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Fan et al. recently performed in situ analysis of oxygen isotopes in garnet grains from the Dongping gold deposit, shedding new light on the source and subtle evolution of ore-forming fluids: highly variable $\delta^{18}$O contents within individual grains reveal multiple pulses of magmatically derived fluids that mixed with a large volume of meteoric water throughout the history of gold mineralization.

Data obtained on CAMECA IMS 1280 at WiscSIMS Laboratory, Department of Geoscience, Univ. of Wisconsin–Madison, USA.


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Water in Planetary Bodies

Guest Editors: Yves Marrocchi and Pierre Beck

The Quest For Water
Yves Marrocchi and Pierre Beck

We Drink Good 4.5-Bilion-Year-Old Water
Cecilia Ceccarelli and Fujun Du

Ocean Worlds In Our Solar System
Julie C. Castillo-Rogez and Klára Kalousová

Water in Differentiated Planets, the Moon, and Asteroids
Anne H. Peslier and Maria Cristina de Sanctis

Recent Advances in our Understanding of Water and Aqueous Activity in Chondrites
Lionel G. Vacher and Wataru Fujiya

Origin of Water in the Terrestrial Planets: Insights from Meteorite Data and Planet Formation Models
André Izidoro and Laurette Piani
PARTICIPATING SOCIETIES

The Mineralogical Society of the UK and Ireland is an international society for those working in the mineral sciences. The society aims to advance the knowledge of the science of mineralogy and its application to other subjects, including crystallography, geochemistry, and environment. The Society News Editor is Kevin Murphy.

Website: www.minsoc.org
Contact: info@minsoc.org
Society News Editor: Kevin Murphy (kevin.murphy@minsoc.org)

The Clay Mineral Society (CMS) began in 1952, was founded as the Clay Minerals Committee of the US National Academy of Sciences – National Research Council. In 1962, the CMS was incorporated as a non-profit organization of individuals interested in clay and related disciplines. Membership benefits include a subscription to Elements, a reduced subscription to the Clay Minerals Society Newsletter, and access to discounted subscriptions to the American Journal of Science.

Website: www.cms.org
Contact: cms@clays.org
Society News Editor: Bhabananda Biswas (bhabananda.biswa@unsw.edu.au)

The Geochemical Society (GS) is a non-profit organization founded in 1955 for scientists and students interested in the study of geochemistry. The purpose of the Society is to promote the advancement of scientific knowledge through the exchange of information, ideas, and research.

Website: www.gsgeochem.org
Contact: office@appliedgeochemists.org
Society News Editor: Costanza Bonadiman (bonadiman@iu.edu)

The Mineralogical Association of Canada was incorporated in 1955 to promote the advancement of knowledge of mineralogy and the related disciplines of petrology, geochemistry, and economic geology. Any person interested in the sciences of minerals or mineralogy and related disciplines is eligible to be a member of the Association. Membership benefits include a subscription to Elements, a reduced subscription to Geoscience Canada, and reduced registration fees at conferences.

Website: www.macc.org
Contact: office@geocan.org
Society News Editor: Yvette Monette (yvette.monette@geocan.org)

The European Association of Geochemistry was founded by 35 governments and is a non-profit organization dedicated to promoting geochemical information. The society is a dynamic association that organizes the Goldschmidt Conference® in Europe, publishes Geochemical Perspectives and Geochemical Perspectives Online, recognizes scientific excellence through awards, and supports research and education.

Website: www.eage.eu.com
Contact: info@eage.eu.com
Society News Editor: Alina Williams (williamsa@eage.com)

The International Association of GeoChemistry (IAGC) has a preeminent international geopolitical focus since 1967. Its principal objectives are to foster cooperation in the advancement of applied geochemistry by sponsoring scientific symposia and conferences organized by its working groups and by supporting the production and publication of Journal, Applied Geochemistry. The Association functions through its committees of IAGC and is administered by its Council, comprising an executive and ten ordinary members.

Website: www.iage-society.org
Contact: businessoffice@iagc-society.org
Society News Editor: Chris Gardiner (BusinessOffice@IAGC-Society.org)

www.socminet.it
Contact: socminet.it
Society News Editor: Costanza Bonadiman (bonadiman@iu.edu)

The International Association of Geoanalysts (IAGA) is a professional organization representing the international community interested in the advancement of geochemical sciences. The society is dedicated to promoting the advancement of geochemical sciences and to the development of the scientific community through the exchange of information and ideas.

Website: www.geoanalyst.org
Contact: jmc@bgc.org
Society News Editor: Alia Cruz-Uribe (alia.cruzuribe@jwu.edu)

The Polskie Towarzystwo Mineralogiczne (Polish Society of Geology of Poland) was founded in 1969. It aims to promote the interests of Polish geochemistry, crystallography, and economic geology. The society promotes links between the Polish geochemical sciences, geology, and technology through its annual conferences, field trips, and publications. Membership benefits include subscriptions to Mineralogy and Elements.

Website: www.pts.org.pl
Contact: pts@pts.org.pl
Society News Editor: Anna Pietranik (anna.pietranik@uwr.edu.pl)

The Sociedad Española de Mineralogía (Spanish Society of Mineralogy) was founded in 1975 to promote research in mineralogy, petrology, and geochemistry. The society organizes annual meetings and conferences and the training of young researchers via seminars and workshops. Membership benefits include subscriptions to Mineralogía y Meteorología, Geología, and Elements.

Website: www.sem.org
Contact: pmin@min.edu
Society News Editor: Anna Pietranik (anna.pietranik@uwr.edu.pl)

The Swiss Geological Society was founded in 1882 and comprises specialist groups in mineralogy, petrology, sedimentology, and paleontology. The society is part of the Swiss Academy of Sciences and promotes the advancement and dissemination of scientific research in Switzerland. The society coorganizes the annual Swiss International ScienceColloquium and publishes the Swiss Journal of Geosciences (SGJ), which is now fully “open access.” Membership benefits include free access to the SGJ and participating in the SfG.

Website: https://geolsoc.ch
Contact: office@geolsoc.ch
Society News Editor: Julienn Allar (julienn.allar@swisstech.ethz.ch)

The Mineralogical Society of America (MSA) was founded in 1933 for scientists, collectors, and educators who share an interest in the study of meteorites and minerals. The society promotes links between mineralogists and materials and their parent asteroids, comets, and planets. Membership benefits include subscriptions to the American Mineralogist, Meteoritics and Planetology, and Elements. The society organizes annual meetings, workshops, and field trips, and it supports young planetary scientists worldwide.

Website: www.mineralogical.org
Contact: meteo@mineralogical.org
Society News Editor: Cari Corrigan (corrigan@jwu.edu)

The Japanese Association of Geosciences and Geochemistry (JAG) was established in 1967 by merging the Mineralogical Society of Japan, founded in 1895, and the Alpine Association for the Study of the Earth, founded in 1882. The JAG covers the fields of mineralogy, geochemistry, and petrology. Membership benefits include subscriptions to the Journal of Mineralogical and Petrological Sciences (JMP), the Geochemical Journal, and Elements.

Website: www.jams.ac.jp
Contact: KY10422@nifty.ne.jp
Society News Editor: Yusuke Seto (seto.y@yomiuri-u.ac.jp)

The International Association on the Genesis of Ore Deposits (IAGOD) was established in 1963 to promote international cooperation and to increase knowledge in the field of the genesis of ore deposits: it is affiliated to the International Union of Geological Sciences (IUGS). The society organizes quadrennial symposiums and the International Geological Congress and SGa Biennial Meetings. The society promotes links with other groups and commissions promote ore deposit research and sponsor an international speaker seminar. The society organizes annual meetings and supervises the publication of proceedings.

Website: www.iagod.org
Contact: http://iagod.net/node/87
Society News Editor: Simon Jowitt (simon.jowitt@unl.edu)

Affiliated Societies
The Mineralogical Association of Canada, the European Mineralogical Union, and the International Association for the Study of Clays are affiliates of elements.

The affiliated status is reserved for those organizations that serve as an “umbrella” for other groups in the fields of mineralogy, geochemistry, and petrology but that do not themselves have a membership base.
ONE MINERAL TO RULE THEM ALL

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Your starter for ten: what is the connection between the minerals: olivine, garnet, ice, magnetite, and quetzalcoatlite? Anyone?

The answer (of course!) is that they are all past winners of the annual mineralogical nerd fest known as the Mineral Cup (@mineralcup)—a Twitter competition founded in 2017 by University of Hull geology professor Eddie Dempsey following a seemingly innocuous tweet of his claiming that “quartz is undeniably the greatest of all minerals.” (see link below for the full origins story). The resulting replies (largely questioning his life choices) led to the now annual event that runs throughout the month of September to identify the “best” mineral from a set of 32 candidates (chosen by an ever-evolving set of community-defined rules and judged on an idiosyncratic range of criteria, ranging from the soundly scientific to the utterly bizarre). I am writing this editorial just as the 2022 competition has come to a dramatic close with fluorite beating zircon convincingly in the final on the basis of its “cubic habit, octahedral cleavage, rainbow of colours, and of course its fluorescent glow...”.

Although the mineralogical trash talk and WWF-style memes are a lot of fun (see below for a typical example), the Mineral Cup provides a much needed reminder of the power of minerals to engage and inspire us—more than any of the other copycat competitions that quickly sprung up in its wake (DinoCup, anyone?). According to the organisers, this year’s competition racked up 3.7 million impressions, with each match averaging 100 to 150 replies or quote-tweets campaigning for their minerals, totaling over 3500 photos, stories, facts, and arguments. This provides a great opportunity for people of all ages to engage with our subject, and is a fantastic educational resource for all (be honest, how many of you could give the formula of 2021 winner quetzalcoatlite? I certainly couldn’t, but having checked it out, it is now included as a case study in cation coordination environments and the importance of tellurium for the energy transition in my mineralogy class). If you ever need a reminder of why we decided to specialise in the study of these amazing natural materials, or a way to inspire the next generation of mineralogists, the Mineral Cup is just the ticket.

Working with guest editors Yves Marrocchi and Pierre Beck on this issue of Elements “Water in Planetary Bodies” reminded me of undoubtedly the hardest fought and most controversial battle for the Mineral Cup Crown in 2019: quartz versus ice. This battle brought out the very worst in the “not a mineral” crowd, with shock, horror, and even anger expressed that a substance not even stable at room temperature and pressure could be ever considered a mineral in the first place, never mind one capable of beating quartz—the mineral that started it all! I urge those people to take a journey through this issue: drill through the icy crusts of Europa, Enceladus, Ganymede, and Titan, skate across the ice-filled Korolev crater of Mars, sample the icy deposits at the Moon’s south pole, then tell me that ice is not a worthy candidate for the mineralogical champion of champions! If we needed any starker reminder of the importance of water in all its forms, this issue urges us to consider Earth’s planetary twin Venus—once a potentially habitable, water-rich planet with similar mass, size, and density to our own, driven for reasons still debated past a critical tipping point that led to a runaway greenhouse effect and the dry hellscape of 450 °C surface temperatures it enjoys today. Closer to home, ice is now arguably the world’s most endangered mineral; an entire species pushed to the verge of extinction by human-induced changes to the thermodynamic habitat where it thrives. We’d do well to heed the warning from our planetary neighbours...

So enjoy the ride as Marrocchi and Beck guide you through the story of water from the birth of the Solar System to the present day. And for the ice naysayers: you’ll miss it when it’s gone!

Richard Harrison

The Story of the Mineral Cup: https://eddiedempsey.wordpress.com/2017/10/15/the-first-mincup/
ABOUT THIS ISSUE
At first glance, the presence of water may appear as a very earthy characteristic. However, observations of the Universe and Solar System have revealed a very different reality where water molecules are omnipresent in liquid, gaseous, or solid form. From cold molecular clouds to magma oceans and the young Solar System, water is a major constituent and player in astrophysical and geological processes. Within our Solar System, water has been found to occur and react in asteroidal, lunar, and planetary environments. In fact, most water molecules have borne witness to the Solar System’s formation and evolution over the past 4.5 billion years.

This issue of *Elements* details the diversity of environments and processes where water is present and involved, offering a journey through space and time seen through the spectrum of this fundamental molecule.

SOLICITING NEW VOICES
*Elements* regularly publishes short, 1- to 2-page feature columns in addition to our thematic content and society news items. We welcome your contribution on any topic you think would be of interest to the mineralogy–geochemistry–petrology community. Please submit your ideas to Esther Posner (editorialteam.elements@gmail.com) or to the individuals mentioned below. We look forward to hearing from you!

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

**People in the News** highlights the accomplishments of members of our communities, awards they have received, or exciting new projects in which they are engaged. We rely on members to bring to our attention the relevant people.

**Teaching Mineralogy, Geochemistry, and Petrology** presents ideas and tools for effective teaching and the resources that are available to instructors. With recent demand for online instructional tools, such a column is more important than ever!

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

**Life in Science** focuses on ways to make all stages of your career as a geoscientist (as student, professional, or retiree) easier and more satisfying.

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

**Elements’ Toolbox** presents new technological developments of interest to our readers. Articles focus on instrumental techniques, analytical and compositional methods, as well as on laboratory design.

**Meeting Calendar** is a list of workshops, short courses, and conferences that are of interest to the mineralogy–geochemistry–petrology community. Contact Andrea Koziol (akoziol1@udayton.edu) to add your meeting to the list.

**Parting Shots**, always placed at the end of the magazine, provides a lighter contrast to the serious stuff in the earlier pages. Intriguing, beautiful, or baffling photographs take the reader on a relaxing voyage into the web of connections that make the realm of *Elements* so enthralling.

**GeoScience Slam** is a unique corner for creative arts related to geoscience. We welcome your geo-inspired poetry/prose (<2000 words) or artwork. Don’t be shy! This feature is a fitting place for your artistic talents.

**Elements Heritage** preserves the history of individuals who contributed to the development of the fields of mineralogy, petrology, and geochemistry. These articles are not solely focused on scientific contributions, but also on their personal story, details that capture the “human” aspect behind the scientist.

Richard Harrison, Becky Lange, Janne Blichert-Toft, Esther Posner, and Jodi Rosso

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**Elements Issues on Space**

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Meet the Authors

**Pierre Beck** works on the mineralogy and chemistry of different types of extraterrestrial materials, ranging from Martian meteorites to carbonaceous chondrites. He uses laboratory-based experimental setups to characterize the infrared properties of extraterrestrial materials, their mineralogy, organochemistry, and connection with known Solar System small bodies. He is currently a professor at the Institut de Planetologie et Astrophysique de Grenoble at the Université Grenoble Alpes in France. He was previously a postdoctoral fellow at the Geophysical Laboratory at the Carnegie Institution for Science, USA. He completed his PhD in 2005 at the École Normale Supérieure de Lyon, France.

**Julie Castillo-Rogez** is a geophysicist interested in the formation and evolution of icy moons and dwarf planets. Her research focuses on the feedbacks between geochemical and physical evolution in order to predict the properties of potential ocean worlds and inform future spacecraft missions. After completing her PhD in 2001 at the University of Nantes in France, she moved to the Jet Propulsion Laboratory in Pasadena, California, USA, first as a postdoctoral fellow and then as a research scientist. She has been the Project Scientist for NASA’s Dawn extended mission, and is currently a co-investigator on the Europa Clipper mission.

**Cecilia Ceccarelli** is an astronomer at the Institut de Planétologie et d’Astrophysique de Grenoble at the Université Grenoble Alpes in France. After her PhD in cosmology at the University of Rome, Italy in 1982, she has worked on star formation and astrochemistry. She has been involved with the ESA (European Space Agency) satellites ISO (Infrared Space Observatory) and HSO (Herschel Space Observatory), as well as numerous observation campaigns with major radio telescopes (e.g., IRAM, ALMA, VLA). In 2006, she was awarded the prize of “Femme Scientifique de l’Année” (Woman Scientist of the Year) by the French Minister of Research. She has led numerous projects in star formation and astrochemistry. In 2017, she was awarded an ERC (European Research Council) Advanced Grant for the project “The Dawn of Organic Chemistry” and, in 2018, a MSCA (Marie-Slowovska-Curie-Action) ITN (Initial Training Network), entitled “Astro-Chemical Origins”.

**Maria Cristina De Sanctis** is a planetary scientist working in the field of planetary surfaces, icy satellites, and small bodies of the Solar System. She received a degree in physics and PhD in astronomy, and is a senior researcher at the Institute for Space Astrophysics and Planetology in Italy. She is an expert in instrumentation for planetary missions, in particular multispectral cameras and imaging spectrometers, data processing, and thermal evolution of planetary bodies, including comets and asteroids. She is involved in a large number of space missions and experiments, and is a member of international boards and committees for Solar System exploration.

**Fujun Du** is an astrophysicist at Purple Mountain Observatory in China, which he joined in 2017. He earned his PhD from the Max Planck Institute for Radio Astronomy, Germany in 2012, and then did postdoctoral research at the University of Michigan, USA. He mainly works on the chemistry of the interstellar medium and protoplanetary disks. Through modeling, he has explained the observed abundance of hydrogen peroxide, and predicted the existence of the hydroperoxyl radical, which was later observationally confirmed. He has also explained the observed deficiency of CO and water in a sample of protoplanetary disks and the existence of hydrocarbon rings in high-resolution images of two disks, by invoking a spatially differentiated elemental distribution of carbon and oxygen.

**Wataru Fujiya** is an associate professor at Ibaraki University in Japan. In 2012, he received his PhD from the University of Tokyo, Japan, where he studied carbonate minerals in chondrites. He then moved to the Max Planck Institute for Chemistry at Mainz in Germany and worked as a postdoc with Dr. Peter Hoppe. In 2015, he took up a position at Ibaraki University, Japan. His research interest is the origin of water and other volatiles in planets and small bodies. He is involved in the initial analysis team of JAXA’s Hayabusa2 mission, and in the sample analysis working team of JAXA’s Martian Moons eXploration (MMX) mission.

**Andre Izidoro** is a Welch Fellow at Rice University, USA. After completing his PhD in 2013 at São Paulo State University in Brazil, he moved to France for post-docs at Université Côte d’Azur and Université de Bordeaux. He has also held a FAPESP Young Investigator Fellow position in São Paulo, Brazil. He uses computer simulations to understand planet formation and dynamical evolution in our Solar System and beyond, with special focus on the origin of terrestrial worlds.

**Klára Kalousová** is a geophysicist interested in the long-term thermal and structural evolution of icy moons and dwarf planets that harbor deep liquid oceans. She uses computer simulations to study large-scale deformation, as well as heat and material transport within these bodies’ interiors. In particular, she focuses on the partial melting of ice layers and subsequent meltwater percolation through these layers towards the internal ocean. After a PhD en-cotutelle between Charles University (Czech Republic) and Nantes University (France) obtained in 2015 and a postdoc at the Jet Propulsion Laboratory (California, USA), she is now an assistant professor at the Department of Geophysics at Charles University.

**Yves Marroccoli** is a cosmochemist specialized in ion probe (SIMS) analysis of primitive meteorites. His research focuses on understanding the conditions and chronology of the formation of the first solids of the Solar System. He also studies the hydration conditions of asteroids and the physicochemical conditions of their geological evolution during fluid circulations. After a PhD in rare gas geochemistry obtained in 2005 and a postdoc at George Washington University in Saint Louis, USA, he is now a researcher and deputy director of the Centre de Recherches Pétrographiques et Géochimiques in Nancy, France.
Anne Peslier is an igneous petrologist. Her research focus has been on water (aka hydrogen) in the Earth’s upper mantle and in Martian meteorites. Her goal is to understand how water is distributed in the interior of differentiated planetary bodies and the processes that lead to that distribution, what is the origin of water in terrestrial planets, and how did water influence planetary evolution. After 15 years at NASA-Johnson Space Center, USA, she is currently an affiliate faculty member at New Mexico State University, USA.

Laurette Piani is a cosmochemist whose research focuses on the origin and distribution of volatile elements, such as H, C, O, or S, in the early Solar System. She conducts petrological observations and chemical and isotopic analyses of meteorites using bulk and in situ techniques, such as secondary ion mass spectrometry (SIMS), to understand the main steps of the formation of their volatile-bearing components. After completing her PhD in 2012 at the National Museum of Natural History in France, she worked as a postdoctoral fellow at Hokkaido University in Japan and at the Centre de Recherches Pétrographiques et Géochimiques (CRPG) in France. She became a CNRS research scientist at CRPG in 2018.

Lionel Vacher is currently a CNES postdoctoral fellow at the Institut de Planétologie et d’Astrophysique de Grenoble, France. He received his PhD in geosciences from the University of Lorraine, France, in 2018. His thesis focused on the mineralogical and isotopic analysis of carbonate and serpentine minerals in hydrated chondrites to decipher the origin of water and retrace the physicochemical conditions of aqueous alteration. He completed a postdoctoral position with Ryan Ogliore at Washington University in St. Louis, USA, in 2021 on the analysis of paired oxygen and sulfur isotope systematics in cosmic symplectite using secondary ion mass spectrometry.

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THE GOLDEN AGE OF MINERALOGY: REFLECTIONS BY IMA MEDALISTS

Frank C. Hawthorne (IMA Medalist 2009; Distinguished Professor Emeritus, University of Manitoba, Canada)

Traditionally, mineralogy has involved the description of minerals via their properties, chemical composition, and occurrence. Minerals constitute a significant part of the Earth and rocky planets, and most Earth and planetary scientists work on some aspect of minerals and their response to changing conditions. As a result, the justification for doing mineralogy is almost always framed in terms of how useful it is to contiguous disciplines. Mineralogists are rarely funded to look at scientific questions that are fundamental to mineralogy itself. Why do minerals have the chemical formulae that they do? Why do minerals have their particular bond topologies? What are the atomic-scale reasons why minerals are stable over specific ranges of pH, Eh, temperature, pressure, and activities of their various constituents? What are the relations between bond topology and both the enthalpy and entropy of formation? What are the environmental controls on various crystal forms and habits? What mechanistic details control the sequence of crystallization and dissolution of minerals in specific environments? These questions have tended to be ignored in the past because they are intractable to standard theoretical methods and are seen as of no immediate practical use to other branches of science. Moreover, many mineralogists do not seem interested in such matters, perhaps because mineralogy lacks a rigorous way to consider such problems and standard theoretical methods cannot deal with the size, complexity, and disorder of most minerals: e.g., veblenite, K₄[Si₂Na(Fe²⁺;Fe³⁺)₂Mn₂] Nb₃Ti(Si₂O₇)(Si₂O₁₁)O₄(OH)₆(H₂O)₃ (Câmara et al. 2013).

There has been some recent work directed toward putting mineralogy on a more rigorous basis and attempting to address some of the questions mentioned above. Hawthorne (2015) has provided a bond-topological basis for mineralogy that can address many of these problems. Quantification of the structure hierarchy hypothesis (Hawthorne 2014) and the development of specific structure hierarchies—e.g., borates, sulfates, uranyl oxysalts, tellurium oxocompounds, and silicates—have led to a much greater understanding of the factors affecting the crystallization of hydroxy-hydrated oxysalts and crystallization sequences of such minerals. Mineral evolution (Hazen et al. 2008) focuses attention on large-scale spatial and temporal mineral parageneses from early stellar materials to surficial Earth and planetary environments. The complexity of an atomic arrangement (Krivovichev 2013) has given a quantitative measure of what was hitherto only a qualitative idea, and there is the possibility of relating complexity (Shannon entropy) to questions of mineral diversity (Christy 2018; Krivovichev et al. 2018).

Although the characterization of new minerals is a baseline activity in mineralogy, novel approaches to understanding the chemical compositions, structural arrangements, and behavior of minerals in the spatial, temporal, and thermodynamic diversity of Earth and planetary environments are critical if mineralogy is to advance beyond empirical scientific activity. Significant progress is dependent on younger mineralogists becoming involved in the recent advances mentioned above and developing new rigorous methods to further our understanding of minerals and their behavior at the most basic level.

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The International Mineralogical Association (IMA) was officially launched at its first general meeting in Madrid, in April of 1958. Electron-microprobe analysis had then just been developed by the French physicist Raimond Castaing, and the first microbeam analyses of geological samples (less than 1 µg in weight!) were about to be published by him in collaboration with the Swedish mineralogist Kurt Fredriksson. Within a decade, further experiments by Castaing and his students would pave the way for secondary-ion mass-spectrometry and electron energy loss spectroscopy, which enabled mineral analysis at the nanoscale. Significantly, these discoveries made in university labs also gave a powerful impetus to the development of a wide range of microbeam instruments. The emergence of synchrotron facilities in the mid-1970s and the harnessing of laser radiation for quantitative analysis, imaging, and spectroscopy in the 1980s opened new horizons for mineral scientists—particularly, in the areas of poorly crystallized and amorphous materials, phase transitions, extreme environments, and trace-element and isotope measurements—and stimulated interdisciplinary and cross-field research, which firmly up the position of our science in the study of rocks, the Earth’s interior, geochemical processes, and the biosphere. Space exploration pushed the frontiers of this research first to our celestial companion and, in the past 15 years, to asteroids and comets. Last but not least, the rapid spread of computer networks and supercomputers in the 1990s to early 2000s helped revolutionize our understanding of minerals in the context of Earth’s history and planetary evolution and ushered in the new era of mineral informatics.

Looking at this brief retrospect, one could argue that the last 60 years have been the Golden Age of Mineral Sciences. Indeed, in 1958, the 12 premier mineralogical journals cumulatively published fewer than 400 research papers in English, Russian, German, French, Italian, and Japanese. By comparison, ~600 articles were published in 2021 just on zircon, according to the Web of Science! Today, the Scimago Journal Rank lists 70 periodicals whose titles include the word “mineral,” with their scope ranging from bone metabolism to ore processing, and their geography extending from Mexico to China. The number of known minerals has increased from some 1,150 “grandfathered” by the IMA in 1958 to an impressive 5,780 species currently listed on the website of the IMA Commission on New Minerals, Nomenclature and Classification. It truly must have been a tremendous experience working through this Golden Age of discoveries, breakthroughs, and innovation! Have we, as mineral scientists, now approached an intellectual plateau, and what does the future hold? Can our developmental milestones help the younger generation of researchers choose the right career path?

For the present Perspectives, we have asked the recipients of the IMA Medal of Excellence (www.ima-mineralogy.org/Medal.htm) to reflect on their personal “Golden Age” experience and share their thoughts on the past, present, and future of mineral sciences. This is the first in a series of two Perspectives columns organized by the IMA. Here we feature passages composed by Distinguished Professor Emeritus Frank C. Hawthorne (University of Manitoba, Canada) and Professor Nikolay V. Sobolev (V.S. Sobolev Institute of Geology and Mineralogy, Russia), the latter of whom sadly passed away earlier this year. This column thus marks some of Prof. Sobolev’s final written contributions to the scientific community. The second part of this series will appear in Elements’ December issue (vol. 18, no. 6), featuring passages written by Rodney C. Ewing, Gordon E. Brown, Jr., both of Stanford University, USA, and Robert M. Hazen of Carnegie Institution for Science, USA. The IMA Medal was established in 2006 as a lifetime achievement award that recognizes the excellence and impact of one’s contribution to knowledge, rather than the length of one’s publication list.
Apart from encapsulated crystals, fluid inclusions are quite typical of illustrate the close ties between mineralogy, geology, and mineral of the Arkhangelsk kimberlite province in NW Russia. These examples mondiferous pipe) and has contributed significantly to the discovery fields in Siberia (especially for the discovery of the Yubileynaya dia­ have been highly successful in the exploration of the Yakutian kimberlite have been used in kimberlite exploration since 1969. Later on, these garnets with diamonds in such xenoliths, as well as of minerals and fluids encapsulated in diamond crystals, made it possible to develop a parage­netic classification similar to the one used for crustal igneous rocks. For example, the incorporation of Na in garnets and of K in clinopyroxenes associated with diamonds in peridotitic and eclogitic xenoliths was used to distinguish mantle diamond–pyrope facies from graphite–pyrope facies lacking such features (Sobolev 1977). The composition of kimberlite indicator minerals was used for para­genetic classification purposes (e.g., garnets representing harzburgite­dunite, lherzolite, and wehrlite parageneses). Further paragenetic refinement is based on the composition of minerals that coexist with diamonds in mantle xenoliths and are present as inclusions in diamonds (Fig. 1), i.e., clinopyroxene-free harzburgite and/or dunite paragenesis of low-Ca, high-Cr pyrope garnets. These developments were of prac­tical importance because the indicator mineral chemistry had widely been used in kimberlite exploration since 1969. Later on, these garnets indicating diamond potential were dubbed “G10”. Indeed, the applica­tion of the newly developed “mineralogical mapping technique” has been highly successful in the exploration of the Yakutian kimberlite fields in Siberia (especially for the discovery of the Yubileynaya dia­mondiferous pipe) and has contributed significantly to the discovery of the Arkhangelsk kimberlite province in NW Russia. These examples illustrate the close ties between mineralogy, geology, and mineral deposit research.

Apart from encapsulated crystals, fluid inclusions are quite typical of some diamonds. The significance of hydrocarbons and CO₂ for diamond formation, first postulated 60 years ago (Sobolev 1960), has received much support in recent theoretical and experimental work simulating upper-mantle conditions. Many attempts have now been made to deter­mine the composition of potential fluids, which required cutting-edge analytical equipment. For example, volatile components (including hydrocarbons) in garnet from diamondiferous metamorphic rocks in the Alps have been analyzed by Raman microspectroscopy (Frezzotti 2019). The predominance of higher hydrocarbons (pentane to hexa­decane) and their derivatives at low levels of methane were determined by gas-chromatography mass-spectrometry for diamond-, garnet-, and olivine-hosted fluid inclusions in diamondiferous peridotites of the Udachnaya mine in Yakutia (Russia), suggesting that such hydrocarbons are major species in parental mantle fluids (Sobolev et al. 2019). In the first approximation, the diamond-forming medium will likely turn out to be an unusual ultrapotassic-carbonate-chloride-silicate-water­hydrocarbon fluid.
The Quest For Water

Yves Marrocchi¹ and Pierre Beck²

1 Centre de Recherches Pétrographiques et Géochimiques CRPG-CNRS
54501 Vandœuvre-lès-Nancy, France
E-mail: yvesm@crpg.cnrs-nancy.fr

2 Univ. Grenoble Alpes CNRS, IPAG
38000 Grenoble, France
E-mail: pierre.beck@univ-grenoble-alpes.fr

W ater played a key role in shaping the Solar System—from the formation of early solids to the processes of planetary and moon formation. The presence of water in molecular clouds influences the initial abundance and distribution of water in the circumsolar disk, which, in turn, affected the water budget of the terrestrial planets and, therefore, their geological activity and habitability. On Earth, surficial and deep-water cycles have largely governed the planet’s geodynamical and geochemical evolution. This issue focuses on the past and present distribution of water within the Solar System and how this important molecule affects astrophysical and geological processes.

**KEYWORDS:** water; planetary bodies; density; circumsolar disk; meteorites

**WATER: THE GAME-CHANGER MOLECULE**

Water is a tiny molecule (~3 Å), present in massive amounts within the Solar System, that accounts for ~50% by mass of all condensable species in a gas of solar composition (Lodders 2003). Water had a fundamental influence on the structure of the circumsolar disk that surrounded the Sun 4.56 billion years ago and the mechanisms by which early solids formed during its evolution (Fig. 1). Water represents a significant fraction of the building blocks of planetesimals (i.e., 0.2–10 wt.%, Vacher et al. 2020) and, therefore, participated in the processes of planetary formation. In addition to being fundamental to the development of life on Earth, this peculiar molecule drives large-scale planetary differentiation processes, magma evolution and volcanism, and the development of atmospheres (Gaillard et al. 2021). Water is thus the crucial molecule that establishes and controls the limits of planetary habitability, i.e., the ability of planetary bodies to develop and sustain life. Within the Solar System, the ability of Earth to support water in its three forms—vapor, liquid, and solid—makes it a unique planet (Fig. 1). Throughout Earth’s history, the “visible” water has been distributed among distinct reservoirs: the oceans, the cryosphere (i.e., ice sheets and glaciers), the atmosphere, and terrestrial storage; the latter corresponding to surface and root-zone soil moisture, groundwater, rivers, and lakes, as well as water stored in vegetation. If the oceans represent the main reservoir, with an estimated amount of water of ~1.4 × 10²¹ kg, an additional 0.15 ocean masses is stored in other surficial reservoirs (Hirschmann 2006). This visible water is characterized by constant motion, which is referred to as the water or hydrological cycle (Fig. 1). Solar-driven evaporated surficial waters (i.e., oceans, lakes, rivers, streams, land surface, and plants) are transferred into the atmosphere under the action of wind, where they experience condensation to form clouds and water droplets, as well as ice crystals (Fig. 1). Hence, atmospheric water comes back to the Earth’s surface through precipitation (i.e., rain or snow), replenishing the earthbound parts of the surficial water cycle and percolating downward to form groundwater, which slowly moves through rocks and surface materials to end up in streams, rivers, and lakes, with some water going back directly to the oceans (Fig. 1). The volume of surficial water and its evolution throughout Earth’s history are thus key parameters that control Earth’s climate and habitability.

**Figure 1** Schematic representation of astrophysical and terrestrial environments where water plays a key role. Within the circumsolar disk, water-ice grains could have been formed locally or have been inherited from the molecular cloud from which the Sun formed. The distribution of water-ice grains within the disk depends on the location relative to the snowline, a limit that corresponds to the distance from the Sun at which the temperature is low enough for water to condense (~150–170 K). Depending on their accretion location, planetary bodies thus can incorporate a significant amount of water that will influence their geodynamical evolution and water cycle, such as on Earth.
The question of how much water there is on Earth is not trivial to answer, as surficial water represents only a fraction of Earth’s total water budget. Although it was discovered in recent decades that a significant quantity of water is stored in the Earth’s mantle (which is also the case for other rocky planetary bodies), its precise estimation is still the subject of very active debate. This difficulty lies in the fact that—contrary to refractory elements—volatile elements are lost and fractionated during magma degassing, making the estimation of water abundance in different mantle source regions difficult. Depending on the mantle-derived rocks considered (either those emitted along mid-ocean ridges or at oceanic islands), between 0.1 to 2.5 times the mass of surficial reservoirs could be stored in the mantle (Hirschmann 2006). Another estimate based on the noble gas systematics of the Earth’s mantle suggests that the bulk Earth water content could correspond to 10 ± 5 ocean masses (Marty 2012). Even by considering the largest estimate of water stored in the mantle, the Earth appears surprisingly dry, as water represents less than 1% of our planet’s mass. This peculiar characteristic is thus a key constraint for understanding the origin and evolution of Earth’s water.

The amount of water on Earth, and its transfer between the different terrestrial reservoirs, plays a key role in controlling the geological processes and behavior of the solid Earth (Fig. 1). Deep-Earth water is mainly incorporated as point defects in the silicate minerals of the mantle. The addition of H into nominally anhydrous minerals profoundly changes their physical properties (i.e., mineral strength, electrical conductivity, diffusion rates of other constitutentsions, seismic properties). Water also has a significant influence on mantle rheology and viscosity, as well as the solidus of the mantle and, therefore, the melting regime. Taken together, water greatly affects mantle convection and plate tectonics, which in turn influence the influx of water to the mantle through the subduction of wet oceanic lithosphere and back to the surface via mid-ocean ridge, arc, and hotspot volcanism. The ubiquitous presence of water makes this molecule fundamental for astrophysical, cosmochemical, and geological processes, and highlights the importance of understanding its evolution in time and space throughout the 4.56 billion year history of the Solar System.

**WATER IN THE SOLAR SYSTEM: WHERE, HOW, AND HOW MUCH?**

Given its significance in planetary and biological evolution, water has been searched for and found throughout the Solar System. Quantifying its abundance and distribution is not easy business, as only a few samples from planetary bodies are available on Earth compared to the stunning diversity of worlds in our Solar System. However, water can be detected using infrared remote sensing techniques at the surface of planetary objects (Fig. 2), because the strong dipole moment of the O–H bond leads to particularly strong absorption in the infrared spectral range. Water, as well as hydrated or hydroxylated minerals, can be identified and distinguished by analyzing reflected sunlight based on specific absorption features around 1.4, 1.9, 2.2–2.3, and 3 µm (Fig. 2). It can also be observed remotely from the rotational modes of water molecules that can be probed by radio telescopes and, depending on the abundance of water in the line of sight, its isotopic composition may be determined (hydrogen having two stable isotopes: hydrogen H and deuterium D, expressed as the D/H ratio). Water D/H ratios can also be accessed by in situ mass spectrometry measurements onboard orbiters or landers.

Depending on particle density, water-ice grains under high vacuum will sublimate at temperatures over 100–150 K. This limit, known as the water snowline (Fig. 1), was effective during the circumsolar disk evolution where its location was a direct function of the stellar luminosity, accretion rate, and gas density. Although its position is generally expected to drift inward during disk evolution (from ~ 3 to 1 AU; astronomical unit AU = Earth–Sun distance = 150 × 10^6 km). The position of the snowline (and its evolution over time) is a fundamental question, because it controls the amount of water available in the asteroidal- and planetary-accretion regions, a characteristic that, in turn, controls the geodynamic evolution of asteroidal and planetary bodies. The snowline is located near Jupiter’s orbit under current Solar System conditions, but specific local conditions at the surface of planetary bodies could disturb this limit and impact the water distribution. Water ice is thus predominantly unstable today at the surfaces of the (atmosphere-free) Moon and Mercury, but has been detected at locations permanently shaded throughout their whole revolution around the Sun. In addition to water ice, -OH-related absorption bands have been also detected at the surface of the Moon at high latitude with a suggested abundance of the order of 100s of µg·g⁻¹ of water. Both signatures have been interpreted to reflect an exogenous origin, either from micrometeorites, asteroidal and/or cometary impacts, or by the impact-triggered transformation of solar wind–implanted hydrogen into water molecules.

**Figure 2** Examples of the detection of water ice and hydrated minerals based on infrared reflectance spectroscopy on several Solar System objects. A menagerie of clay minerals has been identified on Mars based on diagnostic absorption related to metal–OH vibration harmonic and combinations, as well as hydrated phases in the form of sulfates (the example of a mono-hydrated Mg-sulphate is shown), zeolite, or opals. The signature of water ice is also shown as observed on the north polar cap of Mars together with observations of ice on Europa and Charon (McCord et al. 1998; Grundy et al. 2016). Changes in the shape of the water-ice absorption among these three objects can be seen around 1.6 µm, which are related to temperature. Mars spectra are from the CRISM database. Photo credits (top to bottom): ESA/DLR/FU Berlin; NASA/JPL/DLR; and NASA/JHUAPL/SWRI
The density and temperature of the Venusian atmosphere preclude the presence of water-ice deposits on the surface, as well as the presence of most hydrous minerals (but not all). There has been speculation about the amount of water hosted in the interior of Venus, but further evidence through dedicated space missions is needed. In the case of Mars, water has been identified all over the planet, whether in the form of ice, hydrated minerals, and possibly brines (Fig. 2). While the presence of clay minerals in ancient Martian terranes offers a window into past water cycles, there is also an active surface–atmosphere water cycle today. Two massive permanent ice caps have been identified in the north and south poles of the red planet, which provide enough water to fill the Mediterranean Sea. The redistribution of these ice masses in response to Mars’ orbital evolution led to “Quaternary” geological processes identified by their morphological fingerprints.

The asteroid belt hosts a menagerie of objects that probably formed in very different locations in the Solar System. To first-order, there is a dichotomy between darker and brighter objects that echoes the dichotomy found in meteorites between ordinary and carbonaceous chondrites (DeMeo and Carry 2014). The silicate-rich asteroids (S-type) do not show strong evidence of hydration on their surface, in line with the general dryness of ordinary chondrites to which they are associated (typically 0.1 wt.% H$_2$O; Vacher et al. 2020). On the contrary, C-type asteroids, which make up roughly half of the mass of the main belt, often show strong evidence of phyllosilicate minerals based on observations of a deep 3-µm band (Usui et al. 2019; Fig. 3). The strength of this feature is most marked when observed on the Moon, for instance, and suggests the presence of a significant amount of equivalent water (>5 wt %) on their surfaces. The meteorite record of aqueous alteration and phyllosilicate production is presented in Vacher and Fujiya (2022 this issue).

The observation that some main-belt asteroids are active, i.e., that they eject a significant amount of dust, is suggestive that, together with OH-bearing minerals, a significant fraction of water ice is present in asteroids, which blurs the boundary with comets. The outer part of the asteroid belt, as well as Jupiter’s Trojan asteroids, is dominated by particular types of objects, the P- and D-types, which share strong optical similarities with comets, and can be envisioned as dormant comets (Vernazza and Beck 2017). However, unlike C-type asteroids, they generally do not show strong evidence for water ice or hydrated minerals at their surface, although water is probably a major constituent, as indicated by their density and potential D-type-derived meteorites. Their thermal evolution was possibly cold enough to preclude the melting of water and production of phyllosilicate, at least on their surface.

Density is the strongest constraint we have today to infer the abundance of water in the interior of small bodies. Accurate density estimates are limited to only a tiny portion of the overall population, but suggest different bulk compositions for S-, C-, and to some extent D-type asteroids (Fig. 4; Vernazza et al. 2021). The density of 100-km-sized, S-type asteroids is in the range of 3000–4000 kg/m$^3$, which is in agreement with measurements on ordinary chondrites found on Earth, and implies a low fraction of water in their interior (Fig. 4). By comparison, the density of C-type asteroids is significantly lower (~1000–2000 kg/m$^3$ for 100-km objects; Fig. 4), which suggests that they are composed of an important fraction of low-density material (presumably water ice and/or hydrated minerals; Fig. 3). Density estimates for D-type asteroids are rare, but the recently obtained value for 87-Sylvia (1330 ± 70 kg/m$^3$) is slightly lower than that estimated for C-types of similar size (Fig. 4; Vernazza et al. 2021). Estimating the bulk water content of asteroids is not straightforward, as it requires constraints or hypotheses on their porosity. Interestingly, density and diameter are correlated for a given class of asteroid, which is interpreted by an increase of porosity in smaller objects, thus allowing the bulk composition of asteroids to be estimated. For instance, the 2060 ± 200 kg/m$^3$ density of the 420-km-diameter C-type asteroid 10-Hygeia could be explained by a volume mixture of 20% porosity, 55% rock/metal, and 25% water ice.

Comets are, by definition, objects emitting dust as a consequence of volatile sublimation at their surface. Overall, water is the major volatile species within comets, but other volatile species, such as CO or CO$_2$, may play a role in their activity. While the water loss rate from a comet can be determined from the ground, the determination of the water/dust ratio is more complex and requires accurate modeling of the light scattered by the dust particles. Detailed observations in the 3-µm region of the nucleus of comet 67P Churyumov Gerasimenko revealed the general absence of water ice on its surface, and that hydrogen is instead present in surface material in the form of ammonium salt and aliphatic organics (Fig. 3). If the surface seems “dry,” the low density of the few comet nuclei observed by spacecraft (~500–2000 kg/m$^3$; Fig. 4) points toward a significant fraction of interior volatiles. Estimates based on the Rosetta mission are in the range of 10–50 vol% water.
Density of various types of Solar System objects as a function of diameter (McKinnon et al. 2017; Vernazza et al. 2021). Due to the possible presence of porosity, asteroids, centaurs, and trans-Neptunian objects seem to present density-diameter trends. Still, a general decrease of density is present with heliocentric distance that can be explained by an increasing fraction of water ice. The C-type panel (center) also shows the density of D-type asteroid (87) Sylvia (light green) and dwarf planet (1) Ceres (yellow). (Davidsson et al. 2016; Fulle et al. 2019) and an equivalent uncompact density of approximately 1800–1900 kg/m$^3$ (McKinnon et al. 2017).

Optical observations of trans-Neptunian objects (TNOs) and centaurs (objects on unstable orbits between Jupiter and Neptune) have revealed the presence of water ice on their surfaces (Barucci et al. 2008, see also Charon in Fig. 2), but not systematically. When present at the surface, water ice appears to be in a crystalline form, rather than amorphous, which is at odds with a very low-temperature origin (≤50 K, i.e., directly inherited from the protosolar nebula) and suggests that it may have been thermally processed. The largest known TNOs have well-constrained densities that are lower than C-type asteroids of similar size (except for 1Ceres). In the case of the Pluto–Charon system, the determined values are 1850 and 1700 kg/m$^3$, respectively, which translates to 30–40 wt.% of water ice

Looking at the overall picture, if water is present at least locally at the surface of all types of Solar System objects, density estimates suggest that the fraction of volatiles, including water, is higher in objects distant from the Sun. It appears that the fraction of water is homogeneous among C- and D-type asteroids, comets, and TNOs (within an order of magnitude to be conservative), while the inner Solar System is depleted in water compared to these objects. Understanding this global picture requires a determination of the astrophysical origin of water (and thus what constituents were incorporated into the Solar System) and how and where planetary bodies accreted.

**ORIGIN, AMOUNT, AND DISTRIBUTION OF WATER WITHIN THE EARLY SOLAR SYSTEM**

The current understanding of the astrophysical origin and pathways of water toward planetary systems is presented in the article by Ceccarelli and Du in this issue. In the cold and diffuse environment of the interstellar medium (ISM), water may dominantly exist in the form of water-ice grains (Fig. 1). In the diffuse ISM, the presence of water ice has only been observed within density-increased molecular clouds where water molecules form through reactions between O and H atoms in the gas phase and/or at the surface of interstellar dust via catalyzed processes (see Fig. 2 in Ceccarelli and Du in this issue). The latter implies an intimate association of water and refractory grains (silicates or carbon-rich grains) at the onset of star formation. Whatever the processes involved, fundamental questions are related to the amount and origin of water present in the starting material from which the Solar System formed (before disk evolution processing) and how its distribution evolved over the 4.567-million-year lifetime of the disk. Several approaches can be followed involving more or less straightforward methods. For instance, calculating how elements with solar abundances partition within silicates, carbon-rich grains, sulfides, CO, and H$_2$O allows a water/dust ratio of ~1 to be estimated (Min et al. 2011). Depending on the amount of carbon incorporated into carbonaceous dust, the dust density estimates range from 1450 to 1800 kg/m$^3$. Interestingly, these values are in the range estimated for Pluton and Charon and suggest that their bulk composition may correspond to that of primordial Solar System building blocks (although other large TNOs, like Eris or Haumea, have higher densities). In addition, the inferred water/dust content seems much higher than that estimated for comet 67P and for carbonaceous chondrites. The latter show solar abundances for most elements except for the most volatile, which are characterized by water/rock ratios ranging from 0.01 to 0.4 (Marrocchi et al. 2018). However, such estimations correspond to final values,

and a significant fraction of the initial water may have been degassed during secondary alteration processes of carbonaceous asteroids (Vacher and Fujiya 2022 this issue).

In theory, a more direct approach would be to measure the abundance and H and O isotopic compositions of water trapped in meteorites at both bulk and in situ scales, as they bear invaluable information on the source and abundance of water accreted by asteroids (Deloule and Robert 1995; Alexander et al. 2012). This proves difficult in practice, however, as immediately after reaching the Earth’s surface, meteorites are exposed to terrestrial moisture and precipitation that could significantly affect their initial water contents and isotopic characteristics (Vacher et al. 2020). Furthermore, secondary minerals formed through fluid circulation within meteoritic parent bodies are intimately mixed with H-bearing organic compounds, thus impeding the accurate estimation of hydrogen isotopic compositions retained in hydrated minerals (Piani et al. 2018). However, recent studies have overcome these difficulties by developing new analytical procedures, which allow the estimation of the water concentrations and isotopic compositions to be precisely determined in a large set of meteorites (Vacher et al. 2020; Piani et al. 2018). If they confirm that the meteorites formed in the outer Solar System are water-rich (McCubbin and Barnes 2019), it also appears that meteorites formed in the inner Solar System are characterized by higher water abundances than previously thought (Vacher et al. 2020). This led to a paradigm shift where the inner Solar System could no longer be considered as completely dry and volatile-poor, these characteristics...
having a strong influence on the accretion processes within the disk (Lichtenberg et al. 2021), as well as on the redox states of the processes that controlled the evolution of the terrestrial planets (Gaillard et al. 2021). From an isotopic perspective, it appears that the asteroidal water budget corresponds to (i) a mixture between water below the water-ice sublimation temperature (Piani et al. 2021), taken together, this implies that the water distribution within the early Solar System resulted from complex processes involving local production and molecular cloud legacy, and that the asteroidal water budget depends on both their location and timing of accretion within the disk. This issue of Elements describes several aspects that may have acted in setting the current distribution of water throughout the Solar System. It begins by presenting how water was produced in the molecular cloud from which the Solar System was formed, and how water molecules may have been distributed in the solar protoplanetary disk (Cecarelli and Du 2022 this issue). At that point, water is present in the vapor phase or as water-ice grains associated with tiny refractory grains. The next step is a big one: growing planetesimals and then terrestrial planets. The mechanism from which planetesimals can grow and how the dynamical evolution of the early Solar System could have been key in delivering water in the early Solar System is presented in Izidoro and Piani (2022 this issue). Overall, a major constraint on the possible sources of water is the D/H ratio. Peslier and De Sanctis (2022 this issue) present and discuss the variation of water abundance and isotopic composition among various types of inner Solar System materials. We also focus on two different situations where liquid occurred or occurs today in the Solar System. Vacher and Fujiiya (2022 this issue) present how carbonaceous chondrites record hydrothermal reactions that occurred just a few million years after the Solar System formed. Finally, many large Solar System objects are now recognized as past or present “ocean worlds”, and are a major focus of current Solar System exploration. This is presented in Castillo-Rogez and Kalousová (2022 this issue).

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We look forward to receiving your proposal!
Water is crucial for the emergence and evolution of life on Earth. Recent studies of the water content in early forming planetary systems similar to our own show that water is an abundant and ubiquitous molecule, initially synthesized on the surfaces of tiny interstellar dust grains by the hydrogenation of frozen oxygen. Water then enters a cycle of sublimation/freeze-out throughout the successive phases of planetary system formation, namely, hot corinos and protoplanetary disks, eventually to be incorporated into planets, asteroids, and comets. The amount of heavy water measured on Earth and in early forming planetary systems suggests that a substantial fraction of terrestrial water was inherited from the very first phases of the Solar System formation and is 4.5 billion years old.

**INTRODUCTION**

The Solar System was born 4.5 billion years ago, after a long and complex process that led to the planets, asteroids, and comets we see today. Reconstructing what happened is not simple—after all, we only have at hand the final products of the process. It is like deciphering the recipe of a tasty complex cake from the single piece of it that we eat. Only an experienced cook might succeed, exactly because of their experience with other cakes. For astronomers, it is the same: we can try to reconstruct the history of the Solar System by gaining experience with other planetary systems presently forming in the Milky Way.

The study of star and planet formation is one of the most recent fields in astronomy. A major reason is that early forming planetary systems are cold objects that emit photons in the millimeter to infrared wavelengths, which are largely absorbed by the terrestrial atmosphere. Although many aspects of Solar System formation are still poorly understood, the major phases of the process are now well established (e.g., Caselli and Ceccarelli 2012). Most relevant for this article, the history of water in the Solar System is intrinsically connected to these stages, which can be summarized in four major steps, as illustrated in Figure 1.

**STEP 1:** The story starts in a cold (~10 K) and relatively dense (~$10^5$ molecules/cm$^3$) clump of a molecular cloud in the Milky Way, the seed from which a solar-type planetary system is born (Caselli et al. 2012). As in average galactic clouds, gas (whose most abundant element is hydrogen, followed by helium, oxygen, and carbon) is mixed with tiny (~0.1 µm in radius) grains of silicate and carbonaceous dust. Given the very low temperatures, when oxygen atoms or molecules encounter the dust grains, they remain frozen on the surface. On the contrary, the lighter H atoms hop around the grain surfaces, and when they encounter the frozen oxygen, they react and form water (e.g., Dulieu et al. 2010), as schematically shown in Figure 2. In this first step, almost all available elemental oxygen becomes trapped into water ice.

**STEP 2:** Under the gravitational force, the molecular cloud clump becomes increasingly dense until matter freely collapses towards the center, forming a so-called protostar. The gravitational energy is now transformed into heat and, at a few tens of astronomical units (au: 1 au is the average distance of the Earth from the Sun) from the protostar center, dust is heated up to a temperature around 100 K, where the frozen water enveloping the grains sublimes. In these regions, called hot corinos, whose sizes are similar to that of the Solar System, water becomes the most abundant molecule (Ceccarelli 2004). To provide an order-of-magnitude sense of the water abundance, a typical hot corino contains about 10,000 times the water in the Earth’s oceans. So, at this stage, there is plenty of water, even though it is gaseous and not liquid (see also van Dishoeck et al. 2021).

**STEP 3:** The initial small rotation of the molecular cloud clump eventually causes the formation of a disk of material around the nascent star, called a protoplanetary disk. This is a crucial phase because the water that formed in STEP 1 and released into the gas in STEP 2 largely recondenses in the coldest zones of the disk. There, the dust grains become again enveloped by icy mantles, in which the previous history is now stored. Thus, dust grains are the guardians of water inheritance.

**STEP 4:** Planets, asteroids, and comets form in protoplanetary disks from the agglomeration of the dust grains. Some of them contain the oldest water-ice with the imprint of its origin, as we will see later in this article. The water trapped in the agglomerated grains is subsequently released in the rocky planets and kept frozen in distant and cold asteroids and comets.
INTERSTELLAR FACTORIES OF HEAVY WATER

As briefly explained above, most of the water in the protostellar and protoplanetary phases is synthesized during the cold phase of STEP 1 (Fig. 1). This process, illustrated in Figure 2, is relatively simple: hydrogen atoms landing on the grain surfaces hydrogenate oxygen by successive additions. Yet, the extreme conditions of the matter in the molecular cloud clumps, caused by the very low temperature (~10 K), trigger a very peculiar phenomenon, called super-deuteration (Ceccarelli et al. 2014).

Deuterium, the heavy isotope of hydrogen, is (only) produced during the first seconds after the Big Bang, in a ratio of about 1/100,000 with respect to H. If it was statistically distributed in water, the abundance of heavy water (HDO), would be then about 10⁻⁵ times that of normal water (H₂O). However, in hot corinos, the HDO/H₂O ratio is only a bit less than 1/100. To make things even more extreme, the doubly deuterated water D₂O is 1/1000 with respect to H₂O, namely about 10⁷ times larger than what would be estimated from the D/H elemental abundance ratio (Coutens et al. 2012).

Basically, these extremely large deuterated ratios are caused by the enhanced number of D atoms with respect to H atoms landing on the grain surfaces at the moment of water formation. In turn, the root of the enhancement is the asymmetry of the reaction H₃⁺ + HD → H₂D⁺ + H₂ with respect to its reverse reaction H₂D⁺ + H₂ → H₃⁺ + HD. The latter is inhibited at low (~20–30 K) temperatures because of the lower zero-point energy of H₂D⁺ with respect to H₃⁺; thus, deuterium atoms are transferred from HD, the major D reservoir in cold molecular gas, to H₂D⁺, then to D, and eventually to water (e.g., Tielens 1983). There are no other ways to obtain this large amount of heavy water in hot corinos nor in general. Therefore, abundant heavy water is a hallmark of water synthesis in the cold molecular cloud clump during the STEP 1 era.

PROTOPLANETARY DISKS, WHERE PLANETS ARE BORN

During the early stages of star formation (spanning STEPS 3 to 4), young stars are surrounded by a protoplanetary disk of gas and dust, in which planets are forming. Their existence is due to the conservation of angular momentum (Hartmann 2009). The original molecular cloud in which stars form inevitably has a certain amount of angular momentum. As the cloud shrinks, it spins, maintaining a centrifugal force, which impedes radial mass flow so that matter tends to infall parallel to the rotation axis, and in this way a flattened disk is formed. Vertically, the disk is supported by thermal pressure. The mass of a disk is usually about two orders of magnitude lower than that of the central star; hence, it is the stellar gravity that dominates the rotation dynamics of the disk. In such nearly Keplerian rotation, the angular velocity is a decreasing function of radius. The angular velocity gradient leads to internal friction in the disk, which causes angular momentum and matter to transfer. Gas and dust gradually migrate and are either accreted into the central star, assimilated into the 10,000 terrestrial oceans. STEP 3: In protoplanetary disks, the hot corino water is frozen into ices enveloping the grains. STEP 4: The dust grains coagulate into larger rocks that eventually become planets, asteroids, and comets; some of the ices fabricated in STEPs 1 and 2 are transmitted in this way to the final planetary system.

**Figure 1** Sketch of the four major steps involved in the formation of a planetary system similar to the Solar System and of water (Courtesy of M. De Simone), as described in the text. STEP 1: In cold (≤10 K) and dense clumps, water is formed on the surface of the interstellar grains. STEP 2: In the hot corinos of protostars, water is observed in a quantity equivalent to more than 10,000 terrestrial oceans. STEP 3: In protoplanetary disks, the hot corino water is frozen into ices enveloping the grains. STEP 4: The dust grains coagulate into larger rocks that eventually become planets, asteroids, and comets; some of the ices fabricated in STEPs 1 and 2 are transmitted in this way to the final planetary system.
forming planets, or may escape to outer space. During these processes, delicate structures can be formed, some of which are directly imaged by state-of-the-art telescopes, such as the Atacama Large Millimeter/submillimeter Array (ALMA) (e.g., Andrews et al. 2018). The first image showing rings and gas in the dust distribution of protoplanetary disks is shown in Figure 3. Finally, the disk dissipates and a planetary system is born. The protoplanetary disk stage usually lasts a few million years.

As a remnant of the star formation process, the initial chemical composition of the disk largely inherits that of the original molecular cloud clump (STEP 1). Carbon and oxygen easily combine to form carbon monoxide molecules, with the remaining oxygen mostly going into water, either in the gas phase or ice. It is tempting to think that water in protoplanetary disks will end up in planets that are being made. However, the actual history of terrestrial water may not be so simple (see also Izidoro and Piani 2022 this issue).

Protoplanetary disks are heated mainly by the central young star (FIG. 4). Energetic photons (from visible to ultraviolet light and X-ray) emitted by the star can be scattered and/or absorbed by the dust particles in the disk. Dust particles get heated when gaining energy and re-emit photons. The re-emitted photons tend to be at longer wavelengths than the absorbed ones, because the dust grains cannot be as hot as the central star. As these re-emitted photons propagate outwards, they are repeatedly absorbed and scattered, becoming less energetic and eventually escaping from the disk. The disk is thus hotter in the inner region and colder in the outer region. The exact thermal structure depends on many aspects. For example, heating by turbulent viscosity within the disk and by external UV and cosmic rays may also play a role, and the total mass and distribution of matter in the disk also influence how photons propagate in the disk, which determines the thermal structure.

Deriving a disk’s thermal structure is generally a complicated task and is calculated using sophisticated computer codes (e.g., Oka et al. 2011). However, in a very simplified model, where the disk is assumed to be optically thin (i.e., nearly transparent for light propagation), the disk temperature can be easily calculated by balancing the projected stellar flux with the re-emitted flux at each location of the disk. For the present-day Solar System, the temperature calculated this way is 278 K at the radial distance of the Earth and 170 K at 2.7 AU (Hayashi 1981). This sets the “snow line” of water in the present-day Solar System. When the Solar System was younger, however, its disk was cooler and the snow line was closer to the center, up to ~1 AU (Morbìdelli et al. 2016). Water mainly exists as gas inside the snow line, and is largely, but not entirely, frozen beyond the snow line. Different molecules condense at different temperatures, hence they have different snow lines. Besides being a chemical division boundary, the snow lines may also have dynamical effects. For example, it has been found that the gap locations in the HL Tau disk coincide with the condensation front of ammonia and clathrate hydrates (Zhang et al. 2015). One explanation for this coincidence is that, at the snow lines, dust grains coagulate more efficiently, creating the observed patterns of rings and gaps. The concept of a snow line is related to the “habitable zone” of a planetary system, in the sense that the latter is usually defined based on the existence of liquid water. However, the origin and sustenance of life depends on many factors (e.g., stable magnetic field, protection against frequent asteroid impact, tectonics) and a definition based merely on the existence of liquid water may not be satisfactory.

**STEAMING HOT WATER VAPOR**

It is well established that a large amount of warm (>100 K) water vapor exists in the inner region of protoplanetary disks (FIG. 5). While the ground-based observation of astronomical water is usually hindered by the water vapor in the Earth’s atmosphere, the inner region of protoplanetary disks could be considerably warmer than the Earth’s atmosphere, which can excite transitions that are not significantly absorbed by the atmosphere.
The observed water vapor lines are fitted with sophisticated models to obtain a temperature of the emitting region of a few hundred to one thousand Kelvin (Salyk et al. 2008; Pontoppidan et al. 2010). The excitation conditions and Doppler line broadening of the water lines show that they are emitted from a region spanning a few au around the central star. The spectral feature of some water lines shows that part of the water vapor may be in disk winds (Salyk et al. 2019). The two hydrogen atoms of water molecules generally have parallel or anti-parallel spins. This leads to the existence of two forms of water molecules, ortho and para, which is a purely quantum mechanical effect. It is difficult to change the spin orientation of hydrogen atoms at low (<100 K) temperature, thus the relative abundance of ortho and para water only depends on the temperature at which the water formed. Lower temperatures are associated with smaller ortho-to-para ratios, thus its measure from water lines can be used to infer at which temperature the water formed, namely its formation temperature.

**FREEZING COLD WATER**

Water also theoretically exists in the gas phase in the outer part of a disk, where the temperature is extremely cold, (e.g., Dominik et al. 2005; Woitke et al. 2009; Du and Bergin 2014), although its abundance (relative to hydrogen) can be very low (10⁻²⁰–10⁻²⁹). The temperature of dust grains is 10–30 K in these regions; thus, the frozen water is not able to thermally sublimate. However, cosmic rays may play a crucial role. While cosmic rays may be attenuated by the magnetic field of the star (Cleeves et al. 2014), they could still deposit a significant amount of energy to the dust grains, which drives water into the gas phase. The low density of the outer region also allows the scattered UV photons from the star to penetrate, which helps desorb water.

Unfortunately, the theoretical predictions described above do not quite match the observations. For example, one deep search with the Herschel Space Observatory showed that cold water vapor emission is only firmly detected in 2 out of 13 disks (Du et al. 2017), with only upper limits for the other 11. Even in the two positively detected cases, the measured values are much lower than model predictions. To explain this discrepancy, after exploration of the parameter space, the total abundance of oxygen available to chemical processes has to be reduced by up to two orders of magnitude relative to normal astrochemical models. The rationale behind this is that the element oxygen, presumably mostly in the form of water ice in the outer disk, becomes chemically inactive because the dust grains covered by water ice coagulate and settle down into the midplane of the disk, thus depleting the atmosphere of the outer disk of oxygen. These detailed processes have been modeled (e.g., Krijt et al. 2020). The shortage of oxygen also leads to a reduction of carbon monoxide, which is indeed seen in many disks (Long et al. 2017). As a consequence of oxygen depletion, carbon, which may also be depleted but not as severely, is set free from the carbon monoxide molecule and combines with hydrogen through a chain of reactions to form hydrocarbons. This is seen in ALMA images as hydrocarbon rings (Bergin et al. 2016).

Could there be “wet” dust grains (i.e., grains covered with liquid water) in some area between the hot and cold regions of a protoplanetary disk? A glance at the phase diagram of water informs that this would be very unlikely. At a temperature of ~280 K, the minimum vapor pressure for water to be in the liquid phase is 1 kPa, which amounts to a water vapor number density of approximately 3 × 10¹⁷ molecules/cm⁻³ and a corresponding total gas density (mostly hydrogen) that would still be at least four orders of magnitude higher; a density rarely seen in protoplanetary disks.

**HEAVY WATER AND ARIADNE’S THREAD**

As shown throughout this article, water is synthesized in large quantities during the early phases of the formation of a planetary system similar to our own and, likewise, at the birth of the Solar System. A crucial question is whether and how much of this 4.5-billion-year-old water reached Earth. There are two major observational quantities that help to constrain theories on the origin of terrestrial water: the amount of water and its degree of deuteration, namely, the ratio of heavy over normal water, HDO/H₂O. In principle, more than enough water formed during STEPS 1–3 and the question is rather how much it could have been transmitted to Earth (see Izidoro and Piani, 2022, this issue). Here we focus on the second observational parameter, water deuteration, which provides an incredibly strong constraint on terrestrial water. Figure 6 provides an instructive hint as
to what probably happened by comparing the HDO/H$_2$O values in terrestrial water with those of hot corinos—the only objects where HDO has so far been detected in early forming, solar-type planetary systems—as well as in Solar System objects, namely comets, Enceladus, and meteorites (Ceccarelli et al. 2014). “Heavy over normal” water on Earth is about 10 times larger than the elemental D/H ratio in the Universe and consequently at the birth of the Solar System, in what is called the solar nebula. As explained above, this is a very precise indication that at least part of the water that arrived to us formed in the original molecular cloud clump from which the Solar System was born, as observed in hot corinos. Based on Figure 6, approximately 1% to 50% of terrestrial water was inherited from the very first phases of the Solar System’s birth (see also Cleeves et al. 2014).

The water in comets and asteroids (from which the vast majority of meteorites originate) was also inherited since the beginning in large quantities (Fig. 6). Earth likely inherited its original water predominantly from planetesimals, which are supposed to be the precursors of the asteroids and planets that formed the Earth, rather than from the comets that rained on it.

In conclusion, the amount of heavy water on Earth is our Ariadne thread, which can help us to come out from the labyrinth of all possible routes that the Solar System may have taken.

**OLD GOOD WATER**

While isotopic evidence (namely, the HDO/H$_2$O ratio) suggests that Earth’s water has its origin 4.5 billion years ago and was probably brought to Earth with planetesimals, the exact processes of how this happens remain far from clear. The issue is quite involved because the origin and evolution of Earth’s water is inevitably connected with other important participants on this planet, e.g., carbon (e.g., Mikhail and Füri 2019), molecular oxygen, and the magnetic field. They are all part of the same history, from the origin of worlds to the origin of life. The dynamical and chemical roles played by water (and other volatile species) before and during planet formation also require clarification, namely, how important they are in aiding planetesimal growth, and how they help sequester other molecules by forming ice mantles or clathrates.

Here we presented a simplified early history of the Earth’s water according to the most recent observations and theories. A good fraction of terrestrial water likely formed at the very beginning of the Solar System’s birth, when it was a cold cloud of gas and dust, frozen and conserved during the various steps that led to the formation of planets, asteroids, and comets, and was eventually transmitted to the nascent Earth. How the final passage happened is another fascinating chapter, described in Izidoro and Piani (2022 this issue).

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Ocean Worlds In Our Solar System

Julie C. Castillo-Rogez and Klára Kalousová

Spacecraft-based missions have discovered an increasing number of ocean worlds in our Solar System, with even more candidates awaiting confirmation. The science of ocean worlds shares some commonalities with that of Earth’s oceans, making them exciting targets of future exploration. A major known difference, however, is that ice shells up to tens of kilometers thick may present barriers to the introduction of chemical gradients necessary for life’s development over the long term. Hence, ocean worlds differ substantially in terms of their energy budget and chemistry, with Europa and Enceladus being currently considered the most promising candidates for life-search missions.

Keywords: ocean worlds; liquid water; habitability; life origin; Europa; Enceladus

WHAT IS AN OCEAN WORLD?

Exploration of the giant planet systems by the Voyager spacecraft revealed recent and potentially ongoing geological activity on several moons, suggesting that these bodies might still be warm and thus host deep liquid water layers. The potential presence of deep liquid is exciting from an astrobiological point of view. Geophysical investigations carried out by follow-on missions confirmed that deep oceans are harbored on two of the icy Galilean satellites, Europa and Ganymede, as well as on Saturn’s moons Titan and Enceladus. Ocean worlds differ in their prospect for long-term heating (tidal vs. radiogenic heating), as well as in their size, with Enceladus being the smallest confirmed ocean world at ~252 km radius and Ganymede being the largest one at ~2634 km radius. Recent exploration of Ceres and Pluto also suggests that dwarf planets could host at least residual oceans.

The diverse observations returned by the Galileo and Cassini missions are at the origin of the field of ocean world science, which builds on our understanding of terrestrial oceanography, but expands it to a broader range of conditions (pressure, temperature, gravity, pH, redox) commensurate with those expected in icy bodies. The Galilean and Saturnian ocean worlds have liquid layers tens to hundreds of kilometers thick that may undergo dynamical processes akin to those observed on Earth (e.g., interactions with the underlying seafloor and the overlying ice layer). A major difference with respect to Earth is that these alien oceans are shielded from the outside environment by an ice shell. Depending on their history, they could potentially evolve as closed systems that remain in chemical equilibrium in the absence of processes that would continuously sustain new chemical gradients. However, material exchange between the deep interior and surface is expected to take various forms across the ocean world spectrum, with Enceladus directly outgassing oceanic material from its south pole and Europa and Ceres presently exhibiting geological evidence for conduits between the ocean and surface. Conversely, Ganymede does not display any ongoing geological activity, at least based on available data.

This paper reviews the state of knowledge of the confirmed ocean worlds (Galilean satellites, Titan, Enceladus; Fig. 1), relict ocean worlds (Ceres), and candidate ocean worlds (e.g., Callisto, some Uranian satellites, Pluto, Triton). We then synthesize the understanding of ocean world evolution gained from reviewing the ocean world population as a whole, and discuss plans for future exploration of these bodies over the next two decades.

![Image of ocean worlds](image-url)

The state of knowledge of confirmed ocean worlds (dark blue), residual ocean world Ceres (light blue), and candidate ocean world Triton (yellow) against the roadmap to ocean worlds (ROW, Hendrix et al. 2019). See text for details. Note that in ROW, the oceans do not need to extend on a global scale.

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1 Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California, 91109, USA
E-mail: julie.c.castillo@jpl.nasa.gov

2 Department of Geophysics
Faculty of Mathematics and Physics
Charles University
Prague, 18000, Czech Republic
E-mail: klara.kalousova@mff.cuni.cz
**confirmed ocean worlds**

The evidence for liquid ocean in the interior of Europa comes from the Galileo magnetometer measurements, which are best explained by a magnetic field induced in a subsurface, electrically conductive liquid layer by variations of the Jovian magnetic field along Europa's orbit (Soderlund et al. 2020 and references therein). The tectonically active surface, as well as the plume signature suggested by Hubble Space Telescope (HST) observations, further support the presence of an ocean in Europa's interior (Soderlund et al. 2020 and references therein). Galileo magnetometer data were also obtained at Ganymede, but their interpretation is complicated by the occurrence of an internal dynamo generated inside Ganymede's metallic core. Complementary evidence for a deep ocean comes from HST observations of Ganymede's auroral ovals whose positions are controlled by the magnetic field lines, which vary over time, thus forcing the ovals to oscillate. The magnitude of these oscillations points toward the existence of an internal ocean (Saur et al. 2015). The presence of a deep ocean in Enceladus is expressed via geophysical (libration), chemical (silica grains), and geological signatures in the form of cryovolcanic activity at its south pole (Soderlund et al. 2020 and references therein). A deep ocean in Titan is inferred from the moon's large tidal deformation and obliquity, as well as evidence from the Cassini mission, which suggest decoupling of an outer ice layer from the solid rocky interior (Sotin et al. 2021 and references therein).

**relict ocean worlds**

Icy bodies that do not benefit from tidal heating as a major heat source are likely to be in an advanced stage of freezing. This is the case for dwarf planet Ceres, which displays recent salt exposures in two vast regions: carbonate and chloride evaporites in Occator crater (De Sanctis et al. 2020) and carbonate-covered Ahuna Mons, Ceres' highest mountain. In both cases, geological and gravity observations, as well as thermal evolution models, indicate these features were sourced from a residual liquid layer with a high concentration of salts and silicate particles located below the crust (Castillo-Rogez et al. 2021 and references therein). The brine source under Occator crater has been inferred to be a few hundred kilometers in extent (Raymond et al. 2020). Dynamical processes in these “muddy” layers are different from the processes expected in icy moons. Muds are of great interest for astrobiology as they offer large surface areas for reactions between organic compounds and minerals, potentially also involving local chemical gradients produced by radiolysis (see Castillo-Rogez et al. 2021). The processes that presently preserve liquid inside Ceres may apply to a variety of bodies with limited heat budgets, as discussed below. The potential presence of organic compounds in the brine layer makes Occator evaporites a prime target for future in situ or sample return missions.

**Candidate Ocean Worlds**

The Galileo magnetometer data for Callisto were first interpreted as an induction response of a deep ocean; however, the observed magnetic signature might also be ascribed to Callisto's ionosphere (Soderlund et al. 2020 and references therein). If a global ocean in Callisto's interior is confirmed, then it is likely in an advanced freezing stage, considering that moon's limited heat budget.

Uranus' moons Ariel and Miranda display features that indicate geological activity less than 1 Gyr ago. These two moons are not currently involved in any eccentricity, resonance, and Ariel's low eccentricity (0.0012) suggests that it is not presently undergoing tidal dissipation. Per its high obliquity, Miranda may be subject to obliquity-driven tides, but is otherwise too small to preserve liquid beyond a timescale of a few hundred My. The other Uranian moons (Titania, Oberon) are larger and predicted to host deep oceans at present (Hussmann et al. 2006), although crater-based chronology indicates old surfaces.

Neptune's moon Triton is a Kuiper belt object that was captured, as evidenced by its retrograde orbit. Its youngest surface among all icy moons (<10 My, even younger than Europa and Enceladus) classifies it as a candidate ocean world (Hansen et al. 2021). Furthermore, Triton's remarkable plumes (up to 10 km high and extending over hundreds of kilometers) may have endogenic origin (see Hansen et al. 2021). Although it is not involved in any eccentricity, its high obliquity suggests Triton might benefit from obliquity-driven tides whose output could be of the same level as radiogenic heating (Chen et al. 2014). Lastly, Triton displays evidence of a rich chemistry that involves nitrogen and carbon ices, as well as tholins, a group of carbon–hydrogen–nitrogen compounds formed by the irradiation of short nitrogen- and carbon-rich molecules. Hints for the presence of a deep ocean in Pluto come from the tectonic expression of the reorientation of an icy shell mechanically decoupled from the interior (Keane et al. 2016). Although it is about the same size and density as Triton, Pluto's heat budget is much lower, limited to radiogenic decay heat. However, Kimura and Kamata (2020) demonstrated the preservation of a >100-km-thick ocean in Pluto at present over a wide range of thermal evolution conditions.

**characteristics of ocean world evolution and environments**

**Drivers of Evolution**

The long-term evolution of ocean worlds is driven by various energy sources that act at different times and on different timescales (see Hussmann et al. 2010 for a review). First, accretion energy from the conversion of impactor kinetic energy could drive internal melting in large moons, such as Europa or Ganymede, and lead to the formation of an ocean and primitive atmosphere. For smaller bodies, accretional heating was probably too small to drive significant melting. For a time of accretion less than 5 My after the formation of calcium–aluminum inclusions, bodies could also benefit from the decay of short-lived radioactive elements (26Al, 60Fe). If the interior was sufficiently warm, differentiation of layers as a function of density (e.g., ice–rock separation, iron core formation) could proceed, and the associated release of potential energy could further enhance internal differentiation. Tidal despinning of moons into the synchronous rotation state and tidal heating generated during Triton's capture could also result in significant melting.

The decay of long-lived radioactive elements (238U, 234U, 235Th, and 40K) can supply energy for billions of years, and is the dominant long-term energy source for most ocean worlds along with tidal heating resulting from periodic variations of gravitational forces in moons on eccentric orbits and close to their planet. This is the case of Europa and Enceladus whose long-lived oceans are maintained by tidal heating. Other moons (Ganymede, Titan) might have also experienced periods of pronounced tidal heating over the course of their history, and obliquity-driven tidal dissipation may be important in the ocean of Triton. Finally, the release of latent heat during ocean crystallization can also significantly contribute to the long-term energy budget, especially in the case of large ocean worlds. For example, the crystallization of Europa's ocean over 100 My
would lead to heating rates comparable with the present-day radiogenic heating rate (Hussmann et al. 2010).

The energy accumulated and/or generated in the interior of an ocean world is transported toward the surface and radiated into space. Heat can be transferred by diffusion (conduction) or by convection depending on the particular setting of each ocean world interior (see review by Hussmann et al. 2010). In the first case, heat transport is slow and depends mainly on the thermal conductivity of the particular material, which itself depends on temperature, porosity, and/or composition. Heat diffusion transfers energy through thin ice shells, as well as through the outer, cold regions of thick ice shells called stagnant lids. Convection typically occurs in the ice shell if it is thick enough (≥20 km, depending on other parameters) and/or if its viscosity (resistance to flow) is low (~10^{13}–10^{15} Pa·s at the melting temperature). Convection can initiate if the ice layer becomes unstable to buoyancy-driven flow. In most

**Figure 2** Illustration of possible mechanisms driving the exchange of material between a deep ocean and the surface. (A) Shallow melting and water advection to the ocean, (B) Oceanic water injection and jet activity, (C) Upwelling from the ocean associated with band formation, (D) Oceanic water excavation due to break-through impact. Impact-driven activity (D) applies to all icy bodies with direct evidence at Ceres. The other mechanisms are more relevant to icy moons, but mechanism (B) has been observed directly only at Enceladus. Mechanisms (A and C) are illustrated with examples found on Europa and Ganymede.

Sketches are reproduced from Soderlund et al. (2020) with permission from Springer. Images and credits can be found in NASA Photojournal: (A) PIA00591 (34 × 42 km), Photo: NASA/JPL/ASU; (B) PIA06247 (125 × 125 km), Photo: NASA/JPL/SPACE SCIENCE INSTITUTE; (C) PIA02573 (258 × 166 km), Photo: NASA/JPL/Brown University; (D) PIA22480 (~20 km across), Photo: NASA/JPL-CALTECH/UCLA/MPS/DLR/IDA/PSI.
cases, buoyancy is due to positive thermal expansivity (i.e., warm material being less dense than cold material), but compositional effects may also play a role (e.g., salts or silicate particles would reduce ice buoyancy). Heat transfer by convection is considerably more efficient than that by diffusion and may result in the fast freezing of an ocean world interior in a few hundred million years in the absence of tidal heating and/or chemical compounds that affect the efficiency of the convection process. Anti-freezing compounds, such as ammonia or chlorides, can depress the freezing point by tens of degrees. However, theoretical work and observations (e.g., Ceres) indicate that ammonia is more likely to be removed from the ocean to form ammoniated salts and clays. Finally, insulating materials, such as gas clathrates, can significantly slow down heat transfer and explain the long-term presence of oceans in Titan (Kalousová and Softon 2020), Ceres (Castillo-Rogez et al. 2021), and Pluto (Kamata et al. 2019).

The conditions leading to the preservation of liquid in Ceres, and possibly in Pluto, is an emerging topic of interest with applications to other dwarf planets and icy moons with little or no tidal heat. The contribution of abundant clathrate hydrates in the outer ice shell and the release of fluids as a result of thermal metamorphism of the rocky mantle are actively being investigated. Lastly, large impacts could represent a local heat source that could drive transient geological activity, as can be observed at Ceres (Raymond et al. 2020).

Exchange of Material Between Interior and Surface
The exchange of material between the deep ocean and the surface is important for at least two reasons. First, the surfaces of some ocean worlds (e.g., Europa, Titan, Ceres, Triton) contain organic molecules and/or oxidants that represent a potential source of chemical energy necessary for life development; hence, whether that material can get to the ocean is of utmost interest. Second, the transport of material from the ocean to the surface allows the investigation of the ocean environment and the search for potential biosignatures at the surface.

Material exchange can occur by impacts (Fig. 2D) and cryovolcanism accompanied by outgassing (Soderlund et al. 2020). The presence of $^{40}$Ar in Titan’s atmosphere and the replenishment of its atmospheric methane indicate some degree of interior–surface–atmosphere exchange (Sotin et al. 2021) for which cryovolcanism has been suggested, but its occurrence remains debated. If the ice shell is only a few kilometers thick, a direct exchange path may exist through fractures that span the total shell thickness. This is the case for Enceladus, whose ocean material is released to space via large faults in its south polar region (Fig. 2B). In the case of Ceres and likely other bodies with residual oceans and thick ice shells, upwelling of deep material may have a passive origin, for example, owing to internal stresses generated in the liquid reservoir released via impact (Fig. 2D). If convection occurs in a thin shell (e.g., as in Europa or Ganymede), material transfer may be facilitated by a combination of material advection to/from the shallow subsurface and other mechanisms (e.g., impact, cryovolcanism, tectonics) through the stagnant lid (Fig. 2A and 2C, Soderlund et al. 2020). Although a thick stagnant lid up to half of the total shell thickness would likely represent a barrier to material exchange, the lid thickness could be substantially reduced by the presence of a surface insulator, such as methane clathrates (Kalousová and Softon 2020).

Compositional heterogeneities within the ice shell, due to impurity entrainment during its crystallization (e.g., Buffo et al. 2020), would also play an important role in the shell dynamics, thus affecting surface–ocean exchange processes.

Chemical Characteristics of Oceans
Ocean material exposed on ocean world surfaces generally vanishes on a scale of a few tens of millions of years as a result of erosion from small impacts, lateral mixing, and degradation by space radiations. Chlorides, carbonates, and ammonium or ammonia have been identified at Ceres and Enceladus (Postberg et al. 2011; De Sanctis et al. 2020), which is characteristic of an alkaline environment (e.g., Marion et al. 2012). Whether the relative concentrations of these materials are representative of the source or have been altered by their emplacement mechanisms is uncertain. Chlorides have also been identified at Europa (Trumbo et al. 2019), as well as sulfates, although the origin of the latter, endogenic or exogenic (from Io), remains debated. Oceanic material released at Enceladus’ south pole also includes a vast array of organic compounds (Postberg et al. 2018). Indeed, under the moderate pressures (10s of MPa) of deep oceans, hydrogen (H$_2$) released by serpentinization accumulates and creates reducing conditions. Sulfur preferentially occurs in the form of sulfides, ammonia in the form of ammonium, and accreted CO$_2$ may be speciated between carbonates and bicarbonate ions (Marion et al. 2012).

Internal evolution models indicate that ocean worlds with thick oceans (10s of km) have temperatures close to the water melting temperature (approximately 265–270 K depending on pressure). In the case of icy bodies that are or may be holding residual oceans (e.g., Pluto, Ceres, and icy moons with limited tidal heating), the liquid temperature may be depressed at the eutectic of carbonate/ammonium/chloride mixtures (~250 K), as has been inferred for Ceres (Raymond et al. 2020).

A major open question in the evolution of ocean worlds is the extent of chemical gradients at present. Impactor material can represent a local but regular source of fresh material embedded in melt chambers produced by impact heating. Radiolytically produced oxidants on Europa’s surface can also be entrained into its shell by impacts or other resurfacing processes. Water radiolysis is another mechanism proposed to create local chemical energy, especially in the porous region of rocky mantles. Lastly, fluids released from the thermal metamorphism of large rocky mantles can replenish the ocean in oxidants (e.g., CO$_2$, SO$_2$). Although on large moons (e.g., Ganymede, Titan) the rock is separated from the ocean by a layer of high-pressure ice polymorphs (Fig. 2C), fluids released at the rock–ice interface can percolate through the ice layer owing to their density, which is lower than that of the high-pressure ice, thereby reaching the ocean (Kalousová et al. 2018).

FUTURE STEPS IN OCEAN WORLD EXPLORATION
This is an exciting time for ocean world exploration. Several missions are under development (Europa Clipper, JUpiter ICy moons Explorer (JUICE), Dragonfly to Titan) and several concepts are being evaluated by NASA and the European Space Agency (ESA) as part of their programs for the upcoming decade (Fig. 3). We briefly summarize them here.

Upcoming Missions and Projected Science Return
JUNO, NASA’s New Frontiers mission to Jupiter performed flybys of Ganymede and Europa in 2021–2022 in its extended mission. The new constraints on the interior
structure and ocean properties derived from these flybys are being assessed at the time of writing. Europa is the primary target of NASA’s flagship mission Europa Clipper that would perform more than 40 close flybys, most of which below 100 km altitude. The main goal of the mission is to investigate Europa’s habitability. High-resolution imaging would also help identify a suitable landing site for a future lander. Scheduled to launch as early as October 2024, the spacecraft would reach Europa’s orbit in the early 2030s. The payload comprises optical remote sensing (UV, visible, and infrared) and in situ compositional instruments (mass and particle spectrometers) to characterize Europa’s surface composition, ice-penetrating radar to determine the ice shell thickness and structure, a magnetometer to constrain the depth and salinity of the subsurface ocean, and a thermal imager to search for recent or ongoing cryovolcanic activity (Howell and Pappalardo 2020).

JUICE (Jupiter Icy moons Explorer) is the first L-class ESA mission. Scheduled to launch in 2023, it would insert into orbit around Ganymede in 2032 after several flybys of Callisto and Europa. The one-year investigation of Ganymede would involve extensive visible imaging and imaging spectrometers (ranging from UV to sub-mm wavelengths), a laser altimeter, radar sounder, radio science package, magnetometer, and plasma sensors. The main mission objectives at the Galilean moons include the determination of the icy shell thicknesses, search for shallow subsurface liquid, and characterization of the deep oceans. The JUICE mission should also inform on Ganymede’s geological processes and surface composition and constrain its internal mass distribution (Grasset et al. 2013).

Recently selected by NASA, the New Frontiers mission Dragonfly would investigate Titan and search for prebiotic chemical processes that may have been common to both Titan and Earth. Scheduled for launch in 2027, it would land on Titan’s surface nine years later. Dragonfly is designed as a rotorcraft lander, capable of flying up to 10 km at once between landing sites. The scientific payload would consist of cameras; mass, gamma-ray, and neutron spectrometers; a seismometer; and a meteorology package. During the nearly three-year-long science phase, Dragonfly would explore different environments (dune fields, impact crater floors) to study the prebiotic chemistry taking place in Titan’s atmosphere and on its surface, investigate the methane cycle, and characterize the subsurface liquid reservoirs, including the global ocean (Lorenz et al. 2018).

Ocean World Exploration Concepts that May Become Priorities for the Next Decade

The interest of the international community for a mission to the systems of Uranus or Neptune has led to the design of investigations that could search for and characterize deep oceans in the large moons in these systems, in particular with magnetometer measurements (e.g., Cochrane et al. 2021). The recent Planetary Science and Astrobiology decadal survey (NASEM 2022) recommends a Uranus Orbiter and Probe as NASA’s next flagship mission priority (Fig. 3). Although emphasizing system-level exploration, this concept includes a focus on ocean world science, targeting Miranda.

Enceladus is the only ocean world where the material from the rock–ocean interface is directly accessible by sampling its spectacular plumes. A life search mission at Enceladus has thus been identified as a second flagship-class priority for the next decade (NASEM 2022), based on the Orbilander concept by MacKenzie et al. (2021). The Voyage 2050 report from ESA also identified a mission to an icy moon of Jupiter or Saturn as its first L-class mission in the 2035–2050 timeframe.

NASEM (2022) also highlights several ocean world targets for medium-class missions that may be competed in the 2023–2032 timeframe: sample return from Ceres’ evaporites, Titan Orbiter, Triton Orbiter, and an Enceladus multi-flyby mission. Altogether, the next decade of planetary exploration promises to address many questions about the processes driving ocean world evolution and reveal which ocean worlds host habitable environments.

CONCLUSIONS

The emergence of life on Earth is not well understood, but certainly involved a complex environment. A hydrothermal emergence of life in black smokers on Earth’s deep oceanic floor is one of two competing hypotheses (Russell et al. 2014). Hence, the prospect for volcanic activity on Europa’s seafloor (Běhounková et al. 2021) makes it a serious candidate for a life search mission. Hydrothermal circulation in Enceladus’ porous core could also be favorable for advanced prebiotic chemistry (Barge and White 2017). In situ missions to both bodies are currently under consideration. The case for an origin of life in other bodies is debated because of the lack of mechanisms supplying long-term chemical energy. Furthermore, even if life could start and thrive in some ocean worlds, the absence of a recent exposure mechanism would prevent the discovery of biosignatures on their surfaces. Knowledge gained from future spacecraft missions investigating different types of ocean worlds would bring new insights into the pathways leading to long-lived habitable environments and test if ocean worlds can exist beyond Saturn.

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The distribution of water in differentiated Solar System bodies depends on many factors including size, distance from the Sun, and how they incorporated water. Most of this water is likely locked as hydrogen in mantle minerals and could amount to several Earth oceans worth in mass for the largest planets. An essential compound for the development of life, water also has a tremendous influence on planetary evolution and volcanism. Only Earth has an active exchange of water between surface and mantle. Surface water on other differentiated bodies mostly results from degassing by volcanoes whose mantle sources are inherited from magma ocean processes early in their history. Airless bodies also acquire surface water by impacts, spallation, and from the solar wind.

**INTRODUCTION**

Water is a key ingredient for life but also plays fundamental roles in the evolution of planets and asteroids. Solar System bodies that experienced internal melting, resulting in the formation of crust, mantle, and core, are labeled as “differentiated” or “terrestrial” bodies. Water in the interior of terrestrial bodies has a tremendous influence on how they cool and differentiate, how rocks deform, how magmas develop, how volcanoes erupt, and how atmospheres and oceans form. Most water is locked in silicate minerals in the mantles of differentiated bodies as trace element hydrogen (H) bonded to structural oxygen. The term water has been colloquially used to refer to this H and is traditionally reported in μg/g H₂O. In the mantle, which is the largest layer by volume in differentiated bodies, these trace amounts of H locked in minerals (tens to hundreds of μg/g H₂O) sum up to the equivalent of several terrestrial oceans in mass inside Earth and possibly in other planets. When the mantle partially melts, H is preferentially partitioned into the melt and is thus classified as an “incompatible” element. When these melts reach the planetary surface during magma ocean or volcanic events, they degas, releasing H as H₂O, H₂, and other H-bearing molecules depending on how oxidized the system is, along with other highly volatile elements (e.g., carbon, sulfur). This degassing can result in the formation of atmospheres (Earth, Mars, Venus) and liquid and frozen water (Earth and Mars) on the surface of planets of sufficient size to retain these volatiles by gravitational pull. Additional H may be acquired on the surface of airless bodies (e.g., the Moon) via solar wind implantation, cosmic ray spallation, or delivery by impactors. This contribution summarizes our current knowledge on the main reservoirs of water in differentiated planets, the Moon, and asteroids in terms of quantities and isotopic ratios (deuterium/hydrogen (D/H) ratio, expressed here in the δD notation in ‰).

**EARTH’S WATER**

The uniqueness of Earth in the Solar System comes from the presence of oceans of water on its surface and the ongoing plate tectonic regime that results in an active exchange of water between the interior and surface (ocean and atmosphere) of the planet. This system is dynamic with constant recycling of water through the Earth, from water input at subduction zones to water output when volcanoes degas at the surface, as well as likely exchange between Earth’s deeper layers (Fig. 1).

As a result, water is unevenly distributed in Earth, with most of it—one to seven Earth oceans’ mass depending on estimations—stored in the mantle as H in silicates (e.g., Peslier et al. 2017). For the crust and upper mantle, we have direct samples (crustal units, crustal and mantle xenoliths, orogenic massifs, abyssal peridotites) and indirect samples (crystallized partial melts from the mantle such as mid-ocean ridge basalts, MORB, and oceanic island basalts, OIB) in which water contents have been measured, primarily by transmission Fourier transform infrared spectrometry (FTIR) and secondary ion mass spectrometry (SIMS). The MORB source (upper oceanic asthenosphere) contains ~50–230 μg/g H₂O, while the OIB sources, being more diverse in composition and depth, are more water-rich (100–750 μg/g H₂O; Fig. 1). The mantle lithosphere, whether under continental or oceanic crust, also has water contents from 50 to 200 μg/g H₂O. Studies of mantle lithosphere xenoliths show that the variation in water contents is mostly linked to metasomatism, i.e., water-bearing fluids or melts circulating through and reacting with the mantle lithosphere (e.g., Peslier et al. 2017). The δD of the upper mantle is estimated to be approximately ~100‰ from the analysis of mantle xenoliths, ~60‰ to ~90‰ from MORB

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1 Jacobs, NASA-Johnson Space Center  
Mail Code K33  
Houston, TX 77058, USA  
2 Dept. of Geological Sciences  
New Mexico State University  
Las Cruces, NM 88011, USA  
E-mail: apeslier@nmsu.edu  
3 Istituto di Astrofisica e Planetologia Spaziali, INAF  
Via del Fosso del Cavaliere 100  
00133 Roma, Italy  
E-mail: mariacristina.desanctis@inaf.it
analyses, and values as low as −200‰ have been suggested from data on melt inclusions in primitive basalts (Peslier et al. 2017). The relatively low water content of olivine, the main phase of the mantle lithosphere, plays a role in the rigidity of tectonic plates because the strength of olivine increases with decreasing water content (Karato 2006). The upper mantle likely becomes progressively more water-rich with depth, as water solubility increases with pressure in olivine (Peslier et al. 2017). Consequently, in contrast to the lithosphere, the water in olivine facilitates the convection of the asthenosphere by lowering its viscosity (Karato 2006).

Water contents are less constrained deeper in the Earth (Fig. 1), where indirect estimates are obtained using a combination of experimental petrology, mineral physics, and geophysics (e.g., electrical conductivity and seismic attenuation; Karato 2006; Peslier et al. 2017). An exception is one water-rich ringwoodite inclusion found in a diamond originating from the mantle transition zone. This diamond comes from parts of the mantle transition zone thought to be very water-rich (10,000 μg/g H₂O), likely related to subducting water-rich slabs that sometimes stagnate at these depths, while other parts are relatively dry (<6000 μg/g H₂O; Fig. 1). The water content of the lower mantle is a matter of debate, with contradictory results from experiments on its main phases. However, minor water-rich phases are stable in the lower mantle (e.g., hydrous Mg and Al silicate minerals called phases B, D, H, d, and Egg), brought down by subducted slabs that can penetrate all the way to the core–mantle boundary. The H content of the core is unknown, but could constitute an important reservoir of “water” in the Earth because of the high solubility of H in liquid and solid iron.

Figure 1 Sketch showing current estimations of water content and δD distribution in the Earth. Blue arrows show where the major transfers of water occur between layers. Black dotted arrows indicate asthenospheric mantle convection patterns. SZ = subduction zone; MOR = mid-ocean ridge; OI = oceanic island.

The water content of Earth’s interior and surface has evolved over time. Based on the similarity of the δD (≤−100‰) and other isotopes of the Earth’s mantle to the main building blocks of Earth (enstatite chondrites, ≤−100‰ to −150‰; Fig. 2), water in Earth could have been acquired during the planet’s accretion from the solar nebula (Peslier et al. 2017; McCubbin and Barnes 2019; Izidoro and Piani 2022 this issue). Others argue that most of Earth’s water could have been acquired later, after the planet was already differentiating into core and mantle, and that this water could instead come from carbonaceous chondrite type material (Fig. 2) from the outer Solar System (Peslier et al. 2017; Vacher and Fujiya 2022 this issue). As still growing protoplanets, Earth and other terrestrial bodies are thought to have captured an H₂ atmosphere from the solar nebula, which they likely lost to space in the first billion years (Gy) by being blown off by the extreme UV radiation from a young Sun (Lammer et al. 2018). The next step is the formation of surface magma oceans caused by heat dissipation during a period of giant accretionary impacts, including the one that formed our Moon (Elkins-Tanton 2012). The magma oceans at the surface of Venus, Earth, and Mars degassed and formed a “steam” atmosphere of primarily CO₂ and H₂O (Lammer et al. 2018). The majority of this atmosphere is retained, despite some being ejected during the largest impacts (Elkins-Tanton 2012). After the magma oceans finally solidify, atmospheric cooling over millions of years results in water condensation and liquid water on planetary surfaces. Based on the ages of the oldest banded iron formations that formed from anoxic sedimentary deposition, and of the oldest detrital zircons, it is estimated that oceans were present on Earth as early as 3.8–4.2 billion years ago (Ga) (e.g., Wilde et al. 2001). The final and still ongoing redistribution of Earth’s water is ruled by plate tectonics, which started ~3 Ga (e.g., Debaille et al. 2013). Plate tectonics allows oxidized wet material, such as sediments, serpentinitized oceanic crust, and water seeping in fractures at the bending of the plates above mantle wedges, to be subducted into the mantle (Fig. 1). The oxidation process of the mantle was particularly effective after the rise of life-induced oxygen in the atmosphere, 2.2–2.5 Ga (Catling and Zahnle 2020). Melting of this oxidized material has allowed N₂ gas to be released by volcanoes (as opposed to ammonia being incorporated into rocks under reduced conditions), especially at subduction zones (Catling and Zahnle 2020). This resulted in the N₂-dominated composition for the Earth’s atmosphere. In addition, CO₂ is captured as carbonates via continental weathering, which is sustained by the continuous presence of liquid water on the planet’s surface (Lammer et al. 2018). The temperature variations of the Earth’s atmosphere, mainly regulated by the carbon cycle and greenhouse effect (Catling and Zahnle 2020), and resulting global air circulation, generate a low-altitude cold trap. This tropopause layer at 15–18 km makes water condensate and fall back to the surface, instead of being lost to space over time (Wordsworth and Pierrehumbert 2013). Earth’s plate tectonics and resulting deep water cycle were therefore essential players that allowed our planet to harbor and sustain life on its surface.

The possibility that water is present at the surface of the Moon is crucial for future human exploration. There appears to be water incorporated in lunar regolith (the “soil” derived from the long history of impacts that have pounded the rocks at the surface of our satellite) and ice deposits in the permanently shadowed craters of the poles (Fig. 3C). These sources of water could potentially be harvested for long-term human habitation of the Moon. The evidence for water at the lunar surface is primarily derived from spectroscopic and radar data (McCubbin et al. 2015 and references therein). In particular, Chandrayaan-1’s Moon Mineralogy Mapper (M3), NASA’s Cassini’s VIMS spectrometer, and NASA’s Deep Impact/EPOXI probe have detected a spectral signal at ~3-μm wavelength, consistent with either water...
and water present in the lunar exosphere can be chemically implanted by solar wind. A portion of this water can be retained in impact glasses, resulting in a transient atmosphere at specific locations where high water contents, suggesting that volcanic activity could have occurred. Finally, some areas of the lunar surface show anomalously high hydrogen isotopic composition (on a log scale of the D/H ratio) of differentiated planetary bodies from their mantle to their surface compared to those of enstatite chondrites (EC), carbonaceous chondrites (CC), and comets (Oort cloud and Jupiter types). IOM = insoluble organic matter. The striped white and red pattern for Earth and Mars shows the extent of lower δD values that have been suggested for the mantle of these planets. The question marks for Mercury and Venus indicate that the δD of their interior is not known.

(H₂O) or hydroxyl (OH) on the lunar surface. Recent detection from Earth by the NASA/DLR Stratospheric Observatory for Infrared Astronomy (SOFIA) of a 6-μm emission feature at high lunar latitudes is also likely owing to the presence of molecular water on the lunar surface (Honniball et al. 2021). Moreover, the presence of larger water-ice deposits in the permanently shadowed craters of the poles has been detected by the Lunar Prospector Neutron Spectrometer and confirmed by the neutron detector onboard the Lunar Reconnaissance Orbiter (Fig. 3C) and the Lunar Crater Observation and Sensing Satellite. The near-infrared reflectance spectra provide a global view of water at the lunar surface through the identification of OH or H₂O absorptions in the ~2.6- to 4-μm wavelength region.

Several mechanisms for the origin of water in lunar soil have been proposed (McCubbin et al. 2015; Honniball et al. 2021). One derives from the solar wind, which mainly contains charged protons that interact with airless planetary surfaces. The protons bond to the oxygen atoms of minerals present at the surface and get implanted in the top few microns. This “water” is then mixed in deeper during reworking of the regolith following impacts. Implantation by solar wind is evidenced by the low δD (~−550‰) measured in lunar soil, which is close to that of the solar wind (~1000‰). Impacts on the lunar surface are also believed to contribute to the polar water-ice deposits. Impacts can release cometary and meteoroidal water into the exosphere and also free solar wind-implanted H₂.

A portion of this water can be retained in impact glasses, and water present in the lunar exosphere can be chemisorbed on grain surfaces. Spallation, the formation of chemical elements via nuclear fission, including hydrogen from the interaction of surface rocks with cosmic rays (highly charged particles from space), can also add water to lunar rocks and regolith, thereby increasing their δD. Finally, some areas of the lunar surface show anomalously high water contents, suggesting that volcanic activity could generate a transient atmosphere at specific locations where water could be trapped.

A temperature dependence has been evidenced for the geographical distribution of surface water, with content increasing toward the poles. A portion of the water released by impacts may migrate to cold traps in permanently shadowed regions where it may remain in the form of ice. Surface water abundances can also vary over a lunar day, suggesting formation and migration of water toward cold traps present at polar regions. This water is likely stored within glasses or in voids between grains sheltered from the harsh lunar environment. However, the weak equatorial 3-μm bands obtained by the Lunar Atmosphere and Dust Environment Explorer (LADEE) are consistent with the uppermost few cm of the regolith being mostly desiccated. The LADEE and M3 data are also consistent with the low water abundances estimated at the equator by SOFIA measurements (Honniball et al. 2021). Conversely, SOFIA data at high latitudes indicate that the regolith is not desiccated, supporting several inferences that show an increase in hydroxyl from the equator to higher latitudes.

An assessment of the water distribution and isotopic characteristics in the Moon’s interior is necessary to understand the origin of the Moon’s water in the context of planetary formation (addressed in Izidoro and Piani 2022 this issue) and evolution. For this purpose, the various types of lunar rocks brought back by astronauts of the 1969–1973 Apollo missions, by the 2020 Chang’e 5 mission, and found as lunar meteorites, are being systematically analyzed. Trace amounts of water are found in all types of Moon rocks, allowing the role of water during the stages of our satellite’s history to be deciphered, in particular during the formation of its crust and later volcanism. The key is to determine how water was distributed in the crust and mantle during these events, and how much was lost by degassing from magmas at the surface of our satellite. Any volatile released during degassing is mostly lost to space because the Moon is too small to retain an atmosphere (Elkins-Tanton 2012; Hauri et al. 2017).

A few μg/g of water have been detected in feldspars from lunar highland rocks (Hui et al. 2017). These represent the oldest Moon rocks, forming 4.3–4.4 Ga by flotation of plagioclase at the top of the crystallizing lunar magma ocean (Elkins-Tanton 2012; Hauri et al. 2017). The resulting crust is dominated by plagioclase and currently covers 83% of the Moon’s surface. From these measurements, it has been speculated that the lunar magma ocean contained ~650–2500 μg/g H₂O with a δD of ~300‰ ± 110‰ (Hui et al. 2017; Fig. 2). In contrast, δD values ranging from ~750‰ to 800‰ (Fig. 2) are measured in highland apatites, a volatile (H, Cl, F)-rich phosphate that crystallizes late in a magma solidification sequence (Robinson and Taylor 2014; McCubbin et al. 2015; Robinson et al. 2016). The lunar magma ocean could have had pre-degassing δD values as low as those of the low-δD apatites, while the high δD of the plagioclase are thought to result from the preferential loss of H over D during H₂ degassing prior to crust formation (Hui et al. 2017). The remaining 17% of the Moon’s surface comprise mare basalts that erupted 3.9–2 Ga, which are crystallized melts sourced in the lunar mantle. The wide δD range of the mare basalt apatites (~280‰ to 1450‰) is interpreted as H isotope fractionation during various degrees of volcanic degassing of melts with δD initially in the lower part of the range, i.e., inherited from their mantle source (Robinson and Taylor 2014; McCubbin et al. 2015; Hauri et al. 2017; Hu et al. 2021). Using melt inclusions in

![Figure 2](https://example.com/image2.png)
olivine, the mantle source of primitive lunar basalts was determined to contain as much as or less water than the source of MORB on Earth (80–410 or 10–130 μg/g H₂O depending on the calculation assumptions; Hauri et al. 2017; McCubbin et al. 2015), while analyses of melt inclusions in ilmenite from the youngest Mare basalts suggest that their mantle source is water-poor (1–5 μg/g H₂O; Hu et al. 2021).

All of the rocks mentioned above are from the crust, meaning that any estimate of the water content and δD of the lunar interior must be calculated and has large uncertainties (Robinson and Taylor 2014). Moreover, the overwhelming evidence for degassing processes implies that most analyzed rocks degassed. Consequently, the water contents listed above are likely minimum values and most δD are higher than pre-degassing values. Nevertheless, the presence of trace amounts of water in lunar minerals first implies that the giant collision of a Mars-size object with the proto-Earth, which is thought to have formed our Moon, apparently did not result in total H loss as previously assumed. Water was incorporated at the time of the Moon’s accretion and redistributed in its interior during its differentiation. The water and δD of the lunar mantle are likely heterogeneous, with regions having δD (Fig. 2) close to solar nebula values (< ~300‰) inherited from the time of the Moon’s accretion, and regions with higher δD (~300‰) and lower water contents dating from the time of magma ocean degassing (McCubbin et al. 2015; Hauri et al. 2017; Hu et al. 2021). A more complete understanding of lunar water will be achieved once more primitive samples (i.e., similar to mantle composition) are brought back and analyzed. Mantle samples may have been excavated during large impacts and may be found at the central peaks, peak rings, and regoliths of the largest lunar basins. For this reason and because of the potential for ice deposits, the South Pole Aitken region, the largest impact crater on the Moon, is targeted by planned U.S., European/Russian, Japanese, and Chinese missions.

**MARS WATER**

Water once flowed on Mars, possibly even forming oceans, as evidenced by two main observations (Filiberto and Schwenzer 2018 and references therein). First, geomorphological features evidenced from orbiting spacecrafts are consistent with river channels, canyons, river deltas, and shorelines. Second, chemical analyses performed from space (e.g., by γ-rays, infrared and thermal emission spectrometry on Mars Odyssey, Mars Global Surveyor, Mars Express) and by rovers (e.g., by spectrometry of α-particles, X-rays, gas chromatography, thermal emission, and Mössbauer on NASA Pathfinder, Mars Exploration Rovers Spirit and Opportunity, and Mars Science Laboratory’s rover Curiosity). These analyses of the planet’s surface show that alteration minerals formed in rivers and lakes. In particular, a shift from phyllosilicates to sulfates indicates that Mars’ climate shifted from wet to dry ~3.5 Ga. For about the last 3 Gy, alteration mineralogy has been dominated by anhydrous ferrous oxides—giving Mars its characteristic red color—and wind erosion has ruled. Water on the surface of Mars is presently locked in ice at the polar caps (Figs. 3E and 4A), but also as underground ice and salty liquid water lakes beneath the polar ice (Filiberto and Schwenzer 2018; Orofino et al. 2018). The drying of the climate has been attributed to atmospheric H loss to space, combined with sequestration in the crust in the form of hydrous alteration minerals. Preferential loss of H relative to D during this H escape process resulted in the particularly high δD of the Martian atmosphere (~5000‰; Fig. 2). Atmospheric H loss is a result of the small size of Mars (a third of Earth’s) and consequently low gravity, and of a core dynamo having stopped early in Mars’ history, i.e., no magnetic field being generated to shield the planet from solar wind (Lammer et al. 2018).

Estimating how much water the interior of Mars contains and its δD compared to Earth helps us model planetary formation (Izidoro and Piani 2022 this issue). We are fortunate to have samples from Mars as meteorites, and research is ongoing to analyze water in their various phases, primarily using SIMS. All but one (a crustal breccia) meteorites from Mars are crystallized igneous melts, ranging from cumulate (e.g., nakhlites) to basaltic (shergottites; Udry et al. 2020 and references therein). Shergottites, the most common Martian meteorite type in our collection, have a huge range of radiogenic isotopic compositions, larger than Earth’s MORB and OIB combined, with two compo-
sitional end-members: “depleted” and “enriched” (Udry et al. 2020). These terms refer not only to radiogenic isotopes, but also to concentrations in incompatible trace elements, such as light rare earths (REEs), and redox conditions. The meteorites’ compositional differences result from partial melting of compositionally different regions of the Martian mantle (Fig. 4B). After magma ocean degassing and solidification, Mars never had plate tectonics as on Earth, but stayed in a “stagnant-lid” regime, implying little or no mantle convection, and no surface material input into the mantle (Elkins-Tanton 2012). Consequently, the Martian mantle regional compositions, including water content and δ D variations, are thought to be inherited from magma ocean crystallization processes (Dudley et al. 2022 and references therein). The lava flows from which shergottites and nakhlites originate erupted <2.4 Ga, which is significantly later than magma ocean processes (Udry et al. 2020).

Calculating the water content of the mantle helps us to constrain the evolution of Mars, from its differentiation to its most recent volcanism, but—given that all Martian meteorites are samples of its crust—some assumptions are required. First crystallized phases (e.g., Mg-rich olivine, pyroxene, and their melt inclusions) are best to estimate the water content of a parent melt, because their water content is less likely to have been affected by crystallization and degassing processes (Dudley et al. 2022 and references therein). The water content of the mantle source of each meteorite can be calculated from that of the parent melt, although large uncertainties are generated through this method. The use of Martian meteorite phases to calculate the water content of the Martian mantle is further hampered by the water content and δ D being affected by weathering processes on Mars and Earth, and by shock effects when the rock was blasted off from the Martian surface by a meteor impact (Dudley et al. 2021).

This is evidenced by the wide range of δ D values measured in Martian meteorite phases, which is thought to result from the mixing of two main sources: mantle with low δ D (≤300‰–400‰) and surface (up to 5000‰ measured for the Martian atmosphere; Greenwood et al. 2018; Fig. 2). All of these effects imply that the current estimates of the water characteristics of the Martian mantle shown in Figure 4B are to be taken with a grain of salt. Nevertheless, the water content of the Martian mantle appears to be variable. The water content of shergottite sources is low for the depleted endmember (15–47 μg/g H₂O; Usui et al. 2012) and higher for the enriched endmember (245–900 μg/g H₂O; Dudley et al. 2022). This is consistent with the incompatible behavior of water, where the depleted mantle source underwent a greater extent of incompatible element removal during magma ocean crystallization than the enriched source (Fig. 4B). Nakhlites, pyroxene-rich cumulates, have low to intermediary water contents in their mantle sources, consistent with their relatively depleted isotopic and other trace element characteristics (60–180 μg/g H₂O).

The δ D and other isotopes, such as those of N, Cl, and rare gases, are used to understand where Mars water originates (Izidoro and Piani 2022 this issue). The Martian mantle has heterogeneous δ D is controversial. Some argue that the high δ D (~4000‰) measured in some phases of enriched shergottites is, in fact, a mantle signature and not the result of interaction with surficial Martian material (McCubbin and Barnes 2019), while others posit that enriched shergottites have lower δ D (~300‰), as measured in the earliest crystallized phases (Dudley et al. 2022). If the latter interpretation proves correct, then the δ D of the mantle sources of all types of Martian igneous meteorites are similar within uncertainties (~300‰–400‰). These values are higher than that of the Earth’s upper mantle (~−100‰); a dichotomy perhaps inherited from the two planets having different “feeding zones” during accretion owing to their respective distances from the Sun (Izidoro and Piani 2022 this issue). The crustal breccia meteorite NWA 7034 is water-rich (6000 μg/g H₂O) and records δ D (330‰–2000‰) intermediary between those of the Martian mantle and atmosphere (Udry et al. 2020). Although two rovers recently landed on Mars (NASA Mars 2020 Perseverance and China’s 2021 Zhurong), the uncertainties on the water characteristics of deep Mars will only be resolved once un-altered igneous rocks are returned from Mars by robotic missions or by astronauts.

VENUS WATER

Venus is considered an “Earth-like” planet because they have a similar size and bulk composition (Greenwood et al. 2018 and references therein). However, the environment of Venus is completely different, with surface temperatures of 460 °C, and a dense atmosphere (92 bar) consisting of 96.5% CO₂ and 3.5% N₂ (Fig. 3D). These characteristics are explained by a runaway greenhouse effect having occurred in the past, which led to the complete evaporation of oceans presumed to have been present. However, another scenario is that Venus was always too hot for water to condense into oceans (Greenwood et al. 2018). Hydrogen escape would then have taken place early and rapidly, consequently
driving off many other atmospheric constituents. The H escape scenario is confirmed by the high δD (82,000‰–1,600,000‰; Fig. 2) measured in Venus’ atmosphere by the Pioneer spacecraft relative to Earth’s (~0‰).

Regarding the interior of Venus, atmospheric N and C have been used as proxies to estimate that it contains 10 to 100 times less, or the same amount, of water in its mantle as Earth’s (0.12–3000 μg/g H₂O; McCubbin and Barnes 2019). It is likely that Venus accreted with an amount of water similar to that of Earth, because collisional processes by water-bearing planetesimals affected Venus and Earth in a similar way. Although Venus has no plate tectonics, its surface has evidence of resurfacing by recent volcanism, as imaged by the Magellan spacecraft. However, models predict that this volcanic activity, involving mantle downwelling and upwelling and surface degassing, will likely never fully deplete the Venusian mantle of volatiles (Greenwood et al. 2018).

**MERCURY’S WATER**

Mercury was thought to be depleted in volatile elements largely due to its close vicinity to the Sun. However, the first data from the Mariner 10 mission indicated the presence of H, He, and O in an exosphere, and ground-based observations observed additional exospheric Na, K, and Ca (Greenwood et al. 2018 and references therein). Moreover, radar data taken from Earth evidenced polar ice deposits, later confirmed by the MESSENGER spacecraft. Neutron data by MESSENGER indicated that Mercury’s radar-bright polar deposits contain a H-rich layer below a surficial layer less rich in H (Fig. 3B). Combined radar and neutron data suggest that the H-rich layer consists of nearly pure water ice, derived dominantly from meteoritic and cometary impacts. Other discoveries from MESSENGER indicate that Mercury could contain as much interior water as Mars, having a K/Th ratio most similar to Mars, and a low oxygen fugacity calculated for its silicates (McCubbin and Barnes 2019). Moreover, its morphologic features are consistent with explosive volcanism, including pyroclastic deposits and vents. Modeling of the spatial extent of these deposits show that their formation would require a magma with quite high volatile content. Furthermore, it has been estimated that Mercury’s explosive volcanism has been occurring over a long period of time (from 3.8 to 1 Ga). Nevertheless, Mercury’s volatile inventory, including water, is still an open question.

**WATER IN VESTA AND THE HED METEORITES**

The differentiated asteroid 4 Vesta is located in the asteroid belt between Mars and Jupiter. It is thought to be the parent body of most of the meteorites belonging to the howardite-eucrite-diogenite (HED) clan. This is based on remote spectral data, especially from the NASA Dawn spacecraft that specifically visited this asteroid in 2011, that match the spectral properties of HEDs obtained in the laboratory (e.g., McSween et al. 2019). Eucrites are basalts and gabbros, diogenites are cumulates of ultramafic compositions, while howardites are a brecciated mix of the two from impacts. As described above for the Moon and Mars, analyzing the water content and δD in these asteroid samples helps refine models of solar nebula accretion and volcanism in extraterrestrial bodies. The mineralapatite in eucrites yields a large δD range, from ~500‰ to 700‰ (Fig. 2), interpreted as a δD increase when H was lost during volcanic degassing and thermal metamorphism (Sarafian et al. 2014; Stephant et al. 2021). The pyroxenes, one of the first crystallized phases from the eucrite parent melt, contain low water contents (~20 μg/g H₂O) compared to terrestrial pyroxenes (typically 100s of μg/g H₂O) and the δD are consistently low at ~ −260‰ ± 70‰ on average (Stephant et al. 2021). All HEDs are crustal lithologies, but from the least thermally metamorphosed eucrite analyzed, the water content of the Vesta mantle (~70 μg/g H₂O) is estimated to be lower than that of the MORB source and its δD is estimated to be ~ −370‰, i.e., lower than that of Earth’s upper mantle (~ −100‰; Fig. 2). Vesta is thought to have accreted earlier than Mars, Earth, and even chondrites, from a region of the proto-solar nebula that had a low δD and differed from that where chondrites formed (McCubbin and Barnes 2019; Stephant et al. 2021). Perhaps small bodies like Vesta or the Moon cooled fast enough for their magma oceans to crystallize a conductive lid, blocking most degassing early (Elkins-Tanton 2012). They would then have experienced less overall degassing than larger planets, thereby preserving a low mantle δD inherited from their accretion material. Alternatively, low-δD areas may exist in the mantles of all differentiated bodies; however, those from large planets like Earth have not been sampled by mantle melts.

On Vesta’s surface, Dawn’s spectrometers detected the signature of OH in the spectra of the darkest areas of the asteroid’s equatorial regions that would indicate a water content as high as 400 μg/g H₂O (De Sanctis et al. 2012). The distribution of the OH signature, shaped as pits and dark patches (Fig. 3A), suggests an exogenic origin, likely delivered by infalling primitive asteroids that are common in the asteroid belt. This material may have been delivered during the early evolution of Vesta (after differentiation and crustal formation), either ~10 My after the formation of the first solids or later, during a purported (and controversial) period of late heavy bombardment, when primitive outer Solar System objects were implanted in the outer part of the asteroid belt (De Sanctis et al. 2012).

**WATER IN OTHER ACHONDRITE METEORITES**

The only other meteorite groups from differentiated parent bodies that have been analyzed for water are angrites and aubrites. Angrites are the oldest basaltic and gabbroic meteorites ever found and are remnants of the first generation of differentiated Solar System bodies. They predate Earth, Mars, and Vesta’s accretion, having formed within the first 2 My, and having differentiated within the first 4 My of the Solar System’s history (McCubbin and Barnes 2019). The earliest crystallized phase in angrites, olivine, has < 20 μg/g H₂O, and their first formed melt inclusions contain 600–17,500 μg/g H₂O. From these measurements, it is calculated that 150–2750 μg/g H₂O could be present in the mantle of the angrite parent body (Sarafian et al. 2017; Deligny et al. 2021). Spallation-corrected δD values range from ~150‰ to 60‰ in olivine and from ~348‰ to 118‰ in their melt inclusions. Phosphates, which formed later in the crystallization sequence, have a wider δD range (~200‰ to 1000‰; Fig. 2) with the higher values having likely resulted from the melt degassing H₂ (Sarafian et al. 2017).

Aubrites accreted from the same solar nebula material as enstatite chondrites. They are typically breccia with mineralogy dominated by pyroxene and very reduced compositions. Aubrites analyzed by bulk-rock gas mass spectrometry record δD of ~ −155‰ to −70‰ (Fig. 2), i.e., similar to that of Earth’s upper mantle (Lorenz et al. 2021; Izidoro and Piani 2022 this issue). This is expected because Earth is thought to have formed mainly from enstatite chondrite-like material from which it may have also acquired most of its water (Izidoro and Piani 2022 this issue).
CONCLUSION

The ranges of water contents and δD of the interior and surface of differentiated Solar System bodies are inherited from their long history, starting with initial accretion from the solar nebula, through their impact record, differentiation into crust–mantle–core, and volcanism, to their peculiar surface alteration processes. The presence of water at the surface depends on the delicate balance of size, surface temperature, atmospheric composition, if present, and distance from the Sun. Expanding analyses to the whole range of extraterrestrial material available as meteorites, combined with experiments at magma ocean and core–mantle conditions, will improve our understanding of the distribution of water in the Solar System in the immediate future. However, sample return missions will be essential to properly constrain the role of water in the evolution of each terrestrial planet, moon, and asteroid. Observations of extraterrestrial planetary systems at different stages of evolution will also be crucial to understand how water influences planetary evolution, the creation of habitable zones, and planetary surface conditions favorable to life.

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**Recent Advances in our Understanding of Water and Aqueous Activity in Chondrites**

Lionel G. Vacher¹ and Wataru Fujiya²

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Water played a critical role in the evolution of rocky material and planetesimals in the early Solar System. Many primitive asteroids (the sources of chondrites) accreted a significant amount of water ice and were affected by aqueous alteration and/or fluid-assisted metamorphism. These secondary parent body processes have strongly modified the primary mineralogy of chondrites in favor of a wide diversity of secondary phases that formed by interaction with water. The mineralogical and isotopic characterization of these secondary phases in chondrites and returned samples from hydrous asteroids Ryugu and Bennu can help us reconstruct the dynamical evolution of water in the early Solar System and understand the timing and mechanisms of aqueous alteration on hydrous asteroids.

Keywords: asteroids; chondrites; aqueous alteration; secondary minerals; isotopes; sample return missions

**INTRODUCTION**

Chondritic meteorites are rocks from undifferentiated asteroids. They represent an important record of the Solar System’s early geological history - 4.6 billion years ago. Chondrites account for >80% of the total meteorite population and consist of three dominant components accreted together to form chondritic parent bodies: chondrules; Ca,Al-rich refractory inclusions (CAIs); and fine-grained matrix (Fig. 1A). The matrix material consists of an assemblage of diverse materials that incorporated a significant proportion of water ice grains, at least ~10–15 wt.% H₂O. After their accretion, chondrites experienced aqueous alteration and/or metamorphism on their parent bodies, resulting in important modifications to their mineralogy and chemical and isotopic compositions. These “secondary” characteristics form the basis of the classification system for chondrites, in which seven petrologic types are recognized (from 1 to 7), where type 1 is assigned to the most aqueously altered chondrites, and type 7 represents the most thermally metamorphosed chondrites (see Weisberg et al. 2006 for a review).

Among chondrites, carbonaceous chondrites (a subset of chondrites, divided into nine groups, namely, CI, CM, CR, CY, CO, CV, CK, CB, and CH) of types 1 to 3 have experienced different aqueous alteration histories: (1) low-temperature hydrothermal alteration for petrologic types 1–2 (CI-CM-CR-CY groups); and (2) fluid-assisted metamorphism for petrologic type 3 (CO-CV groups) (Fig. 1B).

Most of the hydrated carbonaceous chondrites with petrologic types 1–3 have preserved their secondary mineralogy and, therefore, offer the unique opportunity to study aqueous alteration processes that started ~4–5 million years after the birth of the Solar System. A combination of mineralogical, experimental, modeling, and isotopic studies on these secondary minerals can be achieved to reconstruct the source of water accreted by chondritic asteroids, their accretion time, and the physicochemical conditions of aqueous alteration that affected these hydrated asteroids.

**ORIGINS OF WATER IN CHONDRITES**

Stable water isotopes (¹⁶O, ¹⁷O, ¹⁸O, H, and D) in chondrites are powerful tools to trace the origin of chondritic water and track the chemical processes that occurred on their asteroidal parent bodies. At present, almost all of the water in chondrites is retained as hydroxyl (OH) groups or atomic O in various hydrated minerals. Therefore, the hydrogen (D/H) and oxygen (δ¹⁷O,δ¹⁸O; see glossary) isotopic composition of chondritic water is usually inferred indirectly from bulk and in situ measurements of secondary minerals that formed from water–rock interaction.

At least two main water ice reservoirs with distinct H and O isotopic compositions are commonly inferred for the origin of water in chondrites: (1) locally derived water, directly condensed from the nebular gas; and (2) outer disk water ice, formed in the coldest part of the disk and/or inherited from the parent solar molecular cloud (Alexander et al. 2012) (Fig. 2A). Due to low-temperature chemistry, interstellar ice is enriched in D by ~2–3 orders of magnitude compared to the solar nebular H₂. In the early stages of the protoplanetary disk evolution, D-rich pre-solar ice was transported into the warm regions of the inner Solar System and subsequently re-equilibrated with the D-poor nebular H₂. Thus, it is thought that the D/H isotopic ratio of water ice in planetary bodies increases with increasing heliocentric distance (Jacquet and Robert 2013). Similarly, the wide range of mass-independent O isotopic anomalies (Δ¹⁷O = 8¹⁷O – 0.52 × 8¹⁸O) observed in most Solar System materials is interpreted as the result of isotopic mixing between inner Solar System material (Δ¹⁷O = 0‰) with the influx of ¹⁶O-poor H₂O ice (Δ¹⁷O >> 0‰) formed by a CO self-shielding process (see glossary) in the outer part of the protoplanetary disk or in the parent molecular cloud (see Yurimoto et al. 2008 for a review).
Deciphering the origin of chondritic water using H isotopes is challenging because hydrated chondrite matrices consist essentially of a complex mixture of hydrated minerals and organic matter (the two main H-carrier phases), which are intimately mixed at the sub-micrometer scale. To solve this problem, Alexander et al. (2012) proposed that the D/H composition of chondritic water can be approximated from whole-rock D/H and C/H measurements by subtracting the organic-derived D/H from their bulk H isotopic compositions. They showed that the D/H ratios of C-free phyllosilicate are D-poor (D/H = 70 to 100 × 10−6) relative to D-rich comets (up to 530 × 10−6). This result implies that chondrite parent bodies accreted a dominant D-poor local water ice without a significant influx of D-rich outer disk or interstellar water into the asteroid accretion region or the role of isotopic fractionation on asteroidal parent bodies. For instance, Alexander et al. (2010) suggested that the H isotopic composition of water in chondrites could have been modified on the asteroidal parent body and become isotopically heavier due to (1) metal oxidation and subsequent loss of isotopically light H2 and/or (2) the isotopic exchange of H between D-poor liquid water and D-rich organic components. Process (1) would have preferentially enriched the most metamorphosed chondrites in D. In process (2), only chondrites that experienced sufficiently high temperatures (>200 °C) and/or a long duration of aqueous alteration could have been affected by this process (Piani et al. 2021).

**Oxygen Isotopes**

The variation in O isotopic compositions of secondary minerals is much smaller than that for H isotopes (Fig. 2C). For instance, the Δ17O values of carbonate, magnetite, phyllosilicate, and fayalite (Fe-rich olivine) in carbonaceous and ordinary chondrites only show modest mass-independent O isotopic variations, ranging from ~ −5‰ to +7‰ (see Yurimoto et al. 2008 for a review). However, it should be noted that the O isotopic compositions of secondary minerals are essentially controlled by isotopic exchange between 16O-poor initial water with 16O-rich anhydrous minerals prior to their formation. Thus, these Δ17O values likely represent lower limits on the initial water composi-

**Figure 1** Dominant components of chondrites and their classification. (A) False-color map of the CV chondrite Allende (Mg: red, Ca: green, and Fe: blue), revealing the distribution of chondrules and Ca,Al-rich refractory inclusions (CAIs) embedded in a fine-grained matrix. Image courtesy of Ryan Ogliore. (B) Schematic representation of the chondrite classification (Adapted from Weisberg et al. 2006). The role played by thermal metamorphism increases from type 3 to 7 while the degree of aqueous alteration increases from type 3 to 1. OC: ordinary chondrite. CV, CO, CM, CR, CY, and CI: carbonaceous chondrite groups.

**Figure 2** Spatial distribution and isotopic compositions of the different water reservoirs in the early Solar System. (A) Simplified view of the repartition of the water ice reservoirs in the protoplanetary disk. The snow line represents the distance from the Sun where the temperature is low enough (~170 K) for water ice grains to form. (B) Distribution of D/H ratios for water in ordinary (OC) and carbonaceous (CV, CO, CM, CR, CI) chondrites, comets, and interstellar water ice. (C) Distribution of mass-independent oxygen isotopic anomalies (Δ17O) recorded by secondary minerals in chondrites. Cosmic symplectite (COS) is an assemblage of 16O-poor magnetite and pentlandite.
tion accreted by chondrite parent bodies. Although high $\Delta^{17}O$ values are predicted by fluid flow models in carbonaceous chondrites (up to $\sim +16\%$, Young et al. 1999), the initial O isotopic compositions of chondritic water do not seem to show significant $^{16}O$ depletion (up to $\sim +7\%$ in OC chondrites, Yurimoto et al., 2008), in contrast to what is observed for H isotopes.

Outer disk water ice is predicted to be extremely heavy, but there have only been a few reports of very heavy O isotopic signatures in chondrites. The heaviest O isotopic signature of water ($\Delta^{17}O = +85\%$) was found in cosmic sylmplectite (COS, an assemblage of $^{16}O$-poor magnetite and pentlandite) in the primitive carbonaceous chondrite Acfer 094 (Sakamoto et al. 2007). Although CO self-shielding models predict very extensive $^{16}O$-depletion in the outer water ice ($\Delta^{17}O$ up to $\sim +300\%$), the O isotopic composition of the $^{16}O$-poor reservoir is still poorly known and needs to be better constrained. Consequently, the lack of significant $^{16}O$ depletion in chondritic water suggests that chondrite parent bodies preferentially accreted locally derived water ice with near-terrestrial $\Delta^{17}O$ values. An alternative explanation could be that mass-independent O isotopic anomalies of chondritic water ice may have been erased before their incorporation into the chondritic parent bodies due to reprocessing in the protoplanetary disk (Fujjya 2018).

**CONDITIONS OF AQUEOUS ALTERATION IN CHONDRITES**

**Stable Isotope Geothermometry**

Even though much progress has been made in understanding the alteration conditions of chondrites (see Brearley 2006 for a review), the physicochemical conditions under which aqueous alteration took place remain only partially understood. Among secondary minerals, carbonate, magnetite, and fayalite minerals are of primary importance because their O isotopic composition can be used as a paleothermometer to constrain the temperatures of aqueous alteration (Fig. 3A and 3C). Their temperatures of formation can be estimated using either (1) the mass-dependent O isotopic fractionation between a secondary mineral and water, which requires knowing the initial O isotopic composition of the parent fluid, or (2) the mass-dependent O isotopic fractionation between two coexisting phases that precipitated from the same parent fluid in isotopic equilibrium.

In types 1–2 carbonaceous chondrites, most studies have focused on carbonate minerals and the data are in good agreement with low-temperature alteration ($\sim 250 \, ^{\circ}C$). For example, the relatively high $\delta^{18}O$ fractionation determined in situ for calcite–magnetite assemblages in CR chondrites indicates alteration temperatures in the range of $\sim 60–90 \, ^{\circ}C$ (Jilly-Rehak et al. 2018). Similarly, the small $\delta^{18}O$ fractionation for bulk calcite, phyllosilicate, and magnetite minerals in CI chondrites suggests slightly higher alteration temperatures, in the range of $\sim 50–150 \, ^{\circ}C$ (Clayton and Mayeda 1999). In CM chondrites, bulk O isotopic measurements of carbonate and serpentine from several CM chondrites suggest that these two minerals are not in isotopic equilibrium (i.e., did not precipitate from the same fluid), but recorded, instead, a change in composition of the fluid with increasing alteration (Benedix et al. 2003). In fact, carbonate precipitation in CM chondrites was probably complex and episodic, resulting in the formation of two main populations of carbonate: (1) an early $^{16}O$-poor generation formed before serpentine; and (2) a later $^{16}O$-rich generation formed after serpentine. Considered separately, the first generation appears to form at lower temperature ($\sim 0–70 \, ^{\circ}C$) than the second generation ($\sim 100–250 \, ^{\circ}C$), suggesting that the O isotopic compositions of CM carbonates likely recorded an increase of the alteration temperature with time (see Suttle et al. 2021 for a review).

In type 3 chondrites, determining the alteration temperatures of CO and CV chondrites is more complex because these chondrites experienced only limited aqueous alteration. However, the low mass-dependent O isotopic equilibrium reported for fayalite–magnetite in CO and CV chondrites suggests a significantly higher alteration temperature than that of types 1–2 chondrites, from $\sim 150 \, ^{\circ}C$ for CV chondrites to $500 \, ^{\circ}C$ for CO chondrites (Marrocchi et al. 2018).

**Mineralogy and Stability Fields of Secondary Phases**

The restricted stability fields of hydrous minerals, such as serpentine and clays in types 1–2 chondrites, are particularly sensitive indicators of aqueous alteration and can place limits on the physicochemical conditions during aqueous alteration. In less-altered CM chondrites (petrologic subtype CM2.9–2.7 in the Rubin et al. 2007 classification), the most abundant alteration products are tochilinite–cronstedtite intergrowths (TCIs) (Fig. 3B), whereas chrysotile–greenalite serpentine solid solution dominates in more altered occurrences (subtypes CM2.2–2.1) (Velbel et al. 2015). Thermodynamic simulations and hydrothermal experiments indicate that TCIs formed under reducing conditions (low $O_2$ fugacity), at moderate temperatures ($\sim 50–150 \, ^{\circ}C$) and neutral to alkaline pH (pH $\approx$ 7–12) (e.g., Pignatelli et al. 2016). As alteration progressed, the fluid composition evolved to become more reducing, as indicated by the presence of Fe$^{2+}$ in the greenalite solid-solution end-member in CM2.2 and 2.1 chondrites (Velbel et al. 2015). The alteration conditions of CI–CR chondrites are less constrained than those of CM chondrites because of their scarcity, but these two groups of chondrites probably shared similar alteration conditions, as suggested by the presence of serpentine interlayered with saponite in their matrices. Constraints provided by mineralogical observations and thermodynamic modeling indicate that aqueous alteration at lower temperature ($\sim 0–70 \, ^{\circ}C$) than the second generation ($\sim 100–250 \, ^{\circ}C$), suggesting that the O isotopic compositions of CM carbonates likely recorded an increase of the alteration temperature with time (see Suttle et al. 2021 for a review).

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alteration in CI chondrites occurs at a high water/rock ratio relative to CM chondrites, neutral to alkaline pH (pH = 7–12), and moderate temperature (−20–150 °C) (Brearley 2006).

Although type 3 carbonaceous chondrites do not contain a high abundance of hydrous minerals, CV and CO chondrites contain a wide diversity of secondary anhydrous phases, such as Ca–Fe–rich silicates (i.e., hedenbergite associated with andradite; Fig. 3D), magnetite, Fe-Ni sulfide, and Na-Al-Ca–rich feldspathoids. Recent mineralogical studies on Ca–Fe–rich and Na-Al-Ca–rich secondary silicates in CV and CO chondrites argue for a formation in a fumarolic-like reduced environment from hot hydrothermal vapor (~200–600 °C) (Ganino and Libourel 2020).

MODELING OF AQUEOUS ALTERATION AND FLUID CIRCULATION IN CHONDRITE PARENT BODIES

Chronology of Aqueous Activity and Thermal Modeling

Combined physical and chemical models of aqueous alteration on carbonaceous parent bodies have been constructed. These models aim to account for the characteristics of aqueously altered carbonaceous chondrites, especially in terms of their mineralogy and isotopic compositions. These physical models have simulated the thermal evolution associated with fluid flow in carbonaceous asteroids, which are required to satisfy the chronological constraints from carbonaceous chondrites. For example, carbonates in carbonaceous chondrites formed ~4–5 My after the birth of the Solar System, placing a constraint on the time when aqueous alteration initiated. In most models, thermal conduction is calculated within asteroids of a few tens of km in diameter heated by the decay of radionuclides (e.g., Fujiya et al. 2012). If the ambient temperatures of such small asteroids are assumed to be low (~ −100 °C), they cool quickly within millions of years by thermal conduction. Thus, radioactive nuclides with half-lives comparable to the cooling timescale were effective heat sources in the early Solar System. Among short-lived radionuclides, 26 Al was the major heat source because of its short half-life of ~700,000 years, high decay energy of 4 MeV per atom, and abundance in the early Solar System. Thermal models have concluded that the carbonaceous parent bodies of aqueously altered carbonaceous chondrites likely formed 3–4 My after the birth of the Solar System to satisfy the carbonate age constraints and achieve a relatively low peak temperature of 250 °C under which aqueous alteration took place (Fig. 4).

Fluid Flow Models

Some models have incorporated fluid flow in asteroids either as exhalation flow from the interior to the surface driven by vapor pressure or as fluid convection driven by buoyancy (e.g., Palguta et al. 2010). The extent of fluid flow is controlled by the asteroid permeability. Permeability is a measure of the ability of a porous material to transmit fluid, and is not unambiguously determined for “initial” carbonaceous asteroids. The models invoking fluid flow often assume a relatively high permeability (up to 10^{-19} m²), consistent with that of terrestrial sediments. However, the extremely fine grain size observed in primitive carbonaceous chondrites suggests that these asteroids may have had a much lower permeability than previously estimated (down to 10^{-19} m²) (Bland et al. 2009). As a result, the distances of fluid flow in carbonaceous asteroids would have been limited to only hundreds of microns at most. Thus, whether fluid flow in carbonaceous asteroids actually occurred still remains unclear. The limited fluid flow may be consistent with the apparent isochemical nature of CM chondrites, i.e., their chemical compositions are as expected from aqueous alteration in a closed system. Furthermore, carbonates with a wide variety of C isotopic compositions (δ^{13}C = -20‰ to 80‰) are observed within mm-sized thin sections of CM chondrites, suggesting heterogeneous fluid compositions, which reflect varying physicochemical conditions and, thus, limited mobility of the aqueous fluids (see Suttle et al. 2021 for a review). On the other hand, the depletion of thermally mobile trace elements in hydrated and then metamorphosed chondrites provides evidence for open system loss and fluid-assisted escape of these elements.

An alternative asteroid model describes the structure of the carbonaceous parent bodies as giant convecting mud balls (Bland and Travis 2017). In this model, it is assumed that solid materials making up the parent bodies were not lithified when liquid water circulated through the asteroid. Consequently, solid materials in the parent bodies could have behaved as a mobile mud moving together with aqueous fluids, rather than a rigid, spatially fixed rock. One important implication from this model is that the chemical compositions of aqueously altered carbonaceous chondrites will necessarily be kept because the system is thoroughly mixed. The individual mud particles are predicted to have undergone aqueous alteration under varying physicochemical conditions, such as temperatures and redox states during convection, and to have subsequently been brought together to form the aqueously altered carbonaceous chondrites. Thus, this model potentially explains the heterogeneous O and C isotopic compositions of carbonates observed in single CM chondrite specimens. Finally, this model predicts the size-sorting of particles during mud convection. This means that large particles (>100 μm) could have sunk to the core of the parent bodies, and that the mantle would have been dominated by fine particles. CI chondrites are the most aqueously altered chondrites and do not contain chondrules, which are mm- to sub-mm-sized silicate spherules of olivine and pyroxene once melted in the solar nebula. Therefore, CI chondrites may represent the mantle of their mud-ball parent body from which chondrules sank to the parent body’s center. It is
argued that the mineralogy and geochemistry of dwarf planet Ceres are consistent with CM/CI-like chondrites. However, Ceres has experienced more advanced alteration, likely due to convection, which increased the effective water/rock ratios (McSween et al. 2018).

POSSIBLE TESTS ON AQUEOUS ALTERATION MODELS BY SAMPLE RETURN MISSIONS

Sample Return

Recently, two space missions aiming to bring extraterrestrial samples back to Earth, so-called sample return missions, have successfully collected surface materials from volatile-rich, primitive carbonaceous asteroids. The Hayabusa2 spacecraft of the Japan Aerospace Exploration Agency (JAXA) reached the near-Earth Cb-type (see glossary) carbonaceous asteroid (162173) Ryugu in June 2018 (Watanabe et al. 2019). This spacecraft carried out touch-down operations twice in February and July 2019 and acquired ~5.4 g of material from the surface of Ryugu. The second touch-down site on Ryugu was located ~20 m from the artificial crater (~2.7 m depth) created by the Small Carry-on Impactor (SCI) in April 2019. Thus, it is likely that not only surface materials but also subsurface materials were acquired. The Hayabusa2 spacecraft delivered its collected samples to Earth in December 2020. NASA's OSIRIS-REx spacecraft also reached another near-Earth B-type (a subcategory of C-type) carbonaceous asteroid (101955) Bennu in December 2018 (Lauretta et al. 2019). The spacecraft collected a plentiful amount of surface materials, expected to be >60 g. The OSIRIS-REx spacecraft began its two-year journey back to Earth in May 2021 and will return with its samples to Earth in September 2023.

Aqueous Alteration on the Ryugu and Bennu Parent Bodies

Asteroids Ryugu and Bennu both have a spinning top–shape (i.e., a pronounced equatorial ridge) (Fig. 5A), low density of ~1.2 g/cm³ consistent with a rubble-pile structure with a high porosity, and a low geometric albedo of approximately 4.4%–4.8%. The rubble-pile structure and high porosity suggest that these asteroids are re-accreted fragments generated by catastrophic disruption of their original, larger parent bodies. The Near-Infrared Spectrometer (NIRS3) on the Hayabusa2 spacecraft has detected a weak and narrow absorption feature at ~2.7 μm in the surface materials across the entire surface of Ryugu (Fig. 5B), corresponding to OH-bearing minerals (phyllosilicates) that resemble those observed in CI chondrites experimentally heated to 500 °C (Kitazato et al. 2019) (Fig. 5C). Similarly, the SCI experiment of Hayabusa2 also revealed a slightly stronger ~OH absorption of the excavated materials found near the artificial impact. It is likely that both the surface and subsurface materials of Ryugu contain hydrous minerals, but underwent heating in the range of ~300–700 °C (temperatures where phyllosilicates dehydrate), and that surface processes, such as space weathering and radiative heating, have induced subtle spectral changes of the uppermost surface. Overall, these observations suggest that (1) hydrous minerals are ubiquitous on Ryugu’s subsurface, (2) Ryugu materials are likely thermally metamorphosed, and (3) the primary thermal metamorphism occurred on the original, larger parent body of Ryugu.

An apparent absorption feature at ~2.7 μm, similar to that observed for CM and CI chondrites, can be found for all of the spectra of Bennu acquired by the OSIRIS-REx Visible and InfraRed Spectrometer (OVIRS). It is known that the exact position of the ~2.7-μm band minimum varies with mineral and chemical composition. The band center of Bennu occurs at 2.74 μm, consistent with petrologic subtype CM2.1–2.2 and corresponding to the most aqueously altered CM chondrites. The detection of spectral absorption at 0.55 μm, corresponding to magnetite, also supports the affinity of Bennu with heavily altered CM or CI chondrites. These observations suggest that Bennu materials have a phyllosilicate-dominated composition. The deeper 2.7-μm band of Bennu than that of Ryugu indicates that Bennu is less heated than Ryugu and that their materials differ from each other (Hamilton et al. 2019).

The returned samples from Ryugu and Bennu will first tell us whether their spectra actually correspond to carbonaceous chondrites in our collection, and whether they are asteroidal materials we have not yet obtained as meteorites. The variability of the sample’s mineralogy and chemistry will provide crucial information about the structure of their original, larger parent bodies. The timescales of heating by 36Cl are much shorter than the timescales of cooling determined by the thermal conductivity. Therefore, we can expect that the peak temperatures experienced by large asteroids do not drastically vary from the center to the subsurface regions of the asteroids. Thus, if we find diverse mineralogy and chemistry among individual specimens in the returned samples, then the original asteroids may have been relatively small. Moreover, we may find evidence for fluid flow in the returned samples, such as carbonate veins filling fractures. It should be noted that centimeters-thick,
roughly meter-long bright carbonate veins were found from remote sensing observations on Bennu (Kaplan et al. 2020). The analyses of the returned samples will unveil the evolution of the carbonateous asteroids, and help to understand the fate of the water that these asteroids accreted in the early history of our Solar System.

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Bland PA and 11 coauthors (2009) Why asteroid taxonomy — Classification of asteroids according to their reflectance spectra, i.e., the change in reflectance with wavelength. C-complex asteroids, including Ryugu and Bennu, tend to have weak UV features and relatively flat to bluish spectra at longer wavelengths. The average visible albedo of C-complex objects is ~6%, and ~60% of observed C-complex objects have 3-μm bands, indicating hydrated silicates on their surfaces.

Glossary

Delta notation — The delta notation (δ) represents a per mil (%: 10−3) deviation of the isotopic ratio of a given sample from a terrestrial standard value. The isotopic ratios of an element are often expressed by the delta notation because their natural variation is commonly small, on the order of 1% or less.

CO self-shielding — Carbon monoxide (CO) molecules at the surface of the parent molecular cloud or protoplanetary disk are dissociated by UV irradiation. The intensity of UV with the wavelengths of dissociation lines for abundant C17O rapidly attenuates at the surface, which is referred to as self-shielding. This process can produce a selective enrichment in 13CO for CO gas in the deeper region, because less abundant C17O and C18O can still be dissociated by UV there.

ASTEROID TAXONOMY

Classification of asteroids according to their reflectance spectra, i.e., the change in reflectance with wavelength. C-complex asteroids, including Ryugu and Bennu, tend to have weak UV features and relatively flat to bluish spectra at longer wavelengths. The average visible albedo of C-complex objects is ~6%, and ~60% of observed C-complex objects have 3-μm bands, indicating hydrated silicates on their surfaces.

FACTORS AFFECTING 13CO ENRICHMENT OVER 12CO

δ13CO at the surface of a protostellar disk is a function of three factors: (1) atomic H (H) and C (C1) abundances, (2) the CO abundance, and (3) the UV intensity at the protostellar disk surface. The CO abundance is determined by the ratio of the CO abundance in the protostellar disk to the CO abundance in the ISM, and the UV intensity is determined by the distance of the protostellar disk from the Sun. The UV intensity is also affected by the UV flux from the Sun, the distance of the protostellar disk from the Sun, and the dust content of the protoplanetary disk.

The UV intensity at the surface of a protostellar disk is a function of the UV flux from the Sun, the distance of the protostellar disk from the Sun, and the dust content of the protoplanetary disk. The UV flux from the Sun is determined by the solar luminosity and the distance of the protostellar disk from the Sun. The distance of the protostellar disk from the Sun is determined by the age of the protostellar disk. The dust content of the protoplanetary disk is determined by the dust-to-gas ratio and the UV intensity at the surface of the protoplanetary disk.

The dust-to-gas ratio is determined by the gas content of the protostellar disk and the dust content of the protostellar disk. The gas content of the protostellar disk is determined by the gas-to-dust ratio and the UV intensity at the surface of the protostellar disk. The gas-to-dust ratio is determined by the gas-to-dust ratio and the UV intensity at the surface of the protostellar disk. The UV intensity at the surface of the protostellar disk is a function of the UV flux from the Sun, the distance of the protostellar disk from the Sun, and the dust content of the protoplanetary disk.
W

water condensed as ice beyond the water snowline, the location in the Sun’s natal gaseous disk where temperatures were below 170 K. As the disk evolved and cooled, the snowline moved inwards. A low temperature in the terrestrial planet-forming region is unlikely to be the origin of water on the planets, and the distinct isotopic compositions of planetary objects formed in the inner and outer disks suggest limited early mixing of inner and outer Solar System materials. Water in our terrestrial planets has rather been derived from H-bearing materials indigenous to the inner disk and delivered by water-rich planetesimals formed beyond the snowline and scattered inwards during the growth, migration, and dynamical evolution of the giant planets.

KEYWORDS: water; planet formation; disk evolution; snowline; meteorites

WATER CONTENT AND ISOTOPIC COMPOSITIONS OF PLANETARY MATERIALS

The origin and existence of water on Earth and the other terrestrial planets is a long-standing problem in planetary science. Liquid water covers more than 70% of the Earth’s surface, yet this reservoir (hereafter “oceans”) corresponds to only 0.025% of Earth’s total mass. The main reservoir of Earth’s water is most likely hidden in its interior (Peslier and De Sanctis 2022 this issue). Contrary to the Earth’s surface, where hydrogen is mainly present as H₂O molecules, “water” in Earth’s interior corresponds to hydrogen incorporated in minerals, magmas, and fluids. During planetary evolution, hydrogen in these reservoirs can bond with surrounding oxygen to form water at the appropriate temperature and pressure conditions. Recent estimates based on mantle-derived rocks suggest that between one and seven Earth oceans’ masses could be stored in the mantle. Earth’s core could also contain a significant amount of hydrogen, although the exact quantity remains poorly constrained (Fig. 1A).

Given the limited number of Martian meteorites, and the absence of Venusian and Mercurian meteorites, estimating the water content for the bulk Mars, Venus, and Mercury is rather difficult. The study of Martian meteorites indicates that the Martian mantle does contain water, although in smaller proportions than the Earth’s mantle, and probably with a much more heterogeneous distribution. Liquid water was also once present on the Martian surface (Peslier and De Sanctis 2022 this issue). Venus could contain significant amounts of water in its mantle, in quantities comparable to that of Earth’s mantle (McCubbin and Barnes 2019). It is likely that Venus shared a similar accretion history to Earth and was initially wet, although it probably remained in this state for only a short period of time (<1 Gy; Peslier and De Sanctis 2022 this issue).

The presence of H, possibly in the form of pure water ice, has been detected at the surface of Mercury, and estimates based on the abundance of other volatile elements in its exosphere (He, Na, K) suggest that Mercury’s mantle could contain as much water as the Martian mantle (McCubbin and Barnes 2019).

Not only planets carry water, but also minor planetary objects such as some asteroids. The terrestrial and giant planets are separated by the asteroid belt, a region populated by a large number of asteroids. Asteroids are thought to be leftovers from the birth of the Solar System and hold records of where and when planet formation started, and how the terrestrial planets obtained their water. The asteroid belt is the major source of meteorites found on Earth. Meteorite analyses and astronomical observations show that the asteroid belt is dichotomous. Rocky, water-poor asteroids associated with the parent bodies of non-carbonaceous chondrites (NCs) are more abundant in the inner belt (ordinary and enstatite chondrite groups in Fig. 1A; hereafter referred to as OCs and ECs, respectively) and dark, potentially volatile-rich asteroids thought to be made of similar materials as the carbonaceous chondrites (CCs) are more abundant in the outer belt and close to Jupiter’s orbit (CC group in Fig. 1A; DeMeo and Carry 2014). This is consistent with the maximum amount of water measured in the different chondrite classes, which broadly increases with the putative orbital radius of their parent body (Fig. 1A). The NC and CC meteorites also have distinct isotopic compositions. There is a clear dichotomy in the distribution of neutron-rich isotopes, such as ⁵⁴Cr or ⁵⁰Ti (Kleine et al. 2020), which suggests that these two reservoirs of planetary materials (NC and CC groups) co-existed when the planets began to form, but remained physically separated during the first few million years of the Solar System’s history. The close orbital proximity of asteroids associated with NC and CC meteorites in the asteroid belt today (DeMeo and Carry 2014) has thus to be explained.
by an additional process that broadly mixed these asteroid groups later (e.g., Izidoro et al. 2022).

Planets may either be born with water or have their water delivered by collisions with water-bearing planetary objects like asteroids. The H isotopic composition of water (expressed as the D/H ratio or in δ notation relative to Earth’s standard mean ocean water) in planetary objects is a key discriminant to trace planets’ main source(s) of water (Piani et al. 2021; Fig. 1B). The Sun’s natal gas disk and Jupiter’s gaseous envelope show very low D/H ratios of \( 21 \times 10^{-9} \) (or \( \delta D = -800\% \)). Earth’s ocean D/H ratio is \( 156 \times 10^{-9} \) (or \( \delta D = 0\% \)), which is a factor of seven higher than that of Jupiter/Sun. Outer Solar System objects, such as the comet 67P/Churyumov-Gerasimenko (Bockelée-Morvan et al. 2015; Fig. 1B), generally show much higher D/H ratios in the sublimated water molecules, with values up to \( 530 \times 10^{-9} \) (or \( \delta D > 2400\% \)). Comets were historically considered to be the most likely source of Earth’s water due to their high water content (about 50%) and water D/H ratio, sometimes similar to that of Earth’s oceans (Bockelée-Morvan et al. 2015). However, if we consider molecules other than water, such as hydrogen cyanide HCN (Fig. 1B), which also are contained in cometary ices, comets would have an average D/H ratio systematically higher than Earth’s oceans, making their contribution to the terrestrial planet water limited (Alexander et al. 2018). The CCs and OCs cannot be easily discriminated on the simple basis of their D/H ratios, as both chondrite classes cover large D/H ranges including that of Earth’s oceans (Fig. 1B). D/H variations have also been measured in minerals of achondrites, such as eucrites, angrites, or aubrites (Peslier and De Sanctis 2022 this issue). Both the NC and CC reservoirs thus seem to have sampled water with a wide D/H range that might result from different degrees of isotopic equilibration between initially D-rich materials—partially preserved in cometary ices—and the D-poor solar gas (Piani et al. 2021).

In the next sections, we briefly review the current paradigm of planet formation and the implications for the nature of material prone to be incorporated into terrestrial planets during their formation.

### PLANETARY GROWTH PROCESSES: FROM DUST GRAINS TO PLANETS

The temperature of gaseous protoplanetary disks broadly decreases with heliocentric distance. Water ice can only be present in regions where the local temperature is lower than the water condensation temperature (~170 K), at the so-called water snowline (e.g., Morbidelli et al. 2016). The first solid grains to condense in the disk have typical sizes of observed interstellar dust grains. They stick together forming millimeter- and centimeter-sized particles called pebbles. Pebbles drift via aerodynamic drag, inducing a flux of mass from the outermost to the innermost parts of the disk (e.g., Johansen and Lambrechts 2017). Pebble drift is a potential way to transfer water-rich solids formed beyond the snowline to the dry inner part of the Solar System (Morbidelli et al. 2016).

Numerical simulations suggest that planet formation “jumps” from millimeter-/centimeter-sized pebbles to ~100 km asteroidal-sized bodies (called planetesimals) due to particle–gas instabilities (Johansen and Lambrechts 2017). Finally, planetesimals grow to protoplanets either via accretion of other planetesimals (“planetesimal accretion”) or of drifting pebbles (“pebble accretion”; Izidoro and Raymond 2018).

The interaction of a growing protoplanet with a mass of ~10 Earth masses (i.e., a giant planet core) with its surrounding gas induces a high gas pressure region just outside its orbit, called a “pressure bump” (Johansen and Lambrechts 2017), that tends to stop drifting pebbles. If the induced pressure bump is sufficiently strong, the forming planet stops growing via pebble accretion and is said to have reached the “pebble isolation mass”. This pebble barrier may drastically affect the growth of any inner planets in the system by regulating the amount of drifting pebbles reaching the inner disk (e.g., Izidoro et al. 2021). The accretion history of terrestrial planets and their ability to accrete wet materials can thus be strongly affected by the formation of giant planets.

### DIFFERENT SCENARIOS FOR THE ORIGIN OF WATER ON TERRESTRIAL PLANETS

#### Oxidation of a Primordial H-rich Atmosphere

As a planet grows, the heat provided by the radioactive decay of \(^{26}\text{Al}\), accretionary impacts, and core formation tends to melt its surface and interior. Protoplanets with masses above ~0.5 Earth masses may be able to accrete gas from the disk and retain a gaseous atmosphere (Lammer et al. 2018). Water can be produced through oxidation of a hydrogen-rich atmosphere interacting with the planet’s molten surface. This process may be an important source of water for terrestrial worlds around other stars (Kite and Schaefer 2021), but does not likely represent a major source of Earth’s water. The D/H ratio of water produced via oxidation of a hydrogen-rich atmosphere should be similar to that of the Sun’s natal disk. However, the D/H ratios of the
Earth’s oceans and Martian rocks are higher than solar (Fig. 1). Hydrogen hydrodynamic escape (Lammer et al. 2018), which was initially proposed as a potential mechanism to increase the D/H ratio of the primordial Earth from solar to the current value, does not seem to have been efficient on Earth (Sossi et al. 2020). This process might have been more important for Mars due to its lower gravity, and for Venus due to its formation location closer to the Sun (Peslier and De Sanctis 2022 this issue).

**Endogenous H-bearing Materials in the Inner Disk**

Even if the disk temperatures did not drop below 170 K in the terrestrial region, hydrogen-bearing solids other than water ice could have contributed to the final water budget of terrestrial planets. This is consistent with the observation of H-bearing phases—organics and anhydrous silicates—in ECs and OCs thought to have formed in the inner disk (Piani et al. 2020; Jin and Bose 2021).

The chemical bonding of water vapor molecules at the surface of solid dust grains allows water to sustain temperatures ≥ 500 K. This adsorbed water was proposed to have provided substantial amounts of water to the terrestrial planets (up to three oceans to the Earth; Drake 2005). Similarly, H\(^+\) implantation in the interstellar medium, or interplanetary silicate grains by ionized nebular gas or solar wind, may have produced trace amounts of hydroxyl (OH\(^-\)) or water in the dust, eventually accreting on terrestrial planets (e.g., Jin and Bose 2021). The low D/H ratios of implanted nebular gas or solar wind may not be consistent with that of primitive (undifferentiated) meteorites or terrestrial planets. However, the extent of the isotopic fractionation associated with the ionization/implantation mechanisms is not yet fully understood (Jin and Bose 2021).

**Snowline Sweeping**

Young gaseous protoplanetary disks are initially very hot and massive. As the disks age, they lose mass and cool. Silicates and water condense at temperatures of about 1400 and 170 K, respectively. In realistic disk models, the snowline is initially around ~10 to ~20 astronomical units (AU) and the silicate line is initially between ~0.1 and ~1 AU (e.g., Morbidelli et al. 2016; Izidoro et al. 2022). Planetesimals and protoplanets that formed entirely from material accreted beyond the snowline are probably born with large water mass fractions. As water ice condenses, the gas beyond the snowline becomes dry. The gas in the disk accretes onto the star moving inwards faster than the snowline. Gas moving from beyond the snowline has no more water vapor to condense (Morbidelli et al. 2016); thus, the delivery of water to the inner regions of the disk requires the drift of pebbles originating from beyond the snowline (Morbidelli et al. 2016). If the water snowline eventually reaches the terrestrial planet region, icy pebbles may either deliver water to pre-existing dry planetesimals and protoplanets or promote the formation of new water-rich planetesimals (Lichtenberg et al. 2021). Water delivery via sweeping of the water snowline may result in Earth-like water contents if pebble accretion is not efficient or if ice pebbles mostly evaporate in the planet’s atmosphere (Johansen et al. 2021), getting recycled in the disk rather than being accreted. Although snowline sweeping may have delivered water to rocky planets around other stars (Fig. 2A), it is unlikely to have played a role in the Solar System. The isotopic dichotomy between NC and CC meteorites suggests that a pressure bump at the snowline or Jupiter’s early formation efficiently prevented water-ice pebbles from the outer Solar System from drifting into the inner Solar System (Brasser and Mojsis 2020; Kleine et al. 2020; Burkhart et al. 2021; Izidoro et al. 2021). Without an efficient pebble barrier, aerodynamic drift would have largely mixed inner and outer Solar System materials. This mixing should have resulted in the formation of planetary objects with isotopic compositions intermediate between NC and CC, but this view is inconsistent with meteorite data. Therefore, even if the snowline eventually reached the terrestrial region, water-rich ice pebbles probably did not (Morbidelli et al. 2016; Izidoro et al. 2022). It thus seems very unlikely that snowline sweeping delivered water to the terrestrial planets.

**Inward Migration of Water-rich Protoplanets**

Moon- to Mars-mass protoplanets (and less massive objects such as planetesimals) are unlikely to have experienced large-scale, gas-driven, radial migration. Earth-mass planets, on the other hand, are massive enough to strongly interact with the gas and migrate typically inwards. If water-rich planets form beyond the snowline, they may eventually migrate inwards, parking at or crossing the terrestrial region (Izidoro et al. 2021). Jupiter’s early formed core or a pressure bump at the snowline is believed to have stalled the growth of the terrestrial planets via pebble accretion before they could become massive enough to migrate significantly inwards, potentially to regions of the disk much closer to the star (Izidoro et al. 2022).

Planetary gas-driven migration has been proposed to explain the origin of the so-called hot super-Earths (e.g., Izidoro et al. 2021). Super-Earths are planets with masses between those of Earth and Neptune. Statistical analyses suggest that 30%–50% of Sun-like stars host super-
Earths with orbital periods shorter than 100 days. The migration hypothesis for the origin of super-Earths is consistent with a broad range of super-Earth compositions, from dry planets to water worlds, depending on whether planetesimals/protoplanets form more efficiently inside or outside of the water snowline (Izidoro et al. 2021).

Some of the best characterized super-Earth systems may have planets holding water, although estimates come with very large error bars (e.g., Raymond et al. 2022). The TRAPPIST-1 is one of these iconic systems in which adjacent planets show rhythmic orbital motions and form a so-called “resonant chain”. In simple terms, resonance occurs if two planets consistently complete an integer number of orbits around the star at the same time. This orbital rhythm is not coincidental, but is the result of gas-driven migration (e.g., Izidoro et al. 2021). The current dynamical configuration of the TRAPPIST-1 system probably represents its dynamical state at the end of the gas disk phase, several billions of years ago. If any planet in the TRAPPIST-1 system contains a large water budget (i.e., ~10 wt.%), this implies that it must have been incorporated during its formation in the gaseous disk. It is unlikely that a large water reservoir could be delivered to this system via impacts with objects from beyond the snowline (e.g., asteroids, protoplanets, and/or comets; see next section), because the very sensitive dynamical configuration of the resonance chain would have been definitely lost (Raymond et al. 2022). The TRAPPIST-1 system and other resonant chains of hot super-Earths, such as TOI-178 and KEPLER-223, likely did not experience substantial water delivery after disk dissipation. Endogenous sources may have contributed at some level to their water budget. However, if these planets formed inside the snowline, by analogy with inner Solar System materials, one would naïvely expect them to have a relatively low water content, potentially lower than 1 wt.%

**External Delivery**

Protoplanets and planetesimals on almost circular orbits can only collide with nearby planetesimals because of limited radial excursion when they orbit the star. Planetary objects on eccentric orbits—like those of comets—spend time both in the innermost and outermost regions of their planetary systems. If water-rich protoplanets or planetesimals formed beyond the snowline are dynamically excited to high eccentricity orbits, they may eventually cross the terrestrial region and deliver water to terrestrial planets via impacts (e.g., Meech and Raymond 2020).

Our current understanding of planet formation and Solar System dynamical evolution allows multiple episodes of water delivery to the terrestrial planets (see also Meech and Raymond 2020), spanning events taking place during the disk phase and potentially post-disk dissipation (Fig. 3). A giant planet core that has just reached pebble isolation mass (i.e., >10–15 Earth masses; see above) accretes gas...
from the disk slowly. When the mass of the core’s envelope is comparable to the mass of the core, “runaway” gas accretion begins and the planet mass doubles over short timescales. As a consequence, this fast-growing planet destabilizes nearby planetesimals and scatters them onto eccentric orbits (Fig. 3A and 3C; Izidoro and Raymond 2018). As Jupiter and Saturn started runaway accretion, a fraction of the planetesimals reaching the inner Solar System were implanted into the asteroid belt via gas-drag assistance. Another fraction was scattered even closer in, inside the water delivery zone (Fig. 3), and collided with the terrestrial planet building blocks delivering water. The low-mass atmospheres of Uranus and Neptune suggest that they either formed later than Jupiter’s and Saturn’s cores or more slowly, and avoided becoming gas giants (Fig. 3A and 3C). As these putative protoplanets beyond the orbit of Saturn grew massive enough, they started to migrate inwards before being stopped by Jupiter and Saturn (Fig. 3D and 3E). The process of migration and accretion of Neptune-mass ice planets (Fig. 3F) sculpted the disk of planetesimals beyond the gas giant planets and scattered planetesimals from the distant regions of the disk into the inner Solar System (Ribeiro de Sousa et al. 2020). This provided another episode of external delivery of water to the terrestrial planets and the implantation of planetesimals into the belt region.

The most successful models of Solar System evolution—those that explain fairly well the current orbits of the four giant planets and orbital architecture of the objects in the very outer Solar System—suggest that the Solar System was born with three ice giants, but that one of them was ejected very outer Solar System—suggest that the Solar System was giant planets and orbital architecture of the objects in the those that explain fairly well the current orbits of the four giant planets and orbital architecture of the objects in the those that explain fairly well the current orbits of the four

**A Hybrid Scenario for the Origins of Earth’s Water**

The Earth’s water isotopic composition is not homogeneous, with the most pristine mantle signatures being depleted in deuterium compared to the Earth’s oceans (Peslier and de Sanctis 2022 this issue). Enstatite chondrites represent a good match to the D/H ratio of the Earth’s primitive mantle (Figs. 1 and 4) and could thus indicate the contribution of an endogenous source to Earth’s mantle water. Enstatite chondrites also have nitrogen isotopic compositions that fit those inferred for the primitive Earth’s mantle (Fig. 4; Piani et al. 2020), indicating that not only water but also other volatile elements might be derived from this endogenous source. Isotopic analysis suggests that the Earth mostly formed from NC material possibly derived from the same reservoir as ECs (Kleine et al. 2020), which accreted inside the snowline (e.g., Izidoro et al. 2022; Morbidelli et al. 2022).

It is not trivial, however, to estimate the amount of water that this endogenous material could have provided to Earth. If one assumes that the Earth is made entirely of ECs, they could have accounted for 3 to 23 ocean masses of water (Piani et al. 2020). On the other hand, it is not clear whether Earth is made from the same EC-like reservoir that we have in our meteorite samples or from an early population that experienced more extensive internal heating—due to the decay of radioactive nuclides such as 26Al—and differentiation, resulting in significative water loss (Peslier and de Sanctis 2022 this issue). If this latter hypothesis is correct, using the water content of ECs to estimate the contribution of endogenous material to the Earth’s water may not be ideal because one may overestimate their contribution. Recent estimates of the water content in achondrites indicate a much lower water mass fraction than that estimated for pristine ECs (e.g., 0.007 wt.% of water in the Vestan mantle; Stephan et al. 2021 and references therein), which may reflect the effect of post-accretion processes dehydrating planetesimals. If one takes, for simplicity, this estimate as representative of the inner Solar System material that formed the Earth, one would expect a water contribution of roughly 0.3 ocean masses. Stronger constraints on the water content of both Earth’s interior and differentiated meteorites would be more than helpful to further investigate this issue (McCubbin and Barnes 2019).

In any case, the Earth’s water is unlikely to have been derived uniquely from NC material. Although the mantle isotopic composition strongly suggests that at least some water came from an endogenous source, the surface reservoirs of the Earth (oceans and atmosphere) are enriched in heavy isotopes compared to the mantle and ECs (Fig. 4). These isotopic compositions could be accounted for by considering the addition of some D- and 15N-rich CC materials to Earth during its accretion history. It is very unlikely that this contribution came from CC pebbles (e.g., Burkhartd et al. 2021), but rather from CC planetesimals that formed beyond the orbit of Jupiter and scattered into the inner Solar System (Fig. 3; Izidoro et al. 2022). A recent model invoking constraints from multiple isotopic systems suggests that Earth and Mars could have accreted up to 4% of their current mass from a CC-like isotopic reservoir (Burkhartd et al. 2021), in agreement with previous estimates for Earth (e.g., Marty et al. 2016; Alexander et al. 2018). If one assumes that, on average, CC-like planetesimals carry a 5% water mass fraction (Fig. 1), this implies that the Earth and Mars received 8.5 and 0.85 Earth ocean masses from this reservoir, respectively, which is consistent with dynamical models (Fig. 3; Izidoro and Raymond 2022).
Cometary materials could also have contributed to the late accretion of volatile-rich material, but mass-balance calculations including nitrogen and noble gases indicate that a cometary contribution to Earth’s water was probably limited to a few percent (Marty et al. 2016), which is also in agreement with dynamical models of Solar System evolution (Fig. 3). Terrestrial planets in the Solar System most likely had a hybrid contribution of water both from endogenous and exogenous sources.

CONCLUSION

Our understanding of the origins of water on terrestrial planets is far from complete, but significant progress has been made in the last decade or so. Terrestrial planets in the Solar System probably carry water derived from both inner and outer Solar System materials. The Solar System’s giant planets’ growth, migration, and dynamical evolution played a key role in delivering water to the inner Solar System via inward scattering of water-bearing planetesimals from the outer Solar System. Jupiter and Saturn probably also controlled water delivery to the inner Solar System by preventing water delivery to the terrestrial region via snowline sweeping (accretion of ice pebbles) and blocking the inward migration of water-rich worlds.

ACKNOWLEDGMENTS

We are very grateful to the reviewers, Alessandro Morbidelli and David Beketa, for their thoughtful comments and suggestions, which tremendously helped us improve the quality of our paper. We are also thankful to Sean N. Raymond for carefully reading our paper and his helpful comments. A. Izidoro acknowledges The Welch Foundation grant no. C-2035-20200401 and NASA grant 80NSSC18K0828 for financial support during the preparation and submission of the work. A. Izidoro also thanks the CAPES-PrInt Program, process number 88887:310463/2018-00, International Cooperation Project number 3266, and CNPq (313998/2018-3). L. Piani acknowledges the French Research National Agency (grant ANR-19-CE31-0027-01). This is CRGP contribution 2814.

REFERENCES


Vacher LG, Fujiya W (2022) Recent advances in our understanding of water and aqueous activity in chondrites. Elements 18: 175-180
DRIFT PUMICE FROM FUKUTOKU-OKA-NO-BA

Kenta Yoshida

Fukutoku-Oka-no-Ba (FOB) is a submarine volcano in the Izu-Ogasawara arc, located ~1300 km south of Tokyo and ~1300 km east of Okinawa, Japan. The 2021 FOB Plinian eruption occurred on 13 August (JST), with an eruption column reaching 16 km in height. A large volume of pumice erupted and drifted westward, arriving at the Nansei Islands after two months of drifting. The pumice further drifted westward, arriving at the Philippines and Taiwan, as well as eastward, arriving at the Kanto area of eastern Japan. Although the Plinian eruption of FOB did not cause any direct disasters, the large amount of drift pumice caused indirect volcanic disasters, such as obstructing the navigation of ships.

Pumice clasts drifted to the Nansei Islands exhibit a variety of colors and textures, providing fruitful information about the 2021 FOB eruption (Yoshida et al. 2022). Most pumice clasts are light gray, vesicular, and have a groundmass containing black enclaves, resembling “chocolate-chip cookies.” Rare black pumice and the main gray pumice components show similar trachytic composition (SiO₂ = 60–62 mass% and Na₂O + K₂O = 8–10 mass%) and similar phenocryst minerals of clinopyroxene, plagioclase, and olivine. The gray and black pumice exhibit contrasting textures: the gray pumice consists of colorless glass with elongated vesicles, while the black pumice consists of brown glass with relatively spherical (non-elongated) vesicles. Raman spectroscopy revealed that the brown color of the glass originates from nanolites of magnetite that are not visible under optical and scanning electron microscope observations. Recent experimental studies indicate that the precipitation of nanolite increases the magma viscosity and could enhance explosive eruptions.

Some black enclaves and black pumice contain magnesian olivine of Mg# (Mg/[Mg+Fe]) = 85–92, which contains mafic melt inclusions. These components strongly indicate that mafic magma was incorporated in the explosive 2021 FOB eruption, even though the composition of the primary magma reservoir remained trachytic. This cryptic mafic magma intruded into the trachytic magma reservoir and provided the heat and volatile components required for the explosive eruption.

The mafic magma temperature recovered from the magnesian olivine was ~1200 °C, while the temperature of the trachytic magma reservoir was estimated from the magnetite to be ~930 °C. Olivine diffusion modeling predicted the timescale of the cryptic magma mixing to be up to 45 days, a relatively short time scale of mafic magma injection.

The petrographical observation of the drift pumice successfully revealed the mechanism of the 2021 FOB explosive eruption, while the drifted and deposited pumice profoundly impacted people’s lives in the related area. Observing pumice clasts on the beach is one of the safest geological field survey methods available. This amazing opportunity will eventually be lost as the deposited pumice clasts drift again with the tides and wind. We hope that normal daily life for those troubled by pumice will return soon, as well as for the many people who watch the pumice and feel concerned about the volcanic activities that occurred more than 1000 km away.

REFERENCES

1 Japan Agency for Marine-Earth Science and Technology, Yokosuka, Japan
These words are from the then 73-year-old Katsuko Saruhashi, a Japanese-born geochemist who pioneered the measurement of CO₂ in ocean water. Saruhashi was born on March 22, 1920, in Tokyo, Japan, and while her parents were supportive of her education, this didn’t necessarily include a higher education degree. She quit her job at an insurance company to attend the Imperial Women’s College of Science, now Toho University, at the age of 21, graduating with a degree in chemistry in 1943.

At first, Saruhashi struggled with a lack of equipment, but Yasuo Miyake, who became an important mentor, arranged for Saruhashi to use the government lab facilities. She later said of Miyake that, for him, it didn’t matter if a researcher was a man or a woman if they showed determination and commitment to pursuing problems. Saruhashi then joined the Geochemical Laboratory of the now Japan Meteorological Agency on Miyake’s research team. There she started measuring CO₂ from Pacific waters, at a time when no one paid any attention to the problem. Saruhashi had to develop her own measuring system, known as Saruhashi’s Table, in which carbon dioxide is determined based on three parameters: temperature, pH, and chlorinity. This work earned her a PhD at Tokyo University in 1957.

Another important contribution was made when Japanese fishermen became mysteriously ill after being downwind of Bikini Atoll, where the US carried out nuclear tests until 1958. That led Saruhashi to carry out measurements of nuclear contaminant fallout to the ocean; a stupendous task given the tiny amounts in an immense body of water. She was able to prove that fallout from tests reached Japan in just 18 months and showed how radiation would disperse in the atmosphere and the ocean, raising concerns about contamination of the Pacific.

As we can gather from her words at the beginning of this text, Saruhashi was deeply concerned about the lack of recognition for women in science. In 1958, she established the Society of Japanese Women Scientists. In 1980, Saruhashi was the first woman elected to the Science Council of Japan, and in 1981, she established the Saruhashi Prize, given each year to a woman who can serve as a role model for young female researchers. This is a small prize funded primarily by Saruhashi and money raised by her co-workers after she retired from the Geochemical Research Laboratory, where she had been director since 1979.

Katsuko Saruhashi died, at the age of 87, in Tokyo, Japan, on September 29, 2007.

REFERENCES

FURTHER READING

By Mário Gonçalves, EAG Communications Committee
EAG CROSSWORD #1
Test and improve your knowledge of isotopes with the first EAG crossword!
Answers at https://www.eag.eu.com/crosswords/

ACROSS
1. Parent of a classical radiogenic isotope system.
5. Isotope anomalies inherited from stars.
6. Process by which an unstable atomic nucleus loses energy.
8. Unreactive elements with useful isotopes.
10. The animal in charge of the pack.
11. Source of an object.
12. In2/lambda.
17. Separates parents and daughters.
18. Difference between two isotopes of an element.
25. Can be studied using $^7\text{Li}$, $^{26}\text{Mg}$, $^{87}\text{Sr}/^{86}\text{Sr}$…
27. Nobody seems keen to have this type of waste dumped near their town.

DOWN
2. Every isotope geochemist’s favourite tool.
3. In the 2017, UK general election, Theresa May claimed to be strong and ________.
4. Parent of platinum-group isotope system.
7. Ionised gas.
13. Stable isotopes of this element trace ocean pH.
15. Real or hypothetical (isotopic) pool.
19. Can be studied using fission tracks, U-Th-He.
20. Glows hot to ionise.
21. Isotope fractionation style.
22. Canonical distillation model.
23. Isotope system for rates of processes.
Goldschmidt is the foremost annual, international conference on geochemistry and related subjects, organized by the European Association of Geochemistry and the Geochemical Society.

Goldschmidt2023 will again be organized as a hybrid meeting to take advantage of the best of the in-person and virtual formats and to open attendance to the widest possible audience.

We look forward to welcoming you to the beautiful city of Lyon, France, and remotely, from 9 to 14 July 2023.

Abstract submission deadline: 1 March 2023 (opens mid-December)

Grant application deadline: 15 February 2023

2023.goldschmidt.info
RENEW YOUR MEMBERSHIP FOR 2023

Geochemical Society members can renew quickly and securely on the GS website: www.geochemsoc.org. Renew by 31 December 2022 to enjoy uninterrupted access to *Elements*, *Geochemical News*, and registration discounts to Goldschmidt2023 and to other conferences. Members have access to the online member directory (available by signing into your profile on the website). You can also choose a two-year membership option to save time and money.

A reduced professional rate of $15 is available to scientists from countries classified by the World Bank as having low-income or lower-middle-income economies. Visit https://www.geochemsoc.org/about/membership/join to learn more about which countries qualify. Students from qualifying countries may apply for free memberships through the Introductory Student Membership Program.

<table>
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<th>2023 Dues Rates</th>
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<tr>
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<tr>
<td>Professional: Low and Lower-middle Income Economies</td>
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<tr>
<td>Senior</td>
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<tr>
<td>Student</td>
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</table>

GS INTRODUCTORY STUDENT MEMBERSHIPS

To increase student participation, the GS grants free memberships to students in countries that are under-represented in the Society. This includes most countries in Africa, Asia (excluding China, Japan, and South Korea), and Central and South America. Introductory Student Memberships offer benefits including print and online subscriptions to *Elements*, the weekly *Geochemical News* email, and discounted registration rates for the Goldschmidt Conference and other scientific meetings. More information is available at www.geochemsoc.org/programs/ism.

DEI COMMITTEES LAUNCH NEW VIRTUAL MENTORING PROGRAM

Geochemists, depending on their location, may have limited access to the resources, opportunities, or expertise necessary to fulfill their professional goals. In May, the GS and EAG announced a new program to provide virtual mentors to students in low-income or lower-middle-income countries. Organized by the societies’ Diversity, Equity, and Inclusion Committees, the program aims to connect these professionals with mentors from across the globe who can assist with these goals.

Three areas of initial focus for mentoring efforts have been chosen:
1. Assistance with graduate school, internship, and fellowship applications
2. Laboratory development and capacity building at targeted institutions
3. Connecting collaborators to execute specific projects

The societies accepted the first round of applications from mentors and mentees in June and expect to open a second round later in the year. Online collaboration tools will be provided to facilitate meetings and communication between mentors and mentees. If the initial pilot program is successful, the societies will consider opening the program to students in additional countries. Potential mentors from all countries may apply now. Geochemical Society or European Association of Geochemistry membership is not required to serve; however, all participants must agree to abide by the GS code of ethics.

Visit www.geochemsoc.org/programs/mentorship-program to learn more.

GS CAREER CENTER

The Geochemical Career Center features job opportunities from employers all around the world. If you are looking for a teaching, research, or postdoctoral position, be sure to add the Career Center to the websites you follow. If you are an employer seeking excellent candidates, the Career Center is a great way to advertise your position to members of the Society. Job postings in the Career Center are also featured in *Geochemical News*, the Society’s weekly electronic newsletter. Visit jobs.geochemsoc.org to get started.
Announcing MSA’s ECN

It is early fall, and once again MSA is closely monitoring membership renewals. At the moment, we are on track to match the steady decline in membership that MSA has been experiencing for many years. At a meeting of AGI’s Leadership Forum earlier this year, I learned that with a few exceptions, declining membership is fairly common for scientific societies in the geosciences. Some might argue that “this is just the way things are right now,” that the propensity to join societies is not part of modern culture and, therefore, declining membership is not something to worry about. After all, one might point to the fact that even with its smaller and declining membership, MSA is actually doing just fine, as it provides many services to the community, including running a flourishing publishing house; providing four lectureships annually, thanks to the generous contribution of Peter Buseck; making prestigious awards that promote the careers of young scientists and recognize the contributions of mid-level and more senior scientists; and hosting important community resources (e.g., databases, Mineralogy4Kids) on its website.

MSA also has a healthy endowment for its size and is led by extremely competent staff. However, if only a few people are directing MSA’s vision and steering its course for the future, its ability to truly serve the scientific community is at risk. A larger spectrum of viewpoints contributing to the leadership’s decision-making will allow MSA to have the largest dataset upon which to decide how to steer its future course. Perhaps one of the most effective means of ensuring that we have a broad spectrum of viewpoints is by making sure that scientists in the early stages of their professional careers, postdoctoral researchers, graduate students, and undergraduates belong to and are actively involved in MSA.

It is for this reason that I am particularly delighted to announce MSA’s newest effort to reach out to, engage, and serve new members: the MSA’s Early Career Network (ECN). The ECN was inspired by the Deep Carbon Observatory’s highly successful ECN and further developed via brainstorming sessions with members of MSA’s Diversity, Equity, & Inclusion (DEI) Committee, Membership Committee, and members of MSA Council. The ECN will be a self-governing network in which early career members of the society, and even those presently outside of MSA who are interested in participating, will help define the goals and outcomes of the network. MSA will support and assist the ECN with infrastructure for ECN communications and by facilitating connections between the ECN and existing membership. Numerous possible benefits of the ECN have been discussed, including mentor/mentee opportunities, a specific listserv for the ECN, and the opportunity to interface with MSA members at more advanced stages of their careers through symposia held annually at GSA and/or an ECN-specific symposium. Brainstorming sessions have highlighted the concept of creating a web-based platform for early career mineralogists to share their work with the hope of providing a resource for connecting with other early career researchers and fostering potential collaborations. Although the ECN is in its infancy, we hope that anyone interested in sharing ideas or participating in such a network will reach out to Ann Benbow at abenbow@minsocam.org to learn more about the next steps and how to get involved.

Contact the MSA Business Office at business@minsocam.org to renew for the coming year.

2023 membership renewals are now underway. The prices have not changed from 2022:

<table>
<thead>
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<th>Membership Type</th>
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<tr>
<td>Regular Member</td>
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<tr>
<td>Early Career Member</td>
<td>$45</td>
</tr>
<tr>
<td>Student Member</td>
<td>$20</td>
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Encourage friends, students, and colleagues to join. Benefits include online access to American Mineralogist and Elements, as well as discounts on publications and registration for Short Courses. Members also have access to the MSA Directory. You can renew or join on MSA’s new website: https://msaweb.org.

MSA’s NEW WEBSITE!

MSA is delighted to announce the launch of its new website: https://msaweb.org. This website is designed to make it easier to find MSA’s many publications and resources, as well as to join or renew membership, find out about awards and grants, and communicate with the MSA Business Office. Please visit the site soon and let us know, via the Contact form, what comments and suggestions you have to make the new site the best possible.

2022 MSA ELECTION RESULTS

MSA is pleased to announce the results of this year’s election for the 2023 Officers and Councilors:

<table>
<thead>
<tr>
<th>Position</th>
<th>Name and Institution</th>
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<tbody>
<tr>
<td>2023 President</td>
<td>Jeffrey Post, Smithsonian Institution, Washington, DC</td>
</tr>
<tr>
<td>2023 Vice President</td>
<td>Donna Whitney, University of Minnesota, Minneapolis, MN, USA</td>
</tr>
<tr>
<td>2023 Councilor I</td>
<td>Daniele Cherniak, University at Albany, SUNY, Albany, NY, USA</td>
</tr>
<tr>
<td>2023 Councilor II</td>
<td>Melissa Sims, Johns Hopkins University, Baltimore, MD, USA</td>
</tr>
</tbody>
</table>

MSA offers its congratulations to the Officers and Councilors and its thanks to all those who ran for office this year.
**2022 MSA Awardees**

At the 2022 Annual Meeting of the Geological Society of America, MSA was pleased to recognize the winners of its 2022 awards. These are:

**Roebling Medal** for scientific eminence as represented primarily by scientific publication of outstanding original research in mineralogy:

John Valley, University of Wisconsin, USA

**Dana Medal** in recognition of sustained outstanding scientific contributions through original research in the mineralogical sciences by an individual in the midst of his or her career:

Cin-Ty Lee, Rice University, USA

**MSA Award** in recognition of outstanding published contributions to the science of mineralogy by relatively young individuals or individuals near the beginning of their professional careers:

Benjamin Tutolo, University of Calgary, Canada

**Contributions**

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

**MSA 2023 Deadlines**

- **March 1, 2023:** This is the deadline for applications to MSA’s student research grants: The Kraus Crystallography Grant (one grant for $5,000) and the Mineralogy/Petrology Grant (two grants for $5,000 each). Information about applying and an application template are on the MSA website under Grants & Awards: https://msaweb.org. For more information, contact Ann Benbow at the MSA Business Office: abenbow@minsocam.org

- **June 1, 2023:** This is the deadline for submitting nominations to MSA’s four awards: The MSA Award, the Distinguished Public Service Medal, the Dana Medal, and the Roebling Medal. For more information about the awards and how to submit, visit the MSA website under Grants & Awards: https://msaweb.org.

**Minerals Day**

The third annual Minerals Day was celebrated on October 10, 2022, the Monday of Earth Science Week. The day featured live presentations by GemKids, as well as by celebrated mineral photographer, Jeff Scovil. New resources were added to the Minerals Day website, as well as a two-sided downloadable poster on “Minerals Around the House”. Minerals Day co-sponsors included the American Geosciences Institute, Earth Science Week, Essential Minerals Association, the U.S. Geological Survey, the Gemological Institute of America, and GemKids. The website is www.mineralsday.org.

**2023 Calendar**

The 2023 16-month calendar from Lithographie is now available on the theme of Tsumeb. The calendar is available from MSA for $12. Look for it on the MSA website under Publications: https://msaweb.org.

**Events**

**2023 Tucson Gem & Mineral Show.** Once again, MSA is a co-sponsor of an all-day symposium with the Friends of Mineralogy and the Tucson Gem & Mineral Society. The date of the symposium is Saturday, February 11, 2023 and the theme is Silica Minerals. For more information, visit the Friends of Mineralogy website at: https://www.friendsofmineralogy.org/
AIPEA was founded in 1948 to promote international cooperation in clay research and technology. A hallmark AIPEA event is the quadrennial International Clay Conference (ICC), the most recent of which—the 17th ICC—occurred on 25–29 July, 2022 in Istanbul, Türkiye. The theme was “New Interfaces: Bridging Continents and Cultures with Clays,” with 323 participants from 40 nations, 2/3 of whom attended in person and 1/3 by video conference. The conference was co-organized by the Clay Science Society (Türkiye) and the Clay Minerals Society (USA). We wish to thank the organizing committee for convening an in-person meeting in the present complex context: Selahattin Kadir (General Chair, Eskişehir Osmangazi Univ., Türkiye), Paul Schroeder (Co-Chair, Univ. Georgia, USA), Asuman Gönal Türkmenoğlu (AIPEA Representative, Middle East Technical Univ., Türkiye), and Fahri Esenli and Emin Çiftçi (Istanbul Technical Univ., Türkiye), both of whom served as Secretary. The conference was scheduled to take place in 2021, but was postponed to 2022 due to the Covid-19 pandemic. A complete report on the conference is available from the AIPEA website (https://www.aipea.org).

The conference opened with a one-day CMS workshop led by George Christidis on “Advances in the Characterization of Smectite in Bentonites,” and the Scientific Programme itself covered four days. Some of the presentations (especially plenary lectures) will be available on the AIPEA, CMG, or CMS YouTube channels when appropriate permissions are arranged. The book of abstracts is also available on the AIPEA website.

The ICCs also provide the opportunity for AIPEA to recognize contributions by esteemed colleagues, and to support the research endeavours of students and early career scientists. Conference Plenary lecturers included recipients of the AIPEA Medal, awarded to active scientists in recognition of their outstanding contributions to clay science, who shared their inspiring research outcomes with the participants:

- David Bish (Indiana Univ., USA) presented “The wonders (and implications) of disorder in clay minerals”.
- Hongping He (Guangzhou Institute of Geochemistry, China) presented “Transformation of 1:1 type clay minerals into smectite under hydrothermal condition”.
- The 2022 recipient of the Bradley Award, Denys I. Grekov (Nantes Univ., France), lectured on “Adsorption of methane and carbon dioxide by water-saturated clay rocks”.
- Warren D. Huff and Saverio Fiore were recognized with the AIPEA Fellow Award for their life-long activity promoting clay science and supporting the clay science community.

Student presentation awards were sponsored and judged jointly by AIPEA and CMS. Best oral presentation: Bidemi Fashina (Texas A&M Univ., USA); Oral runner-up: Aasim Shaffi (Univ. College London, UK); Best poster presentation: Karolina Rybka (AGH Univ. Science and Technology, Poland); and Poster runner-up: Eleanor Olegario (Univ. of the Philippines, Quezon City, Philippines).

Seven students received AIPEA travel grants: Adrian Lorenzo Hernández (Spain), Andrea García Vicente (Spain), Biljana Milovanović (Serbia), Julien Talon (France), Klaudia Dziewiałka (Poland), Pauline Corentin (France), and Zvonka Gverić (Croatia).

Students receiving travel grant awards from President Reiner Dohrmann during the closing ceremony. Left to right: Adrian Lorenzo Hernández, Andrea Garcia Vicente, Biljana Ilovanovic, and Julien Talon.

Dr. Gianni Vettese (Univ. Helsinki, Finland) and Dr. Ranjan Paul (Natl Bureau of Soil Survey, India) were awarded AIPEA Early Career Clay Scientist (ECCS) Travel Grants, and Dr. Jemaa Amakrane (Univ. Mohammed Premier, Morocco) and Dr. Javier García Rivas (Univ. Complutense, Spain) were recipients of AIPEA ECCS Research Grants. The ECCS activities also included a presentation of its objectives, a networking event, and a meeting with editors of the three major clay science journals. Additional awards were presented by CMS and the CMG of the Mineralogical Society (UK & Ireland).

The conference concluded with a field trip organized by Orhan Yavuz, Paul A. Schroeder, Emin Çiftçi, and Hüseyin Demir to the Şile Clay Deposits on July 30, 2022.

Bruno Lanson (right) wearing the AIPEA Presidential Medal for the first time, being congratulated by outgoing President Reiner Dohrmann.

Dr. Pauline Corentin (right) with Aasim Shaffi and Zvonka Gverić, with Karolina Rybka receiving the AIPEA-CMS best poster presentation award from AIPEA President Reiner Dohrmann, Treasurer Alberto López, and AIPEA General Secretary Peter Ryan. Aasim Shaffi receiving the AIPEA+CMS runner-up oral presentation award.

Klaudia Dziewiałka (Poland), Pauline Corentin, and Zvonka Gverić.
AIPEA

Each ICC is an occasion to announce new members of the AIPEA Council and new officers. Bruno Lanson (France) will take over from Reiner Dohrmann (Germany) as AIPEA President, and Bruno will continue in the role of Chair of the Nomenclature Committee. Chun Hui Zhou (China) will step in as Vice-President, and Peter Ryan (Secretary – USA) and Alberto López Galindo (Treasurer – Spain) will continue in their respective roles. Reiner Dohrmann will serve as Past-President. The AIPEA Council for 2022–2025 is comprised of Samar Chandra Datta (India), Cliff Johnston (USA), Erzsébet Harman-Tóth (Hungary), Tanya Peretyazhko (Ukraine, USA), Adi Radian (Israel), Tsutomu Sato (Japan), Jeanne B. Percival (Chair, Teaching Committee – Canada), Liva Dzene (Chair, Early Career Clay Scientists Committee – Latvia, France), Steve Hillier (Representative of the 18th ICC – UK), and Saverio Fiore (Webmaster, Chair of the Hazardous Minerals Committee – Italy).

We conclude with some future conference news: The 18th ICC will be held in Dublin, Ireland, on July 13–18, 2025 (https://icc.aipea.org/). The bid was led by Steve Hillier and Kevin Murphy on behalf of the CMG of the Mineralogical Society (UK & Ireland), and we all look forward to participating in 2025! Between now and then, we look forward to the upcoming EUROCLAY 2023 in July in Italy (https://euroclay.aipea.org/), and also draw your attention to the International Joint Conference Clays Application & Valorization (CAV2022) and Minerals & Materials Sciences (MMS2022) (https://www.scientevents.com/cav2022/).
MESSAGE FROM THE PRESIDENT, JOHN CARRANZA

It is a great honour that the Association of Applied Geochemists (AAG) has bestowed upon me to serve as its President for 2022–2023. I thank Dennis Arne for leading the AAG strongly over the past two years, which were made difficult by the Covid-19 pandemic. So difficult were those two years that the AAG was unable to celebrate its 50th anniversary at the 29th International Applied Geochemistry Symposium (IAGS), which was scheduled originally for November 2020 in Viña del Mar, Chile. I also thank Brian Townley, chair of the local organizing committee, for persevering in the organization of the 29th IAGS in those two difficult years. We are now hopeful, even though Covid-19 has not yet fully gone away, that we will be able to finally hold the 29th IAGS in the same Chilean city on October 16–22, 2022.

Dennis Arne will continue to serve on the Executive Council as Past President and chair of the Awards and Medals Committee, along with Gwendy Hall (Treasurer) and Dave Smith (Secretary). I thank Yulia Uvarova for agreeing to take on the role of AAG Vice President and as coordinator of the Regional Councillors. I welcome the new councillors for 2022–2023, namely Renguang Zuo, Alexander Seyfarth, Cliff Stanley, Jamil Sader, and Thomas Bissig (with Alexander and Jamil both starting their first term). I acknowledge the existing councillors for 2021–2022, namely Patrice de Caritat, Dave Heberlein, Paul Morris, Ryan Noble, Pim van Geffen, and Steve Cook. The AAG Council is further supported by its Regional Councillors, namely Kate Knights (UK and Republic of Ireland), Joao Larizzatti (Brazil), Brian Townley (Chile), Pertti Sarala (Northern Europe), Benedetto de Vivo (Southern Europe), and Iftikhar Malik (Southeast Asia). We have a new Regional Councillor for Northern Africa, Silas Sunday Dada, and Theo Davies continues as Regional Councillor for Southern Africa.

I thank the outgoing councillors (2020–2021) Maurizio Barbieri, Thomas Bissig, Steve Cook, Beth McClennenahan, David Murphy, and Yulia Uvarova for their contributions in the last two years, and Steve Cook for his role as chair of the Awards and Medals Committee. David Murphy continues as chair of the Education Committee, Beth McClennenahan continues as Coordinator for EXPLORE, and Steve Cook continues as the Business Manager for EXPLORE. The other Fellows who will continue their service to AAG are Paul Morris (chair of New Membership Committee), David Cohen (chair of the Symposia Committee, and coordinator of the AAG Student Paper Prize and the Geoscience Councils), Scott Wood (editor of GEEA), and Tom Meuzelaar (webmaster of the AAG website). It will be a pleasure working with the above-mentioned Fellows, as well as with AIArsenault, AAG’s business manager, and I thank them in advance for the support and contributions they will be providing AAG during my term.

In spite of the rescheduling of the 29th IAGS, we had a 5% increase in our membership during 2021. This is a positive sign, but we need to be more proactive in promoting and engaging with the next generation of [applied] geochemists. To this end, the AAG council has endorsed a number of projects, a few of which I mention here. First, the development of a continuing professional development program (CPD) is progressing under the expert leadership of David Cohen. Second, a special volume of papers on the fundamentals of exploration geochemistry will be published in GEEA, with Thomas Bissig, Ryan Noble, Beth McClennenahan, and Dennis Arne as guest editors. The topics/papers that will be included in this special volume will capture some of the collective knowledge and wisdom held by Members and Fellows of the AAG, and will provide some of the content for the CPD program. Hopefully, once completed, these and other existing and future projects of AAG will attract new memberships. We hope to increase not only the number of young Members and Fellows, but also the number of Senior Members and Fellows because the recently revised AAG by-law has removed the necessity of establishing whether a Senior Member or Fellow is actually retired and replaced it with just a set age of 65 for eligibility.

Finally, let us hope that 2022 is the year the Covid-19 pandemic ends, and I hope to meet many of you at the 29th IAGS.

RECENT ARTICLES PUBLISHED IN EXPLORE

The following abstract is for an article that appeared in issue 192 (September 2021) of the EXPLORE Newsletter.

“Geochemistry of LCT Pegmatites in Part of Northeastern Nasarawa State, North Central Nigeria”

A. Chukwu¹, S.C. Obiora², and T.C. Davies³

The pegmatites in northeastern Nasarawa occur within the reactivated belt of the basement complex of Nigeria. These pegmatites consist predominantly of complex pegmatites (rare-metal enriched) situated in southern parts of the map area, whereas simple pegmatites occur in the northern parts of the map area. These pegmatites intruded a gneiss-migmatitic gneiss complex consisting of metasedimentary rocks with granitic gneisses and biotite gneisses. The complex pegmatites are composed of quartz, albite, and muscovite with tourmaline. Garnet, ilmenite, and minor tin-columbite-tantalite mineralization constitute accessory minerals, contrasting with the simple biotite-microcline pegmatites. These pegmatites are highly peraluminous, however, the rare-metal pegmatites are much more fractionated than the simple pegmatites. The rare metal pegmatites are relatively enriched in Rb, Li, Cs, B, Be, Nb, and Ta, with low K/Rb and Al/Ga ratios relative to the simple biotite-microcline pegmatites. All of these pegmatites are likely product of anatectic fractionation of sedimentary rocks, and possibly derivative from granitoid complexes.

1 Department of Geology, Ebenyi State University, Abakaliki, Nigeria
2 Department of Geology, University of Nigeria, Nsukka, Enugu, Nigeria
3 Department of Geosciences, University of Lagos, Lagos, Nigeria

The full article of the above abstract can be viewed at: https://www.appliedgeochemists.org/index.php/publications/explore-newsletter...
The objective of these guidelines is to provide clear instructions for reporting surficial geochemical results, together with the requisite supporting information to evaluate those results for accuracy, integrity, and credibility. The target audience for these guidelines is anyone charged with reporting geochemical results, which includes, but is not limited to, company geoscientists, external consultants and contractors, government scientists, and university scientists and students.

This edition of the document consists of a brief general discussion on contextual information, sampling, quality control sample insertion and reporting, sample preparation, laboratory analysis, analyses in the field, data compilation and integration, and data presentation. Specific guidelines are provided by experts for the following survey types.

- Drainage surveys
- Lake sediment surveys
- Surface soil surveys
- Biogeochemical surveys
- Glacial sediment surveys
- Gas surveys
- Water surveys
- Rock sample surveys
- Lithogeochemical surveys

Free copies of the report can be downloaded from: https://www.appliedgeochemists.org/publications/writing-geochemical-reports-3rd-edition
The Mineralogical Association of Canada (MAC) is pleased to announce its medal and award winners for 2022.

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

This year’s awardee is Dr. Roberta L. Flemming, a Professor in Earth Sciences and Director of the Power and Mineral X-ray Diffraction Facility at Western University. She was born and raised on the Niagara Peninsula and graduated from Brock University (1985) with a BSc in Geology and Chemistry. At Brock, she discovered her love for solid state nuclear magnetic resonance spectroscopy (NMR) during her fourth-year thesis with Dr. J. Stephen Hartman. She received her MSc (1990) and PhD (1997) in Geological Sciences from Queen’s University, studying under Dr. Ron Peterson, where she combined NMR spectroscopy with X-ray crystallography and high-temperature mineral synthesis, studying spinel group minerals. She held a Killam Post-Doctoral Fellowship at the University of Alberta (1997–1999) with Dr. Robert Luth where she studied aluminous pyroxenes synthesized at high pressures. She has been at Western University since 2000, where she has enjoyed research and teaching in mineralogy for over 20 years. She was awarded a CFI-funded Micro X-ray Diffractometer in 2002, which performs in situ XRD, and she analysed her first kienkerlite indicator minerals (KIMs) (garnets from Dr. Herb Helmsteadt) and her first meteorite (Southampton Pallasite) with the micro-XRD in 2003. Roberta’s research program uses minerals as interpretive and predictive tools to reveal past and present processes on Earth and other planetary bodies including the Moon and Mars. Her research program involves innovative applications of in situ X-ray diffraction and NMR spectroscopy, and allied methods such as EPMA and XRF, to study Earth and planetary materials to understand Solar System evolution. She uses solid state NMR and XRD to quantify minerals as recorders of temperature in the early Solar System and terrestrial mantle rocks, by making systematic observations of mineral composition, crystal structure, and cation distribution (order-disorder) for key mineral suites, to derive thermodynamic parameters and equilibration temperatures. She uses in situ XRD to correlate crystal structural parameters to chemical composition in minerals, including meteorites to aid classification (e.g., H, L, LL), and KIMs for application to diamond exploration. She is pioneering the development of in situ XRD to interpret and quantify minerals as recorders of crystal deformation resulting from tectonic deformation (strain) and meteorite impact (shock) in Earth and planetary materials. She has recently begun calibrating strain using experimentally shocked rock-forming minerals, as well as evaluating strain at a smaller scale using EBSD. She is also leading a multidisciplinary team of researchers, with funding from the Canadian Space Agency, to develop a “Miniaturized In-situ X-Ray Diffractometer for Mineralogical Characterization of Planetary Surfaces (ISXRD)” with a focus on Mars. Her research has benefited greatly from working with many excellent collaborators at Western, across Canada, and internationally. She has supervised 37 BSc, 20 MSc, and 7 PhD thesis students, and published over 70 research papers. She considers it a privilege to have been able to supervise and collaborate with so many outstanding students over the past two decades.

She is an enthusiastic teacher and mentor to students of all ages, and she is committed to public outreach. She was awarded Western’s Faculty of Science Outreach Award in 2020. Last year, she co-chaired GAC-MAC 2021, hosted by Western in London, Ontario, and she co-organized the 14th Canadian Powder Diffraction Workshop-Berry School, also at Western.

**Young Scientist Award to Dr. Pilar Lecumberri-Sanchez**  
(University of Alberta)  
The MAC Young Scientist Award recognizes a young scientist who has made a significant international research contribution as a promising start to a scientific career. The areas of research considered are any or all of those covered by the Mineralogical Association of Canada. The scientist will have received their PhD not more than 15 years before the award. The scientist must be a Canadian working anywhere in the world or a scientist of any nationality working in Canada. Research areas include mineralogy, crystallography, petrology, geochemistry, mineral deposits, and related fields of study.

The 2022 Young Scientist Award goes to Dr. Pilar Lecumberri-Sanchez, an assistant professor at the University of Alberta. She obtained her BSc in geology at Universidad Complutense de Madrid, Spain, and her PhD at Virginia Tech, USA. She completed a three-year Marie Curie postdoctoral fellowship at ETH, Zurich, Switzerland, and worked as a researcher for one year at the University of Arizona, USA. Pilar’s expertise is in mineral deposits and fluid geochemistry. Her current research focuses on the tungsten-gold occurrences in the Tungsten belt (Yellowknife, Northwest Territories (NWT)), orogen gold mineralization in the Yellowknife Gold Belt (NWT), and epithermal mineralization in the Toodoggon district (British Columbia), all in Canada.

**Hawley Medal for the best paper published in The Canadian Mineralogist in 2021**

The Hawley Medal is awarded to Drs. Andrew J. Kaczowka (Camceco Exploration), T. Kurt Kyser (deceased, formerly from Queen’s University), Tom G. Kotzer (University of Saskatchewan), Matthew I. Leybourne, and Daniel Layton-Matthews (Queen’s University).


The winning paper describes a robust technical approach to characterizing the mineralogy and geochemistry of the polymetallic unconformity-related Cigar Lake uranium deposit (Saskatchewan, Canada). Elements of concern for both uranium metallurgical processing and the downstream environment were identified. A wide range of analytical techniques were used for the mineralogical characterization including X-ray diffraction (XRD), scanning electron microscopy with mineral liberation analysis (SEM-MLA) to determine mineral proportions, and electron microprobe analysis (EMPA) to quantify elemental substitutions of the mineral phases. Finally, the spatial distribution of the elements of concern and their mineral hosts were outlined in plan view sections across the deposit using geostatistical modeling software—a key outcome linking the geology to the process metallurgy of the deposit. The success of this holistic geometallurgical approach that integrates the geochemical, mineralogical, geological, and geospatial characteristics of the Cigar Lake deposit makes this paper an outstanding contribution to the 2021 Canadian Mineralogist.
Dr. Andrew J. Kaczowka (Cameco Exploration)

Andrew Kaczowka completed his BSc with honours at the University of Regina in 2010 and his MSc at Queens University in 2018. He has worked at Cameco Corporation for the past 12 years as a Sr. Mine Site Geologist and more recently as a Sr. Exploration Geoscientist. Andrew worked at the Cigar Lake uranium mine from 2013 to 2021, where he was a strong proponent of using and integrating geological, geochemical, and mineralogical data to optimize mining and milling. Andrew’s current work and research focus is on ore deposit metallogeny, exploration geochemistry, and geospatial modeling. Andrew is an avid uranium explorer hoping to contribute to the discovery of new economic deposits.

Dr. Tom G. Kotzer (University of Saskatchewan)

Thomas Kotzer is a professional geoscientist with over 30 years of experience in industry and academia. His main interests are associated with the global application of advanced technologies to understand complex geochemical, mineralogical, and hydrogeologic relationships within nuclear power generation and radioactive material storage, mineral exploration, and mining. He has held senior scientific, technical management, and oversight positions at Atomic Energy of Canada, Canadian Light Source, Cameco Mining and Exploration, AEL-AMS Laboratories, and SRK Consulting. Throughout his career, he has maintained an active and ongoing relationship with academia as an adjunct professor and graduate student mentor and supervised and provided field support and funding to collaborative academic research programs.

Dr. Matthew I. Leybourne (Queen’s University)

Matthew Leybourne is a Professor of Geochemistry and Analytical Geochemistry in the Department of Geological Sciences and Geological Engineering at Queen’s University, Kingston, Ontario. His research is focused on developing new analytical methods especially related to solution and laser ablation ICP-MS and low-level trace element determinations, the geochemistry of fluids associated with ore deposits (groundwater, marine water, and hydrothermal systems), geochemical exploration, the petrogenesis of igneous rocks, and the timing of the onset of plate tectonics. Matt is Co-Director of the Queen’s Facility for Isotope Research (QFIR) and is a faculty member of the Arthur B. McDonald Canadian Astroparticle Physics Research Institute in the Department of Physics, Astronomy and Engineering Physics.

Dr. Daniel Layton-Matthews (Queen’s University)

Daniel Layton-Matthews has been a faculty member at the Department of Geological Sciences and Geological Engineering at Queen’s University and a co-director of the Queen’s Facility for Isotope Research (QFIR) since 2007. His research group has focused on the physical and chemical dispersal of elements in the near-surface environment with an emphasis on ore systems. His global collaborative research program has strong ties with industry, government, and academic researchers and has been involved with the supervision of 103 BSc, MSc, and PhD students. Dan received a MAC scholarship in 2002, served as a MAC councillor in 2003–2005, and was the recipient of the GAC Harvey Gross Award and Distinguished Lecturer Award for the Association of Applied Geochemistry. Dan’s current research group is focused on the mobility and deposition of metals and metalloids and developing methods for the measurement of isotopic ratios and element contents in complex geological and biological media.

MAC AWARDS – CALL FOR NOMINATIONS

Peacock Medal

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

Young Scientist Award

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

Leonard G. Berry Medal

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

Nominations for the 2023 medals and awards are to be submitted to Andrew Conly (Department of Geology, Lakehead University, 955 Oliver Road, Thunder Bay, ON P7B 5E1, CANADA; E-mail: aconly@lakeheadu.ca).

Please submit your nominations by 31 December 2022. Check our website, www.mineralogicalassociation.ca, for additional details.

SUDBURY 2023 GAC-MAC-SGA JOINT ANNUAL MEETING

May 24–27, 2023

Laurentian University, in Sudbury, Ontario, Canada

Discovering Ancient to Modern Earth – Découvrir la Terre Ancienne à Moderne

REQUEST FOR ABSTRACTS

Join us in for the Joint Annual Meeting of the Geological Association of Canada (GAC), Mineralogical Association of Canada (MAC), and Society for Geology Applied to Ore Deposits (SGA), which will be held on 24–27 May 2023 at Laurentian University in Sudbury, Ontario, Canada.

Abstract Submissions: will be open from November 2022 through 1 February 2023, with late abstracts accepted at a higher fee between 2 February and 1 March 2023. Get more info at https://event.fourwaves.com/Sudbury2023/pages.

Hoping to see you in Sudbury!
YOUNG SCIENTISTS AWARDED

The Best Master and Best PhD Thesis Awards are given annually by the Mineralogical Society of Poland and recognize outstanding and original contributions in the areas of mineralogy, petrology, and geochemistry. Many excellent contributions were submitted in 2021, making it virtually impossible for the jury to choose a single winner. It was not until after long discussions that the jury decided to award three prizes, two for doctoral and one for master dissertations. Congratulations to the winners! We hope it is a great start to their illustrious scientific careers.

The Best Master Thesis of 2021 was written by Kamil Bulcewicz. The awarded work “Record of metamorphism in metapelites of the Izera-Kowary unit in the area between Śnieżka and Okraj Pass” was carried out at the Institute of Geological Sciences of the University of Wrocław (Poland) under the supervision of Jacek Szczepański. In his master’s thesis, Kamil used pseudo-sections and classical geothermobarometry tools to recreate the record of metamorphism in mica slate with garnet. Kamil reconstructed burial depths of metapelites at ca. 60 km, followed by nearly isothermal decompression and subsequent retrograde under greenschist facies conditions. He suggested that the switch between the two exhumation stages may have occurred at shallower depths and higher temperatures than previously proposed.

Kamil continues his work with high-pressure rocks at the University of Wrocław as a PhD student. He is a new but already highly praised academic teacher. Kamil loves fieldwork so much that he has also decided to work at the Polish Geological Institute.

The Best Doctoral Thesis of 2021 was written by Michał Bukala. The awarded work “Subduction processes recorded by the Baltica outer margin in the Scandinavian Caledonides” was carried out at the Faculty of Geology, Geophysics and Environmental Protection, AGH University of Science and Technology in Kraków (Poland) under the supervision of Jarosław Majka. The presented work is a collection of four thematically related publications focused on metamorphic processes that took place within a subducting plate during the Caledonian Orogeny in the early Paleozoic. Regional P-T-t-d paths were reconstructed and presented in his publications, but other general geological processes were also addressed, including (1) the relationship between progressive dehydration reactions and seismic activity (Bukala et al. 2020a; https://doi.org/10.3389/feart.2020.594453), (2) burial and exhumation of the buoyant continental crust (Bukala et al. 2020b; https://doi.org/10.3390/min10040295), and (3) the role of fluid in metamorphic reactions and (meta)stability of mineral paragenesis (Bukala et al. 2018; https://doi.org/10.1111/jmg.12306; Holmberg et al. 2019; https://doi.org/10.2478/geoca-2019-0027).

Michał’s research interest has evolved from metamorphic petrology (primarily utilizing thermobarometry and U-Pb geochronology) towards (micro)structural geology, emphasizing the role of fluid–rock interactions and seismically induced deformation under high-pressure conditions. So far, the results of his process-oriented research have been applied to understanding the dynamics of Scandinavia, Svalbard, and the Greenland Caledonides. Taking the position of assistant professor at the Polish Academy of Sciences (Kraków, Poland), he has shifted his research to the younger orogenic setting of the Carpathians.

The award in the category of Best PhD thesis was also received by Arkadiusz Krzątała for the work “New and rare minerals from paralava of the Hatrurim Basin, Israel” carried out at the Institute of Earth Sciences, at the University of Silesia in Katowice (Poland). His PhD thesis supervisor was Irina Galuskina. The main aim of Arkadiusz’s research was to describe new and rare minerals from coarse-grained paralavas of the Hatrurim Complex. This is a unique complex of pyrometamorphic rocks distributed in the territory of Israel, Jordan, and the State of Palestine. The complex consists of high-temperature/low-pressure rocks (sandine facies) and products of their low-temperature transformations. In his doctoral thesis, Arkadiusz proposed a model of formation of barium-vanadium mineralization in enclaves. He showed that, despite many years of research, these rocks are not fully explored and still contain unknown minerals. The most important achievement of his doctoral thesis was the discovery of a new mineral bennesherite Ba2Fe2+2Si2O7, named for the Ben Nesher Mount in Israel. This is the first barium mineral of the melilite group.
EDITORIAL

Dreaming about the future publishing system…

We are still in a transition period, with all its uncertainties and the normal apprehension linked to change. Let us imagine that we have reached a steady state with a single economic publishing system accepted by all. Which one would you prefer?

1. The past system where researchers do not have to pay to publish and have access to published work, with the condition that they are at a sufficiently wealthy institution, which is able to pay for the access licenses.

2. The diamond open access system where researchers do not pay themselves for publishing cost (and remain unaware of the costs and resource consumption), but someone else does, and everybody has access to all publications, past and present.

3. The gold open access system where researchers pay the cost of their publications (being fully aware of the costs associated to every single publication), and everybody has access to all publications, past and present.

The first economic system is certainly not the most open, inclusive and fair system. It was also proven to be an unsustainable system with strong economic limitations. As we have seen, constant and uncontrollable inflation of publication costs, led to severe financial problem for many research institutions and libraries.

The second one, the diamond system may appear at first as the most attractive and the fairest one. However, it moves back to the past approach where publishing costs (direct and indirect) are hidden from authors. Some claimed that the bankruptcy of the past system was, in part, due to the fact that researchers where never involved in the financial decisions and were ignorant about them and their consequences. Authors are the main actors in the publishing system and should not remain passive and unaware of the financial questions. It is like residents of a building who do not need to pay the bill for heating costs. Some may even keep the windows open in the winter, especially if they do not even know how much it costs. The hidden costs inherent in the ‘diamond’ system may repeat some mistakes of the past. Through subsidies, agreements between publishers and institutions, or any other funding systems, the real cost of publications will remain unknown and potentially out of control, which affects the whole research community financially.

The gold open access system offers the possibility for authors to know how much it cost to have their article published in any journal. Personally, I have a preference for this model, as it is most transparent and empowering to authors. As authors have to pay directly the cost of their publications, they are confronted with the consequences of their decisions. Even in the gold open access model, we must remain vigilant. If institutions and libraries propose to sign direct agreements with publishers, shortcutting the researcher’s involvement, the role of researchers will again be diminished. Such agreements are complex and it is nearly impossible to estimate individual costs and to regulate global costs. This is probably not the most transparent way to use public funding (i.e., taxpayers’ money).

I anticipate your objection: “but, the researchers will have to pay from their research credits…” Not necessarily, if the institutions decide to systematically reimburse the cost of APCs to the researchers. It is a pretty easy decision to take for them. This system has the potential to offer many advantages, for both researchers and institutions. It would need another editorial to fully explore them.

As researchers who publish, we must care about the costs of articles. We need to have an informed understanding of the role we play with the choices we make. Every time we choose to submit an article to a specific journal, we are making a stand on the publishing model that we support.

The gold open access system, as we know it, may not be the economic model for publishing that will be finally generalized in the future. I do not even know if the European Journal of Mineralogy (EJM) will remain a gold open access journal forever. Notwithstanding, currently it is the fairest and most sustainable system we can propose. It offers transparency and the tools the research community and institutions need to regulate the economic dimension of the publishing system.

J. Ingrin
Managing Editor of EJM

INTERNATIONAL ECLOGITE CONFERENCE

10–13 July 2022, Lyon, France

Over the past 40 years, the International Eclogite Conference (IEC) has become a “must go” event for researchers interested in the processes of mountain formation, subduction, and exhumation of oceanic and continental lithosphere, and (ultra)high-pressure metamorphism. After 40 years, it was decided to bring this series of conferences back to France where the first IEC was organized in 1982 and where two centuries ago, in 1822, the mineralogist René-Just Haüy created the name “eclogite”, meaning “chosen rock”. After a rendez-vous in the Museum national d’Histoire naturelle in Paris, “in the footsteps of Haüy”, the main meeting was organized at the École Normale Supérieure in Lyon, from July 10th to 13th, 2022. Two pre- and post-conference field trips were also organized, respectively, in the Armorican Massif and the Italian Alps.

Unfortunately, circumstances prevented many colleagues, especially Russian and Chinese, from joining the conference, so most of the participants came from Europe and the Americas. About a hundred contributors, including 20 online, made 110 presentations, in the form of talks...
Report of the Meteorite Nomenclature Committee

The Nomenclature Committee (NomCom) continued its work throughout the second year of the global pandemic. During the past year, the discovery of new meteorites continued, although some meteorite-collecting efforts have been postponed or paused due to the pandemic (e.g., ANSMET).

The work of the NomCom would be impossible if not for the dedication of many individuals, including all of the NomCom members, meteorite finders and classifiers, and repository curators. I would like to thank them for their tireless effort to make the global inventory of meteorites available for scientific study. I also want to acknowledge the global community of meteorite collectors because they help drive the demand to find new meteorites, and the scientific community reaps benefits from those efforts. Special acknowledgement goes to outgoing NomCom chair Audrey Bouvier (Universität Bayreuth) who finished her three-year term at the end of 2021. We also welcomed a new member to NomCom in January: Katherine Joy (University of Manchester, UK). We are very happy to have her on board!

NomCom is currently composed of nine appointed members: Francis McCubbin (Chair; NASA, JSC, USA), Massimo D’Orazio (Università di Pisa, Italy), Cyrena Goodrich (LPI-USRA, USA), Anggar Greshake (Museum für Naturkunde Berlin, Germany), Juliane Gross (Rutgers University, USA), Katherine Joy (The University of Manchester, UK), Mutsumi Komatsu (Sokendai, Japan), Bingkui Miao (Guilin University of Technology, China), and Devin Schrader (Deputy Editor, Arizona State University, USA), and three ex-officio NomCom members: Jérôme Gattacceca (MetBull Editor; CEREGE, France), Jeff Grossman (Database Editor, NASA, USA), and Nancy Chabot (MetSoc Vice President; JHU APL, USA).

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

As of this writing, there are just under 70,000 approved meteorites in the Meteoritical Bulletin Database, including over 13,000 with a classification description, and notably over 520 lunar meteorites (totaling about 886 kg of material) and 330 Martian meteorites (totaling about 260 kg of material). That’s right, humans have found and identified over a metric ton of Moon and Mars sitting on Earth’s surface!

Meteorites, Dense Collection Areas, and Type-Specimen Repositories: The 2020 entries of the MBDB, totaling 2790 meteorites, have been published in the Meteorite Bulletin, No. 109, by Gattacceca et al. (2021). The full write ups of 1249 non-Antarctic meteorites and supplementary tables can be found online as Supporting Information and in the MBDB Archive. The MB 109 includes 17 approved falls, as well as 21 new DCAs and five new type specimen repositories. Meteoritical Bulletin No. 110, containing new meteorites, DCAs, and type-specimen repositories approved in 2021, is in preparation and will be submitted later this year to Meteoritics & Planetary Science.

Meteorite naming: Remember to send your write-ups for new and provisional names to NomCom at least three weeks before submitting your conference abstract or manuscript to journals to avoid potential issues with naming and classification and delays in publication. A list of instructions on how to attain a meteorite name can be found at https://www.lpi.usra.edu/meteor/naming.php. The release of the write-up to the MBDB may be held on request if there is an embargo from publishers.

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

Francis McCubbin
Chair of the Nomenclature Committee
NASA Johnson Space Center

Reference

Gifts and Grants Guidelines

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

To support these activities, the Society has created an Endowment Fund. The majority of the Endowment consists of the General Fund, which can support one-time activities that are not part of the normal Society business. The Endowment Fund also has named funds, the Nier Fund, the McKay Fund, and the TIM Fund, which were established for the specific purposes. Details about activities supported by all of these Funds can be found under: Activities Supported on the society website. For those who wish to assist in this mission, donations can be made to the General Fund or to any of the specific Funds (see Ways to Contribute on the society website, https://meteoritical.org/grants).

Annual Meeting Schedule

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<tr>
<th>Year</th>
<th>Meeting</th>
<th>Dates</th>
<th>Location</th>
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<tr>
<td>2022</td>
<td>85th</td>
<td>August 14–19, Glasgow, UK</td>
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<tr>
<td>2023</td>
<td>86th</td>
<td>August 13–18, Los Angeles, USA</td>
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<td>2024</td>
<td>87th</td>
<td>July/August TBD, Brussels, Belgium (EU)</td>
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<td>2025</td>
<td>88th</td>
<td>July TBD, Perth, Australia.</td>
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<td>2026</td>
<td>89th</td>
<td>July/August TBD, Frankfurt, Germany (EU)</td>
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Renew Your Membership Now!

Please don’t forget to renew your membership for 2022. Students, this is particularly important if you are interested in applying for one of our student presentation awards, as you must be a member to be eligible. You can renew online at: https://meteoritical.org/member/join
I am sad to report that our friend and colleague Klaus Keil passed away peacefully on Friday, February 25th, 2022, at home after a long battle with cancer. He was 87 years old. Klaus was Emeritus Professor, former Director of the Hawai‘i Institute of Geophysics and Planetology, and former Interim Dean of the School of Ocean and Earth Science and Technology. Klaus was an outstanding scientist, spectacular mentor, educator, and leader, dedicated family man, and enthusiastic tennis player. His academic and science leadership skills glittered at the University of Hawai‘i since 1990, and at the Institute of Meteoritics at the University of New Mexico from 1968 to 1990.

Klaus was a pioneer in the use of the electron microprobe in meteoritics and in petrology and mineralogy in general. In the early 1960s, he worked with colleagues at NASA Ames Research Center, Ray Fitzgerald and Kurt Heinrich, to make the first energy dispersive X-ray spectrometer for use in microanalysis. This device was the first to focus on terrestrial and extraterrestrial geological materials, and the first to use a solid-state lithium-drifted Si detector. Over his long and illustrious career, Klaus studied practically every type of meteorite and lunar sample, addressing big problems in planetary science, from chondrule formation to pyroclastic eruptions on the Moon and achondritic bodies, from asteroid disruption to the composition of the Martian surface. His accomplishments were recognized through awards of the Leonard Medal from the Meteoritical Society, the J. Lawrence Smith Medal of the National Academy of Sciences, and election as a Legends Fellow of the Microanalysis Society, in addition to numerous other accolades including the main belt asteroid Keil and the extraterrestrial mineral keilite, (Fe,Mg)S, named in his honor.

A long time ago someone told me, with astonishment in his voice, “Everything Klaus touches turns to gold.” Klaus was an alchemist. He made his own gold through his imagination, ability to synthesize diverse data, hard work, and the ability to motivate research in his group. The real gold, though, goes to all of us who benefitted from his research, leadership, and mentorship, especially those of us who have had the pleasure and honor to work with him and to be his friend.

Jeff Taylor

IN MEMORIAM: KLAUS KEIL

Contributions will be presented in a special issue of the European Journal of Mineralogy, now open for submissions.

The next IEC is set for 2025 in California.

Samuel Angiboust and Gaston Godard
Website: https://iec14.sciencesconf.org/

IEC Merit Awards 2022: Best Talk and Best Poster

Two distinctions were awarded during the International Eclogite Conference.

- **Best Talk**: T. A. Markmann presented a petrogeochemical model perspective on the interplay between rock transformation and aqueous fluid production in subduction zones. This study is in collaboration with P. Lanari.

- **Best Poster**: J. F. Vieira Duarte, on oxide-silicate petrology and geochemistry of subducted hydrous ultramafic rocks beyond antigorite dehydration (Central Alps, Switzerland). This project is in collaboration with T. Pettke, J. Hermann, and F. Piccoli.

Jeff Taylor
Internal Structure

After welcoming the German-Austrian-Swiss Clay Group DTTG as an associated member, the DVGeo is seeing a growing interest from other organizations to join or—at least—to cooperate. The societies in the umbrella association are discussing possibilities to work more closely together in order to speak with one voice and reduce administrative costs.

Revival: Conference of the Geosciences Departments

From the DVGeo’s point of view, the German university landscape has so far lacked an organization that discusses developments in geoscientific research and teaching. Therefore, it initiated the new formation of the Conference of Geosciences Departments.

Representatives from 20 universities came together for the (online) kick-off meeting in March. Claudia Trepmann from LMU Munich was elected as interim spokesperson. More universities attended the second meeting in May, which included the adoption of a constitution and the election of a team of spokespersons. The DVGeo will be happy to support this new organization.

Geosciences in School

Because Germany is one of the countries in Europe where geosciences are not offered as a school subject, the DVGeo is trying to broaden geoscientific knowledge in schools. The members of the DVGeo have been offering interesting tools that are used by schools for a long time, e.g., the Mineralogical Teaching Kit of the DMG, mileko.

One of the DVGeo’s first goals was to connect these individual actions with each other. As a next step, all offers are to be collected and made easily available on the internet. Because responsibility for school education in Germany lies with the federal states, each federal state must additionally be addressed individually. In Berlin, further training events for teachers in the field of geosciences will be offered this year and we hope to expand this success.

Tamara Fahry-Seelig (Berlin)
Prof. Dr. Hartmut Schneider is the recipient of the Agricola Medal of the DMG in 2022 for his outstanding research in the field of Applied Mineralogy. Hartmut Schneider studied mineralogy at the University of Tübingen where he obtained his diploma in 1969. Two years later, in 1971, he received his PhD with a thesis on the transformation behavior of biotite. He then worked as an assistant professor at the University of Karlsruhe. In 1976, he became the department head of the German Industrial Institute for Ceramics and Refractories (DIFK) in Bonn with a research focus on high-temperature materials and refractories, high-temperature behavior of SiO₂ phases and silica refractory bricks, refractory grade bauxites, transformation of aluminosilicates to mullite, and transition-metal doping of mullite. He finished his habilitation in 1986 at the University of Münster on the synthesis, properties, and applications of mullite. From 1989 to 1990, he was a member of the board of directors of the DIFK. In 1990, he moved to the Institute of Materials Research at the German Aerospace Center in Cologne where he was head of the Ceramics Department until 2006. In that period, he continued his research on the crystal chemistry and properties of mullite. In 1996, he became a professor at the University of Hannover. He was also a guest professor at the University of Vienna and the National Taiwan University in Taipei. In 2013, he was awarded as a Fellow of the University of Bremen where he is still active with his research on mullite. The scientific work of Hartmut Schneider is internationally recognized, as expressed by the Japanese Government Research Award in 1990, the German Lilienthal award in 1995, and his appointment as a Fellow of the American Ceramic Society in 2013. He has published more than 270 scientific papers in international journals. The workshop “Mullite and Mullite Ceramics” was organized in 2006 to honor his scientific work.

Reinhard Fischer (Bremen)

The European Mineralogical Union (EMU) annually sponsors international workshops (EMU Schools) where experts give review lectures starting at the traditional university level, but also providing the participants with insights to understand even the latest trends in the covered field.

The proposed Volume 21 of the EMU Notes in Mineralogy entitled “Chemical geodynamics of the Earth’s mantle; new paradigms” will be edited by Costanza Bonadiman (University of Ferrara, Italy) and Elisabetta Rampone (University of Genoa, Italy), both representing the Italian Society of Mineralogy and Petrology (SIMP), who were the main organizers of the MEREMA School.

This volume will cover the scientific issues presented in the past second edition of the MEREMA International School on Mantle Dynamics, as well as contributions from the first edition (MEREMA 2017 Winter School), with the aim of following a common thread of the Earth’s mantle dynamics.

Thanks to the contribution of top-level scientists who took part in both school editions, together with scientists who contributed to the contents, this volume will assess the cutting edge knowledge of chemical differentiation and dynamics of the mantle as a whole system, and will explore the effects of reaction mechanisms at the Earth’s major interfaces: the core–mantle–boundary (CMB) and the crust–mantle boundary. Different methodological approaches and disciplines (petrology, geochemistry, mineral physics, and geophysics) will offer an overview of the Earth’s mantle whole system beyond the line of reasoning driven by the physics of the continuum medium.

The main topics that this volume will address are:

1) Chemical differentiation and internal structure of the Earth;
2) Tomography and rheological properties the Earth’s mantle;
3) Origin and length scale of chemical/isotope mantle heterogeneities;
4) Transfer of heterogeneities from the deep mantle to the melting mantle source regions and finally to the extruded melts.

Such a volume will serve as an essential guide for the international geochemical, petrological, and mineralogical community, allowing them to understand the dynamics of the Earth’s mantle well beyond the important geophysical aspects.
Yves Tardy (1939–2022) passed away this year. He began his professional career in the “Centre de Sédimentologie et Géochimie de la Surface” headed by Georges Millot at the University of Strasbourg, France. As a geologist, geochemist, soil scientist, and enthusiastic teacher, he trained an outstanding group of students and researchers. He was instrumental in the transition of the study of solids in soils and alterites toward the study of natural waters, as early as in his PhD thesis (1969). In the dominating ideas of the time, kaolinite and even more gibbsite minerals were considered as indicators of tropical climates. However, after Dejou at INRA in Clermont-Ferrand, Tardy found them in granitic arenas of the French Massif central; thus, they form presently. In the French Vosges mountains, he identified aluminous vermiculites that were mineralogically different, but geochemically equivalent to kaolinite in terms of the Si/Al ratio. This is what he called “disguised monosialitization”, a concept referring to the definitions given in the study of laterites by the German geochemist Harrassowitz, and later generalized by Georges Pédro. On the basis of the experimental weathering studies by the latter, and specifically the mol ratio SiO2/(sum of bases) in solutions, Tardy focused on the chemical composition of natural waters. This allowed him to show the actuality of rock weathering and soil formation. Soils and alterites are not simply the heritage of landscapes, but the result of rock weathering and soil formation. The same processes are active today, with slow, but indeed measurable rates, non-negligible even at the scale of human life. He then elaborated the idea that major, minor, and trace elements migrate different distances according to their solubilities and pedoclimatic conditions. This is what he called “ion chromatography in landscapes,” a precursor of the concept of “critical zones.” Reactions between alterites and soils and solutions must not be considered only as mass transfer. Chemical equilibria must also be considered. The calorimeter must complete the balance. Tardy then introduced in France the application of solutions/mineral equilibria, developed by Robert M. Garrels in the USA, generalizing the well-known oxido-reduction (corrosion) diagrams designed by Marcel Pourbaix in Belgium. Tardy then played a pioneering role by importing and adapting the first computer geochemical models developed by Harold C. Helgeson at Berkeley for metallogeny, just 50 years ago, when they were still embryonic, as even the Fortran language was not yet stabilized. He initiated the Water-Rock Interaction group in the IAGC, which held its first meeting in Prague in 1974 and still exists. As early as the 1980s, he launched with Henri Martin, professor at the Catholic University of Louvain in Belgium, and Udo Schwertmann, professor at the University of München in Germany, and was the first President of the European Network of Laterites and Global Environments (EUROLAT) in the very first European program “Help and stimulation for research”, created in 1985 that accompanied the first generation of post-doctoral exchanges in the Europe of 12 countries at the time.

The interdisciplinary PIRAT (Programme interdisciplinaire de recherches sur les altérations tropicales) program aimed to study the impact of climate change on weathering, sedimentation, and carbon fluxes, relying on three joint studies: lateritic profiles, paleolakes, and large river watersheds. Thus, several generations of French and foreign students benefited from this support. Major results were obtained, e.g., about the hydroclimatic conditions of formation of minerals in laterites, impacts of hydroclimatic variations on lacustrine sedimentation, the role of rock weathering as a sink of atmospheric CO2 and fluxes of inorganic carbon in solution exported by rivers to the ocean. All of these results are recorded in three fundamental treatises, of which Tardy is the author or leader: Tardy Y (1986) Le cycle de l’eau. Climats, paléoclimats et géochimie globale. Masson, 338 pp; Tardy Y (1997) Petrology of laterites and tropical soils. Balkema, 408 pp; Tardy Y and 5 coauthors (2009) Carbon and water cycles, Amazon River Basin applied geochemistry. Atlantica. 479 pp.

With his expertise in the field of African soils and evaporitic environments, Tardy developed a school in France on natural salts and brines, e.g., Chott El Jerid (Tunisia), Lake Chad (central Africa). These then formed the foundation of the new school that Tardy laid, combining soil and water analyses with geochemical and hydrological modeling, with a constant eagerness to keep a strong anchorage in field studies—in Africa, especially for laterites of which he was particularly fond; in Europe; and in Brazil, with the monitoring of the chemical composition of large rivers. Yves Tardy was a scientist of international reputation and a fantastic leader of all the French and foreign teams he created and stimulated over so many years, and the teams who have followed, developed, and diversified the tracks he opened.

Guilhem Bourrié, Abdallah Droubi, Bertrand Fritz, Hélène Paquet, Anne Probst, Jean-Luc Probst, and Fabienne Trolard
THE PRESIDENT’S CORNER

As my term as CMS President comes to an end, let me say what an honor it has been to serve the society in this capacity. It has been yet another unprecedented year as the world continues to adapt to the COVID pandemic. This year, CMS leadership has made improvements to one of the society’s core functions, that of transferring knowledge of clay mineral science and technology. Content from our annual meetings (programs, abstracts, and plenary lectures) is being made available free of charge to the scientific community through our website. We are also working to improve communication with the larger clay science community through our social media pages and our email lists. In the coming months, expect to see additional changes based on your responses to the Membership Questionnaire. In closing, I encourage all of you to be active in your service to the CMS and to clay science. I look forward to meeting with you in person at our annual meetings or other scientific conferences.

Jeffery Greathouse, CMS President

CMS STUDENT RESEARCH AWARD WINNERS

Congratulations to Maria Arizaleta from Earth & Atmospheric Sciences, University of Alberta (Canada), Yuqing Bai from Comenius University in Bratislava (Slovakia), Himanshu Yadav from the Indian Institute of Technology Guwahati (India), and Savannah Rathbun from the Department of Geology and Geological Engineering, University of Mississippi (USA) for each winning a 2022 CMS Student Research Grant! Here we feature two of the grant winners, and the rest are forthcoming in the next issue.

Maria Arizaleta’s research is focused on characterizing and assessing the carbonation of clay minerals in alkaline lake sediments, and investigating the associated implications. More specifically, she studies the chemical conditions during the transformation of authigenic Al-poor, Mg-rich phyllosilicates into carbonate minerals. She conducts laboratory and field experiments, while applying various analytical techniques and modelling. The conditions required for the co-existence and transformation of mineral phases are poorly understood. Therefore, her research will help develop better quantitative geochemical models for environments like lake sediments and their potential for carbon sequestration.

Yuqing Bai is studying in the Department of Mineralogy, Petrology, and Economic Geology at Comenius University in Bratislava, Slovakia. His current research interests are clay minerals, oil sands, and oil sand tailings. His dissertation is focused on characterizing the mineralogy, chemical composition, and surface properties of mature fine tailings from Alberta oil sands. The CMS research grant will help him assess the parameters and their detrimental effects on extracting nonaqueous bitumen from oil sands solids. Receiving the support and guidance of Dr. Marek Osacký and Dr. Peter Uhlík, he will tailor the parameters of model oil sands (e.g., content of kaolinite, illite, illite–smectite, carbonate, quartz). This will help identify the components and compare their impacts on nonaqueous bitumen extraction.

GLIMPSE OF CMS AT THE 17th ICC, 2022

The International Clay Conference (ICC) occurs every four years. The 17th such conference was held at the Hilton Istanbul Maslak on 25–29 July 2022. It was a collaborative effort between The Clay Science Society (Türkiye) and The Clay Minerals Society (USA) under the theme of “New Interfaces: Bridging Continents and Cultures with Clays.” The archived conference website is available at: https://icc2022.aipea.org/ and a full ICC report has been published on the AIPEA website.

The total number of attendees was 323 (191 in-person and 132 online) from 40 countries. A total of 294 papers (228 oral and 66 posters) were presented.

Eight eminent scholars presented Plenary Lectures. They were David Bish, Yael Mishael, Hongping He, Lynda Williams, Young-Shin Jun, Jin-Ho Choy, Michael Hochella, and Denys I. Grekov, many of whom were CMS awardees in 2021 and 2022. Take a moment to read their biographies on our past News Pages.

The best and runner-up oral and post-presentation awards were jointly sponsored and judged by AIPEA and CMS. Read a summary of them on the news page of AIPEA in this issue.

CMS also sponsored student travel awards. The awardees are:

- Luka Badurina, Texas Tech University, USA;
- Yuqing Bai, Comenius University of Bratislava, Slovak Republic;
- Amal Kanti Deb, University of Newcastle, Australia;
- Bidemi Fashina, Texas A&M, USA;
- Anna Jedras, AGH University of Sci & Tech, Krakow, Poland;
- Chia-Wei Lin, Texas A&M, USA;
- Xinxiang Ma, Nanjing University, China;
- Chiemenla Okorafor, University of Lagos, Nigeria;
- Jonathan Smolen, University of Connecticut, USA;
- Sen Wang, Queensland University of Technology, Australia;
- Maggie White, (Blair Jones/Jane Flynn Awardee for highest scoring Travel Grant), Newcastle University, UK;
- Himanshu Yadav, Indian Institute of Tech Guwahati, India; and
- Chaoyun Ying, Huazhong Agricultural University, China.

Don’t forget to renew your membership!
NEWS FROM LONDON

Our EDI (Equality, Diversity, and Inclusivity) report is complete and can be downloaded from the Mineralogical Society website (www.minersoc.org/EDI-report-2022.pdf). The survey was assembled by a Council-appointed committee of individuals who are either members of Council or who represent the Special Interest Groups (SIGs). The committee includes: J. Lloyd (President), S. Gibson, M.-L. Bagard, E. Deady, J. Horák, H. Pendlowski, F. Cooper, L. Kelly, O. Lord, J. Scarlett, and K. Murphy (Executive Director, Chair). Future versions of this committee will include EDI officers of the SIGs appointed since this process began. Drafts of the survey were made available to members of Council for comment. The survey also drew inspiration from a number of other such survey documents, including that published by EDIG (Equality, Diversity and Inclusivity in the Geosciences), a University College Dublin–based EDI group. Many thanks to them all.

Key findings

■ 75% of people with a mental health condition had experienced discrimination. 62% of people with no such condition had experienced discrimination.
■ 47% of men with mental health challenges felt that their workplace was not inclusive.
■ 75% of people with a physical health condition had experienced discrimination.
■ In terms of ethnicity, it seems clear that people from an ethnic background other than White British, Irish, Welsh, or Scottish (~59%), were more likely (up to 79% of ethnic groups) to have experienced discrimination.
■ Also confirmed is that a significant proportion (33%) of our respondents have found their place of work not to be “inclusive”.
■ Strong support was given for suggestions presented in the survey about how best to make our organization more EDI-conscious.
■ There was a sizeable proportion of respondents (5%) who reacted negatively to the survey, to the lines of questioning and even to the need for a survey. It is the view of some that “we do not have a problem.” Such responses are treated respectfully here, but the direction of travel will support the clear majority view, which suggests that the Society should adjust its modus operandi in as many areas of activity as possible. (Such comments, reproduced in Appendix 3 under the heading “Rejection”, are not condoned by the Society or its EDI committee. We do hope to use these comments to help our development of an EDI approach.)
■ Don’t ask people from marginalized groups to be the bearers of a disproportionate load in terms of attempting to achieve diversity in committees.
■ Ensure that changes, e.g., in terms of funding, awards, publications, etc., do not remove emphasis from scientific endeavours, i.e., that those from marginalized groups will not value an award if they feel it is being given because they are from a marginalized group rather than on the basis of their abilities.

Actions

■ We will appoint a Council-level EDI officer; SIGs will each also appoint an EDI officer.
■ As we move into the future, we will think about how the Society can influence EDI matters in a broader context, and not just in simple Society terms (e.g., who joins our subject and from where, and what will their experiences be in 2030 in comparison to 2020?).

RECENT CONTENT IN CLAY MINERALS

■ We will review activity in terms of meetings, publications, awards, grants, and lectures to ensure that all of our colleagues have the sense that they are welcome in our organization.
■ We will measure our performance in terms of ensuring equity, diversity, and inclusivity across all of what we do.
■ We will attempt to influence those around us. Can we provide a model that our members can bring to their places of work? To their research groups? To their classrooms? Our aim should be to lead by example (rather than acting as a watchdog with punitive powers).
■ We will examine options for influencing those who have not yet considered our subject as a possible career. Some would say that the demographic breakdown in our science should reflect that in society as a whole. At present, it does not. There is an argument that cultural norms exist, which means that people from certain demographics choose not to enter science as a career. However, there are groups of people that do not appear in many categories, geoscience among them. Our aim should be to achieve a level of exposure of our science, such that anybody who would like to consider geoscience as an area of interest or as a career should feel that they are welcome to try it and feel that they have an equal chance of success.

The end of the survey (analysis of the data, publication, etc.) should merely represent the beginning of a life-long process for the Society. We received much encouragement from respondents for the actions we proposed. We also received advice not to be “woke”, and to avoid the trap of ticking cultural EDI boxes, but without actually seeking “real” change.

In all of the above, there is no shortcut to success. Individuals will still rely on merit to succeed. However, it is the Society’s job to provide an equal opportunity for all. Merit will be the deciding factor, but support/advocacy/mentorship will be provided equitably to those who want it to help their chances of succeeding with awards/bursaries/publishing success.

■ Assessing trace-element mobility during alteration of rhyolite tephra from the Dinaride Lake System using glass-phase and clay-separate laser ablation inductively coupled plasma mass spectrometry Luka Badurina, Branimir Šegvić
■ Measurement of apparent sintering activation energy for densification of clays André Biava Comin, Alexandre Zaccaron, Vitor de Souza Nandi, Jordana Mariot Incenete, Thuani Gesser Muller, Alexandre Gonçalves Dal Bó, Adriano Michael Bernardin, Michael Peterson
■ Analysis of tiles produced from a schist material and their ultraviolet, near-infrared, mid-infrared, longwave-infrared and far-infrared spectra Hulya Kuru Mutlu, Atakan Mutlu
■ Analysis of the chemical composition and phase structure of ‘Ru-type ware’ bodies under the influence of firing temperature – CORRIGENDUM Bo Wu, Weijuan Zhao
■ Preparation of layered double hydroxide films using an electrodeposition and subsequent crystal growth method Noriyuki Sonoyama, Shizuka Yamada, Tomoki Ota, Haruna Inagaki, Patrick K. Dedetemo, Satoshi Yoshida
■ Removal of alkaline nitride from lubricating oil by modified clays Mingrong Chen, Naiwang Liu, Li Shi, Xuan Meng
■ Enhanced alumina extraction from kaolin by thermochemical activation using charcoal Amr B. ElDeeb, Vyacheslav N. Brichkin, Martin Bertau, Mahmoud E. Awad, Yulia A. Savinova

Visit https://www.cambridge.org/core/journals/clay-minerals for links to this and other content.
RESEARCHERS FROM THE SPANISH SOCIETY OF MINERALOGY (SEM) WORKING ON THE LA PALMA VOLCANO

Mineralogic and geochemical study of ashes, leachates and fumarolic deposits of La Palma eruption. M. Pilar Mata Campo, Javier Martínez Martínez, and the IGME CSIC research TEAM of Cumbre Vieja eruption

From the early moment of the volcanic eruption of Cumbre Vieja (La Palma island, Spain), several scientists from the CN IGME (CSIC) have been working near the volcano day and night, monitoring lava, gas, and ash deposits. One of the most important tasks carried out during the eruption has been called the “Cinderella operation,” where a periodic sampling of ashes was carried out along the island in order to study their composition, the evolution during the eruption, as well as the adsorbed materials present on the particle surfaces that, once dispersed, may affect vegetation, livestock, or people.

The nature and mineralogy of the basaltic lava (tephrite–basanite) is also detected in the composition of the ashes, mostly tachylites and sideromelanes with different grain size ranges, as a function of the distance from the source of emission. The composition of the leachates, analyzed according to international protocols, and the study of the salts investigated by electron microscopy on the surface of the ashes, indicate the presence of F and Al salts as micron-sized crystals. The products precipitated from the fumarolic exhalations during the final phases of the volcanic eruption, producing a wide spectrum of ammonium salts, sulfur, sulfates, etc., which are now the target of intense research.


The strombolian eruption of Cumbre Vieja on the island of La Palma took place between September 19 and December 13, 2021. The emitted materials are lavas and pyroclasts with a basanite and tephrite geochemical composition. The volcanic flows occupy a surface of 1,173 hectares, and the pyroclasts extend tens of km² around the eruptive fissure. The land reclaimed from the sea by the lava flows is about 50 hectares. Some 1,628 buildings (homes, factories, industrial buildings, businesses, schools, temples) were affected by the eruption, 7,000 residents were evacuated, and 72.5 km of public roads were covered by lava flows.

For this reason, with the goal to rebuild the affected private and public buildings and infrastructures, the GEOGAR research group (attached to the IOCAEG, Institute of Oceanography and Global Change, of the University of Las Palmas de Gran Canaria, Spain) collected samples of lava and pyroclasts to determine the geotechnical, geochemical, and petrographic characteristics, and possible uses of these volcanic materials (e.g., construction aggregates, agricultural and gardening uses).

In addition, the GEOGAR group and collaborators from Barcelona (Spain) from the University of Barcelona and Museum of Natural Sciences collected some samples of hydrothermal mineralization associated with fumaroles that appear in the main volcanic cone, secondary cones, as well as in fissures in nearby areas in February 2022. Along the fissures and cracks, there are fumaroles emitting hydrothermal volatiles (aqueous fluids with sulfur, carbon, chlorine, and fluorine), and precipitates are forming in and around the emission zones. Preliminary mineralogical studies (SEM, EMPA, XRD, petrographic microscope) confirm that outcrops contain native sulfur; carbonates of Ca, Na, etc.; sulfates of Ca, Mg, Fe, Na, etc.; chlorides of Na; and fluorides containing Ca, Mg, Na, Al, etc.
During the 2021 Virtual Goldschmidt Conference, Pieter Bots (University of Strathclyde, Scotland) and Bettie Higgs (University of Cork, Ireland) convened Session 14e ‘Diversity and Inclusion in the Geosciences’, where talks were followed by a special panel discussion. This panel discussed a set of observations and questions intended to give focused attention to areas in which advancing equity could have significant positive outcomes for diversity and a wider sense of belonging in geochemistry. In contributing to this panel, researcher Anya Lawrence (University of Birmingham, UK) gave a response, which the audience and conveners found so striking that they immediately sought to facilitate this being published, as realised here.

Statement and Question: Recruitment is often said to be based on merit and interview performance. However, it has been shown/argued that these are inherently biased in favour of people that ‘fit in’ instead of ‘stand out’ (e.g., biases exist in student evaluations for teaching staff in higher education), and minorities ‘are less likely to be viewed as future leaders, in part because they may be perceived to not have traditional qualities we associate with leadership (e.g., decisiveness, competitiveness)’. How should we change recruitment to be more inclusive?

This statement is actually quite personal for me because I am a real-life example of someone who has an intersectional identity and belongs to several minority groups, who was actively discriminated against by standard recruitment practices when I was an undergraduate applying to do a PhD. Here, I write about my personal experiences and then follow this up with some suggestions for how recruitment can be more inclusive.

The reason I was able to speak at the recent Goldschmidt conference, as someone who is autistic and really struggles with social communication, was primarily because it was virtual. I could take part from a safe space where I wasn’t having to worry about giving eye contact, understanding body language, being overwhelmed by lots of sensory stimuli like noises, smells, and movement, all of which face-to-face conferences involve. I also had the chance to prepare for the conference for several months in advance, and the organizers were so helpful in giving me a detailed schedule and idea of what to expect. Finally, I had my mum and dad, who are my carers, really close by, watching the session that I was presenting in and being there just in case I needed their help.

Yet when I applied to a well-known UK doctoral training partnership, I was denied this much-needed support. I was given no idea of what to expect on the day of the interview. When I arrived at the interview with my one of my carers, we were made to sit in an open departmental common room where there were lots of unknown staff members and students walking in and out, often staring at us whilst they did so, plus loud conversations going on, tea and coffee being made, food being carried in and out, and so on.

We had to wait like this for over 20 minutes before someone came to tell us that the interviews always ran late. When I did actually get called for interview, I had to go in alone, as my carer wasn’t allowed to be present. I had to stutter my way through long verbal responses to questions that were written in ambiguous language that I struggled to understand. All of this was done to apparently make sure that recruitment was ‘fair for all the other candidates’. Yet interviews requiring intense social communication aren’t fair for autistic people, like myself, who find most social situations extremely anxiety provoking and frightening. They aren’t fair for those of us who are completely non-verbal or have learning difficulties. In fact, they aren’t fair for most people who belong to minorities, as any visible marker of difference—like skin colour, a mobility aid, or cross-dressing—can shape the expectations and behaviour of the interviewers.

In terms of merit-based recruitment, I know with hindsight that I was written off before I had even applied. You see, as a disabled person who finds just leaving the house daunting and requires a huge amount of support from my carers to help me manage my daily life, I had completed all of my undergraduate studies through distance learning with the Open University. By studying from home, which offered safety and calm, I hadn’t been able to generate the impressive CV, boasting international conference presentations, summers spent doing unpaid internships, and public outreach that the recruiters favoured. Even though I was doing well academically, really enthusiastic about my studies, and eager to be the first person in my family to do a PhD, none of this mattered against the biased selection criteria.

1 School of Geography, Earth and Environment
University of Birmingham, Birmingham, UK
E-mail: a.lawrence.2@bham.ac.uk
Needless to say, I wasn’t recruited by the doctoral training partnership. I have had to struggle along, doing my doctoral project with a minimal fee waiver and no salary, whilst those who were more confident than me at interviews, more affluent than me in their lifestyle, and more able than me were awarded a salary, expenses, full fee payment, and a package of training and professional development opportunities for their own research projects.

But I’m still here. I feel so lucky to have been given the opportunity to share my experiences at conferences like Goldschmidt so that no minority person applying to do a geoscience PhD, postdoctoral fellowship, lectureship, or any other academic position should have to go through what I went through.

I think that, firstly, interview panels and merit-based recruitment criteria shouldn’t be the only way that candidates are assessed for academic positions. If you look at leading multinational software corporations like Microsoft and SAP, they use a variety of methods to evaluate potential applicants, including initial online assessments and technical skills assessments, and the interview process itself typically lasts between one to three weeks. At the beginning of this process, all candidates are offered in-person or virtual meet-and-greets, and during the interview period, candidates take part in soft-skills exercises themed on team-building, communication, and work simulations. In this way, global corporations are able to get to know the applicants personally and see if they are suited for the role. This approach also maximizes the corporations’ ability to uncover the hidden talents of candidates that were unlikely to have shone through had highly stressful, one-off interviews been their sole recruitment procedure.

Secondly, where panel interviews are required, I think it’s really important that the panels comprise people with different backgrounds and as diverse a mix of seniority as possible, with postdoctoral fellows as well as professors present. Diverse interview panels can make the whole interview process a lot less stressful for applicants who represent minorities, as it is just so inspiring to be able to look across that table and see someone who looks like you who has made it in academia. Diverse interview panels also help reduce unconscious bias in hiring, and showcase to the applicants that a geoscience department or research group is serious about diversity and inclusion.

Finally, what I think is key to remember for recruitment is that equality is not equity. Many of the recruitment methods currently used in academia claim to be concerned with creating equality. Equality means ensuring that everyone has the same opportunities and receives exactly the same treatment and support. However, by this premise, those who require more support beyond this initial level to succeed do not have equal opportunities as those who do not. Equity is about giving people what they need, in order to make things fair. It means giving people from marginalised groups support and treatment that is proportionate to their own circumstances in order to ensure that everyone has the same opportunities, such as providing more support to a disadvantaged student so they can reach their full potential. Therefore, to create true equality of opportunity, equity is needed to ensure that everyone has the same chance of getting there.

Anya Lawrence is a researcher at the University of Birmingham (UK) with interests ranging from rock magnetics, geochemistry, and structural geology to transformative emancipatory research, understanding the intersection of different types of identification, and accessibility advocacy. As an intersectional individual, Anya is determined to help improve EDI (equality, diversity and inclusion) in geography, earth and environmental sciences, and wider academia.
2022


October 9–12  Materials Science and Technology 2022, Pittsburgh, PA, USA. Web page: www.matscitech.org/

November 27 - December 2  MRS Fall Meeting, Boston, MA, USA. Web page: https://www.mrs.org/meetings/events/fall-meetings-exhibits/2022-mrs-fall-meeting-exhibit.

December 12–16  AGU Fall Meeting, Chicago, IL, USA. Web page: www.agu.org/Events/Meetings/Fall-Meeting-2022.

2023

January 9–11  1st Workshop on Ices in the Solar System: A Volatile Excursion from Mercury and the Moon to the Kuiper Belt and Beyond, Montreal, Canada. Web page: http://www.hou.usra.edu/meetings/ices2023/.


March 26–30  American Chemical Society Spring Meeting, Indianapolis, IN, USA. Web page: www.acs.org/content/acss/meetings/acssmeetings/about/future-meetings.html.


June 18–23  Asteroids, Comets, Meteors Conference, Flagstaff, AZ, USA. Web page: www.hou.usra.edu/meetings/acm2023/.


August 13–18  86th Annual Meeting of the Meteoritical Society, Los Angeles, CA, USA. Website forthcoming.


November 26 – December 1  MRS Fall Meeting, Boston, MA, USA. Web page: https://www.mrs.org/meetings-events/fall-meetings-exhibits/2023-mrs-fall-meeting.


2024


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