibe.ch/services/events/conferences/contased_2021/announce/index_eng.html

**June 30–July 2** Earth Mantle Workshop (EMAW), Toulouse, FR. Web page: emaw2021.sciencesconf.org/


**July 12–16** 17th International Clay Conference, Istanbul, Turkey. Web page: icc.aipera.org

**July 12–17** 2021 Summer School: Metamorphism of Metamorphism, Pavia, Italy. Web page: www.minerologylab.com/event/schoolmetamorphism2020/

**July 21–23** International Archean Symposium, Perth, WA Australia. Web page: 6ias.org

**August 1–5** Microscopy & Microanalysis 2021, Pittsburgh, PA, USA. Web page forthcoming


**August 14–21** 84th Annual Meeting of the Meteoritical Society, Chicago, IL, USA. Web page: www.metsoc2021-chicago.com

**August 16–21** 36th International Geological Congress, Delhi, India. Webpage: www.36igc.org

**August 22–26** Fall ACS National Meeting & Exposition, Atlanta, GA, USA. Web page: www.acs.org

**August 24–26** 9th International Conference on Mineralogy and Museums, Sofia, Bulgaria. Web page: www.bgminsoc.bg

**August 29–September 2** EMC2021 3rd European Mineralogical Conference, Cracow, Poland. Web page: www.emc2021.ptm.eu

**September 8–10** Tourmaline 2021, Elba Island. Web page: www.tur2021.com/

**October 4–6** Martian Geologic Enigmas: From the Late Noachian Epoch to the Present Day, Houston, TX, USA. Web page: www.hou.usra.edu/meetings/martianenigma2021/


**October 24–29** 29th International Applied Geochemistry Symposium (IAGS), Viña del Mar, Chile. Web page: iags2021.cl

**November 28–December 3** 2021 MRS Fall Meeting, Boston, MA, USA. Web page: www.mrs.org/fall2021

**December 13–17** AGU Fall Meeting, New Orleans, LA, USA. Details forthcoming

**2022**


**July 2022** International Archean Symposium, Perth, WA Australia. Web page: 6ias.org

**July 10–15** Goldschmidt Conference, Chicago, IL USA. Web page forthcoming

**August 14–19** Meteorsical Society Annual Meeting, Glasgow, UK. Web page forthcoming

**August 15–19** 12th International Kimberlite Conference, Yellowknife, NT, Canada. Web page: www.12kic.ca

**August 21–25** Fall ACS National Meeting & Exposition, Chicago IL, USA. Web page: www.acs.org/

**October 9–12** Geological Society of America National Meeting, Denver, CO 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 (more meetings are listed on the calendar she maintains at https://sites.google.com/a/udayton.edu/akoziol1/home/mineralogy-and-petrology-meetings). To get meeting information listed, please contact her at akoziol1@udayton.edu

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