

# *Mineralogical Society of America*

## Centennial Symposium

The Next 100 Years  
of Mineral Sciences

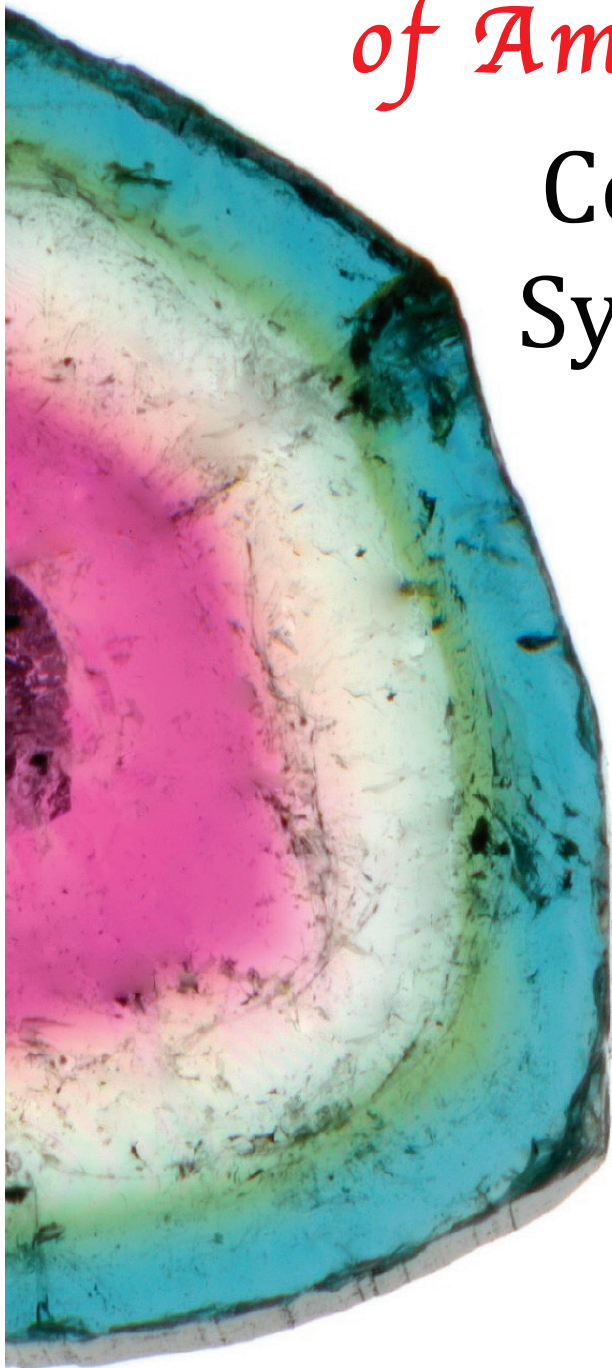
June 20-21, 2019

Carnegie Institution  
for Science Building  
Washington, DC

1919 - CENTENNIAL - 2019



Mineralogical Society of America



# Greetings from the President!

Welcome to the celebration of MSA's 100th anniversary! Thank you for attending this unique symposium to help us chart the course for the next 100 years! I am excited to hear our member-proposed, moderated hour-long theme sessions and to integrate the science and the social parts of this meeting – especially in the wonderful settings of the Carnegie Institution for Science building and the Smithsonian's Gem and Mineral Hall. To memorialize this event, each session will produce a chapter that will appear in a *Reviews in Mineralogy and Geochemistry* volume dedicated to MSA's Centennial.

While this event would not have been possible without the tireless efforts and innovative ideas of the organizers, I would also like to thank those at MSA "headquarters," especially our Executive Director of 25 years, Alex Speer, and our newly hired Executive Director, Ann Benbow, as well as the sponsors who provided much-needed financial support. In addition, I would like to recognize all of those past researchers and educators who have contributed to our field as we acknowledge their efforts to gain a better understanding of the roles minerals play in the natural world and every aspect of our lives. Scientific discovery on Earth and other planets starts with the careful study of minerals, as will be demonstrated by the subjects we will hear and discuss over the next two days.

Finally, it is an honor for me to serve as MSA's president during this time, and to realize the positive impacts the society has made in general, and specifically in my career. As I consider MSA's trajectory over last 100 years, however, I worry that we have somewhat separated ourselves from two groups we used to serve: the "amateur" mineralogist and the minerals industry. Without the former, many of us would lack materials to study and admire for their esthetic beauty, while the latter provides us with the very materials we require for everyday life. I hope that over the next century we can regain closer relationships with these partners while pursuing the much-needed scientific research highlighted in this symposium.



Mickey Gunter  
2019 MSA President

## *And from the organizers!*



Peter Heaney

Thank you for joining in this celebration of the Mineralogical Society of America's 100<sup>th</sup> birthday! We are thrilled that you are here to honor the achievements of our predecessors and to share ideas about where we are going. During the moderated discussions, the coffee breaks, and the evening reception at the Smithsonian, don't be shy about offering your proposals for the road ahead – and how MSA should be getting us there.



Steven Shirey

This symposium reflects the work of many players, and we want to express our gratitude to all of the people who are putting it together. We thank the scores of MSA members who responded to our solicitations for theme colloquia. They ranged from graduate students to seasoned scientists. It is impossible to encompass in two days the entirety of MSA's mission, and we did our best to craft a meeting that reflects the diversity of people, of disciplines, and of nationalities who come together in our Society. We thank all of the MSA Council officers and MSA staff in Chantilly, VA who have sharpened our vision for this celebration over the past four years. We are grateful to the Carnegie Institution for Science for logistical support and for subsidizing the use of their administrative building for our meeting. Michelle Scholtes has done a wonderful job as our on-site meeting organizer. Ana Lojanica has served as an outstanding Special Events Coordinator with the Carnegie Institution for Science. We ask you to join us in thanking all of our sponsors, whose financial support made this symposium a reality.

After many years of planning, we look forward to seeing MSA members seated in the beautifully renovated Carnegie auditorium to hear world-renowned authorities in the many areas where our Society has exerted a deep intellectual impact. Let's start shaping MSA's next century!

**Schedule of Theme Colloquia**  
**Thursday, 20 June 2019**  
**Morning Program**

*8:20-8:25 am:* Welcome from Mickey Gunter, 2019 MSA President

*8:25-8:30 am:* Welcome from the organizers

*8:30-9:30 am:* Sustainable Development and Use of Mineral Resources

- Gordon Brown (Stanford University): The environmental legacy of mercury, gold, and asbestos mining: Evaluation of long-term impacts
- Michael Hochella (Virginia Tech): Newly discovered environmental impacts of mineral resource utilization: Direct and indirect incidental nanomaterials
- Moderator: Georges Calas (Université Pierre et Marie Curie)

*9:30-10:30 am:* Linking Metal (Bio)geochemical Cycling from the Atomic to the Landscape Scale

- David Singer (Kent State University): From atoms to mountains: New frontiers in X-ray science
- Michael Schindler (Laurentian University): Nano-mineralogy: A new dimension to understand the fate of metal(loid)s in the environment
- Moderator: Patricia Maurice (Notre Dame University)

*10:30-11:00 am: Coffee and snacks*

*11:00-Noon:* A Second Golden Age for Metamorphic Petrology

- Ross Angel (University of Pavia): The importance of physics to thermobarometric research
- Lucie Tajcmanová (Universität Heidelberg): What's Next? Exploring the future of metamorphic geology
- Moderator: Sarah Penniston-Dorland (University of Maryland)

*Noon-12:10 pm: Photo on Carnegie Steps*

*12:10 pm - 1:00 pm: Lunch*

**Schedule of Theme Colloquia**  
**Thursday, 20 June 2019**  
**Afternoon Program**

*1:00-2:00 pm:* Advances in Mineral Analysis: What Improvements Will We See in the Chemical and Isotopic Analysis of Minerals?

- Michael Wiedenbeck (DGFZ-Potsdam): SIMS and related technologies: Where they stand, where they are headed, and where things need to go
- Simon Jackson (Geological Survey of Canada): LA-ICPMS mineral analysis: Prospects for development and improved integration with other technologies
- Moderator: Paul Sylvester (Texas Technical University)

*2:00-3:00 pm:* Unraveling the Roots of Continents: From Paleo-island Arc to Mature Continental Crust on Earth

- Othmar Müntener (Université de Lausanne): Lower crust formation and differentiation constrained by field studies and experimental petrology
- Roberta Rudnick (UC Santa Barbara): Earth's continents through time
- Moderator: Mattia Pistone (Université de Lausanne)

*3:00-3:30 pm: Coffee and snacks*

*3:30-4:30 pm:* Mineral Inclusions in Diamonds from the Deep Earth

- Fabrizio Nestola (University of Padua): In-situ, ambient analysis of diamond-captured mantle transition zone and lower mantle minerals
- D Graham Pearson (University of Alberta): The diamond record of plate tectonic recycling of H, C, N, and B
- Moderator: Steven Shirey (Carnegie Institution for Science)

*4:30-5:30 pm:* Museum Mineral Collections in the next 100 years

- Kim Tait (Royal Ontario Museum): Making mineral collections relevant in the 21<sup>st</sup> Century
- Aaron Celestian (Natural History Museum of Los Angeles County): Unlocking the collections: Making minerals accessible in the next 100 years
- The GIA Distinguished Moderator: Jeffrey Post (National Museum of Natural History)

*5:30-6:15 pm: Wine and beer*

*7:00-10:00 pm: Evening reception at the National Museum of Natural History*  
*Sponsored by GIA*

**Schedule of Theme Colloquia**  
**Friday, 21 June 2019**  
**Morning Program**

*8:20-8:30 am:* Welcome from Eric Isaacs, President of the Carnegie Institution for Science

*8:30-9:30 am:* Synchrotron-based Studies of High-Pressure Mineral Behavior

- Przemyslaw Dera (University of Hawaii): Putting the squeeze on silicate chains: Unusual coordination states accompanying the densification of pyroxenes and amphiboles
- Jin Zhang (University of New Mexico): Elastic anisotropy and phase transitions in the Earth's upper mantle
- Moderator: Carl Agee (University of New Mexico)

*9:30-10:30 am:* Mineralogy Beyond the Boundaries of Earth: Advances in the Mineralogy of Mars

- Elizabeth Rampe (Johnson Space Center): New perspectives of ancient Mars: Mineral diversity and crystal chemistry at Gale crater, Mars from the CheMin X-ray diffractometer
- Harry McSween (University of Tennessee, Knoxville): The mineralogy of Mars from rocks in hand
- Moderator: Douglas Ming (Johnson Space Center)

*10:30-11:00 am: Coffee and snacks*

*11:00-Noon:* The Future of Data-Driven Discovery in Mineralogy, Crystallography, and Petrology

- Shaunna Morrison (Carnegie Institution for Science): The future of data-driven discovery in mineralogy and crystallography
- Simone Runyon (University of Wyoming): The future of data-driven discovery in petrology and geochemistry
- The Rob Lavinsky Distinguished Moderator: Robert M. Hazen (Carnegie Institution for Science)

*Noon-12:10 pm:* Materials of the Universe (MotU) Initiative

- Alexandra Navrotsky (UC Davis and Arizona State University)

*12:10-1:00 pm: Lunch*

**Schedule of Theme Colloquia**  
**Friday, 21 June 2019**  
**Afternoon Program**

*1:00-2:00 pm:* Applied Mineralogy as a Tool to Research the Provenance and Technology of Ancient Ceramics

- Michael Tite (Oxford University): The mineralogy of opaque ceramic glazes: Development in the Islamic world and Europe from the 7th to the 16th centuries CE
- Gilberto Artioli (University of Padova): Modern mineralogy and ancient pots: The archaeometry of ceramics
- Moderators: Pamela Vandiver (University of Arizona) and Robert Heimann (Technische Universität Bergakademie Freiberg)

*2:00-3:00 pm:* Scientific Characterization of High-Value Gemstones

- Wuyi Wang (Gemological Institute of America): Challenges in the identification of synthetic diamonds
- Mandy Krebs (Gemological Institute of America): Determining the provenance of colored gemstones
- Moderator: Thomas Moses (Gemological Institute of America)

*3:00-3:30 pm: Coffee and snacks*

*3:30-4:30 pm:* The Societal Relevance of Apatite

- The C2/m Mineralogy Distinguished Speaker John Hughes (University of Vermont): The geological and agricultural significance of calcium phosphate apatite
- Jill Dill Pasteris (Washington University in St. Louis): Biomineralization and biomaterials: Apatite and the human body
- Moderator: John Rakovan (Miami University of Ohio)

*4:30-5:30 pm:* Minerals and Industry: Evaluating the Real Impacts of Mineral Dusts on Human Health

- Ann Wylie (University of Maryland): What makes an amphibole “asbestos”? History and status of regulatory issues dealing with amphiboles
- Matthew Sanchez (R J Lee Group): Mineral misidentification in connection to potential hazards of mineral dusts
- Moderator: Jessica Elzea Kogel (National Institute for Occupational Safety and Health)

*5:30-6:30 pm: Wine and beer*

# Abstracts of Talks

In

# Program Order



**Mineralogical Society of America**



**Abstracts**  
**Thursday, 20 June 2019**  
**Morning**

**Theme Colloquium 1:**

**Sustainable Development and Use of Mineral Resources**

Moderator: Georges Calas (Université Pierre et Marie Curie)

**The environmental legacy of mercury, gold, and asbestos mining:  
Evaluation of long-term impacts**

**Gordon E. Brown, Jr.<sup>1,2</sup> Michael F. Hochella, Jr.<sup>3,4</sup>, and Georges Calas<sup>5</sup>**

<sup>1</sup> Department of Geological Sciences, School of Earth, Energy & Environmental Sciences, Stanford University, Stanford, CA 94305-2115, USA (gordon.brown@stanford.edu)

<sup>2</sup> Department of Photon Science, SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, CA 94025, USA

<sup>3</sup> Department of Geosciences, Virginia Tech, Blacksburg, VA 24061, USA (hochella@vt.edu)

<sup>4</sup> Energy and Environment Directorate, Pacific Northwest National Laboratory, P.O. Box 999, Richland, WA 99352, USA

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The founding of MSA in 1919 followed closely in time the discovery of x-ray diffraction (XRD) in 1912 by Max von Laue, which marked the beginning of our ability to determine the atomic-level structures of crystalline solids, including minerals, and to relate structure to properties in a quantitative way. The field of mineral sciences provides an excellent example of the idea that major advances in science are made when new experimental methods, new characterization and computational tools, and new theories become available. In addition to XRD, a number of other molecular-level characterization methods developed over the past 90 years have had major impacts on the mineral sciences, particularly transmission electron microscopy (TEM), electron microprobe analysis (EMPA), various types of lab-based spectroscopies (*e.g.*, UV-Vis, FTIR, XPS, Mössbauer), and, most recently, synchrotron radiation (SR)-based methods such as x-ray absorption spectroscopy (XAS) and micro-x-ray fluorescence ( $\mu$ -XRF) imaging. We will show how some of these methods, particularly TEM and SR-based XAS and  $\mu$ -XRF imaging, have resulted in major advances in the characterization of complex environmental samples, including nanomaterials, from mining-impacted ecosystems. Evaluation of the long-term environmental impacts of mining and ore beneficiation is a particularly important and timely application of mineral sciences, given the growing demand for mineral resources and their sustainable development by Earth's human population, which is expected to grow to ~10 billion people by 2050.

This presentation will discuss some of the environmental impacts of mining and ore beneficiation using as examples, historic gold, mercury, and asbestos mining in northern

California, USA, current gold mining in Paracatu, Minas Gerais, Brazil, which is one of the largest surface gold mines in the world, and arsenic contamination in the Sierra Nevada Foothills, California, USA, Paracatu, and Carnoules, France, a former Zn mine where a diversity of microbial life greatly influences the forms of As which vary depending on season in an acid mine drainage environment. The characterization methods discussed above have enabled us to determine the molecular-level speciation (local atomic-level environments, oxidation states, and phase association) of environmental contaminants and the minerals with which they are associated, even at ppm levels. Of particular importance is the unique ability of SR-based XAS to determine the speciation of elements adsorbed at mineral/aqueous solution interfaces or sequestered in precipitates associated with mineral surfaces. Understanding the molecular-level speciation of contaminants in mining-impacted environments is key to predicting their potential bioavailability to organisms, as will be illustrated by several examples of contaminant speciation associated with gold, lead, and zinc mining. We will also discuss how mineral surface reactions have concentrated strategic elements, such as the medium and heavy REEs adsorbed on clay minerals, which form major REE deposits in Southern China, and Ni, Co, and Sc adsorbed on or sequestered in Fe-(oxyhydr)oxides in low-grade Ni-Co-containing laterites in New Caledonia and in unusually high-grade Sc-containing laterites in Eastern Australia. Detailed characterization studies of the geochemical processes that concentrate these elements in laterites are leading to a new understanding of the physicochemical conditions needed to form such deposits.

## **Newly discovered environmental impacts of mineral resource utilization: Direct and indirect incidental nanomaterials**

**Michael F. Hochella, Jr.<sup>1,2</sup>, Gordon E. Brown, Jr.<sup>3,4</sup> and Georges Calas<sup>5</sup>**

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<sup>2</sup> Energy and Environment Directorate, Pacific Northwest National Laboratory, P.O. Box 999, Richland, WA 99352, USA

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<sup>4</sup> Department of Photon Science, SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, CA 94025, USA

<sup>5</sup> Institut de mineralogy, de physique des matériaux et de cosmochimie, Sorbonne Université, 4 place Jussieu 75005 Paris, FRANCE

Much of the sustainable development of mineral resources and its societal impact have to do with the legacy of mining. Now in the 21<sup>st</sup> century, mining activities bring more than 350 Gt of rock to the Earth's surface each year. There is clearly no end in sight for the continuation of this activity. Even with advanced recycling, the need for more and different metals, overall, never diminishes. However, whether a mine's productivity lasts for months, decades, or even longer, environmentally sustainable development of new mining is clearly more important than ever. The same is true for old and closed mines. In many hundreds of thousands of mostly legacy mining sites in the world today, deleterious environmental consequences are all too common. Devastating impacts to places and people can last decades, centuries and even millennia unless remediation measures are seriously pursued. Therefore, it behooves us to understand as much as possible about these contamination processes, for which mineralogy is an essential core science needed in all cases. This

immediately brings to mind nanomineralogy, a rapidly developing field which will be shown in this presentation to be highly relevant to the environmental impact of mining, the environmental legacy of mining sites, and their societal impacts.

Within the entire Earth system, massive quantities of nanomaterials are continuously produced and distributed by natural processes that occur in the atmosphere, hydrosphere, continents, and soils of the Earth, including within all present and past mining sites and surrounding areas. However, beyond naturally-occurring nanomaterials/nanominerals, it is also critical to consider incidental nanomaterials. These exist due to any human activity, but their formation is completely unintentional, and most often unexpected. Even more telling and in the great majority of cases, they go completely unnoticed.

It is important to also recognize that there are two principal types of incidental nanomaterials, both relevant to mines, mining areas, and mined materials. *Direct incidental nanomaterials* form directly from some human activity, for example, digging or using explosives in an open pit mine which generate nanomineral dust particles that travel locally, regionally, and even globally in the atmosphere. *Indirect incidental nanoparticles* form as a result of anthropogenic Earth modification, followed by natural production of nanomaterials that would not have occurred without the original human impact. For example, bringing sulfides to the Earth surface in a mining operation typically generates acid mine drainage, producing nanomaterials which would not otherwise have been produced.

In this talk, multiple examples will be given of recently discovered direct and indirect incidental nanomaterials related to mining and its legacy. We will show an example of a direct incidental nanomaterial that very unfortunately is likely toxic to humans. This phase is an oxygen-deficient titanium oxide, produced in a coal power plant's high temperature firebox. These suboxide nanophases are generated during coal burning from  $\text{TiO}_2$  minerals naturally present in coal. Representatives of indirect incidental nanomaterials are schwertmannite and green rust nanominerals observed in post-mining environments that are linked to the mobility of toxic heavy metals in the environment.

# Theme Colloquium 2: Linking Metal (Bio)geochemical Cycling from the Atomic to the Landscape Scale

Moderator: Patricia Maurice (Notre Dame University)

## From atoms to mountains: New frontiers in X-ray science

David M. Singer<sup>1</sup>

<sup>1</sup>Department of Geology, Kent State University, Kent, OH 44242 (dsinger4@kent.edu)

Following the development of synchrotron X-ray sources in the 1970s, the application of these bright sources as spectroscopic and scattering tools to Earth Sciences became apparent by the 1980s and quickly opened possibilities for exploring the mineral-water interface in a way that had been previously unavailable<sup>1</sup>. By the late 1990s, these techniques had shown the complex interplay between the mineral-water interface and biogeochemical processes that control element cycling within soil rhizospheres<sup>2</sup>. At the turn of the 21<sup>st</sup> century, a summary of established and emerging techniques highlighted pathways to further explore the mineral-water interface and promote linkages across disciplines and how synchrotron data can be applied to wider spatial and temporal change.<sup>3</sup> Parallel approaches started to progress, with one focusing on developing cutting-edge techniques to provide molecular-scale information. The second aimed to bridge the six to nine orders of magnitude between the information these techniques provided and the larger hydro(bio)geochemical context in which they occur. Over the past decade, this work has been extended to elucidate coupled processes within the Earth's Critical Zone. Key components of these systems include how mineral-water interfaces associated with plant roots and soil organisms can form porous, aggregated structures which give rise to a patchwork of interconnected microenvironments.<sup>4</sup> Further, despite the extreme heterogeneities within the Critical Zone, patterns are observed across scales.<sup>5</sup> This talk will highlight studies that link molecular-scale information to mesocosm- and field-scale hydro(bio)geochemical and mineralogical results using established and emerging synchrotron X-ray spectroscopic, scattering, and tomography techniques such as Quick-XAS, and micro-X-ray Absorption Spectroscopy and micro-X-ray Diffraction mapping. Major themes will include mineral weathering and soil formation, element cycling in complex redox settings, and contaminant transport in physically heterogeneous media.

1. Bassett, W.; Brown Jr, G., Synchrotron radiation: applications in the earth sciences. *Annual review of earth and planetary sciences* **1990**, *18*, (1), 387-447.
2. Brown, G. E., Jr.; Foster, A. L.; Ostergren, J. D., Mineral surfaces and bioavailability of heavy metals: A molecular-scale perspective. *Proceedings of the National Academy of Sciences* **1999**, *96*, (7), 3388-3395.
3. Rivers, M.; Sturchio, N.; Fenter, P.; Sutton, S., *Applications of synchrotron radiation in low-temperature geochemistry and environmental science*. 2002; Vol. 49.
4. Chorover, J.; Kretzschmar, R.; Garcia-Pichel, F.; Sparks, D. L., Soil biogeochemical processes within the critical zone. *Elements* **2007**, *3*, (5), 321-326.
5. Brantley, S. L.; Goldhaber, M. B.; Ragnarsdottir, K. V., Crossing disciplines and scales to understand the critical zone. *Elements* **2007**, *3*, (5), 307-314.

# Nano-mineralogy: A new dimension to understand the fate of metal(loid)s in the environment

Michael Schindler<sup>1</sup>

<sup>1</sup>University of Manitoba, Winnipeg, Manitoba, R3T2N2 (mschindler@laurentian.ca)

Transmission electron microscopy (TEM) has been used for decades to directly observe nano- to atomic-scale defect microstructures in minerals and rocks. The development of new TEMs capable of recording chemical distribution maps at the lower nanometer scale and of new preparation techniques such as the Focused Ion Beam have opened ways to explore complex mineralogical and chemical features of environmental interfaces. We are just beginning to explore mineralogical features in nano-size confined pore spaces within soils, sediments, tailings and ore deposits. These pore spaces represent a significant fraction of reactive surface areas on rocks, minerals and organic matter. The higher density of surface charges in these pore spaces relative to their micro- to centimeter-size counterparts results in a decrease in the dielectric constant of water and in its diffusion rates through the pore system <sup>1</sup>. This talk will show that nano- to lower micrometer-size pore spaces also exhibit a unique, diverse and previously unknown mineralogy. This includes unexpected abiotic and biotic-controlled dissolution and nucleation processes such as: (a) formation of spinel group minerals at low-T in micrometer-thick mineral surface coatings, (b) growth and aggregation of Cu-bearing nanoparticles to metallic Cu and Cu-sulfide aggregates in pore spaces of organic matter or organic colloids, (c) formation of larger Pb-As-bearing crystals through a process commonly referred to as *crystallization through particle attachment* <sup>2</sup> and (d) formation of Fe-hydroxides through pressure-induced aggregation of nano-size Fe-hydroxide domains during alteration of volcanic glass under low water-rock ratios. These observations will be discussed in terms of the long-term fate of metal(loid)s or metal(loid)-bearing nanoparticles in the environment.

1. Collin M, Gin S., Dazas B., Mahadevan T., Du J. and Bourg, I.C. (2018) Molecular Dynamics Simulations of Water Structure and Diffusion in a 1 nm Diameter Silica Nanopore as a Function of Surface Charge and Alkali Metal Counterion Identity. *J. Phys. Chem. C* 122, 17764.
2. De Yoreo JJ, Gilbert, PUPA, Sommerdijk NAJM, Penn RL., Whitlam S, Joester D, Zhang H, Rimer JD, Navrotsky A, Banfield JF, Wallace AF, Michel FM, Meldrum FC., Cölfen H, Dove PM (2015) Crystallization by particle attachment in synthetic, biogenic, and geologic environments. *Sci* 349, 498.

## **Theme Colloquium 3:**

# **A Second Golden Age for Metamorphic Petrology**

Moderator: Sarah Penniston-Dorland (University of Maryland)

## **The importance of physics to thermobarometric research**

**Ross John Angel<sup>1</sup>**

<sup>1</sup>Dept. Earth & Environmental Sciences, University of Pavia, Pavia, Italy (rossjohnangel@gmail.com)

Our current understanding of the structure and dynamics of the lithosphere is based firmly on the results of much more than a century of petrology. Observations of the mineral phases present in a rock, and their compositions and microstructures, are interpreted in terms of equilibrium thermodynamics under hydrostatic stress conditions. We all know that this is an approximation because no rock is ever under perfect hydrostatic stress, and all reactions require some degree of over-stepping to drive them. Physical confinement can generate non-hydrostatic stress states and thus non-lithostatic stress, leading to the clear possibility that the metamorphic facies cannot necessarily be interpreted simply in terms of depth of formation.

Isolated solid mineral inclusions trapped inside host minerals at the time of metamorphism are the simplest natural example of a system that demonstrates the challenges and opportunities of characterising and using the anisotropic stresses that always develop through the interaction of grains of different minerals. Mineral inclusions trapped inside host minerals at the time of metamorphism and growth of the host can exhibit stresses when the host mineral and rock are examined at room conditions. The idea of measuring this stress and inferring the entrapment conditions was proposed by Rosenfeld and Chase (*Am. J. Sci.*, 1961), but it is only in the last decade that advances in equations of state and elastic theory have turned the idea into a practical and potentially accurate tool to determine entrapment conditions. The advantage of inclusion geobarometry is that it is not dependent on chemical equilibrium being attained in the rock. Concepts introduced a century ago that link phonon vibrational frequencies to strains allow us to use spectroscopy to map strains in solids and measure inclusion stresses. The same concepts form the basis of equation of state theory which, together with classical physics solutions for inclusion problems, will allow us to infer not only the entrapment pressure and temperature of inclusions, but also the palaeostress state in the rock at the time of entrapment. The subsequent interpretation of the observed mineral assemblages in a rock in terms of its geodynamic history will require the development of the theory of thermodynamics under non-hydrostatic stress together with the integration of rock mechanics and thermodynamics to determine how stress states interact with phase equilibria, and how both evolve with time.

# What's Next? Exploring the future of metamorphic geology

Lucie Tajcmanova<sup>1</sup>

<sup>1</sup>Institute of Earth Sciences, Heidelberg University (lucataj@gmail.com)

Metamorphism imposes first-order control on geodynamic processes. In fact, mineral reactions within the lithosphere, involving deformation, and fluid/melt flow, are responsible for mountain building, volcanic eruptions and triggering earthquakes. Petrologists and structural geologists are driven by the same essential curiosity about metamorphic processes affecting the Earth's crust and lithosphere and use different tools to understand these processes.

In the last 100 years, the work on mineral reactions and microstructures in metamorphic rocks has focused on inverse and forward chemical modeling of phase equilibria and on their description through chemical potential relationships which are believed to control the mass transfer in rocks.

Significant advances have also been made in the analytical techniques developments. Currently, high-resolution analytical devices have become more available to the Earth sciences, and reveal the three-dimensional size, shape and distribution of microstructural features down to the nanometre-scale. Interestingly, the smaller the scale considered, the more heterogeneous an apparently uniform rock sample is. This heterogeneity is not only characterized by variation in chemical composition but also in mechanical properties. This needs to be accounted for.

These new, and I would say sometimes very "fresh" (last 5 years), observations led to re-evaluating the appropriateness of our quantification tools for processes in metamorphic rocks. During mineral reaction, the overall mechanical state of the rock is very important. The mechanical effects may influence element transport and mineral assemblage in rocks which can, in turn, significantly control the mechanical-chemical coupling rates and mechanisms of various processes in the Earth's interior. At present, we can even directly measure stress/pressure variations in rock microstructures using state-of-the-art analytical methods such as HR-EBSD, Raman spectroscopy or X-ray micro-diffraction.

Considering the interplay of metamorphic reaction and mechanical properties in our quantification approaches is critical for correct interpretation of observations in metamorphic rocks. The recent development of the new quantification approaches taking into account mechanics has thus opened new horizons in understanding the phase transformations in the Earth's lithosphere.

In this contribution, the classical tools, developed in the last 100 years, will be discussed taking into account the new analytical and quantification advances in order to underpin the key research directions that metamorphic geology field may explore in next 100 years.

***Abstracts***  
***Thursday, 20 June 2019***  
***Afternoon***

**Theme Colloquium 4:**  
**Advances in Mineral Analysis: What Improvements Will We See in the Chemical and Isotopic Analysis of Minerals?**

Moderator: Paul Sylvester (Texas Technical University)

**SIMS and related technologies:**  
**Where they stand, where they are headed, and where things need to go**

**Michael Wiedenbeck<sup>1</sup>**

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The instrumentation behind fine-scale chemical analyses has seen massive advances over the six decades since the introduction of the first commercial electron probes. Today's laboratory technologies permit isotope ratio measurements at the picogram scale (Secondary Ion Mass Spectrometers), trace element concentration determinations at the femtogram scale (Field Emission Electron Probes), and atomic scale spatial resolution of even minor elements (Atom Probes, TEM and related technologies). In fact, methods are now emerging where the detection limit soon will be defined by the mere existence/absence of single atoms at the  $\mu\text{m}^3$  sampling volume.

Looking into the future, where might this path of progress lead? Will geoscientists of the future be able to recover all information stored in a mineral's composition at the near-atomic scale? Some roadblocks are starting to emerge in this seemingly unstoppable trend toward ever more detailed information. At the  $\mu\text{m}$ -scale our ability to both validate and calibrate high-precision isotope ratio analyses is no longer keeping pace with advances in instrumentation. Simply said, we don't have the "standards" needed to support such work. A second concern, despite improvements in both instrument stability and selectivity, is the lack of progress in the development of more efficient ion sources, pointing to an approaching spatial end-of-the-line for many isotope systems. A third challenge yet to be addressed is the integration of high precision isotope data with ion detector systems capable of concurrently recording the entire inorganic mass spectrum. One final concern is that the ever-increasing capabilities of modern analytical tools tend to correlate with ever increasing user costs.

So what are the key milestones needed for the coming six decades in geochemical microanalysis? First, we need better calibration methods supporting data quality, both at the level of the single facility and for allowing meaningful traceability of data between laboratories. Second, there is a need to develop new ion detection systems that couple



precise isotope ratio determinations with the detection of signals having greatly varying atomic masses and greatly varying ion currents. A third key need of geoscientists is the better integration of data acquisition within a spatial context, as imaging variations in 3-dimensional space can often reveal subtle events recorded by natural processes. However, unlike currently available tomographic methods, the scientist of the future will unlikely be satisfied with taking several hours to analyze sample volumes of only  $0.002 \mu\text{m}^3$ . We will therefore need new technologies capable of sorting atoms and recording data at ion count rates in excess of  $10^8$  ions per second. Finally, and possibly most difficult, is the need for such advances to be decoupled from ever ballooning costs and levels of complexity; even the most exquisite of laboratory technologies is of little use to the geoscientist unable to access it.

## **LA-ICP-MS mineral analysis: Prospects for development and improved integration with other technologies**

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As minerals grow and react, they preserve in their elemental and isotopic distributions a record of the genetic processes that formed and modified them. Trace elements are particularly sensitive as process indicators. The most widely applied technique for characterizing the trace elemental and isotopic chemistry of minerals is laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS).

In the quarter century since the first demonstration that a focused laser beam could be used to provide controlled, spatially-resolved ( $10\text{'s } \mu\text{m}$ ) sampling of geological minerals and that the ablation products could readily be analysed quantitatively by ICP-MS at ppm levels, tremendous technological advances have extended the capabilities and flexibility of the technique, including:

- the shift to progressively shorter wavelength and pulse-width laser systems to improve laser-sample coupling and reduce thermal elemental and isotopic fractionation effects;
- more sensitive ICP-MS instruments (enabling ppb-level detection, smaller spot sizes and U-Pb dating), and application of different ICP-MS technologies, including: multi-collector (MC)-ICP-MS (enabling high precision isotope ratio analysis); triple quadrupole (QQQ)-ICP-MS (enabling on-line removal of interferences using ion beam-reaction gas chemistry and applications such as beta decay system geochronology; e.g., Rb-Sr); time-of-flight (TOF)-ICP-MS (enabling ultra-fast, simultaneous, full mass spectrum analysis). Laser aerosols can even be split between different ICP-MS instruments, enabling simultaneous high-precision isotopic (e.g., Hf), U-Pb and/or elemental analysis of the same ablation volume;

- tandem LA-ICP-MS/laser induced breakdown spectroscopy (LIBS) systems that extend element coverage to light elements (e.g., H, O, F);
- improved sample cell design, stage control and data processing capabilities that allow rapid generation of quantitative 2-D (and 3-D) trace element and isotope ratio/mineral age maps. Using TOF-ICP-MS, element maps can now be generated from full mass spectral analyses of  $\geq 1$  million contiguous spots on a petrographic section (i.e.,  $> 50$  million element concentration measurements) in a few hours.

As LA-ICP-MS analysis targets ever smaller geochemical features, developments will be required to streamline integration of other imaging and analytical techniques (e.g., BSE/CL-SEM, EBSD, EPMA) for optimal analytical target identification. This will require across-technology sample holders and improved LA-ICP-MS viewing optics and stage positioning accuracy. However, the real paradigm shift in LA-ICP-MS data acquisition and interpretation will be driven by its rapid, micro-scale, element and isotopic mapping capability, and its application in unlocking complex mineral histories. As developments in LA-ICP-MS instrumentation slow and analytical capabilities plateau, research emphasis will be placed on new approaches and software for integrating imaging and geochemical micro-beam data together in one platform for rapid visualization, interrogation and interpretation. Machine learning tools will be applied increasingly to the huge data sets generated by LA-ICP-MS mapping for: statistical interrogation of the data, identifying optimal data for specific applications (e.g., low common Pb domains for U-Pb dating), identifying multiple chemical events in complex samples, and predictive analysis of mineral genesis across multiple mapping experiments. Similarly, emphasis will be placed on developing new computational approaches, rather than hardware solutions, to correct fractionation-related biases. Some of these approaches will be illustrated using quantitative LA-ICP-MS elemental mapping of pyrite of multiple geneses from gold mining camps of Canada.

## **Theme Colloquium 5:**

# **Unraveling the Roots of Continents: From Paleo-island Arc to Mature Continental Crust on Earth**

Moderator: Mattia Pistone (Université de Lausanne)

## **Lower crust formation and differentiation constrained by field studies and experimental petrology**

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Estimates of the bulk chemical composition of Earth continental crust are highly variable and range from 55-65 wt% SiO<sub>2</sub> (Rudnick & Gao 2003). In particular, no consensus exists about the composition of the lower crust. While it is appropriate in some places to distinguish an upper, middle and lower crust, more recent studies advocate that in some places middle and lower crust cannot readily be distinguished based on seismic wave speeds, geochemical compositions and heat flow constraints (Hacker et al. 2015). Analysis of global or regional datasets, however, cannot readily disentangle the relevant processes that control the composition of the crust and, in particular, the lower crust. Crucial for this issue are changes in composition over time. Thus, studying one of best known crustal sections – the Ivrea zone in the Alps – provides new insights as it is unique by exposing an almost complete section of crustal rocks of about 30-35 km, approaching close to the crust-mantle transition. The Ivrea zone represents a Paleozoic continental crust section that is affected by Permian transcrustal magmatism on all crustal levels, allowing for evaluation of the temporal evolution of continental crust.

An evaluation of major element chemical trajectories of pre-Permian Ivrea crust and the Permian magmatic addition indicates that the metasedimentary crust is dominated by crustal reworking (mechanical mixing trends), while the magmatic addition closely follows phase equilibria controlled by major element geochemical trends and can be considered as net crustal growth. Recent equilibrium and fractional crystallization experiments designed to understand fractionation processes in the lower crust simulated the liquid (LLD) and cumulate lines of descent (CLD) of primary mantle derived magmas (Müntener & Ulmer 2018). An evaluation of the major element composition indicates that the CLD of hydrous systems is fundamentally different from dry systems. Cumulates derived from hydrous experiments display elevated Al<sub>2</sub>O<sub>3</sub> and CaO contents at low SiO<sub>2</sub>, producing voluminous andesitic to rhyolitic liquids, which closely overlap with compositions of natural systems, while dry systems follow different fractionation paths. Melting experiments on amphibolite or remelting of basaltic to andesitic cumulates equally produce granitic – rhyolitic liquids of similar composition yet their restites do not present the same variability of the CLD of fractional crystallization experiments. Despite widespread evidence for partial melting and assimilation processes during Permian transcrustal magmatic activity, CLDs from experimental studies on lower crustal differentiation in H<sub>2</sub>O-bearing systems are comparable to the magmatic evolution in the Ivrea zone and other crustal sections. Dry

crystallization and moderate amounts of assimilation may provide similar results. This indicates that global datasets from metamorphic terrains at moderate to high pressure can be evaluated for their igneous versus metasedimentary contribution to the bulk continental lower crust.

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## **Earth's continents through time**

**Roberta L. Rudnick<sup>1</sup>**

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Earth is the only planet in our solar system that has continents, which are a by-product of 4.5 billion years of tectono-magmatic evolution. The continental crust is miniscule by mass (only 0.5 wt% of the bulk silicate Earth), but contains significant amounts of Earth's total budget of highly incompatible elements, which include the heat-producing elements K, Th, and U. Because of igneous and metamorphic processes, most of these elements are concentrated within the upper continental crust (UCC). Thus, determining the UCC composition through time provides important information about the bulk crust composition, its impact on heat distribution within the Earth, the tectonic processes that may have generated and influence the crust, as well as the crust's influence on the atmosphere and ocean through chemical weathering feedbacks.

Studies of fine-grained terrigenous sedimentary rocks, including shales and the fine-grained matrix of glacial diamictites allow one to examine how the average composition of the upper continental crust may have changed since ~3.5 Ga, and how the crust may record important events. For example, the rise of atmospheric oxygen is imprinted on the compositions of glacial diamictites: prior to the great oxidation event (GOE) diamictites contain expected concentrations of Mo and V relative to other similarly incompatible elements (Gaschnig et al., 2014). Following the GOE, diamictites are systematically depleted in Mo and V due to their increased solubility in their more oxidized forms (e.g., Mo<sup>6+</sup>, V<sup>5+</sup>). Changes in transition metals (Ni/Co, Cr/Zn, Cr/U) in both shales and diamictites mark a fundamental shift in average UCC from mafic (~11 wt.% MgO) to felsic (3-4 wt.% MgO) in the interval between 3.0 and 2.5 Ga (Gaschnig et al., 2016; Tang et al., 2016; Smit and Mezger, 2017). This shift is not simply a change in the proportion of komatiite, but reflects a significant decrease in basaltic component from ≥60% at 3.0 Ga to present-day proportions by 2.5 Ga (Chen et al., 2019). This fundamental change in crust composition may mark the onset of efficient granite production via plate tectonic processes (Dhuime et al., 2015; Tang et al., 2016) and may have contributed to the rise of atmospheric oxygen by removing oxygen sinks (Lee et al., 2016; Smit and Mezger, 2017).

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## **Theme Colloquium 6: Mineral Inclusions in Diamonds from the Deep Earth**

Moderator: Steven Shirey (Carnegie Institution for Science)

### **In-situ, ambient analysis of diamond-captured Transition-Zone and Lower-Mantle minerals**

**Fabrizio Nestola<sup>1</sup>, Sofia Lorenzon<sup>1</sup>, Paolo Nimis<sup>1</sup>, Chiara Anzolini<sup>2</sup>,  
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Inclusions in diamonds can tell us much of the deep and inaccessible portions of our planet including its mineralogy and the deeper effects of plate tectonics. Recently, great attention has been given in particular to those inclusions which classify their diamond hosts as “super-deep” or “sublithospheric” diamonds, which comprise only ~ 1% of the entire world diamond population (Stachel and Harris 2008). Compared to lithospheric diamonds, which form between about 120 km and 250 km depth, super-deep diamonds are believed to have formed at depths as high as 800 km. But what is the actual depth of formation of super-deep diamonds? Do they come from the Transition Zone (410-660 km depth) and Lower Mantle (below 660 km depth) or some of them form in the Upper Mantle (down to 410 km depth)? Recent advances in X-ray crystallography and theoretical understanding of mineral elasticity now allow us to answer these questions by analyzing inclusions trapped within them. Among these we can mention: *jeffbenite*,  $(\text{Mg,Fe})_3\text{Al}_2\text{Si}_3\text{O}_{12}$  (Nestola et al. 2016; previously known as TAPP), *breyite*,  $\text{CaSiO}_3$  (Brenker et al. 2018; previously known as  $\text{CaSiO}_3$ -walstromite, Joswig et al. 1999, Stachel et al. 2000), *ringwoodite*,  $(\text{Mg,Fe})_2\text{SiO}_4$  (Pearson et al. 2014), *CaSi<sub>2</sub>O<sub>5</sub> with titanite structure* (Stachel et al. 2000, Brenker et al. 2005, 2007), *CaSiO<sub>3</sub> with perovskite structure* (Nestola et al. 2018).

Other inclusions are typically found in super-deep diamonds but, if taken alone, they cannot be unambiguously assigned to specific depth: *ferropericlase*,  $(\text{Mg,Fe})\text{O}$ , which is the most common inclusion in super-deep diamonds (e.g. Brey et al. 2004, Harte 2010), *majoritic garnet*,  $\text{Mg}_3(\text{Mg,Fe,Al,Si})_2\text{Si}_3\text{O}_{12}$  (Moore and Gurney 1985, Stachel et al. 2005, Walter et al. 2011), *low-Ni enstatite* (i.e. enstatite with very low NiO content close to 0.02 wt%,

considered to be retrogressed bridgmanite, as opposed to typical Upper Mantle enstatite with 0.1-0.2 % , is, Stachel et al. 2000) and *larnite*, Ca<sub>2</sub>SiO<sub>4</sub> (e.g. Brenker et al. 2005).

These 9 types of inclusions are not the only ones found in super-deep diamonds, but they certainly are the most representative and abundant ones. Here, we want to provide an overview on the real significance of such important inclusions as depth markers. In particular, we will discuss which inclusion types can definitively prove a Transition-Zone or Lower-Mantle origin of super-deep diamonds, giving mineralogy a new relevance for the understanding of the deepest reaches of our planet.

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## **Diamonds and their inclusions: A unique record of plate tectonic recycling**

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Much of the temporal record of Earth's evolution, including its trace of plate tectonics, is blurred due to the dynamic nature of the crust-mantle system. While zircon provides the highest fidelity crustal record, diamond takes over in the mantle as the go-to mineral, capable of retaining critical information for a variety of geochemical proxies, over billion year timescales.

Here we use diamond and its inclusions to tell the story of the recycling of C, N, O, H and B from the crust to various depths in Earth's mantle. In this story, altered oceanic crust (AOC) and lithospheric mantle will play a prominent role. The carbon isotope record of diamond has long been thought to reflect the mixing of primitive mantle carbon with carbon recycled from isotopically light organic material originating from the crust. A major difficulty has been reconciling this view with the highly varied nitrogen and carbon isotope signatures in diamonds of eclogitic paragenesis, which cannot be interpreted by the same mechanism. Recent work on AOC of igneous origin (Li et al., EPSL in press) shows how isotopically varied carbon and nitrogen can be subducted to great depth and retained in spatial juxtaposition

with the mafic silicate component of AOC to form the complex C-N isotope systematics observed in diamonds and the varied O isotope compositions of their inclusions. In this model a large portion of the  $^{13}\text{C}$  depleted carbon originated from biogenic carbonate within the AOC rather than from overlying sediments. Metamorphosed and partially devolatilized AOC will have very variable C/N ratios and highly variable nitrogen isotopes, explaining why simple two component mixing between organic matter and convecting upper mantle cannot explain the complexity of C-N isotope systematics in diamonds.

Igneous AOC and its underlying altered mantle are considerably more efficient than subducted sediment at retaining their volatile inventory when recycled to transition zone and even lower mantle depths. Hence, this combination of mixing between AOC-derived volatiles and those from the convecting mantle produces the isotopic fingerprints of super-deep diamonds and their inclusions. These amazing diamonds, some worth millions of dollars, can contain pristine ultra-high pressure mineral phases never before seen in terrestrial samples. The first hydrous ringwoodite found in Earth provides evidence in support of a locally water-saturated transition zone that may result from altered oceanic lithospheric mantle foundering at that depth in the mantle. The O isotope composition of deep asthenosphere and transition zone phases document clearly crustal precursors that have interacted with the hydrosphere before residing hundreds of km deep within the Earth. Finally, spectacular blue diamonds contain boron, an element of strong crustal affinities, transported into the deep Earth along with crustal carbon, by the plate tectonic conveyor system.

Diamond – such a simple mineral – and its inclusions, will continue to provide a unique, brightly illuminating light into the darkest recesses of Earth's mantle for many years to come.

## **Theme Colloquium 7:**

### **Museum Mineral Collections in the next 100 years**

The GIA Distinguished Moderator: Jeffrey Post (National Museum of Natural History)

#### **Making Mineral Collections Relevant in the 21<sup>st</sup> Century**

**Kim Tait<sup>1</sup>**

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Mineral collections in museums have a variety of uses: from being an educational resource, to supporting scholarly research, to supporting loans to other museums, to serving as a type specimen repository, all while encouraging physical, and more and more, online visitors, to engage with the natural world. With shrinking budgets and increasing mineral prices, curators need to get creative on how to build the collections. Many museums are moving to foster endowments to sustain positions and acquisitions budgets in perpetuity. Some museums are working with industry partners, private donors, research scientists and minerals collectors to forge new and lasting relationships that are built on preserving and retaining new (and old!) mineral localities. Some mineral dealers are very concerned with the aesthetic aspects of the mineral specimens they are selling; their specimen preparation sometimes loses valuable mineral associations. As mineralogists, all of us need to work with mineral dealers to retain those valuable associations and support “responsible prepping” or capturing representative samples as they are exposed, to make sure these are available for study.

With big data projects and other more comprehensive studies being started, there has been a lot of talk of ways for online databases to be unified, similar to our biological colleagues (GBIF, BioCASE etc) while retaining the samples for future data analysis as new projects arise. The Royal Ontario Museum just successfully completed a large fundraising campaign to receive a new 22,000 piece collection from Thailand, improve the collection storage conditions and are currently working on imaging the collection and transitioning to a new database. This talk will be largely based on the Royal Ontario Museum’s (ROM’s) collections, but will address some of the challenges and successes of museums worldwide.

#### **Unlocking the collections: Making minerals accessible in the next 100 years**

**Aaron Celestian<sup>1</sup>**

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A museum’s mineral collection is an Earth material library ideally designed to acquire, house, curate, conserve, and provide specimens for the advancement of science and public



knowledge. This talk will be based on the experiences of the Mineral Sciences Department at the Natural History Museum of Los Angeles, but will address some of the approaches used by other institutions and for other types of collections. Collections are an important component to the mission of many natural history museums, which aim to make specimens accessible to both researchers and the public. Increasingly, institutions are developing diverse physical and digital approaches to enhance the accessibility of collections and to encourage their use.

The collections at the NHMLA support active and vibrant multidisciplinary research projects and educational initiatives. The Minerals Sciences Department has over 170,000 specimens and more than 300 type specimens, representing over 80% of all known mineral species. The department loans specimens worldwide for both destructive and non-destructive research analyses, builds partnerships with researchers for specimen curation for future scientific usage, lends to other institutions (e.g., the Los Angeles County Museum of Art) for display, and makes materials available to teachers at elementary schools through university. One of the main challenges that NHMLA and other similar organizations will face in the next 100 years is how to continue to provide these valuable services to our constituent communities in the face of ever escalating mineral, infrastructure, and personnel costs and ever dwindling funding sources.

***Abstracts***  
***Friday, 21 June 2019***  
***Morning***

**Theme Colloquium 8:**  
**Synchrotron-based Studies of High-Pressure Mineral Behavior**

Moderator: Carl Agee (University of New Mexico)

**Putting the squeeze on silicate chains: Unusual coordination states accompanying densification of pyroxenes and amphiboles**

**Przemyslaw Dera<sup>1</sup>**

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Earth is a rocky planet, dominated by silicate minerals, which undergo chemical and physical transformations as a function of depth, and thus control properties and dynamics of the planet interior. Global geologic phenomena and processes including deep-focus earthquakes and plate tectonics are often affected by these transformations. Silicon strongly prefers four-coordinated crystallographic sites due to the  $sp^3$  electron hybridization. As a consequence, in silicate minerals characteristic of shallow Earth interior, including the crust and the upper mantle, silicon resides predominantly in tetrahedral sites coordinated by four oxygen atoms ( $IVSi$ ). However, silicon is also capable of forming 5- and 6- coordinated states ( $VSi$  and  $VSi$ ). These hypervalent states are favored at higher pressure and with increased ligand electronegativity. There has been great interest in understanding the occurrence and properties of the least common, penta-coordinated Si phases ( $VSi$ ) both in geophysics, as well as in solid state chemistry. Amorphous solids, melts and liquids can sustain exotic coordination environments such as  $SiO_5$  more easily due to the lack of symmetry and long-range order. At ambient conditions, crystalline silicate minerals with  $VSi$  are extremely rare. In a quest to find previously unknown high-pressure silicate polymorphs characterized by hypervalent  $VSi$  and understand the geophysical consequences of their existence, we used a combination of high-pressure synchrotron X-ray diffraction and density functional theory calculations to systematically explore the family of chain silicate minerals, including pyroxenes, pyroxenoids and amphiboles. This presentation will review systematic phase transition trends and new structural varieties that have been discovered. We investigated the structural aspects of the new transformations and their effects on lattice preferred orientation and transformation fabrics of the high-pressure metamorphic rocks. The results suggest that the presence of  $VSi$  has consequences for chemical reactivity, elastic anisotropy, elastic and plastic deformation, density of the subducted slab and affects buoyancy relative to the surrounding mantle.

# **The anisotropic omphacite in the Earth's upper mantle: Implications for detecting eclogitic materials inside the Earth**

**Ming Hao<sup>1</sup>, Caroline Pierotti<sup>1,2</sup>, Sergey Tkachev<sup>3</sup>, Vitali Prakapenka<sup>3</sup>, and Jin Zhang<sup>1\*</sup>**

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Omphacite is a clinopyroxene solid solution of Fe-bearing diopside and jadeite, and is stable up to about 500 km depth in the Earth's interior. It is also a major mineral component of eclogite (up to 75 vol%). Basalt, which makes up most of the Earth's oceanic crust, transforms into eclogite at the depth  $> \sim 60$  km. Due to the  $\sim 20\%$  higher density of eclogite, it is considered one of the main driving forces for the slab subduction. Subducted eclogite is also an important source of the chemical heterogeneities in the Earth's mantle, which are the potential reservoirs for the enriched geochemical components. Thus, studying the geophysical properties of omphacite at elevated pressure-temperature conditions is of great interest for both the geophysical and geochemical community.

Previous studies have proposed to utilize the unique anisotropic seismic properties of eclogite to identify possible subduction channels and eclogite-rich regions in the Earth's interior. Due to the elastically isotropic nature of garnet and the relatively small proportion ( $< 10$  vol%) of the silica minerals in eclogite, the seismic anisotropy of eclogite is primarily caused by the lattice preferred orientation of omphacite. Thus, in this study, in addition to determining the densities, and isotropic velocities of omphacite at the high pressure-temperature condition, we also paid special attention to the elastic anisotropy of omphacite.

We combined the synchrotron single-crystal X-ray diffraction at Advanced Photon Source, Argonne National Laboratory with offline Brillouin spectroscopy experiments at University New Mexico to investigate the anisotropic thermoelastic properties of omphacite. Incorporated with the preexisting thermoelastic database of other relevant mantle mineral phases, we compared the anisotropic seismic properties of eclogite (slab crust) with pyrolite (ambient mantle) along mantle geotherms down to 500 km depth. The maximum isotropic and anisotropic velocities contrast between pyrolite and eclogite is at 310-410 km, making it an optimal depth range for seismologists to search for eclogite-rich heterogeneities in the Earth's interior. The  $\sim 5\%$ - $7\%$  velocity difference between eclogite and pyrolite also needs to be taken into account when estimating the slab temperatures between 310-410 km depth. Otherwise, the slab temperature could be underestimated by a few hundred K without considering the possible lithology difference.

## Theme Colloquium 9:

# Mineralogy Beyond the Boundaries of Earth: Advances in the Mineralogy of Mars

Moderator: Douglas Ming (Johnson Space Center)

## New perspectives of ancient Mars: Mineral diversity and crystal chemistry at Gale crater, Mars from the CheMin X-ray diffractometer

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The Mars Science Laboratory *Curiosity* rover arrived at Mars in August 2012 with a primary goal of characterizing the habitability of ancient and modern environments. *Curiosity* landed in Gale crater to study a sequence of ~3.5 Ga old sedimentary rocks that, based on orbital visible/near-infrared reflectance spectra, contain secondary minerals that suggest deposition and/or alteration in liquid water. The sedimentary sequence that comprises the lower slopes of Mount Sharp within Gale crater may preserve a dramatic shift on early Mars from a relatively warm and wet climate to a cold and dry climate based on a transition from smectite-bearing strata to sulfate-bearing strata. The rover is equipped with cameras and geochemical and mineralogical instruments to examine the sedimentology and identify compositional changes within the stratigraphy. These observations provide information about variations in depositional and diagenetic environments over time. The Chemistry and Mineralogy (CheMin) instrument is one of two internal laboratories on *Curiosity* and includes a transmission X-ray diffractometer (XRD) and X-ray fluorescence (XRF) spectrometer with a Co-K $\alpha$  source. CheMin measures loose sediment samples scooped from the surface and drilled rock powders. The XRD provides quantitative mineralogy of scooped and drilled samples to a detection limit of ~1 wt.%. *Curiosity* has traversed >20 km since landing and has primarily been exploring the site of a predominantly ancient lake environment fed by groundwater and streams emanating from the crater rim.

Results from CheMin demonstrate an incredible diversity in the mineralogy of fluvio-lacustrine rocks that signify variations in source rock composition, sediment transport mechanisms, and depositional and diagenetic fluid chemistry. Abundant trioctahedral smectite and magnetite at the base of the section may have formed from low-salinity pore waters with a circumneutral pH within lake sediments. A transition to dioctahedral smectite, hematite, and Ca-sulfate going up section suggests a change to more saline and oxidative aqueous conditions within the lake waters themselves and/or within diagenetic fluids. The primary minerals detected in fluvio-lacustrine samples by CheMin also suggest diversity in the igneous source regions for the sediments, where abundant pyroxene and plagioclase in most samples suggest a basaltic protolith, but sanidine and pyroxene in one sample may have been sourced from a potassic trachyte, and tridymite and sanidine in another sample may have been transported from a rhyolitic source. Crystal chemistry of major phases in

each sample have been calculated from refined unit-cell parameters, providing further constraints on aqueous alteration processes and igneous protoliths for the sediments. Perhaps one of the biggest mysteries revealed by the CheMin instrument is the high abundance of X-ray amorphous materials (15 to 73 wt.%) in all samples measured to date. X-ray amorphous materials were detected by CheMin based on the observation of broad humps in XRD patterns. How these materials formed, their composition, and why they persist near the martian surface remain a topic of debate. The sedimentology and composition of the rocks analyzed by *Curiosity* demonstrate that habitable environments persisted intermittently on the surface or in the subsurface of Gale crater for perhaps more than a billion years.

## **The mineralogy of Mars, from rocks in hand**

**Harry Y. McSween<sup>1</sup>**

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Impact melts in martian meteorites contain trapped atmospheric gas that serves as a geochemical fingerprint identifying their planetary source. They are also identified by a unique oxygen isotopic composition. The >100 currently recognized martian meteorites are basalts, gabbros, and ultramafic cumulates (lherzolites, pyroxenites, and dunites) with Fe-rich, low-Al compositions that reflect diverse mantle sources, enriched and depleted in trace elements and radiogenic isotopes. The basaltic meteorites are consistent with orbital remote sensing data that indicate basalts dominate the martian surface. The meteorites allow definitive identification of martian minerals – mafic igneous assemblages, in some cases partly overprinted by aqueous alteration and shock metamorphism. Fe-Ti oxide minerals constrain magmas to have crystallized under relatively oxidizing conditions, and apatite analyses indicate hydrous magmas that lost water on ascent and eruption. The meteorites mostly have young crystallization ages (most are <1.3 Ga), likely reflecting the difficulty in impact-launching older, less coherent rocks. Clusters of Mars ejection ages (determined from cosmic-ray exposure) suggest sampling of perhaps 7-10 impact sites. NWA 7034 and several meteorites paired with it are ancient (4.4 Ga) regolith breccias composed of basaltic clasts. The only other ancient meteorite, ALH 84001, is a 4.1 Ga orthopyroxenite, infamous for its purported evidence for life. The biased young (Amazonian) ages of the samples in hand beg a comparison with ancient (Noachian to Hesperian, >3.5 Ga) rocks analyzed by Mars rovers. The young meteorites have sub-alkaline compositions, whereas the ancient rocks (including ancient NWA 7034) are mildly to strongly alkaline. The compositions of martian magmas have clearly evolved over time, although the explanation for that is unclear. No calc-alkaline or granitic rocks have been encountered, either on Mars or in the martian meteorite suite, reflecting the absence of crustal recycling by subduction. Other geologic units in ancient Mars terrains, interpreted as fluvial, lacustrine, evaporative, hydrothermal, aeolian, or pyroclastic, have not been sampled as meteorites, so these samples, albeit biased in age and petrogenesis, both advance and limit our understanding of the mineralogy of Mars and argue for Mars sample return.

# **Theme Colloquium 10: The Future of Data-Driven Discovery in Mineralogy, Crystallography, and Petrology**

The Rob Lavinsky Distinguished Moderator: Robert M. Hazen (Carnegie Institution for Science)

## **Data-driven discovery in mineral systems: Applications of advanced analytics and visualization**

**Shaunna M. Morrison<sup>1</sup>**

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The key to answering many compelling and complex questions in Earth, planetary, and life science lies in breaking down the barriers between scientific fields and harnessing the integrated, multi-disciplinary power of their respective data resources. We have a unique opportunity to integrate large and rapidly expanding “big data” resources, to enlist powerful analytical and visualization methods, and to answer multi-disciplinary questions that cannot be addressed by one field alone.

Recent years have seen a dramatic increase in the volume of mineralogical and geochemical data available for study. These large and expanding data resources have created an opportunity to characterize changes in near-surface mineralogy through deep time and to relate these findings to the geologic and biologic evolution of our planet over the past 4.5 billion years [1-3]. Using databases such as the RRUFF Project, the Mineral Evolution Database (MED), mindat, and EarthChem, we explore the spatial and temporal distribution of minerals on Earth’s surface while considering the multidimensional relationships between composition, oxidation state, structural complexity [4], and paragenetic mode.

These studies, driven by advanced analytical and visualization techniques such as mineral ecology [5-6], network analysis [7], and affinity analysis, allow us to begin tackling big questions in Earth, planetary, and biosciences. These questions relate to understanding the relationships of mineral formation and preservation with large-scale geologic processes, such as Wilson cycles, the oxidation of Earth’s atmosphere, and changes in ocean chemistry. We can also investigate the abundance and likely species of as-yet undiscovered mineral, as well as estimate the probability of finding a mineral or mineral assemblage at any locality on Earth or another planetary body. Given the spatial and temporal distribution of minerals on Earth, which was heavily influenced by life, we can explore the possibility that Earth’s mineral diversity and distribution is a biosignature that can be used for future planetary evaluation and exploration. These geologic resources also facilitate integration across disciplines and allow us to explore ideas that one field alone cannot fully characterize, such as how the geochemical makeup of our planet affected the emergence and evolution of life,

and, likewise, how life influenced chemical composition and geological processes throughout Earth history.

[1] Hazen et al. (2008) *Am. Mineral.* 93, 1693-1720

[2] Hummer et al. (2018) The oxidation of Earth's crust: Evidence from the evolution of manganese minerals, *Nat. Comm.* (In Revision)

[3] Liu et al. (2017) *Nat. Comm.*, 8:1950

[4] Krivovichev et al. (2013) *Min. Mag.* 77(3), 275-326.

[5] Hazen et al. (2015) *Can. Min.* 53(2):295-324

[6] Hystad et al. (2018) Bayesian estimation of Earth's undiscovered mineralogical diversity, *Mathematical Geosciences* (In Press)

[7] Morrison et al. (2017) *Am. Mineral.*, 102, 1588-1596.

## **The future of data-driven discovery in petrology and geochemistry**

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The successful utilization of big data has direct implications for field-based and laboratory-based petrological and geochemical studies as well as ever-growing “data mining” studies. In considering the major advances in the fields of mineralogy, petrology, and geochemistry, it is important to recognize the various styles and sizes of data that have been available to geologists through time. The petrologic and geochemical fields span tremendous scales, and major milestones in understanding have been contributed to the field across these scales through time. Goldschmidt's (1937) classification of the elements was largely based on the preference of different elements to form distinct minerals within meteorites and predated the vast majority of experimental data on elemental behavior and partitioning. Dana's monumental contribution, the System of Mineralogy (Third Edition, 1850), was developed using available chemical, atomic, and symmetry data even before X-ray diffraction had been invented. As mineral classification became systematically defined, with further aid from continued technological advances, mineral assemblages could be used for even higher-level classification.

The concept of metamorphic facies was introduced by Eskola (1915, 1920), stemming out of a study that focused on Norwegian eclogites. Tuttle and Bowen (1958) employed experimental techniques in order to replicate natural phenomena in a more controlled, observable, and reproducible way: these experiments resulted in the ability to understand the phase relations in granites. These early contributions laid the groundwork for the basic understanding of how elements behave, how minerals form, and how mineral assemblages reflect formation conditions of rocks on Earth. With the increasing availability of more forms of geochemical and petrological data, the compilation of data and application of these datasets to complex questions has become more prevalent. Trace element compositions have contributed to the development of discrimination plots that allow for not only the classification of rock types but the interpretation of, for example, magma sources and amount of crustal contamination. The compilation of zircon age dates, after the advent and

common use of the U-Pb geochronologic technique, has allowed for massive compilations of ages across the world and contributed to the development of our current understanding of the supercontinent cycle through Earth's history.

Currently, there are significant, publicly sourced and publicly available datasets (e.g., NAVDAT, EarthChem, Georoc, etc.) that contain information ranging from whole rock chemical analyses to age dates to isotopic analyses. With the ever-increasing amount of available data, we are able to address more complex questions and look deeper back into geologic history. One such complex question being addressed with big-data approaches is the geochemical footprint of the supercontinent Rodinia and potential driving factors behind its apparent distinct igneous geochemistry. Further, this case study emphasizes the challenge facing any geologist utilizing big-data, in understanding the source of data and the persistent challenge of preservational bias through the rock record.



***Abstracts***  
***Friday, 21 June 2019***  
***Afternoon***

**Theme Colloquium 11:**

**Applied Mineralogy as a Tool to Research the Provenance and Technology of Ancient Ceramics**

Moderators: Pamela Vandiver (University of Arizona) and Robert Heimann (Technische Universität Bergakademie Freiberg)

**The mineralogy of opaque ceramic glazes: their development in the Islamic world and Europe from 7th to 16th century CE**

**Michael Tite<sup>1</sup>**

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It is generally accepted that the first opaque glazed, clay-based ceramics were produced in Islamic Egypt and Syria in the late 7<sup>th</sup> to early 8<sup>th</sup> century CE. The yellow opacifier was Type II lead stannate ( $\text{Pb}(\text{Sn}, \text{Si})\text{O}_3$ ) in a very high lead glaze, and the white opacifier was tin oxide ( $\text{SnO}_2$ ) in a high lead-alkali glaze, these two tin-based opacifiers having been first used by Roman glassmakers in 4<sup>th</sup> century CE. Ancient textual accounts (e.g., Abu'l Qasim in 1301 CE) of glaze production indicate that the production of opaque glazes involved a two-stage process and this has been confirmed by modern laboratory replication. First, a mixture of lead and tin metals were calcined to produce a "calx" (oxide) powder containing Type I lead stannate ( $\text{Pb}_2\text{SnO}_4$ ). In the second stage, to produce the yellow glaze, the calx powder was mixed with a source of silica, and to produce the white glaze, alkaline frit was also added to the calx – silica mixture.

From Syria, the opaque yellow and white glaze technology was transferred to Mesopotamia by the 9<sup>th</sup> century CE, probably in the context of the transfer of the Islamic capital from Damascus in Syria to Baghdad in what today is Iraq in 762 CE. In Mesopotamia, in addition to the continued use of the high lead-alkali opaque white glazes, alkali-lead opaque white glazes were produced. This latter technology was possibly derived from that for the contemporary production of Islamic opaque white glass, i.e. tin-opacified alkali-lime type. It is frequently argued that the extensive use of opaque white glazes in Mesopotamia was the result of a desire to imitate imported Chinese white porcelain in a region lacking suitable white firing clays. However, the opaque white glazes also provided the ideal background for blue-on-white and lustre decorated wares that were introduced at this time.

From Mesopotamia, both opaque yellow and white glaze technology spread eastwards through Iran and into Central Asia (Merv, Nishapur, Samarqand) during 10<sup>th</sup> century CE. Westwards, opaque yellow glaze production appears to have fallen out of use, except in Egypt where it reappeared in 10<sup>th</sup> century CE, but using lead antimonate (Pb<sub>2</sub>Sb<sub>2</sub>O<sub>7</sub>) instead of lead stannate as the opacifier. In contrast, opaque white glaze production continued in Syria and the Levant using a lead-alkali glaze intermediate in composition between the high lead-alkali glaze previously used and the alkali-lead glaze introduced in Mesopotamia. In addition, the opaque white glaze technology spread to Islamic Spain and to Egypt in 10<sup>th</sup> century CE, and from the latter it spread to Tunisia in North Africa, then from Tunisia to Islamic Sicily.

Finally, from Islamic Spain and/or North Africa, the opaque white glaze technology spread beyond the Islamic world into Christian Europe by 13<sup>th</sup> century CE, the outstanding development being the production of Italian maiolica. In addition, within the Islamic world, the final development of the opaque white glaze technology was the production of Iznik ware, which rivalled Chinese porcelain in its magnificence, in Ottoman Turkey in the 16<sup>th</sup> century CE.

## **Modern mineralogy and ancient pots: The archaeometry of ceramics**

**Gilberto Artioli<sup>1</sup>**

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Fired ceramics are the oldest materials made by man using pyro-technological processes. Since the earliest observed use of pottery, dated at about 18.000 BC, the production technology of ceramics became so important and widespread among human cultures that prehistory archaeologists frequently adopt the shape, decoration and typological changes of pottery as markers to define chronological boundaries and culturally homogeneous population groups. The understanding of the chaîne opératoire of ceramics production also yields information on ancient socio-economic systems, technical traditions, and commercial trades. Archaeological, historical and analytical information are thus merged to provide a complete picture of ceramics production, diffusion, and use.

The traditional mineralogical and petrological investigations applied to ceramics are commonly focused on (a) the characterization and provenancing of the raw materials (clays, temper) employed for manufacturing, (b) the interpretation of the production and firing technology, and (c) the authentication of original ceramics materials with respect to imitations and forgeries. Since pottery fragments are the most ubiquitous materials found in archaeological excavations, they are also among the most studied materials, so that abundant archaeometric investigations are available in the literature. The majority of the analytical techniques and methods used to investigate geological samples are perfectly applicable to ceramics bodies. Indeed, the measured mineralogical, petrological, crystal-chemical and textural parameters are often essential towards the interpretation of the

objects, the technological reconstructions, and the definition of archaeological/historical reference groups.

Recent investigations of pottery based on techniques borrowed from other scientific disciplines have remarkably expanded the amount of information extracted from ancient ceramics. Among these, it is worth mentioning the molecular analysis of organic residues extracted from cooking pots. Whereas early attempts were aimed to interpret the food cycle and nutritional habits of the ancient humans using the pots, the systematic application of advanced molecular techniques to residue analysis actually yield surprising insights into past herding and farming behaviours, trades in exotic organics goods, environmental and climatic proxies, and even complementary information on population genetics. In a totally different area, the measurement of the remnant archaeomagnetic field encoded in ancient ceramics is helping geophysicists to extrapolate the Earth's dipole momentum evolution during the last 2000 years.

## **Theme Colloquium 12: Scientific Characterization of High-Value Gemstones**

Moderator: Thomas Moses (Gemological Institute of America)

### **Current Status of Synthetic Gem Diamonds and Their Identification**

**Wuyi Wang<sup>1\*</sup> and Thomas Moses<sup>1</sup>**

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Diamond growth technology has experienced rapid progress in the past 20 years. Gem-quality diamonds can be produced with both HPHT (high-pressure and high-temperature) and CVD (chemical vapor deposition) technologies. While HPHT technology basically mimics the growth conditions of natural diamonds in the earth's mantle, the CVD method actually grows diamond in graphite-stable thermodynamic conditions. Faceted gem diamonds, both colorless and fancy-colored, are commercially produced up to 20 carats, comparable to top-quality natural diamonds. At the same time, millions of melee-size gem diamonds (0.005 carat and up) are produced for the gem trade. Post-growth treatments (mainly HPHT annealing and irradiation under a high-energy beam) can not only remove an undesirable brown color but also introduce many types of fancy colorations such as pink/red and blue. Millions of carats of synthetic gem diamonds are produced annually for the gem trade globally. It is very important for the jewelry industry to be able to effectively and accurately separate synthetic diamonds from natural.

All diamonds have lattice defects, from ppm to ppb concentrations or even lower. Main defects include nitrogen, boron, vacancies, dislocations, and combinations of these. Natural diamonds and their synthetic counterparts are supposed to have different defect configurations, such as defect type, concentration, coexistence, and distribution within a

single crystal. Sometimes this difference can be very minor. Artificial treatment could be applied to intentionally minimize the differences to reduce the possibility of identifying synthetics. Natural and synthetic diamonds have a fundamentally different growth habit. Natural diamonds are dominated by a {111} growth sector. HPHT synthetic diamonds normally have multiple growth sectors such as {111}, {100}, and {110}. CVD diamond typically grows in the {100} direction only, but the uneven growth rate creates striations. The ability to capture defects varies significantly among different growth sectors, which are considered the most reliable features in identification. In gem laboratories, a host of gemological and spectroscopic technologies have been developed to enable this separation. GIA's laboratory can identify every single synthetic diamond produced.

Details of the current status of synthetic gem diamonds and their identification will be reviewed in this presentation.

## **Determining the provenance of colored gemstones**

**Mandy Y. Krebs<sup>1</sup> and D. Graham Pearson<sup>2</sup>**

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The geographic origin of gemstones has emerged as one of the major factors affecting their sale on the colored stone market, in large part due to the prestige attributed to certain regions (e.g. sapphires from Kashmir or emeralds from Colombia) but also because of political, environmental and ethical considerations. Identifying the geographic provenance of a colored stone has, therefore, developed into one of the main tasks for gem-testing laboratories, providing a strong motivation to establish accurate scientific methods.

The properties and features of individual gemstones reflect the specific geological conditions of their formation and the main challenge of origin determination is to find the link between the two. In addition, access to a complete collection of authentic reference samples and analytical data for all economically relevant mining areas worldwide is key. Different techniques have been developed for determining gemstone provenance, including a range of gemological observations, and spectroscopic, chemical, and isotopic analyses<sup>[1]</sup>. These have proven useful in distinguishing the origin of gemstones from different geological settings but for many gemstones (including ruby and sapphire) to reliably distinguish between gems from different geographic regions that share a similar geological setting is not always possible. So far, no unique fingerprint exists, and the geographic origin remains a challenge, especially for high-clarity stones, emphasizing the need for a more powerful tool.

Here we will give an overview of the current techniques, and outline some of the challenges and limitations of geographical origin determination of colored gemstones. In addition, we present new trace element data and the first radiogenic isotope compositions (Sr and Pb) obtained for ruby and sapphire from several different localities of geologically similar deposits. The acquisition of quantitative data of a range of ultra-trace elements along with the most commonly observed elements in ruby and sapphire (Mg, Fe, Ti, Ca, Ga, V and Cr) makes it possible to explore new elements as potential provenance discriminators.

Among the elements consistently above the limits of quantification (Zn, Nb, Ni, and Pb), Ni in particular shows promise as a discriminator for amphibolite-type ruby. Measured  $^{87}\text{Sr}/^{86}\text{Sr}$  and Pb isotope ratios clearly show distinct ranges for the different localities of amphibolite-type ruby, ranges for marble-related ruby and metamorphic blue sapphires from different geographic regions overlap. These results suggest that radiogenic isotopes potentially offer a powerful means of provenance discrimination for different localities of amphibolite-type ruby, their potential for geographical origin determination among marble-hosted ruby and metamorphic sapphire, however, appears to be limited.

Giuliani et al., (2014b). In: *Geology of Gem Deposits*. 2nd Ed. MAC Short Course 44, 113-134.

## **Theme Colloquium 13: The Societal Relevance of Apatite**

Moderator: John Rakovan (Miami University of Ohio)

### **Apatite and society: Non-biological uses**

**John M. Hughes<sup>1</sup> and John F. Rakovan<sup>2</sup>**

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Apatite is perhaps the quintessential example of the linkage between mineral extraction and the growth of society. With the first extraction of petroleum and the development of the gasoline-powered internal combustion engine in the mid-19<sup>th</sup> century, humans became a significant geologic agent for the first time in Earth history. Apatite is by far the most significant source of phosphorus on Earth, and since that time large amounts of the mineral have been extracted and processed as the source of that element for use by society. Apatite is essentially the sole source of phosphorus for use as fertilizer; the remarkable rise in Earth population in the 20<sup>th</sup> century was allowed by the use of apatite-extracted phosphorus used in fertilizer manufacture. The rise in Earth population since 1900 from approximately 1.5b to more than 7.5b is mirrored by the rise of worldwide apatite production from essentially nil to nearly 200 million tons annually; worldwide, per capita phosphorus use is approximately 20 kg apatite per year. Simply, apatite allows society to feed the citizens of the Earth.

Apatite-extracted phosphorus has other significant non-biological uses as well. Apatite and the phosphorus extracted therefrom provide the fluorescing agent for fluorescent lights that have illuminated much of the last century of Earth history; apatite is also a significant lasing material, one that can be easily modified by substituent co-doping to create designer lasers with desirable properties. Apatite has also emerged in the past several decades as a very effective agent of environmental cleanup through PIMS, or *Phosphate Induced Metal Stabilization*. In the PIMS process, bone-seeking elements such as Pb, Sr (including radioactive  $^{90}\text{Sr}$ ), and As are efficiently removed from contaminated water that flows

through a permeable reactive barrier of apatite by precipitating minerals such as Sr-apatite and the Pb apatites, removing those elements from interaction with the biological environment. Apatite has also been effectively used as a solid-state repository for radioactive waste, wherein those elements are sequestered in the solid state as a substituent element in apatite, providing a self-annealing, insoluble storage medium for rad waste. An underlying concern for societal consumption of apatite as a source of phosphorus is the limited abundance of extractable quantities of the mineral; peak phosphorus may be as imminent as a decade in the future.

In addition to these and other non-biological uses of apatite, the mineral is significant for its biological uses and as the framework of the human body; an overview of the biological aspects of apatite are the focus of the second portion of this session.

## **Biom mineralization and Biomaterials: Apatite and the Human Body**

**Jill Dill Pasteris<sup>1</sup>**

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The mineral apatite is biologically and medically essential to humans, as well as beneficial in rarely considered ways. As the crystalline component in the nanocomposite bone, apatite is important to the strength, hardness, and toughness of bone. Chemically, it aids the pH balance in the blood due to its inherent phosphate content and the carbonate substitution it allows. That same inherent composition makes bone apatite a major nutrient storage reservoir and ready source of Ca and P. The breadth of its usefulness arises in part from the tunability of apatite's properties as a function of its chemical accommodation. An obvious example is the difference in the properties (e.g., hardness, solubility) of bone apatite and tooth enamel due mostly to a difference in the amount of carbonate substitution in their respective bioapatites. Because calcium and phosphate are major components of body fluid, apatite also can find itself in medically unhealthy situations, e.g., in kidney and salivary stones, as well as breast "calcifications" whose specific apatite composition can be an indicator of future cancer. In the midst of our concern for apatite in present humans, we should not forget its importance in fossilized human remains. Typically, fossil bone and tooth materials consist of apatite, but of a composition that differs from that of the original bioapatite. To the extent that the original carbon and oxygen isotope signatures are preserved in the fossil apatite (most likely in tooth enamel), its analysis brings better knowledge of past climates, migration patterns, and dietary habits of ancient humans.

The importance of bones and teeth to human well being has made their replacement by synthetic substitutes, i.e., biomaterials, a high priority among researchers in medicine and materials science. Biomaterials, which are designed more to replicate a particular functionality than a specific tissue, range from polymers through alloys to specialized glasses and ceramics. In this context, the abundant types of apatite-based biomaterials are viewed as ceramics. The biggest advantage of such apatitic synthetics is their biocompatibility (i.e., do not stimulate negative reactions in the body) and their ability to stimulate growth of new bone, even to the extent of replacing the synthetic substitute. These apatitic materials are

fabricated as (bone) cements, scaffolds, machined ceramics, and plasma-sprayed hydroxylapatite coatings on metal implants. The apatite can be doped with selected cations and anions to change its physical and chemical properties. Incorporation of pharmaceuticals in apatitic biomaterials enables the controlled time-release of drugs in a localized area.

There are still unanswered questions about apatite in the human body and other forms of bioapatite. The mineralogical, biological, and medical aspects of bioapatite are at the core of a vibrantly multidisciplinary field.

## **Theme Colloquium 14: Minerals and Industry: Evaluating the Real Impacts of Mineral Dusts on Human Health**

Moderator: Jessica Elzea Kogel (National Institute for Occupational Safety and Health)

### **What makes an amphibole "asbestos"? History and status of regulatory issues dealing with amphiboles.**

**Ann G. Wylie<sup>1</sup>**

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Most museum samples of amphibole asbestos were named according to macroscopic properties of the asbestiform habit, while the large ore deposits of asbestos are also characterized by enhanced tensile strength. In regulatory policy and practice, only microscopic characteristics are specified in identification. For polarized light microscopy EPA 93 defines asbestos based on fibril width and habit characteristics. Anomalous optical properties are also ubiquitous. For air and water samples, asbestos has been identified by the federal government as one of six minerals meeting a variety of dimensional parameters, observed either by phase contrast microscopy or electron microscopy. These parameters are neither specific for the asbestiform habit nor relatable to carcinogenic potency, yet they are specified for assessing exposure, establishing cleanliness after asbestos removal, estimating risk, and determining PEL levels. They have also incorrectly been applied to the analysis of bulk materials. Criteria for assessing the presence of hazardous mineral fiber are badly needed to unravel the confusion between fragmented amphibole meeting regulatory criteria and carcinogenic amphibole fiber: several will be discussed.

# **Mineral misidentification in connection to potential hazards of mineral dusts**

**Matthew S. Sanchez<sup>1</sup>**

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Monitoring for asbestos has become a commodity-based analysis and while the standard methods used for routine analysis are based on sound mineralogical foundations, unfortunately the knowledge base and approaches taken by many asbestos testing laboratories have little to no knowledge regarding mineralogy. There is a real and current need for more expertise in mineralogy assessments coupled with the health and regulatory communities to further our understanding of potential health consequences to workers and consumers of minerals in our society. As a result, there continues to be on-going issues that the presence of any amphibole has driven the false reporting of asbestos being present, most notably in the non-mineralogical peer reviewed literature, the popular press, and in litigation in the US. The most current issue is that analysis of talc based powders. The errors in the underlying data of these reports are fundamental; they include primarily the misidentification of talc as anthophyllite asbestos and cummingtonite with small-scale coherent reactions to talc and clino-jimthompsonite as anthophyllite asbestos. The amount of these latter minerals is in the ppm range for historic talcum powders. Characterization of these particles will be shown by PLM, SEM utilizing both EDS and EBSD, and TEM with EDS and SAED.



# ***Logistics***

## ***Theme Colloquia Location***

The main entrance to the Carnegie Institution of Science is located at 1530 P St., NW, Washington, D.C. 20005.

## ***Coffee and Lunch Breaks***

In mid-morning and mid-afternoon, proceedings will break for coffee, tea, soda, water, and snacks in the Carnegie building rotunda. At noon, boxed lunches will be served in the rotunda of the Carnegie Building with seating available inside the ballroom and boardroom, or if the weather permits, outside on the grand stairs. **Food is not permitted in the auditorium.**

## ***Wine and Beer***

At 5:30 pm, following the final theme colloquium of each day, participants are welcome to break for wine and beer (included in the registration) in the rotunda of the Carnegie building.

## ***Bathrooms and Coat Room***

Bathrooms are located on the ground floor at the Carnegie Institution for Science Headquarters. Take a right at the bottom of the stairs and the restrooms will be located on your right. Coats and umbrellas can be left on the coat racks beyond the bathroom on the right.

## ***Wifi***

Registrants can access wifi through the network: Carnegie Guest. No password is required. For security purposes, guests will be required to enter their names and email addresses.

***Thursday Evening Reception***  
***At the National Museum of Natural History***  
***Sponsored by GIA***

From 7 to 10 pm on Thursday, June 20, 2019, attendees of the MSA Centennial Symposium and their registered guests are invited to a reception at the National Museum of Natural History, Smithsonian Institution.

The Janet Annenberg Hooker Hall of Geology, Gems, & Minerals will be open for our private viewing, so this is an opportunity to see the Hope Diamond and touch a Martian meteorite in the refined company of mineralogists. You will be free to walk through the exhibits with drinks and heavy hors d'oeuvres, and of course we will toast MSA's centennial. This evening reception was made possible by a generous grant from the Gemological Institute of America (GIA). Customized champagne glasses are a gift of President Mickey Gunter.

**Registrants will enter the reception at the doors located at Constitution Avenue and 10th Street NW, NOT the doors facing the National Mall.**

Ride Shares/Taxis can be hailed at the side entrance of the Carnegie Building at 1530 P St NW. Public transportation is also available via Metro and Bus. The nearest Metro station to the Carnegie Building is Dupont Circle, a 10-minute walk (see map on next page).

At Dupont Circle, you will take the Red Line towards Glenmont. Transfer from the train at Metro Center (the second stop) to any of the Orange Line (towards New Carrollton), the Blue Line (towards Largo) or the Silver Line (towards Largo) trains. Exit at the first stop, Federal Triangle. The museum is easily accessible by foot from this station (5 minutes). The total travel time from the Carnegie Building to the National Museum of Natural History should be approximately 30 minutes.

**You will need your meeting badge for registration at the reception.** Guests will receive badges at the National Museum of Natural History.

# Walking from Carnegie to Dupont Circle Metro

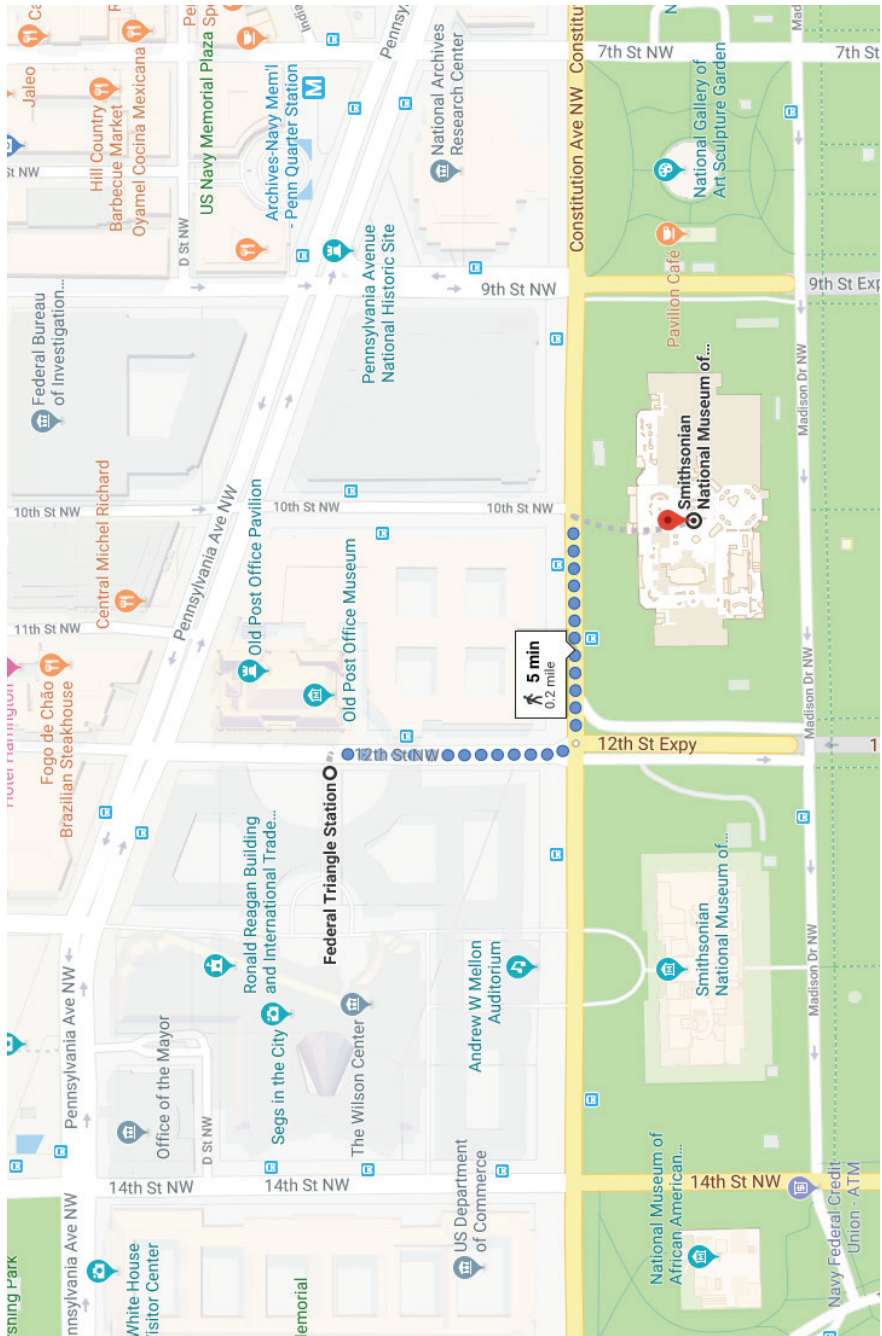


# The Washington DC Metro

Dupont Circle



# Walking from Federal Triangle to the 10<sup>th</sup> and Constitution Ave Entrance of the National Museum of Natural History



# **Congratulations to our Geochemical Society Student Fellows!**

The Geochemical Society (GS) has provided \$2,000 through its Meetings Assistance Program to help four students defray the costs of attending the MSA Centennial Symposium. We thank the GS for its generous contribution and congratulate the four awardees.



Elizabeth Angi-O'Brien  
Miami University of Ohio



Kirkland Broadwell  
Virginia Tech



Cory Eugene Dalton  
Appalachian State University



Zachary Osborne  
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Thanks to our GS Student Fellowship Committee:

Joanne Stubbs (Chair), Huifang Xu, and Katherine Crispin

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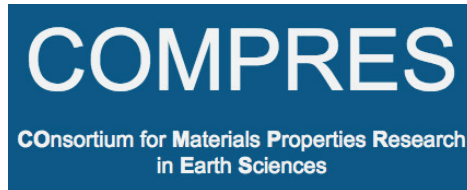
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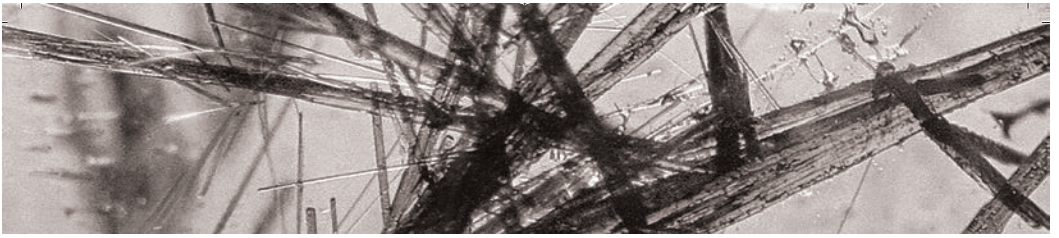
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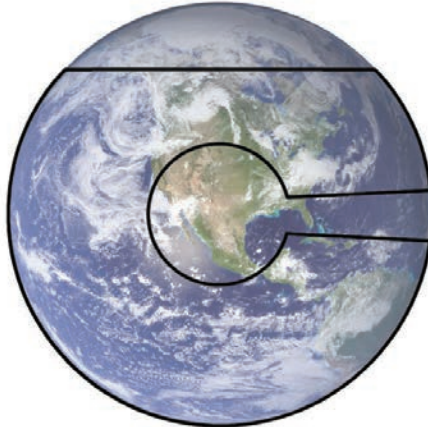
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# A Brief History of the Mineralogical Society of America

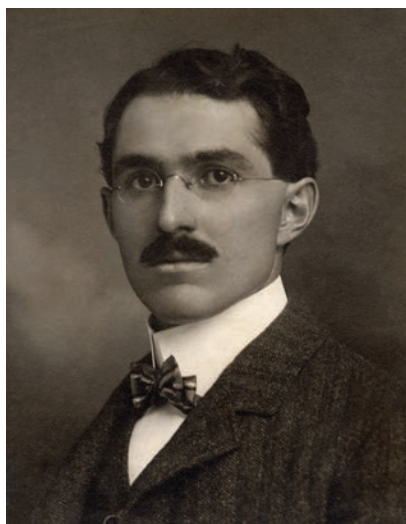
By J. Alexander Speer  
Executive Director Emeritus, MSA

## The Historical Context: Events of 1919

- The 18th Amendment to the United States Constitution, authorizing Prohibition, goes into effect in the United States, and Prohibition begins;
- The United States Congress establishes most of the Grand Canyon as a United States National Park;
- A United States navy seaplane begins the first transatlantic flight;
- The British dirigible R34 lands in New York, completing the first crossing of the Atlantic by an airship;
- The United States Congress approves the 19th Amendment to the United States Constitution, which would guarantee suffrage to women, and sends it to the U.S. states for ratification;
- The Treaty of Versailles is signed and ends World War, but the Treaty fails a critical ratification vote in the United States Senate. It will never be ratified by the U.S.;
- Florida Keys Hurricane kills 600 people;
- **The Mineralogical Society of America is founded.**

## The Founding of MSA

In February 1917 **Edward H. Kraus** (University of Michigan) circulated a typeset letter among 51 mineralogists in the US and Canada inviting them to form an organization which might be called The Mineralogical Society of America. This was a result of discussions over several previous years at the annual meeting of the Geological Society of America. The reason for founding such a society would be to stimulate greater interest in the subject and give wider recognition to the work being done in the Americas. The greatest benefit of such a society was said to be a dignified medium of an independent publication devoted exclusively to publishing of mineralogical papers. Many of the existing publications based in Europe had been unavailable since the start of the war.



Edward H. Kraus

Ann Arbor, Mich., February 5, 1917.

For several years past, some of those attending the annual meetings of the Geological Society of America have discussed the advisability of organizing a separate society composed of persons whose interests lie more especially in the field of Mineralogy. The feeling has been growing that the founding of a Mineralogical Society would do much to stimulate greater interest in the subject and also give wider recognition to the work being done in this field in America. Accordingly, the undersigned, who were in attendance upon the meetings of the Geological Society of America, at Albany, in December, 1916, discussed this question very thoroughly, and it was agreed that the time has come when an organization which might be called "The Mineralogical Society of America" should be formed at as early a date as possible.

While many of the advantages resulting from such an organization are apparent to all interested, the undersigned felt that perhaps the greatest benefit to be derived would be the founding by the society of a journal to be devoted exclusively to the publishing of mineralogical papers. As is well known, there is great need for a dignified medium of publication for the increasing volume of mineralogical investigations which are being carried on in America. Naturally such a publication must be started on a modest basis, and appear perhaps at first as a quarterly. Members of the society would of course receive the Journal free of charge.

With respect to organization and means of publication, mineralogists in America are far behind their colleagues in Europe, but we feel confident that you will respond promptly and favorably to our appeal to unite with us as a charter member in perfecting the organization of this society, the standards of which are to be on a par with those of the Geological Society of America. In order to insure the publication of a journal, which would naturally have a somewhat limited circulation, it was thought advisable that the annual dues be placed at \$10.00.

This letter is being addressed to a selected list of mineralogists in the United States and Canada, and if a sufficient number of favorable replies is received, it is planned to complete the organization sometime during the current year.

Professor Edward H. Kraus, Ann Arbor, Michigan, has been designated to conduct the correspondence looking toward the organization of the society. He will be glad to hear from you at your earliest convenience.

Very sincerely yours,

EDWARD H. KRAUS,	THOMAS L. WALKER,
ALEXANDER H. PHILLIPS,	EDGAR T. WHERRY,
FRANK R. VAN HORN,	HERBERT P. WHITLOCK.

Of the 35 replies received to Dr. Kraus' letter by October 1917, 29 were favorable, but it was suggested formation be delayed. A mimeographed letter was sent by Dean Kraus in October 1917 as a follow-up, arguing that the formation of the organization would be put on hold because of "very unsettled conditions at present". The "very unsettled conditions" were a result of the April 1917 entry of the United States into the First World War, which had been ongoing since July 1914.

The first opportunity to organize a society after the war was at the 1919 Geological Society of America Meeting in Boston, MA. Dr Kraus restarted his efforts to form a society during the spring and summer of 1919. He wrote a draft constitution and circulated it among a few individuals for comment in October 1919. An organizational notice was published in the November 28, 1919 issue of *Science*. Invitation letters to attend the organizational meeting were sent December 12, 1919 to those who had earlier expressed interest in joining.

Leading up to the organizational meeting, three issues occupied Kraus's attention: the name of the society, who should belong, and the promised publication. Various formulations of the words crystallography, mineralogy, petrography, society, and America were suggested. One humorist pointed out that many minerals are "colloidal" and no one seemed anxious to belong to a Colloidal Society of America. In the end, it was concluded that the simplest name, Mineralogical Society of America, was the best.

Initially it was envisioned that only those who had written or published would be or want to be members. It was concluded that the society would best serve the interest of the subject by having as large a following as possible. The society was to promote interest in crystallography, mineralogy, petrography, and allied sciences. Following society practices of the time, however, individuals who had published results of mineralogical research would be fellows whereas members would be individuals engaged or interested in mineralogical work.

Dr. Edgar T. Wherry proposed to Dr. Kraus in a letter dated September 28, 1919 that *The American Mineralogist* (first published July 1916) be incorporated as the new journal of the society. Wherry felt that there would be little demand for two mineral publications in the Americas, and making *The American Mineralogist* a society journal would assure its future. The journal had been having financial difficulties, with any shortfalls covered by what were then significant donations from Roebing and Burrage. As it turned out, the journal was accepted as the society journal



Edgar T. Wherry

along with its original name with the subtitle of "Journal of the Mineralogical Society of America". In part, this was at the insistence of the journal founders and some of its financial supporters. The first issue published by MSA was the January 1920 issue.

Twenty-eight mineralogists attended the organizational meeting at the Harvard University Geological Museum on December 30, 1919, and MSA came into being. The participants were also invited to view the mineral collection of Albert C. Burrage in his home. This impressive collection of gold specimens, along with Bisbee azurites and malachites, subsequently found its way into the Harvard Mineralogical Museum in 1948 as a bequest of Burrage. The outcome of the organizational meeting was published in the February 27, 1920 issue of *Science* (page 219-220).

The MSA Executive Council met the next morning, December 31, 1919 at 8:15 am. At that meeting the details of the offer to make *The American Mineralogist* the society journal, a list of associate editors, affiliation with the Geological Society of America, and the contents of the note to appear in *Science* were all considered. At 11:00 am the first MSA Council met, and it accepted the recommendations of the Executive Council.

MSA had its first annual meeting in 1920. Thereafter MSA focused its attention on improving the journal and the financial health of the society, a task made much easier by Washington Roebling's gift in 1927, but then more difficult by the Great Depression and WW II. Except for initiating the Roebling Medal in 1937 and the MSA Award in 1950, MSA remained pretty much the same for years. Things began to change around MSA's 50th anniversary, slowly at first then more rapidly — special publications in the 1960s, short courses, *Reviews*, and research grants in the 1970s, Lecture Program, AMU Awards, and a stand-alone office in the 1980s, Distinguished Public Service Medal, monographs, textbooks, MSA-Talk, and website in the 1990s, Mineralogy-4-Kids, Ask-a-Mineralogist, Dana Medal, *Handbook of Mineralogy*, GeoScienceWorld, online archive of the *American Mineralogist*, and *Elements* in the 2000s.

[ Reprinted from *SCIENCE, N. S., Vol. LI., No. 1313, Pages 219-220, February 27, 1920* ]

**THE MINERALOGICAL SOCIETY OF AMERICA**

At a meeting held in the quarters of the Department of Mineralogy at Harvard University on December 30 a group of 28 mineralogists from all sections of the United States, including representatives from Canada, organized a new society to be known as the Mineralogical Society of America. This ac-



## List of Past MSA Officers

<b>Year</b>	<b>President</b>	<b>Vice President</b>	<b>Secretary</b>	<b>Treasurer</b>
2019	Mickey Gunter	Carol D. Frost	Bryan C. Chakoumakos	Thomas S Duffy
2018	Michael Brown	Mickey Gunter	Bryan C. Chakoumakos	Thomas S Duffy
2017	George E. Harlow	Michael Brown	Bryan C. Chakoumakos	Thomas S Duffy
2016	Rebecca A. Lange	George E. Harlow	Bryan C. Chakoumakos	Howard W. Day
2015	Steven B. Shirey	Rebecca A. Lange	Andrea M. Koziol	Howard W. Day
2014	David J. Vaughan	Steven B. Shirey	Andrea M. Koziol	Howard W. Day
2013	John M. Hughes	David J. Vaughan	Andrea M. Koziol	Howard W. Day
2012	Michael F. Hochella, Jr.	John M. Hughes	Andrea M. Koziol	Darrell J. Henry
2011	David L. Bish	Michael F. Hochella, Jr.	Mickey E. Gunter	Darrell J. Henry
2010	John B. Brady	David L. Bish	Mickey E. Gunter	Darrell J. Henry
2009	Nancy L. Ross	John B. Brady	Mickey E. Gunter	Darrell J. Henry
2008	Peter J. Heaney	Nancy L. Ross	Mickey E. Gunter	John M. Hughes
2007	Barbara L. Dutrow	Peter J. Heaney	George E. Harlow	John M. Hughes
2006	John W. Valley	Barbara L. Dutrow	George E. Harlow	John M. Hughes
2005	Robert Hazen	John W. Valley	George E. Harlow	John M. Hughes
2004	Michael A. Carpenter	Robert Hazen	George E. Harlow	James G. Blencoe
2003	Douglas Rumble, III	Michael A. Carpenter	David M. Jenkins	James G. Blencoe
2002	Rodney C. Ewing	Douglas Rumble, III	David M. Jenkins	James G. Blencoe
2001	Cornelis Klein	Rodney C. Ewing	David M. Jenkins	James G. Blencoe
2000	William Carlson	Cornelis Klein	David M. Jenkins	Brooks Hanson
1999	John Ferry	William Carlson	Barb Dutrow	Brooks Hanson
1998	E. Bruce Watson	John M. Ferry	Barb Dutrow	Brooks Hanson
1997	David Veblen	Bruce E. Watson	Barb Dutrow	Brooks Hanson
1996	Gordon E. Brown, Jr.	David R. Veblen	Barb Dutrow	Rosalind T. Helz

<b>Year</b>	<b>President</b>	<b>Vice President</b>	<b>Secretary</b>	<b>Treasurer</b>
1995	James J. Papike	Gordon E. Brown, Jr.	Steve Guggenheim	Rosalind T. Helz
1994	Bernard W. Evans	James J. Papike	Steve Guggenheim	Rosalind T. Helz
1993	Alexandra Navrotsky	Bernard W. Evans	Steve Guggenheim	Rosalind T. Helz
1992	Michael J. Holdaway	Alexandra Navrotsky	Steve Guggenheim	James Whitney
1991	Malcolm Ross	Michael J. Holdaway	Maryellen Cameron	James Whitney
1990	Peter Robinson	Malcolm Ross	Maryellen Cameron	James Whitney
1989	Charles W. Burnham	Peter Robinson	Maryellen Cameron	James Whitney
1988	David B. Stewart	Charles W. Burnham	Maryellen Cameron	Gordon Nord
1987	Paul H. Ribbe	David B. Stewart	Henry O. A. Myers	Gordon Nord
1986	Paul B. Barton, Jr.	Paul H. Ribbe	Henry O. A. Myers	Gordon Nord
1985	Hans Eugster	Paul B. Barton, Jr.	Henry O. A. Myers	Gordon Nord
1984	Charles T. Prewitt	Hans P. Eugster	Henry O. A. Myers	Odette B. James
1983	Edwin Roedder	Charles T. Prewitt	M. Charles Gilbert	Odette B. James
1982	Donald H. Lindsley	Edwin Roedder	M. Charles Gilbert	Odette B. James
1981	Gerald V. Gibbs	Donald H. Lindsley	M. Charles Gilbert	Odette B. James
1980	W. Gary Ernst	Gerald V. Gibbs	M. Charles Gilbert	Malcolm Ross
1979	David R. Wones	W. Gary Ernst	Larry W. Finger	Malcolm Ross
1978	Peter J. Wyllie	David R. Wones	Larry W. Finger	Malcolm Ross
1977	F. Donald Bloss	Peter J. Wyllie	Larry W. Finger	Malcolm Ross
1976	E-an Zen	F. Donald Bloss	Larry W. Finger	George W. Fisher
1975	Arnulf Muan	E-an Zen	Joan R. Clark	George W. Fisher
1974	Sturges W. Bailey	Arnulf Muan	Joan R. Clark	Philip M. Bethke
1973	Joseph V. Smith	Sturges W. Bailey	Joan R. Clark	Philip M. Bethke
1972	Hatten S. Yoder, Jr.	Joseph V. Smith	Joan R. Clark	Alvin Van Valkenburg
1971	Julian R. Goldsmith	Hatten S. Yoder	Arnulf Muan	Alvin Van Valkenburg
1970	William F. Bradley	Julian R. Goldsmith	Arnulf Muan	Alvin Van Valkenburg
1969	Francis J. Turner	William F. Bradley	Ralph J. Holmes	Alvin Van Valkenburg
1968	James B. Thompson, Jr.	Francis J. Turner	Ralph J. Holmes	Marjorie Hooker

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1964	Leonard G. Berry	George T. Faust	George Switzer	Marjorie Hooker
1963	Cornelius S. Hurlbut, Jr.	Leonard G. Berry	George Switzer	Marjorie Hooker
1962	Ian Campbell	Cornelius S. Hurlbut Jr.	George Switzer	Marjorie Hooker
1961	E. F. Osborn	Ian Campbell	George Switzer	Marjorie Hooker
1960	Joseph Murdoch	E. F. Osborn	George Switzer	Marjorie Hooker
1959	Ralph E. Grim	Joseph Murdoch	George Switzer	Marjorie Hooker
1958	George E. Goodspeed	Ralph E. Grim	C. S. Hurlbut, Jr.	Marjorie Hooker
1957	D. Jerome Fisher	George E. Goodspeed	C. S. Hurlbut, Jr.	Earl Ingerson
1956	Clifford Frondel	D. Jerome Fisher	C. S. Hurlbut, Jr.	Earl Ingerson
1955	Harry H. Hess	Clifford Frondell	C. S. Hurlbut, Jr.	Earl Ingerson
1954	Sterling B. Hendricks	Harry H. Hess	C. S. Hurlbut, Jr.	Earl Ingerson
1953	J. D. H. Donnay	Hardy V. Ellsworth	C. S. Hurlbut, Jr.	Earl Ingerson
1952	Michael Fleischer	J. D. H. Donnay	C. S. Hurlbut, Jr.	Earl Ingerson
1951	A. Pabst	Michael Fleischer	C. S. Hurlbut, Jr.	Earl Ingerson
1950	George Tunell	Ralph E. Grim	C. S. Hurlbut, Jr.	Earl Ingerson
1949	John W. Gruner	J. D. H. Donnay	C. S. Hurlbut, Jr.	Earl Ingerson
1948	M. A. Peacock	Adolph Pabst	C. S. Hurlbut, Jr.	Earl Ingerson
1947	Martin J. Buerger	Carl Tolman	C. S. Hurlbut, Jr.	Earl Ingerson
1946	Paul F. Kerr	S. B. Hendricks	C. S. Hurlbut, Jr.	Earl Ingerson
1945	Kenneth K. Landes	George Tunell	C. S. Hurlbut, Jr.	Earl Ingerson
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1943	John F. Schairer	John W. Gruner	Paul F. Kerr	Earl Ingerson
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<b>Year</b>	<b>President</b>	<b>Vice President</b>	<b>Secretary</b>	<b>Treasurer</b>
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1934	John E. Wolff	William A. Tarr	Paul F. Kerr	W.T. Schaller
1933	Herbert P. Whitlock	Frank B. Guild	Albert B. Peck	W.T. Schaller
1932	Alexander N. Winchell	Joseph L. Gillson	Frank R. Van Horn	W.T. Schaller
1931	Alexander H. Phillips	William F. Foshag	Frank R. Van Horn	W.T. Schaller
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1928	Esper S. Larsen	Lazard Cahn	Frank R. Van Horn	Alexander H. Phillips
1927	Austin F. Rogers	George L. English	Frank R. Van Horn	Alexander H. Phillips
1926	Waldemar T. Schaller	George Vaux, Jr.	Frank R. Van Horn	Alexander H. Phillips
1925	Arthur S. Eakle	Herbert P. Whitlock	Frank R. Van Horn	Alexander H. Phillips
1924	Henry S. Washington	Washington A. Roebling	Frank R. Van Horn	Alexander H. Phillips
1923	Edgar T. Wherry	George F. Kunz	Frank R. Van Horn	Albert B. Peck
1922	Thomas L. Walker	Frederick A. Canfield	Herbert P. Whitlock	Albert B. Peck
1921	Charles Palache	Waldemar T. Schaller	Herbert P. Whitlock	Albert B. Peck
1920	Edward H. Kraus	Thomas L. Walker	Herbert P. Whitlock	Albert B. Peck

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# *Notes*

# *Notes*

