Extraterrestrial Organic Matter

Formation and Evolution Mechanisms in Space
Delivery of Organic Matter to the Earth Early
Diversity of Complex Organic Matter in Meteorites
Asteroidal Organics from Sample Return Missions
Identifying and Characterizing Extraterrestrial Organic Matter
Implications for the Origin of Life
Extraterrestrial Organic Matter

Guest Editors: Mehmet Yesiltas and Yoko Kebukawa

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The Mineralogical Society of Canada is an international society for professionals working in the mineral sciences. The society aims to advance the knowledge of the science of mineralogy and its application to other subjects, including crystallography, geochemistry, petrology, environmental science, and geological engineering. The society holds annual meetings and publishes the journal Canadian Journal of Earth Sciences. Membership benefits include the journal, and individual, institutional, and Honorary memberships are available.

Website: www.msc-scm.ca

The Clay Minerals Society (CMS) began in 1952 as the Clay Mineralogy Committee of the US National Academy of Sciences – National Research Council. In 1962, the CMS was incorporated as a non-profit organization. The purpose of the Clay Minerals Society is to promote the knowledge of mineralogy, the related disciplines of petrology, and their applications to geology and environmental science. The society holds annual meetings, workshop conferences, and a discount on subscriptions to its journal, Clays and Clay Minerals. Membership benefits include reduced registration fees to the CMS Workshop Lectures, and the journal Clays and Clays Minerals.

Website: www.clay.org

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The Geochemical Society (GCS) is an international non-profit organization founded in 1955 to promote the knowledge of mineralogy, geochemistry, and environmental science. The society holds annual meetings, workshop conferences, and a discount on subscriptions to its journal, Clays and Clays Minerals. Membership benefits include reduced registration fees to the CMS Workshop Lectures, and the journal Clays and Clays Minerals.

Website: www.clay.org

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Website: www.lithsoc.org

The American Geosciences Institute (AGI) is an international organization whose mission is to advance the knowledge of the earth and its environment, and to improve the stewardship of the earth by providing educational programs, research support, and certification of professional geologists. The AGI holds annual meetings, workshops, and publishes the journal GeoScienceWorld. Membership benefits include reduced registration fees to AGI meetings, and a subscription to the journal GeoScienceWorld.

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The American Geophysical Union (AGU) is an international organization that promotes the knowledge of the earth and its environment, and to improve the stewardship of the earth by providing educational programs, research support, and certification of professional geologists. The AGU holds annual meetings, workshops, and publishes the journal GeoScienceWorld. Membership benefits include reduced registration fees to AGU meetings, and a subscription to the journal GeoScienceWorld.

Website: www.agu.org
NEW YEAR, BROADER PERSPECTIVE

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As I write this editorial, festivities of the holiday season are in the air. Wishes of “Happy Holidays” are floating across continents, crossing religious and cultural boundaries. It is not just Christmas or Hannukah or Deepawali—there are people celebrating Lohri, or Ashura, or the Yalda night, or Kwanzaa, or Poush Parbon, or one of many other festivals. Different stories, different legends, some celebrations more prominent than others, but there is one common theme: the human ability to celebrate light at the darkest of times, to seek out and worship the Sun when it is least present (to the extent that these traditions all evolved in the Northern Hemisphere). That ability is called for more than ever this year. As I sit here nursing a warm cup in my palms, I feel grateful for the privilege of having experienced festivals of light in so many different forms—it gives context and perspective to much cultural diversity and difference.

It is similar in science. Growing up as a geologist fed by Carl Sagan science fiction, the blue planet and the Earth were synonymous to me; that is, until I got exposed to other perspectives—planetary perspectives. I came to know that there are other planets in our Solar System that are bluer—the ice giants Uranus and Neptune. Like stories underlying “Happy Holidays”, the reason for the blue is different for these different planets. If water makes the Earth blue, it is methane in the case of Uranus and Neptune. That simple recognition triggers an entire chain of awareness—methane is an organic molecule—we on Earth do not have proprietary rights to organics! All of a sudden, we are also reminded that the boundary between desirable and undesirable is a matter of context—while methane is a harmful greenhouse gas for us on Earth, it is what makes the planets blue and beautiful for Uranus and Neptune.

Once the curiosity is piqued, one wishes to delve deeper into organics elsewhere beyond Earth. You are at the right place with this issue. Not only are organic materials not a matter for only the Earth, they are not even restricted to the Solar System! The interstellar medium and other planetary systems are teeming with an entire armada of organic molecules. It takes superlative analytical efforts to find and characterize them—the authors of this issue tell you how. Pondering primitive organic matter invariably tickles thoughts about the origin of life—while sampling the buffet on offer in this issue, including the diverse pathways along which organic molecules have evolved, I could not resist contemplating the age old question: Are we alone? The authors of this issue do not attempt to leap and provide an answer; they do what scientists do—keep their feet on the ground, even as they explore outer space and deliver data that might be building blocks of the answer some day. For now, this issue shines light on organic matter in the dark and distant recesses of space—I welcome you to undertake the voyage to explore and broaden your perspective.

Sumit Chakraborty
Principal Editor

“We on Earth do not have proprietary rights to organics.”

Three captivatingly blue planets in our Solar System (top): Earth (Credit: NASA), (left) Neptune (Credit: NASA/PL), and (right) Uranus (Credit: NASA, ESA, and M. Showalter (SETI Institute)).
ABOUT THIS ISSUE
Extraterrestrial organic matter—organic molecules beyond our planet—sparks curiosity and fuels the search for their nature, origin, and distribution due to their importance for cosmochemistry and for life. From the dusty surfaces of asteroids and the icy realms of comets, to planetary systems being born, galaxies far away, and atmospheres of exoplanets, scientists have uncovered a cosmic cocktail of carbon-based compounds. These extraterrestrial molecules, akin to the very essence of life on Earth, serve as enchanting hints that the building blocks of life may not be exclusive to our planet. Meteorites, cosmic dust, and other planetary samples carry the fingerprints of “out of this world” organic chemistry, which are, in a sense, cosmic secrets encoded in carbon compounds. As telescopes peer into distant locations and space rovers explore different landscapes, the quest for the origin of organic matter, building blocks of life, intensifies. Analytical developments and access to some of the most pristine organic-rich planetary samples are driving scientists into new frontiers. Thus, more ground-breaking revelations are inevitable.

THE NEXT GENERATION OF ELEMENTS—GET INVOLVED!
Happy New Year, Elements readers!

We are thrilled to bring you Elements’ 20th volume of six fascinating and fundamental thematic issues within the geosciences, starting with “Extraterrestrial Organic Matter”. Whether this Elements issue is your 1st or 114th, we hope that you and your colleagues will enjoy and intellectually benefit from this creatively crafted presentation of review papers, authored by leading experts in the field.

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Designing your own Elements issue is a rewarding career milestone. We enthusiastically encourage you to begin this process and make a lasting contribution to the geoscience literature by submitting a thematic proposal or contacting the Editorial Board to discuss your ideas. Elements themes should generally fulfill the following criteria:

- broadly related to mineralogy, geochemistry, and petrology
- interdisciplinary
- represent established but progressing fields
- interesting to a broad cross section of readers
- have not been adequately represented by Elements before or have advanced considerably since the topic was previously covered

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The future of Elements issues is in your hands. We look forward to hearing from you!

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.

FROM THE EDITORS

Elements February 2024

A sample returned from carbonaceous (C-type) asteroid Ryugu. Left: Inside a vacuum-sealed container. Right: Close-up image of the sample sitting inside the container on the left.

A sample returned from carbonaceous (C-type) asteroid Ryugu. Left: Inside a vacuum-sealed container. Right: Close-up image of the sample sitting inside the container on the left.
Queenie Hoi Shan Chan is a senior lecturer (associate professor) at the Royal Holloway University of London, UK. She obtained her PhD at Imperial College London (UK), and worked as a NASA postdoctoral fellow at NASA Johnson Space Center (USA). She is a planetary scientist and her research focuses on understanding the earliest chemical reactions involving liquid water in the Solar System, and how the individual events turned simple life’s building blocks into increasingly complex molecules that ultimately yielded life. Her work involves the analyses of a range of astromaterials, including meteorites and samples returned by space missions, such as the Hayabusa2 and OSIRIS-REx missions.

Cécile Engrand is a research director at CNRS, currently working at IJClab, Université Paris Saclay, France. An engineer in material science, she has been working on the analysis of micrometeorites for the last 30 years. She received her PhD at the Univ. of Paris Sud (France) and was a postdoctoral fellow at the Naturhistorisches Museum in Vienna (Austria), and in the Department of Earth and Space Sciences at UCLA (USA). Her research interests focus on the analysis of cosmic dust, in particular of cometary particles, for understanding the evolution of dust particles from interstellar space to the current Solar System. She was Co-I of COSIMA, a dust analyzer on board the Rosetta mission, and was involved in two initial analysis teams for the characterization of Ryugu samples brought back by the JAXA Hayabusa2 mission.

Bradley De Gregorio is a research scientist at the U.S. Naval Research Laboratory (NRL) in Washington, DC. His expertise is in nanoscale characterization of organic-mineral relationships in terrestrial and extraterrestrial samples using advanced transmission electron microscopy and synchrotron-based X-ray microscopy. He received his PhD in geological sciences from Arizona State University (USA) for nanoscale analyses of putative microbial fossils in Archean cherts from Western Australia. After gaining experience working with cometary dust grains returned by the NASA Stardust mission to comet Wild2 as a postdoctoral researcher at NRL, he worked briefly as a curator of their Stardust collection at Johnson Space Center (USA). Most recently, he analyzed organic matter in surface regolith grains from the asteroid Ryugu by the JAXA Hayabusa2 mission as part of the Hayabusa2 Initial Analysis Team.

Timothy D. Glotch is a professor of geosciences at Stony Brook University, USA. He uses vibrational spectroscopy from remote sensing platforms and in the laboratory to understand the formation and evolution of the surfaces of Earth, the Moon, Mars, and small bodies. He is interested in developing methods to compare and contrast micro- and nanoscale spectroscopic analyses of meteorites and returned samples and their bulk spectral properties at hand-sample and remote-sensing scales.

Yoko Kebukawa is an associate professor in the Department of Earth and Planetary Sciences, Tokyo Institute of Technology, Japan. She received her PhD from the Department of Earth and Space Science, Osaka University, Japan. Her research interests include organic matter in extraterrestrial materials, and its origins and roles in early Solar System history. She studies organic matter in meteorites using various analytical methods, as well as experimental simulations and kinetic studies, to understand the formation and evolution of organic compounds. She also contributed to the Hayabusa2 Initial Analysis Organic Macromolecule Team for returned samples from asteroid Ryugu.
Zita Martins is an associate professor at Instituto Superior Técnico (IST, Portugal). She graduated in chemistry at IST and obtained a PhD in astrobiology at the University of Leiden (Netherlands). She was an invited scientist at NASA Goddard (USA), an invited professor at the University of Nice-Sophia Antipolis (France), and a university research fellow at Imperial College London (UK). She is a Community Scientist of the ARIEL mission (ESA), team member of the Hayabusa2 mission (JAXA), and Chair of the ESA Expert Team “Moons of the Giant Planets”.

Hideko Nomura is a professor at the National Astronomical Observatory of Japan and the Graduate University for Advanced Studies, SOKENDAI. She completed her PhD in astronomy at Kyoto University in Japan, and post-doctoral research in UMIST and Queen’s University Belfast (UK). She works on modelling physical and chemical structure of protoplanetary disks; temperature and density profiles of gas and dust, grain size, and spatial distributions; as well as the distribution of molecular species, making use of radiative transfer and chemical reaction network calculations. She is also involved in observational projects, especially using ALMA (Atacama Large Millimeter/submillimeter Array) recently.

Matthew A. Pasek is a professor at the University of South Florida in the School of Geosciences at Tampa, Florida (USA). His research is on the chemistry of phosphorus from the solar nebula to the modern environment. He has a PhD in planetary science from the University of Arizona (USA), and a BS in geology and chemistry from the College of William and Mary (USA).

Nami Sakai is a chief scientist at RIKEN, Japan. She received her MS and PhD in physics from the University of Tokyo, Japan. In her master’s research, she focused on the development of super conductor mixer receivers for submillimeter-wave astronomical observations, as well as observations of organic molecules in star-forming regions. She then discovered chemical diversity in star-forming regions in her PhD. Since then, she has studied the origin and future of this chemical diversity, which is important for understanding the commonness or rarity of the primitive environment of the Solar System, in collaboration with researchers in various fields.

Shogo Tachibana is a professor of cosmochemistry at the UTokyo Organization for Planetary and Space Science and Department of Earth and Planetary Science, University of Tokyo, Japan. He is also a specially appointed professor at the Institute of Space and Astronautical Science, JAXA, Japan. His research focuses on the origin and early evolution of the Solar System. In particular, he studies the kinetics of evaporation, condensation, crystallization, diffusion, and isotope exchange of dust in a protoplanetary disk through laboratory experiments. He led the development of the Hayabusa2 sampler system and was responsible for the initial analysis of the sample returned from carbonaceous asteroid Ryugu.

Hikaru Yabuta is a professor at Hiroshima University, Japan. She obtained her PhD in chemistry from University of Tsukuba, Japan, where she conducted organic geochemical studies on Neogene oil formations and the Cretaceous–Paleogene extinction event. During four-year postdoctoral fellowships at Arizona State University (USA) and Carnegie Institution of Washington (USA), her investigation focused on the chemical evolution of organic molecules in meteorites and comets. After coming back to Japan, she has addressed the comet–asteroid continuum by coordinated analysis of Antarctic micrometeorites. She has dedicated herself to Hayabusa2 asteroid sample return missions and led the Organic Macromolecule Team in the initial analysis of the Ryugu samples.

Mehmet Yesiltas is an associate professor in the Department of Space Sciences at Kirklareli University in Turkey. After obtaining his PhD from University of Central Florida (USA), he worked as a postdoctoral researcher with Prof. Timothy D. Glotch in the Department of Geosciences at Stony Brook University (USA). He is interested in the origin and evolution of extraterrestrial organic matter. His research focuses on spectroscopic and microscopic identification and characterization of organic matter in various astromaterials, such as meteorites and returned samples.
Extraterrestrial organic matter forms in a variety of locations in space through different mechanisms. Its nature, distribution, formation mechanisms and locations are of particular interest. Some organic molecules can even be considered as key players for the emergence of life. Although new organic species are continuously detected in the interstellar media, Solar System bodies, and extraterrestrial materials, their formation and evolution are still not fully understood. Ground-based and space observations can detect organic matter in different objects with a range of complexity and diversity, while laboratory investigations of astromaterials allow detailed characterization of extraterrestrial organic matter with high precision. This issue reviews different aspects of extraterrestrial organic matter, including its origin, evolution, diversity, and delivery.

**KEYWORDS:** extraterrestrial organic matter; observations; investigations

**INTRODUCTION**

Extraterrestrial organic matter refers to organic materials whose origin is beyond Earth. So far, all of the detected extraterrestrial organic matter has been considered to be of abiotic origin. The first detections of extraterrestrial organic matter go back to 1806 in the Alais meteorite. Despite decades of work and research, there are still many questions and unknowns on the topic of extraterrestrial organic matter, and scientists continue to conduct extensive studies to be able to answer them unambiguously. The nature and distributions of extraterrestrial organic matter, its formation mechanisms and pathways, formation locations, and detection methods are of particular interest for planetary sciences. New organic species are continuously detected in interstellar media, Solar System bodies, and extraterrestrial materials; nevertheless, it is still not fully known how and through which processes organic matter forms in space. Organic chemistry is based on the presence of carbon, which is generated via helium burning during star formation in different regions of the universe. Elemental and molecular interactions with carbon can then lead to the formation of different products, including organic molecules. The conditions in space (e.g., temperature, energetic particles, UV radiation) can directly affect the chemical reaction and formation pathways, as well as the complexity and diversity of extraterrestrial organic matter. Although how organic matter forms in space is yet to be unambiguously determined, its presence and detailed characterization can potentially yield crucial knowledge regarding its formation mechanisms and evolution under various conditions. Although organic matter has been identified in a number of different astronomical environments, it is not straightforward to answer the question: Where does organic matter form? Carbon, which forms in the interiors of stars, is basically widespread throughout the observable universe, and as such, organic matter can form in many environments (Fig. 1). For instance, observations show that dust and gas in the interstellar space contain organic molecules despite the harsh, unforgiving, and chemically reducing conditions. Some of this organic matter survived the formation of the Solar System and was incorporated into planetesimals, which accreted during the first few million years of our Solar System. Organic matter delivered to Earth via meteorites and interplanetary dust particles (IDPs) can, therefore, in part be of interstellar origin. Organic matter can also form on the surfaces and interiors of asteroids, comets, rocky planets, in protoplanetary disks, within the interstellar medium and clouds, and in nebular clouds (Nomura et al. 2024 this issue). As a result of processes in the parent bodies (e.g., hydrothermal events), the observed organic matter exhibits variations in their molecular functionalities, structures, and complexities.

Many of the efforts in cosmochemistry revolve around the search for the building blocks of organic molecules that are important for life. Ground-based telescopes acquire signals that are often overwhelmed by atmospheric water vapor. However, significant technological developments and advanced instruments continuously aim to provide the most sensitive signals for the detection of extraterrestrial organic matter in distant objects. As a result, astronomical observations have detected a wealth of complex organic molecules, which has reshaped our understanding of extraterrestrial organic matter. For instance, the Atacama Large Millimeter/submillimeter Array (ALMA) telescope has remarkable sensitivity and detection capabilities that allow detection of complex organic molecules in and around many objects. The first detection of cyanides CH$_3$CN and HC$_3$N in a protoplanetary disk surrounding the young star MWC 480 was made by ALMA (Öberg et al. 2015). Glycolaldehyde (CH$_2$OHCHO, the simplest sugar-related molecule) was detected to be surrounding NGC 6334I, a massive star-forming region about 4300 light years away.
from Earth, by utilizing the ALMA’s shortest wavelength capabilities (McGuire et al. 2018). Compared with ground-based observations, space exploration plays a crucial role in the detection and identification of organic molecules in space. Space-based observations offer many advantages, such as providing unobstructed views without the interference of Earth’s atmosphere, observations of many distant objects and regions in ways not possible from the surface of Earth, and selection of organic-rich targets for future missions. Just recently, signatures of complex organic molecules in the icy particles of a protoplanetary disk were detected using NASA’s newly launched James Webb Space Telescope (JWST) (Yang et al. 2022). Previously, the Rosetta space mission detected large organic molecules in the dust particles of comet Churyumov–Gerasimenko (67P/CG), which probably formed in the interstellar medium before the formation of the Solar System (Fray et al. 2016). The Visible and InfraRed Mapping Spectrometer (VIR) onboard the Dawn spacecraft detected signatures of aliphatic hydrocarbons on dwarf planet Ceres (De Sanctis et al. 2017). Remote observations of extraterrestrial organic matter are supported by laboratory investigations of various astromaterials. Advances in high-resolution microscopy, imaging, and spectroscopy systems really push the limits of not only the detection of organic molecule content of primitive astromaterials in the laboratory, but also document their complex properties such as functional groups, diversity, and chemistry variations that may not be resolved by remote observations.

**ORGANIC COMPOUNDS IN THE SOLAR SYSTEM AND BEYOND**

Various organic materials have been found in the diverse environments of the universe (Table 1). The main components observed in the Galaxy are so-called aromatic infrared bands (AIBs), characteristic of polycyclic aromatic hydrocarbons (PAHs). When an intermediate-mass star like the Sun reaches the end of its main-sequence life, it ejects matter into space in a relatively gentle process, forming a planetary nebula. In contrast, more massive stars become novae or supernovae and eject matter into space in a more explosive manner. The emission properties seen in the infrared spectra of carbon-rich planetary nebulae have long been referred to as the unidentified infrared bands (UIBs), which are considered to be related to PAHs, including their derivatives such as partially hydrogenated PAHs, alkyl-PAHs, and nitrogen heterocycles or amorphous carbon with heteroatoms (Kwok 2022). Unlike AIBs, UIBs are not attributed to specific molecules and their origin and nature are not well understood. In the diffuse interstellar medium (ISM), the main molecular composition are large molecules, grains that can survive high radiation doses (e.g., PAHs and their derivatives), and aliphatic components, but smaller organic molecules have also been identified. In dense molecular clouds, most of the volatile species are condensed into ice mantles that surround dust particles due to the low temperatures. The most common ice-phase molecule is H₂O, but there are many other simple molecule is CO, CO₂, HCO, H₂CO, CH₃OH, CH₄, and NH₃ (Sandford et al. 2020). Many other species are found in dense molecular clouds including fullerene (C₆₀), acetonitrile (CH₃CN), acetaldehyde (CH₃CHO), glycolaldehyde (CH₂OHCHO), formic acid (HCOOH), acetic acid (CH₃COOH), methanol (CH₃OH), ethanol (CH₃CH₂OH), ethylene glycol (OCH₂CH₂OH), and methylamine (CH₃NH₂) (Agúndez and Wakelam 2013). In the protostellar disk phases, the physical and chemical conditions vary greatly with disk location, i.e., distance
Comets can contain a variety of organic compounds. When the comet 1P/Halley’s closest approach to Earth took place in 1986, many countries launched a spacecraft to observe the comet, which resulted in the detection of many molecules including water (H₂O), carbon monoxide (CO), carbon dioxide (CO₂), methane (CH₄), ethane (C₂H₆), acetylene (C₂H₂), formaldehyde (H₂CO), methanol (CH₃OH), ammonia (NH₃), hydrogen cyanide (HCN), hydrogen sulfide (H₂S), as well as particles consisting of carbon, hydrogen, oxygen, and nitrogen—the so-called CHON particles (Bockelée-Morvan et al. 2004). Many other comets have been observed since then, and more molecules were detected, such as ethylene glycol (CH₂OH₂), formic acid (HCOOH), methyl formate (HCOOCH₃), acetaldehyde (CH₃CHO), acetonitrile (CH₃CN), cyanoacetylene (HC₃N), formamide (NH₂CHO), and glycolaldehyde (CH₂OHCHO). One of the most detailed cometary investigations was by the European comet explorer mission Rosetta, which conducted observations on comet 67P/CG in 2014. The dust ejected from the comet is estimated to have a mineral to organic mass ratio of about 55:45 with 30 wt.% carbon, indicating a significantly high proportion of organic matter (Bardyn et al. 2017). Having a dust/ice mass ratio of ~2.3 (O’Rourke et al. 2020), the 67P/CG particles (dust + ice) are estimated to contain ~21 wt.% carbon. Many compounds were detected for the first time in comets, such as propionaldehyde (C₃H₆CHO), acetone (CH₃COCH₃), acetamide (CH₃CONH₂), and methyl isocyanate (CH₃NCO). A mass spectrum of glycine, the simplest amino acid, was also observed to be present on comet 67P/CG (Altweg et al. 2016). In an earlier mission, NASA’s Stardust spacecraft collected cometary dust particles from the comet Wild 2 (81P/Wild), which were returned to Earth for laboratory investigations. Among the detected organic molecules is glycine (Elisa et al. 2009), an amino acid used by living organisms to produce proteins. This was the first detection of an amino acid in a comet, and suggests that the building blocks of life are, indeed, widespread in space.

Compared with comets, the direct observation and exploration of organic matter on asteroids have been rather limited until very recently. Asteroids are generally classified according to the visible and near-infrared spectra of their surfaces (the ultraviolet spectral region and albedo may also be considered). Within the context of organic matter, C-type (“carbonaceous”) asteroids are particularly interesting. They lack conspicuous features in their spectra, and their surfaces are thought to be covered with dark material. Because the reflectance spectra of these asteroids are similar to those of carbonaceous chondrites, they are considered to be the parent bodies of these meteorites and to contain organic matter. The first tentative report of organic matter on an asteroid surface was by Cruikshank and Brown (1987) who detected spectral signatures of a carbon–hydrogen stretching mode due to aliphatic hydrocarbons on the surface of asteroid 130-Elektra. Similar organic compounds were also found on the surface of several other carbonaceous asteroids, which indicated that organic material is more widespread than previously thought (e.g., Rivkin and Emery 2010). The Japan Aerospace Exploration Agency’s (JAXA) Hayabusa spacecraft successfully brought back samples from asteroid 25143-Itoikawa, an S-type (“stony”) asteroid that has experienced high temperatures. Nevertheless, it contains small amounts of organic matter. More recently, JAXA’s Hayabusa2 spacecraft returned samples from C-type asteroid 162173-Byugu and unraveled its organic-rich nature and diverse composition (Nakaoka et al. 2023; Yabuta et al. 2023). Most recently, NASA’s OSIRIS-REx space mission has returned precious samples of the spectrally B-type (a class of C-type) asteroid 101955-Bennu. The spacecraft has already detected signatures of organic materials on the surface of Bennu (Simon et al. 2020). These sample return missions will provide the long-awaited insights into their rich organic chemistry, as well as their formation and evolution mechanisms. They will also allow us to study extraterrestrial organic matter from known Solar System objects in their pristine states without the potential contamination risk carried by all meteorites.

Most meteorites are pieces and fragments of asteroids, although a few originate from Mars and the Moon. While asteroid samples are being brought to Earth through space missions, meteorites can be investigated as their analogs. There are more than 70,000 meteorites in the world’s collection as of writing this article, and they can be directly studied in the laboratory to gain insights into from the central star, vertical height in the disk, and time. Many of the gas-phase and gas–grain reactions that occur in dense molecular clouds can also occur in cold regions of the disks. On the other hand, hotter regions of the disks provide environments for catalytic gas-phase reactions—the so called Fischer–Tropsch-type (FTT) reactions. In such reactions, hydrocarbons (from CO and H₂ gases with the help of catalytic mineral grains) and amino acids (in the presence of sources) can form.

### Table 1

<table>
<thead>
<tr>
<th>Category</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chondrites</td>
<td>amino acids, aromatic and aliphatic hydrocarbons, mono and dicarboxylic acids, aldehydes, ketones, purines, pyrimidines, amines, amides, acids, sulphonic and phosphonic acids, fullerenes, hydroxy acids, nucleobases, sugars, N-heterocyclics, macromolecular organic matter</td>
</tr>
<tr>
<td>Asteroids</td>
<td>aromatic and aliphatic hydrocarbons, amino acids, carboxylic acids, N-heterocyclics, macromolecular organic matter</td>
</tr>
<tr>
<td>Comets</td>
<td>HCN, HNC, aromatic and aliphatic hydrocarbons, glycine, amines, acetylene, aldehydes, alcohols, carboxylic acids, hydrocarbons, butanoic acid, methyl formate, formamide, glycylaldehyde, acetone, acetic acid, acetonitrile, isocyanic acid, cyanogen, sulfides, thioles, macromolecular organic matter</td>
</tr>
<tr>
<td>Interstellar medium</td>
<td>aliphatic hydrocarbons, alcohols, acids, aldehydes, ketones, amines, ethers, sugars, ethylene glycol, propenal and propanal, acetone, cyanobenzene, acetylamide, cyanoformaldehyde, cyclopropanone, fullerene, acetonitrile</td>
</tr>
<tr>
<td>Protoplanetary disks</td>
<td>HCN, HNC, formaldehyde, acetonitrile, HNCO, methanol, ethanol, formic acid, acetic acid, glycolaldehyde, acetaldehyde, CH₃CO</td>
</tr>
</tbody>
</table>

* Chondrite: a class of meteorite that originates from asteroids that escaped melting and heavy differentiation.
the organic composition of their parent bodies. The most primitive meteorites are carbonaceous chondrites. They formed from the protoplanetary disk, escaped extreme temperatures and melting in their parent bodies, and many experienced low-temperature aqueous alteration. They contain up to ~3 wt.% carbon, most of which is in organic matter. The Murchison meteorite, which is classified as a CM2 chondrite, is probably the most extensively analyzed meteorite for its organic matter content. From an analytical perspective, organic matter in meteorites can be broadly classified into soluble organic matter (SOM), which can be extracted with solvents, and insoluble organic matter (IOM), which cannot be extracted with solvents and is purified as insoluble residues after demineralization via hydrofluoric acid or hydrochloric acid (Fig. 2). The mass ratio of soluble to insoluble organic matter varies for different samples. This ratio is approximately 3.7 for Murchison, in which a variety of SOM has been detected, including carboxylic acids, amino acids, hydroxy acids, nucleobases, and sugars (Martins and Pasek 2024 this issue). Compounds with tens of thousands of different molecular compositions have also been detected from non-targeted analysis of organic matter extracted with methanol from the Murchison meteorite (Schmitt-Kopplin et al. 2010). For IOM, nondestructive analyses have been applied using various spectroscopic methods such as infrared, Raman, nuclear magnetic resonance, and soft X-ray, or by breaking them down into smaller molecules by chemical or thermal disruption. Although the exact molecular structures of IOM are not known, model structures consist of a complex three-dimensional structure with one to several aromatic rings, with alkyl and carboxy groups connected by alkyl chains, esters, and ether bonds (Derenne and Robert 2010).

Organic matter has also been analyzed within meteorites without chemical extraction or separation. Because the microstructure of meteorites is very fine (sub-micrometer) and organic matter is often finely dispersed among mineral particles, high-spatial resolution techniques such as scanning transmission X-ray microscopy (STXM) and scanning transmission electron microscopy combined with electron energy loss spectroscopy (STEM-EELS) have been used to obtain sub-micrometer to sub-nanometer spatial resolutions. In particular, spatial distributions of phyllosilicates and organic matter often overlap, and organic matter is thought to be finely distributed at the grain boundaries of fine-grained phyllosilicate (Pearson et al. 2002). Some of the organic matter is relatively large and spherical or nearly spherical in shape—these are called nanoglobules and range in diameter from 100 nm to 1 μm. In addition to meteorites, IDPs collected in the stratosphere and micrometeorites recovered from Antarctic ice often contain organic matter as well. The average carbon content of IDPs is ~13 wt.%, although it ranges between 4 and 45 wt.% (Thomas et al. 1994; Fig. 3). Ultracarbonaceous Antarctic micrometeorites (UCAMMs) also contain abundant carbon. Their carbon budget ranges between 22 and 58 wt.% (Dobrica et al. 2012). Some of these particles are considered to be of cometary origin, although they are very small (tens to hundreds of micrometers) and the analysis of their soluble organic matter by extraction is rather difficult and limited. Most of these small extraterrestrial materials are directly analyzed using microscopic methods. Extraterrestrial samples are also prone to contamination with terrestrial organic matter. Regardless of the sample type or method of choice, significant caution must be taken when examining these precious samples.

How and where life emerged on Earth remains a topic of debate. Organic matter starts as a very simple molecule and then transforms into more complex forms as a result of processing under various conditions and interactions with other molecules throughout the universe. Some of these organic molecules are the most important and key players for the emergence of life. In any case, primordial starting molecules are key to understanding the origin of life. It is clear that the building blocks of life are widespread in space, and the delivery of such materials to a rocky planet is certainly possible. Indeed, meteorites, IDPs, and comets likely brought significant amounts of extraterrestrial material to the early Earth, including prebiotic organic molecules, e.g., up to ~10^9 kg/y of organic carbon was estimated to be delivered to the ancient Earth (Chyba and Sagan 1992). This makes extraterrestrial organic matter one of the most exciting research targets in planetary sciences. Potential building blocks of life found in carbonaceous chondrites include amino acids, nucleobases, sugars, and...
The topic of extraterrestrial organic matter is extremely broad, and it is not possible to cover everything in one issue. Our intention with this thematic issue is to review the current state of the subject, especially in light of sample return missions and technological advancements. The chapters in this issue review and highlight several aspects of extraterrestrial organic matter, such as formation regions and pathways, evolution mechanisms, space missions to acquire asteroidal organics, delivery to Earth and beyond, such as on Mars.

IN THIS ISSUE

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Pease MA (2024 this issue) discusses the delivery of complex organic matter to Earth and how subsequent chemical reactions and processes evolved the exogenous organic matter during the evolution of our planet and life. De Gregorio and Engrand (2024 this issue) review the diversity of complex organic matter in carbonaceous chondrites and ultracarbonaceous micrometeorites. Tachibana and Sakai (2024 this issue) review the C-type Ryugu sample analyses from Hayabusa2 and radio and infrared astronomy, and discuss the evolution of organic matter in the early Solar System and in planet-forming regions. Finally, Kebukawa et al. (2024 this issue) review the analytical techniques for the detection, identification, and characterization of extraterrestrial organic matter.

ACKNOWLEDGMENTS

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Tachibana S, Sakai N (2024) Asteroidal organic acids from the sample returned mission Hayabusa2 and their implication for understanding our origins. Elements 20: 31-37
## GLOSSARY TABLE FOR ORGANIC COMPOUNDS

<table>
<thead>
<tr>
<th>Compound</th>
<th>Formula</th>
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</thead>
<tbody>
<tr>
<td>acetaldehyde</td>
<td>CH₃CHO</td>
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<tr>
<td>acetamide</td>
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<tr>
<td>ammonia</td>
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<tr>
<td>amines</td>
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<tr>
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<tr>
<td>pyrimidine</td>
<td>C₄H₄N₂</td>
</tr>
<tr>
<td>sugars</td>
<td>CₙH₂ₙOₙ</td>
</tr>
</tbody>
</table>

R: rest of the molecule
Formation and Evolution Mechanisms for Organic Matter in Space

Hideko Nomura¹, Queenie Hoi Shan Chan², and Hikaru Yabuta³

INTRODUCTION
Our Solar System is thought to have formed from a protosolar nebula. Recent developments in astronomical observations have dramatically improved our understanding of the detailed physical and chemical structure of protoplanetary disks, which are analogs of protosolar nebulae. The signatures of planet formation are found as large-scale structures (e.g., gap, ring, and spiral arms), while molecular line observations reveal material distributions in such planet-forming regions. In particular, high-sensitivity observations by the Atacama Large Millimeter/submillimeter Array (ALMA) have recently found many interstellar complex organic molecules (iCOMs) and rare isotopologues in protoplanetary disks (e.g., Öberg et al. 2021).

Isotope ratios provide a powerful tool for understanding the origins of materials (e.g., Nomura et al. 2023). For example, deuterium fractionation of ocean water on Earth is about ten times higher than the interstellar value, while deuterium fractionation of water in meteorites/asteroids and comets are thought to be a possible source of ocean water on Earth. Meanwhile, knowledge of the abundances of volatile elements (hydrogen, nitrogen, carbon, and oxygen) are also key to understanding the links of materials from planet-forming regions to planetary systems, including our own Solar System.

Volatile elements show a large range of abundances in the bodies of Solar System objects (Fig. 1), which could be caused by the quantities of materials remaining as or contained in solids in the protosolar nebula. In objects in the cold regions distant from the Sun (e.g., comets and ice giant planets), large quantities of volatile elements have remained in ices. In the warmer regions closer to the Sun, only volatile elements incorporated into more complex molecules that are difficult to sublimate from ices can survive. In the hotter, rocky planet–forming regions, only volatile elements retained in refractory materials (which have relatively high condensation temperatures), such as organic matter and hydrous minerals in meteorites, have remained in our Solar System. To quantitatively explain how much volatile elements were incorporated in rocky planets, we need to understand the evolution of matter during planet formation and evolution. This would improve our understanding of the diversity of volatile composition in our own Solar System and in other exoplanetary systems.

CHEMICAL EVOLUTION OF ORGANIC MOLECULES IN THE PROTOPLANETARY NEBULA
Understanding how refractory organic matter formed and evolved in the protosolar nebula is essential to establishing the amounts of volatile elements that are left in our Solar System. In the interstellar medium, molecules are formed in relatively dense regions, called molecular clouds, where ultraviolet radiation from stars, which dissociates molecules, is shielded by dust grains. Meanwhile, stars and planets are also newly formed in molecular clouds, and, therefore, the formation of molecules in the interstellar medium is often described in the context of star and planet formation where materials are gradually heated as a result of the gravitational collapse of molecular clouds that leads to the formation of stars. Because gas phase reactions that form complex organic molecules are inefficient in cold molecular clouds, chemical reactions catalyzed on dust grains are proposed to explain the high abundances of complex organic molecules observed in star-forming regions. At very low temperatures (<20 K) before star formation begins, only hydrogen, the lightest

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element, which can move efficiently on grain surfaces, is added to relatively heavy atoms and molecules to form hydrogenated, saturated molecules such as H$_2$O, CH$_4$, NH$_3$, H$_2$S, and CH$_3$OH. On the other hand, some complex organic molecules, such as HCOOCH$_3$, whose origin cannot be explained by hydrogen addition reactions, have been observed in star-forming regions. To explain the synthesis of such molecules, surface reactions on warm grains have been proposed as the likely mechanism by which they formed. At higher temperatures (30–50 K), hydrogen molecules sublimate into the gas phase, while relatively heavy atoms and molecules can move efficiently on grain surfaces. Hydrogenated, saturated molecules are partially destroyed by ultraviolet radiation to produce radicals, and these radicals react on grains to form unsaturated molecules such as HCOOCH$_3$. When the temperature is high enough (>100 K), water and organic molecules on dust grains sublimate into the gas phase. As a result, they become observable as molecular line emissions/absorptions in star-forming molecular cloud cores. Sublimated molecules react with each other in hot gas phases to produce even more complex molecules. In addition to conventional models of grain surface reactions, models of mantle reactions have also been recently developed as laboratory experiments show that reactions take place inside ice mantles if thermal and/or non-thermal energy inputs assist mobility of icy molecules (e.g., Garrod et al. 2022). Forthcoming James Webb Space Telescope (JWST) observations are expected to reveal new information about the composition of IC0Ms and their formation processes.

The chemistry of the protosolar disk is explained in analogy of the chemistry in star-forming cores, as the temperatures range from ~10 to >100 K in the protosolar disk where materials are heated by irradiation from the protosun, and the temperature profile depends on the distance from the protosun. In the cold outer disk, the freeze-out of gas-phase species on dust grains and subsequent surface reactions proceed until dust grains are locked into larger objects or the disk gases disperse. In warmer regions closer to the protosun, surface reactions on/in warm dust grains can proceed. In hot inner disks, water and organic molecules thermally vaporize into the gas phase. The boundary outside of which a certain molecule exists as a solid is called its ‘snowline’, and the location of the snowline depends on how easily each molecule sublimates. For example, carbon monoxide sublimes at a lower temperature than water, and the location of the CO snowline is around 20–30 astronomical units (AU), while the location of water snowline is around 1–2 AU in protoplanetary disks around Solar-mass stars. Because water is the main component of most astrophysical ices, the mass of ice is significantly reduced inside the water snowline where only refractory organic matter and water contained in hydrous minerals, such as silicate, can exist as solids. Thus, the composition of small bodies (comets/asteroids) created in the protosolar nebula varies significantly inside and beyond the water snowline.

High-sensitivity observations by ALMA have also revealed that the gas-phase elemental abundances are depleted, and that the gas-phase elemental abundance ratios have anomalies in protoplanetary disks, compared with those in molecular clouds. Spatially resolved multi-line observations of CO have shown that gas-phase CO is likely depleted in several disks. Theoretical models suggest that the depletion could be caused by freeze-out of molecules on dust grains; the gas-phase CO is destroyed by ultraviolet radiation from the central pre-main sequence star and/or cosmic-rays, and then less volatile larger molecules form, which are frozen out on dust grains. The timescale of approximately one million years suggested from observations of the gas-phase CO depletion is consistent with theoretical prediction (e.g., Furuya et al. 2022). In addition, recent observations have revealed anomalies in carbon-to-oxygen elemental abundance ratios (C/O ratios) in some disks. In the interstellar medium, as in our Solar System, oxygen is rich (C/O < 1), however, several astronomical observations have shown that carbon is rich (C/O > 1) in the gas-phase at least in some disks, which helps to enhance the formation of organic molecules. Such anomalies could also be caused by freeze-out of less volatile species on dust grains (e.g., Miotello et al. 2019). While depletion of gas-phase elemental abundances of carbon and oxygen by two to three orders of magnitude has been suggested, some observations have shown that depletion of the gas-phase elemental abundance of nitrogen is not significant.

Chemistry involving gas–grain interactions, in particular, are complex in protoplanetary disks because dust grains collide and grow into larger solid bodies, which lead to the formation of rocky planets and cores of gas giant planets. In addition, the gas in the disk is not completely in static orbital motion. Turbulent mixing can stir up the materials in vertical and radial directions in the disks. Recent sophisticated chemical models based upon a full set of gas-phase and grain surface reactions have taken these effects into account and reproduced the depletion of the gas-phase elemental abundances of carbon, oxygen, and nitrogen compared with the interstellar values (Fig. 2). Although astronomical observations provide information of mainly gas-phase species, such state-of-the-art theoretical models will link the brand-new astrochemical and cosmochemical discoveries.
Part of the carbon element frozen onto grains is incorporated into organic molecules. High-sensitivity observations by ALMA have detected iCOMs both inside and beyond their snowlines (Fig. 3). The iCOMs detected beyond the snowline are thought to be desorbed non-thermally, that is, using energy of cosmic rays, ultraviolet radiation, and/or grain surface reactions, from ice mantles on dust grains, as in the case of cold prestellar cloud cores. In the ALMA era, relatively large molecules, such as HCN, CH$_3$CN, CH$_3$CN, C$_2$H$_5$, CH$_3$OH, HCHO, H$_2$CS, CH$_3$OCH$_3$, and HCOOCH$_3$, have recently been detected in protoplanetary disks (e.g., Brunken et al. 2022).

Stirring of materials by turbulent mixing also processes organic molecules in disks. Complex organic molecules formed on ice near the disk midplane are stirred up to the disk surface and exposed to strong ultraviolet and X-ray irradiation from the central star. Various laboratory experiments have been conducted to investigate the process, suggesting that the photochemistry contributes to produce more complex organics, including conversion of aliphatic bonds into aromatic bonds and even isotopic anomalies, similar to those found in meteorites and materials investigated through exploration missions in the Solar System, such as the Stardust, Rosetta, and Hayabusa2 missions (e.g., Sandford et al. 2020).

**Chemical Evolution of iCOMs and Beyond**

Because protoplanetary disks are relatively small and low-luminosity objects, observations of iCOMs in disks are still limited. Meanwhile, larger iCOMs are being discovered and the number of new detections is rapidly increasing in brighter and/or larger-scale objects, based on recent line survey programs using large, single-dish radio telescopes, such as the Yebes 40-m Telescope, Green Bank 100-m Telescope, and ALMA, along with intensive collaborations with laboratory spectroscopists. These discoveries have opened up a new era of interstellar organic chemistry and provide hints regarding the boundary between volatile and refractory phases.

One of the categories of newly discovered large interstellar molecules is cyclic organic molecules, such as indene, cyclopentadiene, ethynyl cyclopentadiene, benzylene, fulvenalene (C$_6$H$_2$CCH$_2$), benzonitrile (C$_6$H$_5$CN), cyanophthalene (C$_5$H$_5$CN), and 2-cyanoinidene (C$_6$H$_5$CN), in cold molecular clouds (e.g., McCarthy and McGuire 2021). These can provide information on the formation pathways of larger molecules, such as polycyclic aromatic hydrocarbons (PAHs) and fullerenes (C$_{60}$, C$_{70}$, and C$_{70}$). On the other hand, such large molecules and carbonaceous dust grains can be partially destroyed to form disintegration products, which can serve as precursors to the various organic species found in meteorites (e.g., Kwok and Zhang 2011). The PAH observations are one of the key science objectives of the JWST. The observations will be performed from distant galaxies to nearby star- and planet-forming regions with high sensitivity and high spatial resolution, which will provide insights into the origin and evolution of PAHs and the life cycle of carbonaceous matter in a variety of astrophysical environments. We note that high-spatial-resolution observations of ALMA have detected salts, NaCl and KCl, together with silicon-bearing species in very hot gas close to newly formed high-mass stars (e.g., Ginsburg et al. 2023). Such salts have previously been observed only in the envelopes surrounding evolved stars where dust grains are being formed. The new discovery by ALMA helps to reveal the components of dust grains, on which organic molecules form, in star- and planet-forming regions for the first time.

Another category of newly discovered large molecules includes prebiotic molecules, mostly formed in ices on dust grains. Recent high-sensitivity and high-spatial-resolution observations, especially by ALMA, have made it possible to detect prebiotic molecules not only in large mass
star-forming regions, but also in Solar-type, low-mass, star-forming regions (e.g., Jørgensen et al. 2020). The simplest amino acid, glycine, has been a target of interstellar molecular hunters for decades, and the detection of precursors of amino acids and nucleic acids (for example, molecules with amide bond and amines), such as formamidine (NH₂CHO), acetamide (CH₃CONH₂), methylformamide (CH₃NH₂CONH₂), urea-carbamide (NH₂CONH₂), hydroxylated-urea-carbamide (NH₂CONH₂OH), vinyl amine (C₂H₃NH₂), ethylamine (C₂H₅NH₂), ethanol-amine (NH₄CH₂CH₂OH), aminoacetoniitride (NH₂CH₂CN), and Z-cyanomethanamine (HNCHCN), have been reported. Small precursors of sugars, such as glycolonitrile (HOCH₂CN) and glycolaldehyde (CH₂OHC), have also been observed, even in a low-mass, star-forming region by the ALMA PILS survey. Future observations by ALMA and/or next-generation telescopes, such as ngVLA and SKA, together with the development of new chemical reaction networks, would create a new possibility in the investigation of the chemistry of formation of iCOMs, including prebiotic molecules, in space, and how refractory organic matter is formed and evolves in star- and planet-forming regions. In addition, iCOM surveys in protoplanetary disks will also proceed further toward understanding how organic matter ends up being incorporated/delivered into planets.

CHEMICAL EVOLUTION OF ORGANIC MOLECULES ON PLANETESIMALS

The Earth is generally thought to have accreted as a relatively anhydrous and volatile-poor body, and several processes have been proposed to explain how volatiles and organic molecules were incorporated into planetesimals in the inner Solar System. Volatile organics evaporate at temperatures above 25 °C within 2.6 AU. The remaining refractory organic solids can persist at temperatures up to about 100 °C around 3 AU in the accretion disk (Nakano et al. 2003) and be transported inward. While ‘wet accretion’ from hydrated minerals locally formed in a much cooler nebula has been considered as one possible process, inward migration and accretion of mm- to dm-sized icy pebbles is an alternative hypothesis that nicely incorporates the Nice and Grand Tack models, which account for the formation and migration history of the planetary bodies in the early Solar System and the associated reshuffling of small bodies during the late stage of nebula evolution (Ciesla and Lauretta 2005).

The inner region of the Solar System was probably warm enough to permit normal thermochemical reactions. In addition, upon accretion, planetesimals provided warm and hydrous environments, where liquid water released from ices melted by heat generated by the decay of short-lived radionuclides (e.g., ²⁶Al, ⁶⁰Fe) can exist near the from ices melted by heat generated by the decay of short-lived radionuclides (e.g., ²⁶Al, ⁶⁰Fe) can exist near the...
The presence of R–CHO and NH₃, formose-type reactions can also produce many other organic compounds, including amino acids, alkylpyridines, and complex insoluble macromolecular compounds (Kebukawa et al. 2020).

Pyrimidine and purine nucleobases play crucial roles to life on Earth as they are components of nucleic acids (RNA and DNA) that terrestrial organisms use to encode genetic information. The interstellar nucleobase pyrimidine has been tentatively identified in star-forming molecular cloud cores (Kuan et al. 2003), and can be formed via abiotic reactions such as solid-state chemistry between HCN and acrylonitrile on grain surfaces. However, the low abundance of pyrimidine suggests that it is easily destroyed by ultraviolet photons or cosmic rays. While nucleobases can be synthesized via ice irradiation, they can also be produced during parent body aqueous alteration by aqueous polymerization of HCN, which necessitates high concentrations (>1 M) of HCN (Fig. 4), reaction of cyanoacetylene with cyanate (in relative dilute solution at pH 8 and room temperature), or the combination of cyanoacetaldehyde with urea (Glavin et al. 2018 and references therein).

**Aromatic Structure Condensation during Thermal Metamorphism**

As parent body thermal metamorphism progresses, aromatization proceeds and the abundance of organic matter decreases. A correlation has been observed between the Raman spectral parameters and H/C ratio of IOM from different meteorites groups and petrologic types, which indicates that the IOM structure changes from disordered to ordered through dehydrogenation with increasing degree of thermal metamorphism (Busemann et al. 2007). X-ray absorption near edge structure (XANES) features at 291.63 eV (1s-\(\sigma^*\) exciton, which is the electronic transition derived from highly conjugated sp² carbon such as graphene), increases with petrologic subtype of meteorites (Cody et al. 2008). However, the thermally metamorphosed

**Low-Temperature Chemical Oxidation**

Solid-state \(^{13}\)C NMR spectra of insoluble organic matter (IOM) from different carbonaceous chondrite groups revealed that relative abundances of aliphatic carbon decrease in the order from least altered to most altered meteorite groups (CR2 > CI1 > CM2 > Tagish Lake), as well as H/C, whereas those of carbonyl carbon slightly increase in the same order (Cody and Alexander 2005). This trend suggests that low-temperature aqueous alteration causes oxidation (conversion of aliphatic moieties into carbonyl carbon) and aromatization of IOM (Cody and Alexander 2005). It has also been found that the relative abundances of amino acids decrease in the similar order of meteorite groups, reflecting that amino acids could have been decomposed through oxidation during aqueous alteration. The relative abundances of soluble organic molecules, especially amino acids, are very low in the Tagish Lake meteorite (Glavin et al. 2018).
subgroups of petrologic type 2 chondrites, which experienced impact-dehydration, exceptionally exhibit very weak 1s–σ∗ exciton intensities in the C-XANES spectra. That is, their IOM structures are not ordered even after experiencing particularly high peak temperatures up to 700 °C. In contrast, petrologic type 3 chondrites, which experienced a lower peak temperature of 300–400 °C but for much longer times, show a highly developed 1s–σ∗ exciton peak in the C-XANES spectra (Cody et al. 2008). Thus, the modification process of IOM by short-term impact heating differs from that by long-term radiogenic heating.

CONCLUSION

A plethora of organic compounds have been identified over decades of astronomical observations and cosmochemical analyses of astromaterials. Smaller molecules, mainly gas-phase organic species, have been observed astronomically in remote environments like molecular clouds. These molecules are considered precursor materials for chemical reactions within our Solar System that led to the formation of more complex molecules. Technological advancements have revolutionized our understanding of interstellar molecular diversity by the remote detection of even solid species, in particularly PAHs and prebiotic molecules like amino acids and nucleobases, that line up with the molecular diversity uncovered by analyzing asteroidal and cometary samples. Continued exploration using both approaches will help to gather knowledge on remotely observed gas-phase species and locally observed solid-phase species analyzed in terrestrial laboratories.

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The inner Solar System—including the planet Earth—was heavily bombarded by comets, asteroids, and their fragments (i.e., meteorites, micrometeorites, and interplanetary dust particles) from 4.56 to about 3.5 billion years ago. This bombardment resulted in a rich assortment of organics delivered to the Earth, as comets and many asteroids contain carbonaceous matter. These organic compounds were likely further processed on the early Earth (e.g., by impact-shock reactions), providing a feedstock of prebiotic molecules to the crust and oceans. In this chapter, we review the mechanisms of organic matter delivery to the primitive Earth, further reactions and processing, and the importance of exogenous material in the evolution of our planet and life.

**Keywords:** organic matter; exogenous delivery; early Earth; prebiotic molecules

**INTRODUCTION**

The preserved impact craters observed on planetary bodies such as Mercury and the Moon (Fig. 1) provide clear evidence that the inner Solar System was bombarded 4.56 to 3.5 billion years ago, with an elevated flux that persisted to ~2.5 billion years ago (Bottke and Norman 2017). Comets, asteroids, and their fragments (e.g., meteorites, micrometeorites, interplanetary dust particles (IDPs)), contain carbonaceous matter, which was delivered to the early Earth (Chyba and Sagan 1992) and may have supplemented endogenous sources. As the first organisms were likely self-assembled by incorporating these newly supplied organic compounds, exogenous organic material may have been a substantial fraction of the organic inventory of the crust and oceans of our primitive planet, ultimately providing the necessary monomers to build the basic unit of life, i.e., the cell. These monomers would then act as the components of polymers and macromolecules (i.e., from amino acids to proteins, from fatty acids to phospholipid membranes, from carbohydrates to polysaccharides, and from nucleobases to nucleotides and then to nucleic acids), operating three fundamental functions of life: compartmentalization, replication, and metabolism (Fig. 2).

In this chapter, we describe the contribution of comets, micrometeorites, IDPs, and meteorites to the organic inventory of the early Earth, as well as further processing of organic matter on Earth that may have led to the existence of an organic matter inventory prior to the emergence of life (prebiotic) that was conducive to promoting the origin of life on our planet.

**CONTRIBUTION TO THE ORGANIC INVENTORY OF THE EARLY EARTH**

The Parent Bodies: Comets and Asteroids

The potential contributions of extraterrestrial material to the prebiotic inventory of the early Earth can be inferred from measurements of their organic compositions. Through ground-based and remote observations in the infrared to millimeter range, nearly 30 organic molecules, including amino acid precursors, have been detected in comets (Biver and Bockelée-Morvan 2019). In-situ space missions, such as the *Rosetta* mission to comet 67P/Churumov–Gerasimenko have further identified more than 60 individual organic molecules (Altwegg et al. 2017), including glycine, alcohols, carbonyls, amines, nitriles, amides, isocyanates, and the polymer polyoxymethylene. However, no aromatic compounds (e.g., benzene, sulfur-bearing species) have been observed (Goessmann et al. 2015; Altwegg et al. 2016), which contrasts with organic matter from carbonaceous chondrites, in which polycyclic aromatic hydrocarbons (PAHs) and sulfur compounds (e.g., sulfonic acids and alkyl sulfonates) have been detected. The sample-return *Stardust* mission, which retrieved dust from comet 81P/Wild-2 (Fig. 3), provided the detection of aromatic compounds and the amino acid glycine (Elisea et al. 2009). In addition, many asteroids also bear organic matter, including the Ryugu asteroid, recently analyzed by the *Hayabusa2* mission (e.g., Naraoka et al. 2023; Yabuta et al. 2023). The *OSIRIS-REx* sample return mission will also provide significant insight into the organic composition of asteroids, especially given that the mission is estimated to have retrieved hundreds of grams of material from the asteroid Bennu. With such a large quantity of material, it is quite likely that the *OSIRIS-REx* data will demonstrate how abundant organics are on carbonaceous asteroids. Given the presence of organics across a multitude of small planetary bodies in the Solar System, fragments of these bodies impacting the Earth’s surface can serve as delivery mechanisms for exogenous prebiotic organic matter.

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Micrometer-sized Particles

Fragments of both stony and cometary material may have reached the early Earth in the form of micrometer-sized particles, i.e., micrometeorites and IDPs, which contain on average around 10% organic carbon by mass. IDPs are small enough (usually less than 30 μm in size) to be collected in the stratosphere, whereas micrometeorites (ranging from 50 μm to 2 mm) rapidly descend to the Earth’s surface and are instead collected from terrestrial sites (e.g., deep sea sediments, Antarctic ice, Greenland lake deposits). Several analyses performed on these particles (especially micrometeorites) have shown the presence of the following organic molecules: PAHs and alkylated derivatives, aliphatic hydrocarbons, amino acids, and ketones (e.g., Matrajt et al. 2004). However, the difficulty in collecting these small-sized particles and their low individual masses (up to 100 ng) prevents the use of a suite of high-precision analyses (e.g., gas chromatography combustion isotope ratio mass spectrometry) necessary to determine the origin of the detected organic molecules (e.g., terrestrial contamination or in-situ presence) (Matrajt et al. 2004). Other types of micrometer-sized particles include ultra-carbonaceous Antarctic micrometeorites (UCAMMs), which are suggested to have been formed in very low-temperature regions of the Solar System (Dartois et al. 2013), and for which analyses of specific organic molecules have not been reported. These “ultra-carbonaceous” micrometer-sized particles are enriched in carbonaceous material, containing up to 90% organic carbon by mass (Dartois et al. 2013).
Meteorites

Most meteorites are samples of asteroids. However, because there exists a continuum between cometary (ice- and volatile-rich) material and asteroids (primarily silicates, oxides, and metals), some meteorites can be considered partially cometary. Meteorites with at least a partial cometary nature include much of the carbonaceous chondrite group. Carbonaceous chondrites represent around 4% of the total falls observed on Earth and have high carbon contents (~3.5 wt%; Alexander et al. 2017), which is mostly organic matter (~3 wt.%) with the remainder being carbonate. Both the soluble and insoluble organic matter present in carbonaceous meteorites consist of a high diversity of chemical structures (Martins 2019). Meteoritic soluble organics include prebiotic monomers (e.g., amino acids, nucleobases, fatty acids, sugars) that can build more complex structures. For example, nitrogen heterocycles, including the purine and pyrimidine nucleobases, have been detected in carbonaceous chondrites (Martins 2018), and are the monomers of DNA and RNA. Sugars such as ribose, arabinose, and xylose, which are part of nucleic acids and serve as metabolic energy (Furukawa et al. 2019), are also present in carbonaceous meteorites, as well as a high diversity of amino acids, which make up proteins (Martins 2019; Fig. 2). Fatty acids up to 12 carbons in length have been detected in meteorites (Naraoka et al. 1999). These types of fatty acids may have formed the first vesicles, which, in present day, require fatty acids with at least eight carbons in length (Apel et al. 2002), or even cell membranes that have carbon chains of 12 to 20 carbons (Deamer and Pashley 1989). Phosphates are biologically important as components of nucleic acids (as part of the backbone of DNA and RNA), as the chemically reactive energy currency molecule adenosine triphosphate (ATP), and are part of cell membranes as phospholipids. Phosphates presently occur on our planet mainly in the insoluble form of calcium phosphates such as apatite.

However, methyl and ethylphosphonic acids (and larger) have been detected in the Murchison meteorite (Cooper et al. 1992), and various reduced oxidation state phosphorus compounds and minerals, including phosphides (Gull et al. 2023), are also present in meteorites. Phosphides release the ion phosphite under mild hydrothermal conditions, such as in evaporating/drying pools on the early Earth. These phosphides oxidize to form condensed P compounds, which can then react with nucleosides (composed by a nucleoside connected to a pentose, such as ribose) to form organophosphorus compounds (Gull et al. 2023; Fig. 4).

Size Distributions and Fluxes

Although the origin of life merely needed to occur once and then spread out to inhabit the Earth, if the amount of organics present on Earth was globally high, then that likely favored the development of life more frequently than through a few localized enrichments. This would have been especially useful if the first life was heterotrophic (requiring organics from its environment) as opposed to autotrophic (able to produce its organics from other carbon sources such as CO₂). Understanding the amount of exogenous organics delivered could, therefore, provide an understanding of how important this material was to the development of life on the early Earth.

Figure 3
Image of the core of comet 81P/Wild 2 taken by the Stardust mission. Diameter is around three to four kilometers. Photo: NSSDC Photo Gallery.

Figure 4
Phosphorus may come from inorganic phases such as (A) schreibersite, as shown in this sample of the pallasite Seymchan, that then reacts with water to release phosphite (HPO_3^{2-}), which can oxidize and phosphorylate nucleosides to yield nucleotides. (B) displays a ^{31}P NMR spectrum of a mixture of reduced P compounds that have been oxidized and then reacted with uridine, and shows a multitude of individual P species, ranging from inorganic P species to nucleotides with phosphate instead of phosphite to nucleotides with phosphate (and even some dimer P species; see Gull et al. 2023).
There are two ways to think about the quantity of organics delivered by extraterrestrial material: (1) how much is delivered by a single rock falling from space to the Earth’s surface, and (2) how common a specific type of rock delivering organics would be, on average. In general, extraterrestrial material that is smaller in size falls at a higher rate than larger material (Rietmeijer 2000). Notably, meteorites are one of the least massive contributors to the total delivered by exogenous material, despite being the most thoroughly analyzed. That said, the organic inventory of meteorites is expected to be similar in terms of organic inventory (both mass and molecules present) to that of objects both smaller (e.g., IDPs) and larger (bolides). Today, the total flux of smaller (<200 μm in diameter) objects to the Earth’s surface is estimated at ~10^7 kg/y. The fall rate for meteorites over 20 g is about 80,000/y (Bland et al. 1996), contributing a much smaller fraction of the total mass accreted (~10^4 kg/y). Larger impactors are much more stochastic: large falls deliver huge amounts of matter infrequently, but averaged over geologic time, they deliver the most total material. (Fig. 5)

**FURTHER PROCESSING OF EXOGENOUS MATERIAL ON THE EARLY EARTH**

Organic matter exogenously delivered to the early Earth would have been further processed during the impact itself and through subsequent reactions (e.g., by impact-shock reactions, ablation-driven synthesis, hydrolysis, adsorption reaction on mineral surfaces). The impact of a comet or asteroid onto the primitive Earth could have generated enough energy to further synthesize new organic molecules. Hydrocode modeling has indicated that at 7.15 km/s (the minimum velocity at which a high degree of chemical reactivity occurs), the peak shock pressure experienced by a comet would be ~50 GPa (Martins et al. 2013), which ab initio molecular dynamic simulations indicate is sufficient to induce amino acid formation. Laboratory work involving hypervelocity impact shock experiments using a typical comet mixture (i.e., ammonia, methanol, and carbonyl compounds) confirmed the synthesis of amino acids under these high-pressure conditions, suggesting a further method for producing the components of proteins (Martins et al. 2013).

Clyba and Sagan (1992) argued that a major role of meteorites in influencing the prebiotic chemistry of the early Earth was not necessarily the delivery of whole material, but instead the addition of energy to the Earth’s upper atmosphere. When asteroidal particles (e.g., meteoroids) enter the Earth’s atmosphere, they are heated by friction and glow as meteors. During this energetic process, atmospheric gas particles can be heated in the meteor tail to form radicals that then recombine, potentially making prebiotic precursor molecules. In this respect, meteor ablation may have been similar to the lightning energy source employed in the Miller–Urey experiment (Miller 1953).

Once exogenous material reached the early Earth’s surface, it would have been subjected to a hotter, wetter environment relative to its asteroidal or cometary parent body. The organic molecules delivered to the surface would have then solvated into water or, if less soluble, could have hydrolyzed into more soluble species (e.g., nitriles hydrolyzing into amides). Additionally, the insoluble organic matter that often dominates the organic component of meteorites (Martins 2018) could have still been available for prebiotic chemistry through hydrolysis over geochemically short timescales (<100 years; see Johnson et al. 2008). Similarly,

Inorganic components such as phosphides could have reacted with water to yield reactive, soluble P compounds that themselves power phosphorylation (Gibbard et al. 2019). Furthermore, meteoritic organics delivered to the Earth, in particular nucleic acid purine and pyrimidine bases, could have adsorbed onto the surface of inorganic solids and self-associated in monolayers, influencing the composition of the primordial genetic architecture (Sowerby et al. 2001). Although nucleotides (the principal component of nucleic acids such as DNA and RNA) have not been detected in meteorites or IDPs, they may have been synthesized on the early Earth from monomers that were exogenously delivered, especially because both sugars and nucleobases are part of the organic inventory of meteorites and because meteoritic minerals have the ability to provide phosphorus for nucleotides (e.g., Fig. 4).

Lipid precursors could have been generated on the early Earth through the solubilization of fatty acids and/or from hydrolysis of longer aliphatic compounds delivered by meteorites. These lipid precursors could have spontaneously self-organized into micelles, bilayers, and vesicles, potentially leading to further reactions including “cellular” division and evolution (Segrè et al. 2001). The assembled lipid membranes could have also coupled with nucleic acids present on the early Earth to produce important biomolecules. For instance, Czerniak and Saenz (2022) recently showed that direct RNA–lipid interactions can modulate ribozyme activity, and that RNA–lipid binding is influenced by the nucleotide content and the base pairing of RNA. Together, these findings demonstrate that, even if meteorites were not a significant source of prebiotic reagents, the components of meteorites could have reacted on the early Earth to yield certain key constituents that could have led to the development of life.
CONCLUSIONS

Laboratory analyses of the soluble and insoluble organic matter of meteorites complement the information obtained by in-situ and sample-return space missions to comets and asteroids (Naraoka et al. 2023; Yabuta et al. 2023), giving the scientific community an overview of the organic content of these primitive Solar System bodies (Martins et al. 2020), and what was exogenously delivered to the early Earth. Further processing of the delivered monomers, by impact-shock, by hydrolysis and aqueous processing, and/or interaction with the minerals on the Earth, would have led to polymers, and later to macromolecules, which may have been used as the building blocks of the earliest forms of life. Studying all of these steps toward complexity—from prebiotic chemistry to biology—provides a fundamental overview of the early Solar System and the ingredients available for the emergence of life.

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Diversity of Complex Organic Matter in Carbonaceous Chondrites, IDPs, and UCAMMs

Bradley T. De Gregorio¹ and Cécile Engrand²

INTRODUCTION

There are many classes of planetary materials in our Solar System that contain carbonaceous matter. The most well-known among these are the carbonaceous chondrite meteorites, identifiable by the dark color of their fine-grained matrix due to incorporation of up to 5 wt.% bulk carbon. Organic matter is also found, to a lesser extent, in ordinary chondrites. Interplanetary dust particles (IDPs) and micrometeorites (MMs), although small (~100 µm or less), can contain significantly more carbon than carbonaceous chondrites—up to 10 to 25 wt.% carbon. The major carbonaceous components in the planetary materials described above include carbonate minerals, soluble organic matter (SOM), and more complex macromolecular carbonaceous matter (Alexander et al. 2017). The SOM fraction includes molecules such as carboxylic acids and amino acids, but by far, the majority of the carbon budget (>75%) is found to be in this complex organic matter. Yet this important component can be difficult to study. A common method for extracting this material is through dissolution of the host material with a series of harsh acid washes and rinsing steps, producing a concentrated organic residue called insoluble organic matter (IOM). However, it has been known since the advent of this approach in the 1970s that this process only recovers ~50% of the complex macromolecular material and none of the SOM. In addition, although IOM residues provide a somewhat representative “bulk” sample of organic matter from a given sample, any useful petrologic context is lost. The alternative approach is to investigate the carbon in situ using various microscopic and nanoscopic techniques on minimally processed samples like IDPs, UCAMMs, and returned samples from spacecraft missions, where producing an IOM residue may not be feasible.

That said, IOM is a good baseline material for comparative studies between chondrite groups and other carbonaceous planetary materials. The composition of IOM (Fig. 1A) ranges from $\text{C}_{100}\text{H}_{75-79}\text{O}_{11-17}\text{N}_{3-4}\text{S}_{1-3}$ in the most primitive chondritic samples (nearly identical to carbonaceous particles measured from comet Halley) to $\text{C}_{100}\text{H}_{920}\text{O}_{9-11}\text{N}_{0-2}$ in thermally modified meteorites (Alexander et al. 2017 and references therein). The macromolecular structure of IOM that corresponds to these compositions consists of small-to-medium sized polyaromatic functional units (1–3 carbon rings for primitive samples, and up to 7–8 rings for thermally modified meteorites) that are highly substituted with N and S atoms and cross-linked by short, highly branched, aliphatic hydrocarbon chains (Fig. 1B; Derenne and Robert 2010). More in depth information about the structure and composition of IOM can be gained from the review by Alexander et al. (2017).
Complex organic matter takes on a variety of forms, often only observable at sub-micrometer length scales. The largest and most well-studied of these are spherical or roundish grains, either solid or hollow, called nanoglobules or globular organic matter (Fig. 2; Garvie and Buseck 2006; Nakamura-Messenger et al. 2006). Found in meteorites, IDPs, and UCAMMs, they range in size from <50 nm to ~2 µm in diameter. Nanoglobules are either isolated within the fine-grained matrix or form small clusters. Larger vein-like clusters have also been observed. Nanoglobules are retained within carbonaceous chondrite IOM residues, making them relatively easy to study en masse. A comparison of nanoglobule populations in IOM across different carbonaceous chondrite groups indicates that they are less prevalent in aequously altered meteorites (like CI and CM chondrites) and most prevalent in the “primitive” CR chondrites (De Gregorio et al. 2013a). Within a given chondrite group, nanoglobules appear to be most prevalent in samples that experienced moderate levels of aequous alteration (e.g., petrologic type 2). Nanoglobules in IOM from the heavily aequously altered (petrologic type 1) CR chondrite GRO 95577 are extensively modified, with vesicular or desiccated textures, physical deformation features, and outer rind structures (De Gregorio et al. 2013a). Vesicular nanoglobules observed in situ within the fine-grained meteorite matrix contain lower nitrogen contents than nearby, unmodified nanoglobules, and nanoglobules with outer rinds are bounded by phyllosilicate layers that are presumably removed by the IOM extraction process (Fig. 2A; De Gregorio et al. 2013b). Nanoglobules observed in anhydrous IDPs and UCAMMs have similar morphologies to those found in primitive carbonaceous chondrites (e.g., Matrajt et al. 2011; Yabuta et al. 2017). These morphological variations, along with their functional group chemistry and stable isotope composition, indicate that nanoglobules have a complicated formation and modification history including both pre-accretion and parent body origins (see Nomura et al. 2024 this issue). Chondritic nanoglobules have nearly identical functional group compositions to that of “bulk” IOM from their host meteorite, except for a slightly higher proportion of carbonyl-bearing (C=O) functional groups like ketones and carboxylic acids (De Gregorio et al. 2013a). A smaller fraction of nanoglobules have a different functional group chemistry indicative of larger polyaromatic domains. These are called “aromatic” or “highly aromatic” nanoglobules to distinguish them from those with IOM-like characteristics. Although the available data are small, it appears that the abundance of aromatic nanoglobules has a strong dependence on the petrologic type of the host rock. They compose about half of all nanoglobules in the mildly heated CO (petrologic type 3) chondrites, and are relatively rare in the heavily aqueously altered type 1 chondrites. The seemingly systematic occurrences of both chemistries would suggest that nanoglobules likely formed on parent bodies. They would primarily be produced by organic condensation reactions between IOM precursor macromolecules during periods of hydrothermal processing. In fact, nanoglobule morphologies are readily produced in experiments that mimic these aqueous alteration conditions (Cody et al. 2011). However, many nanoglobules are enriched in D and/or 15N isotopes, which are interpreted to indicate an interstellar or protosolar heritage (e.g., Nakamura-Messenger et al. 2006). The abundance of isotopically anomalous nanoglobules, irrespective of functional chemistry, is roughly proportional to the isotopic composition of the host IOM. This suggests that nanoglobules are a significant carrier of isotopically primitive organic matter, although it should be noted that isotopically anomalous nanoglobules only account for ~30% of all the anomalous “hotspot” regions in IOM (De Gregorio et al. 2013a). These isotopic data suggest that many nanoglobules are pre-existing components during asteroid and planetesimal accretion, likely formed through irradiation of organic–ice mixtures in the presolar nebula or cold molecular cloud (Nomura et al. 2024 this issue). Occasionally, the outer ~10 nm of some nanoglobules are observed to be enriched in nitrogen, along with a slight increase in aromaticity (Vollmer et al. 2014). The origins of these nitrogen-rich rims could be due to pre-accretion radiation processing, but have also been explained by interaction with asteroidal fluids (Vollmer et al. 2014, 2020). In reality, the populations of nanoglobules that we observe in carbonaceous meteorites, micrometeorites, and IDPs were contributed by both pre-accretion processes and aqueous reactions on asteroids and comets, with modification of their original morphologies and chemistries by further hydrothermal processing.

Apart from nanoglobules, the majority of chondritic IOM consists of a network of connected carbonaceous mesoparticles, in which the larger nanoglobules are embedded (Fig. 2B, 2C). Mesoparticle size and pore size vary from meteorite to meteorite, suggesting a relationship with parent body processing (e.g., Fig. 2B versus 2C). This mesoparticle component of IOM corresponds to “diffuse” or “disseminated” organic matter observed in situ within the

**Figure 1** Composition and macromolecular structure of complex organic matter. (A) Carbon, hydrogen, and nitrogen compositions of complex organic matter in carbonaceous chondrite meteorites, IDPs, and UCAMMs. Data from Alexander et al. (2017) and references therein, and Dartois et al. (2018). (B) Molecular structure model of Murchison IOM developed from 11 independent parameters. Reproduced from Derenne and Robert (2010) with permission from John Wiley and Sons.

**MORPHOLOGY AND CHEMISTRY OF COMPLEX ORGANIC MATTER**

Complex organic matter takes on a variety of forms, often only observable at sub-micrometer length scales. The largest and most well-studied of these are spherical or roundish grains, either solid or hollow, called nanoglobules or globular organic matter (Fig. 2; Garvie and Buseck 2006; Nakamura-Messenger et al. 2006). Found in meteorites, IDPs, and UCAMMs, they range in size from <50 nm to ~2 µm in diameter. Nanoglobules are either isolated within the fine-grained matrix or form small clusters. Larger vein-like clusters have also been observed. Nanoglobules are retained within carbonaceous chondrite IOM residues, making them relatively easy to study en masse. A comparison of nanoglobule populations in IOM across different carbonaceous chondrite groups indicates that they are less prevalent in aequously altered meteorites (like CI and CM chondrites) and most prevalent in the “primitive” CR chondrites (De Gregorio et al. 2013a). Within a given chondrite group, nanoglobules appear to be most prevalent in samples that experienced moderate levels of aequous alteration (e.g., petrologic type 2). Nanoglobules in IOM from the heavily aequously altered (petrologic type 1) CR chondrite GRO 95577 are extensively modified, with vesicular or desiccated textures, physical deformation features, and outer rind structures (De Gregorio et al. 2013a). Vesicular nanoglobules observed in situ within the fine-grained meteorite matrix contain lower nitrogen contents than nearby, unmodified nanoglobules, and nanoglobules with outer rinds are bounded by phyllosilicate layers that are presumably removed by the IOM extraction process (Fig. 2A; De Gregorio et al. 2013b). Nanoglobules observed in anhydrous IDPs and UCAMMs have similar morphologies to those found in primitive carbonaceous chondrites (e.g., Matrajt et al. 2011; Yabuta et al. 2017). These morphological variations, along with their functional group chemistry and stable isotope composition, indicate that nanoglobules have a complicated formation and modification history including both pre-accretion and parent body origins (see Nomura et al. 2024 this issue). Chondritic nanoglobules have nearly identical functional group compositions to that of “bulk” IOM from their host meteorite, except for a slightly higher proportion of carbonyl-bearing (C=O) functional groups like ketones and carboxylic acids (De Gregorio et al. 2013a). A smaller fraction of nanoglobules have a different functional group chemistry indicative of larger polyaromatic domains. These are called “aromatic” or “highly aromatic” nanoglobules to distinguish them from those with IOM-like characteristics. Although the available data are small, it appears that the abundance of aromatic nanoglobules has a strong dependence on the petrologic type of the host rock. They compose about half of all nanoglobules in the mildly heated CO (petrologic type 3) chondrites, and are relatively rare in the heavily aqueously altered type 1 chondrites. The seemingly systematic occurrences of both chemistries would suggest that nanoglobules likely formed on parent bodies. They would primarily be produced by organic condensation reactions between IOM precursor macromolecules during periods of hydrothermal processing. In fact, nanoglobule morphologies are readily produced in experiments that mimic these aqueous alteration conditions (Cody et al. 2011). However, many nanoglobules are enriched in D and/or 15N isotopes, which are interpreted to indicate an interstellar or protosolar heritage (e.g., Nakamura-Messenger et al. 2006). The abundance of isotopically anomalous nanoglobules, irrespective of functional chemistry, is roughly proportional to the isotopic composition of the host IOM. This suggests that nanoglobules are a significant carrier of isotopically primitive organic matter, although it should be noted that isotopically anomalous nanoglobules only account for ~30% of all the anomalous “hotspot” regions in IOM (De Gregorio et al. 2013a). These isotopic data suggest that many nanoglobules are pre-existing components during asteroid and planetesimal accretion, likely formed through irradiation of organic–ice mixtures in the presolar nebula or cold molecular cloud (Nomura et al. 2024 this issue). Occasionally, the outer ~10 nm of some nanoglobules are observed to be enriched in nitrogen, along with a slight increase in aromaticity (Vollmer et al. 2014). The origins of these nitrogen-rich rims could be due to pre-accretion radiation processing, but have also been explained by interaction with asteroidal fluids (Vollmer et al. 2014, 2020). In reality, the populations of nanoglobules that we observe in carbonaceous meteorites, micrometeorites, and IDPs were contributed by both pre-accretion processes and aqueous reactions on asteroids and comets, with modification of their original morphologies and chemistries by further hydrothermal processing.

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fine-grained matrix and aggregated through IOM extraction. However, close examination of individual regions of diffuse organics in situ reveals a wide variety of functional chemistry that does not match that of IOM. Much of this diffuse organic matter has a low proportion of polyaromatic functionality and is rich in oxygen and nitrogen functional groups (Le Guillou et al. 2014). This marked difference between IOM mesoparticles and in-situ diffuse carbon is due to the likely inclusion of SOM or hydrolysable aliphatic chains in the latter, which are removed during IOM extraction, leaving only the acid-insoluble, polyaromatic-rich mesoparticles. As mentioned, diffuse organic matter can contain significant D or $^{15}$N isotopic anomalies, requiring high-resolution transmission electron microscopy (TEM) to visualize and characterize individual nanoscale grains in situ (Vollmer et al. 2020). The isotopically anomalous diffuse carbon analyzed so far appears to contain the same polyaromatic and carbonyl-rich functional chemistry as their larger anomalous counterparts (Flynn et al. 2013). In addition to organic grain coatings, IDPs and UCAMMs can also contain large continuous regions of organic matter not seen in meteorites (Fig. 2E). In IDPs, this “gap-filling” organic matter has a lower abundance of polyaromatic domains and a higher proportion of aliphatic cross-linking side chains than those found in carbonaceous chondrites (Flynn et al. 2003). This material can have various textures of unknown origin, described as “spongy”, “vesicular”, and “smooth” (Matrajt et al. 2011). In UCAMMs, the complex organic matter is generally enriched in nitrogen and sulfur (Yabuta et al. 2017; Dartois et al. 2018), and the relative proportion of polyaromatic to side-chain functionality varies across the regions (Mathurin et al. 2019). The UCAMM organics are in fact a mixture of two or three distinct organic phases. One of these phases contains up to 20 at.% nitrogen, whereas the other phase(s) share similarities in composition with IOM in carbonaceous chondrites (Fig. 1A; Guérin et al. 2020). The high amount of organic matter in these carbon-rich IDPs and UCAMMs can be interpreted as the result of short-term exposure to aqueous fluids on comets and other icy planetsimals (Yabuta et al. 2017) or from extensive radiation processing of ices in the outer regions of the protoplanetary disk (Dartois et al. 2018 and references therein).
AQUEOUS ALTERATION ON ASTEROIDS AND COMETS

Asteroids and comets accreting past the “snow line” of the early solar nebula, which is also outside of the “soot line” where polycyclic aromatic hydrocarbons can condense, will include a significant amount of both water-ice and organic matter. The initial carbonaceous precursor material accreted to parent bodies ranged from simple organic molecules to fully formed carbonaceous grains due to the wide variety of interstellar and/or nebular reaction mechanisms (Nomura et al. 2024 this issue). A combination of radioactive heating from short-lived isotopes like $^{26}\text{Al}$, compression melting, and major impact events led to the formation of hydrothermal fluids on asteroids. Transient aqueous melts were also present on comets (Suttle et al. 2020). These fluids percolated among accreted organic molecules, carbonaceous dust, and mineral grains in the fine-grained matrix. Some soluble organic molecules, such as formaldehyde, will react through well-established chemical pathways to form complex sugars, branched and highly substituted cyclic molecules, and ultimately polyaromatic molecules (Cody et al. 2011). Further cross-linking of these complex polyaromatics results in the complex organic matter and IOM we observe today in carbonaceous planetary materials. Minerals containing transition metals like Fe are also well known to catalyze surface-bound organic reactions, such as Fischer–Tropsch-type synthesis. The combination of these chemical processes when aqueous fluids were present resulted in chemical and morphological modification of pre-existing carbonaceous grains, as well as generation of brand new carbonaceous grains. Fluid-assisted breakdown of D- or $^{15}\text{N}$-enriched carbonaceous grains can result in larger regions of isotopically anomalous diffuse organics in the fine-grained matrix (Floss et al. 2014) or layered organic matter with different isotopic compositions (Fig. 3; Vollmer et al. 2020).

Phyllosilicate clay minerals have been shown to have an increasingly important role in the generation or modification of complex organic matter. These sheet silicates are produced by the breakdown of crystalline and amorphous silicate grains that are prevalent in IDPs and the most unaltered chondrites (Fig. 4A). They are therefore some of the earliest fresh surfaces available for catalyzing organic reactions. Phyllosilicates can interact with organic macro-

**Figure 3** Isotopic enrichment in an organic grain coating in the aqueously altered CR2 chondrite Renazzo. (**Left**) $^{15}\text{N}/^{14}\text{C}$ ratio image from nanoscale secondary ion mass spectrometry, where blue denotes a terrestrial value and yellow denotes significant $^{15}\text{N}$ enrichment over the terrestrial value (several hundred per mil). $^{15}\text{N}$ enrichment varies concentrically in the coating, indicating temporal variations in the isotopic composition of the organic precursor material during aqueous alteration. (**Right**) Corresponding scanning electron microscopy (SEM) image showing the organic matter (black) within the mineral matrix, surrounding a single mineral grain. Reproduced from Vollmer et al. (2020) with permission from John Wiley and Sons.

**Figure 4** Interaction of accreted water-ice and organic matter with silicate minerals. (**A**) Interaction of ice-coated accreted grains during the initial and later stages of hydration and aqueous alteration, after the model of Le Guillou and Brearley (2014). The rapid formation of phyllosilicates from amorphous silicates and hydroxysulfides like tochilinite from sulfides is aided by interaction with organic matter. (**B**) Active interlayer and surface sites on clays and phyllosilicate minerals (highlighted in yellow) that can catalyze organic reactions.
molecules through direct adsorption or chemisorption on the surfaces of individual sheets, or through intercalation between sheets (Fig. 4B). Diffuse organic matter is observed to be intercalated within phyllosilicate layers, even in the most unaltered carbonaceous chondrites, indicating these organic–clay interactions occur rapidly (Le Guillou and Brearley 2014). Laboratory analog experiments with smectite produce not only more complex organic molecules than without smectite but also organic–clay mixtures (Vinogradoff et al. 2020). The unique catalytic environment on phyllosilicate surfaces may also enable formation of distinct organic functionality. For example, evidence for carbonate (CO$_3$) functional groups has been observed occasionally within diffuse organic matter associated with phyllosilicates in in-situ sections (Le Guillou et al. 2014 and references therein), but never in IOM.

**THERMAL METAMORPHISM ON ASTEROIDS**

Some asteroidal bodies accreted a lower proportion of water-ice or a greater amount of short-lived $^{26}$Al, leading to a different style of alteration of accreted organic precursor material. In these planetesimals, organic matter and matrix minerals predominantly show effects of thermal metamorphism rather than aqueous processing. In IOM residues from heated carbonaceous chondrites (petrologic type 3), atomic stacking of polyaromatic domains may be observed, and their lateral dimensions correlate with estimated metamorphic temperatures (Le Guillou et al. 2012). This follows the same metamorphic trends observed in terrestrial kerogens. The functional chemistry of the IOM also reflects this heating history, as polyaromatic functionality is more prevalent and the amount of oxygen-bearing functional groups (e.g., ketones and carboxyl groups) is reduced relative to IOM from aqueously altered carbonaceous chondrites (De Gregorio et al. 2013a).

IOM isolated from CO chondrites, which have all been mildly thermally metamorphosed, frequently contain µm-sized, crescent-shaped, or onion-shaped carbonaceous grains, in addition to nanoglobules. These relatively large morphologies are also often enriched in elements like N, Si, Ca, or S, and have been interpreted to be organic coatings that formed on matrix mineral grains. The internal grain no longer exists, having been removed during acid dissolution for IOM extraction. Heating experiments of organic analogs mixed with olivine have produced macromolecular products via reaction of carboxylic acid functional groups to form cross-linking ester bonds, rather than normal degradation by hydrocarbon “cracking” (Hirakawa et al. 2021). It is possible that synthesis of macromolecular organics on mineral surfaces could incorporate cations chelated by ligand bonds. However, detailed in-situ studies of type 3 CO or CV samples are needed to confirm this hypothesis.

**IRRADIATION OF SPACE-EXPOSED ORGANIC MATTER**

Irradiation of organic matter on the surfaces of icy dust grains in the interstellar medium or early solar nebula is thought to produce some of the precursor organic matter that accreted onto asteroids and comets (Nomura et al. 2024 this issue). However, recent work (e.g., Thompson et al. 2020) has also investigated the effect of space weathering and other surface processes on organic matter after accretion. In the outer Solar System and Oort Cloud, fluxes of galactic cosmic rays and UV irradiation may be significant enough to continue activating organic reactions on comets. At these cold outer Solar System temperatures, nitrogen gas (N$_2$) and ammonia frozen with organic molecules and water ice could be transformed into nitrogen-rich organic matter with similar chemical functionality as the nitrogen-rich organic matter observed in IDPs and UCAMMs (Augé et al. 2016; Dartois et al. 2018). Subsequent sublimation of the ices could leave behind an organic crust on the comet surface, which could be the source materials for the formation of gap-filling, nitrogen-rich, organic matter in IDPs and UCAMMs (Fig. 2E). Further work is needed to understand solid interactions necessary to accumulate and cross-link this material into a coherent macromolecular solid, or whether irradiation processes alone could produce it.

In the inner Solar System, micrometeorite bombardment and solar wind irradiation play a major role in the space weathering of carbonaceous asteroid surfaces. Phyllosilicate clay and serpentine minerals in the regolith decompose through amorphization and partial melting, leading to reduction of iron and formation of nanophase iron metal grains (Thompson et al. 2020). These major redox reactions occur in the presence of diffuse organic matter associated with the phyllosilicates, and the potential effects on the complex organic matter have not been studied, although laboratory experiments to simulate space weathering of carbonaceous asteroids are ongoing. Alteration of complex organic matter as a result of space weathering in this environment could significantly impact the interpretation of carbonaceous materials discovered in surface regolith samples returned from asteroids 162173 Ryugu and 101955 Bennu by the Hayabusa2 and OSIRIS-REx missions, respectively.

**PRESERVATION OF PRE-ACCRETIONARY PHASES**

As organic matter in planetesimals was altered through interaction with parent body fluids and local mineralogy, it has been recognized that complex organic matter can also have an effect on the alteration of inorganic phases. Interstellar and nebular organic precursor materials are retained within IOM residues and in-situ samples as isotopic enrichments of D and/or $^{15}$N in isotopic “hotspots” and morphologically distinct grains like nanoglobules. These isotopically anomalous features somehow resisted destruction by aqueous alteration or thermal degradation. The hydrophobic, “water resistant” character of complex organic matter can be explored by studying additional occurrences of interaction or mixing with inorganic phases. Oxygen-rich presolar silicate grains show a clear destruction trend with parent body aqueous alteration. For example, a foreign, carbon-rich clast found within the CR2 carbonaceous meteorite La Paz Icefield (LAP) 02342 contains a presolar O-rich grain abundance of 360 ppm, which includes both presolar silicates and oxides (Fig. 5; Nittler et al. 2019). In contrast, the surrounding fine-grained matrix contains ~30 ppm presolar O-rich grains. Because this meteorite has been aqueously altered (petrologic type 2), the extremely high C-rich makeup of the clast must be responsible for protecting the internal presolar silicate grains from destruction. On closer inspection, the clast contains many similarities to UCAMMs, such as the extremely high abundance of carbon (~70% carbon by area) and inclusion of amorphous silicates and sodium sulfates. Nanoscale X-ray absorption spectroscopic mapping of the iron oxidation state of minerals found that iron oxides within the carbon-rich clast were more reduced and showed a greater variance in oxidation state than those in the fine-grained matrix. This difference suggests that iron oxides in the surrounding matrix were equilibrated with parent body fluids, yet those within the clast retained much of their original valency.
Complex organic matter may be a protective host to other mineral phases as well that would normally be destroyed by aqueous alteration. Nanoscale electron energy-loss spectroscopy of IOM revealed copious nanodiamond grains hidden within IOM mesoparticles, but not within the larger grains or nanoglobules (De Gregorio et al. 2019). Highly reduced iron carbide grains, which would otherwise be transformed into iron oxides by oxidizing hydrothermal fluids, are retained in aqueously altered meteorites by virtue of their protective organic coatings (Brearley 2021). In IDPs and UCAMMs, primitive amorphous silicates are embedded within continuous regions of complex organic matter (Yabuta et al. 2017; Guérin et al. 2020). The extent to which complex organic matter acts as a barrier to aqueous fluids on asteroid parent bodies is largely unknown and is only beginning to be studied.

CONCLUSION

The unique thermal and fluid processing histories of asteroids and comets resulted in an increase in the diversity of complex organic matter that was present in the early Solar System, creating the range of elemental compositions, morphologies, functional group chemistries, and isotopic compositions we observe today. Advanced microscopy and spectroscopy methods allow in-situ characterization of complex organic matter within the fine-grained matrix of carbonaceous chondrite meteorites and in IDPs and UCAMMs with an unprecedented level of spatial detail. These in-situ studies provide additional petrographic context and access a more holistic picture of complex organic matter than previous studies of IOM residues. As a result, we are discovering that complex organic matter played a more active role in parent body processing, affecting changes of inorganic components even as those components are affecting change of organic materials.

Complex organic matter has continually been deposited on the surface of the Earth since its formation (Martins and Pasek 2024 this issue). As described above, it contains a much greater complexity and diversity than purely interstellar and nebular carbonaceous matter, but it is unclear to what extent this extra diversity influenced the emergence and evolution of life on Earth. As our knowledge of the diversity and intricate formation pathways of complex organic matter grows, future research should explore how much of this material could have provided bioavailable nutrients to early microorganisms.

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Asteroidal Organics from the Sample Return Mission

Hayabusa2 and their Implication for Understanding our Origins

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INTRODUCTION

The C-type asteroid Ryugu samples returned by the Hayabusa2 spacecraft are the chemically most pristine material in the Solar System, as they have not been exposed to terrestrial environments. The organic matter in Ryugu records the molecular evolution from the Sun’s parent molecular cloud chemistry to asteroidal aqueous alteration. In this article, we review the results of Ryugu sample analysis and discuss the evolution of organic matter in the early Solar System by comparing these results with recent radio and infrared observations of protostars and protoplanetary disks.

Keywords: sample return; C-type asteroid; molecular evolution; astronomical observation

The C-type asteroid Ryugu samples returned by the Hayabusa2 spacecraft are the chemically most pristine material in the Solar System, as they have not been exposed to terrestrial environments. The organic matter in Ryugu records the molecular evolution from the Sun’s parent molecular cloud chemistry to asteroidal aqueous alteration. In this article, we review the results of Ryugu sample analysis and discuss the evolution of organic matter in the early Solar System by comparing these results with recent radio and infrared observations of protostars and protoplanetary disks.

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The Solar System was born 4.567 billion years ago, initiated from the collapse of the Sun’s parent molecular cloud core. The infant Sun was surrounded by a protoplanetary disk, where various planets, including Earth, are thought to have formed in the first ~100 million years. Life emerged on Earth, covered with ocean, some 4 billion years ago. Life on Earth then co-evolved with the near-surface environment, and the present Earth’s atmosphere contains ~20% of biogenically produced O2. However, we do not yet fully understand how the Solar System formed, how the Sun’s protoplanetary disk evolved, how, when, and from what the lush Earth became habitable, how life arose on the Earth, and where some form of extraterrestrial life may exist.

The Solar System consists of the Sun, eight planets and their moons, dwarf planets, small bodies such as asteroids (most of which have orbits in the so-called main belt between Mars and Jupiter), and comets with their aphelion in the outer Solar System. The answers to some of the posed questions may be hidden in pristine (i.e., largely unaltered) small bodies that are the first celestial objects formed in the early Solar System. Some of these small bodies have not experienced melting and have kept their original ingredients, thereby containing information on the initial state of the Solar System.

Many meteorites likely came from these small bodies, and the study of meteorites has revealed that (i) the nuclides in the Solar System are of nucleosynthetic origin in various ancestor stars and (ii) various chemical reactions in the early Solar System occurred, depending on the distance from the Sun, prior to the formation of small bodies that resulted in the diverse chemical characteristics of undifferentiated meteorites (called chondrites). However, in most cases, it is not yet clear where in the Solar System the various chondrites come from, and this has made it difficult to understand the formation of the Solar System architecture from meteorites. The exception is the relationship between S-type asteroids and ordinary chondrites. Particles of S-type near-Earth asteroid (25143) Itokawa, returned by the Hayabusa spacecraft, comprised of equilibrated ordinary chondrites, the most common meteorites.

There are chondrites containing organics, the so-called carbonaceous chondrites, some of which also contain hydrous silicates. These chondrites have been a candidate for being the suppliers of water and organics to the early Earth. It has been hypothesized that carbonaceous chondrites are from C-type asteroids, a major group of asteroids, because of their spectroscopic similarity.

Japan Aerospace Exploration Agency (JAXA)’s Hayabusa2 spacecraft aimed to investigate C-type, near-Earth asteroid (162173) Ryugu and bring samples back to the Earth for detailed analysis (Tachibana et al. 2014; Fig. 1). One of the scientific goals of the returned sample analysis was to characterize the asteroidal organic matter because organics in C-type asteroids could have been a possible source material of the emerging life on Earth, and because organic molecules consisting mainly of C, H, O, and N are powerful chemical tracers of the formation environments of stars and planetary systems (e.g., Caselli and Ceccarelli 2012; Sakai and Yamamoto 2013).

Why can organic molecules be powerful tracers of the formation environments of stars and planetary systems? It has been revealed that the chemistry of protostars and protoplanetary disks is diverse; some are enriched in saturated molecules (e.g., CH3OH), while others are enriched in unsaturated carbon chain molecules (e.g., CCH) (e.g., Sakai and Yamamoto 2013; Yang et al. 2021). This diversity likely reflects the difference in the time interval (~10^5–10^6 years) between the cloud formation and the onset of star formation. Thus, the molecular diversity can be a diagnostic probe to understand the physical condition of the regions where stars and planetary systems form (e.g., Yamamoto 2017). The high spatial resolution observations by the Atacama Large Millimeter/submillimeter Array...
(ALMA) have enabled us to observe molecular distributions in protoplanetary disks, showing that the chemical diversity of parent clouds is inherited by the protoplanetary disks (e.g., Sakai et al. 2014). In addition to the radio spectroscopy of organic molecules with ALMA, the James Webb Space Telescope (JWST) has begun its infrared observation to determine the ice compositions in molecular clouds (Yang et al. 2022; McClure et al. 2023), which provide complementary chemical information to the chemistry of gaseous molecules.

This article provides an overview of the analytical results of the Ryugu samples, focusing on organic matter, and discusses its potential importance to understand the origin of the Solar System by comparing them with recent astronomical observations.

**SAMPLE RETURN FROM C-TYPE ASTEROID RYUGU**

Hayabusa2 found that the bulk density of Ryugu (mean radius = 448 ± 2 m) is 1.19 ± 0.03 g cm⁻³, which is lower than that of typical chondrites, suggesting that Ryugu is a so-called rubble-pile, formed through re-accumulation of fragments of an ancestor body that broke up (e.g., Sugita et al. 2022; McClure et al. 2023), which provide complementary chemical information to the chemistry of gaseous molecules.
et al. 2019) (cf. Earth’s bulk density = 5.5 g cm$^{-3}$). The surface is darker than most meteorite samples (Sugita et al. 2019) and shows a weak but ubiquitous 2.72-μm absorption feature of O–H vibration in phyllosilicates, suggesting that Ryugu’s parent body once underwent global hydrous alteration (Kitazato et al. 2019).

Hayabusa2 made its first touchdown to collect surface samples and a second touchdown near an artificial crater that the spacecraft made to collect samples possibly containing sub-surface material (e.g., Tachibana et al. 2022; Fig. 1). The samples collected at the two locations were separately stored in the sample container.

The Hayabusa2 spacecraft delivered its re-entry capsule in December 2020 (Fig. 1). The sample container inside the re-entry capsule was opened in the clean chamber system at JAXA’s Institute of Space and Astronautical Science (ISAS). The returned particles (cm-sized grains to fine powder; 5 grams in total) were black in color, consistent with the color of Ryugu boulders (Fig. 1).

**INITIAL ANALYSIS OF RYUGU SAMPLES**

About 0.3 grams of returned samples were allocated to the Hayabusa2 project for a one-year analysis (initial analysis hereafter). In this section, we briefly review the analytical results of the Ryugu samples allocated to the initial analysis team, which consisted of six sub-teams analyzing the sample with different approaches (e.g., Yokoyama et al. 2022; Nakamura et al. 2022; Okazaki et al. 2022; Noguchi et al. 2023; Naraoka et al. 2023; Yabuta et al. 2023).

The initial analysis of Ryugu samples has shown that the samples have bulk elemental compositions similar to those of the Sun and CI chondrites (e.g., Yokoyama et al. 2022). The latter are the chemically most primitive meteorites, having elemental abundances most similar to the Sun, except for highly volatile elements such as hydrogen and noble gases (Fig. 2). This suggests that the parent planetesimals of both CI chondrites and Ryugu thus formed from the Solar System’s original elemental ingredients without experiencing elemental fractionation processes (except for highly volatiles).

The Ryugu samples are similar to CI chondrites from mineralogical and petrological perspectives as well (e.g., Nakamura et al. 2022; Yokoyama et al. 2022; Noguchi et al. 2023); for example, they are highly aqueously altered rock consisting mostly of phyllosilicates such as saponite and serpentine (Nakamura et al. 2022; Fig. 3). The phyllosilicate matrix contains carbonates (dolomite and breunnerite), iron sulfides (pyrrhotite and pentlandite), and magnetite, all of which are considered to have precipitated from aqueous solution (Nakamura et al. 2022). Assuming oxygen isotope equilibrium between dolomite and magnetite, these two minerals were at equilibrium at 37 ± 10 °C (Yokoyama et al. 2022). The $^{3}$Mn$^{3}$Cr system in carbonates indicates that they formed from an aqueous fluid ~5 (+1.6/−2.1) million years after the formation of the oldest refractory solids in the Solar System (Yokoyama et al. 2022).

The aqueous fluid found in a pyrrhotite grain contained CO$_2$, nitrogen-bearing species, sulfur, and organic compounds (Nakamura et al. 2022). The CO$_2$ in the fluid may have come from CO$_2$ ice, implying that Ryugu’s...
parent planetesimal formed beyond the CO$_2$ snowline of the protoplanetary disk and was later transported into the inner Solar System to be a part of C-type asteroids in the main belt.

The carbon abundance of the bulk Ryugu samples ranges from 3.2 to 6.8 wt.% (Yokoyama et al. 2022; Okazaki et al. 2022; Naraoka et al. 2023; Oba et al. 2023), which is similar to that in CI chondrites. About 2/3 of this carbon is in organic matter (Yokoyama et al. 2022). The bulk nitrogen abundance of 0.07–0.16 wt.% (Okazaki et al. 2022; Naraoka et al. 2023; Oba et al. 2023) is also consistent with CI chondrites. The bulk N/C ratios of the Ryugu samples and CI chondrites are lower than the solar N/C ratio, which suggests that nitrogen was fractionated more than carbon, due to its highly volatile nature, and was not fully incorporated into the building blocks of Ryugu’s parent body. We note that even though Ryugu’s volatile contents are not comparable with those of the Sun, they are among the highest known in any meteorite sample. For instance, the noble gas abundances of the Ryugu samples are similar to or even higher than those in CI chondrites (Okazaki et al. 2022).

Although CI chondrites are mineralogically and petrologically similar to Ryugu, the former contain sulfates and ferrhydrite, which have not been commonly found in Ryugu samples (Nakamura et al. 2022; Yokoyama et al. 2022). The absence of sulfates and ferrhydrite in the Ryugu samples suggests that the CI chondrites have undergone terrestrial weathering, which may have affected the organic compounds to some extent. Therefore, the Ryugu samples are the freshest CI chondrite material that experienced no terrestrial weathering and are, thus, the best samples to serve as a chemical reference for the Solar System.

**ORGANIC MATTER IN RYUGU**

_Raman spectroscopy has shown that the macromolecular organic matter in the Ryugu samples is not structurally ordered, suggesting that it has not been thermally metamorphosed (Yabuta et al. 2023). The macromolecular organic matter contains aromatic and aliphatic carbon, ketone, and carboxyl functional groups, and the following four types are recognized through carbon XANES (X-ray absorption near-edge structure) spectroscopy: highly aromatic, aromatic, IOM (insoluble organic matter commonly found in carbonaceous chondrites)-like, and diffuse carbon associated with a molecular carbonate peak (Yabuta et al. 2023). These four structural types show a correlation with the morphology of organic matter; organic particulates and nanoglobules are often aromatic or highly aromatic, while the organic matter dispersed in the phyllosilicate matrix tends to show IOM-like or diffuse carbon spectra (Yabuta et al. 2023).

Because Ryugu materials experienced severe aqueous alteration in the first several million years of Solar System evolution (Yokoyama et al. 2022; Nakamura et al. 2022), a close association of macromolecular organic matter with phyllosilicates is observed as a result of co-evolution of organic matter and hydrous minerals (Yabuta et al. 2023). Despite such aqueous alteration, the Ryugu samples contain organic matter with hydrogen and/or nitrogen isotopic compositions that are highly enriched/depleted in D and $^{15}$N (Yabuta et al. 2023). These distinct isotope compositions of macromolecular organics may have been inherited from the chemistry in the Sun’s parent molecular cloud or the cold outer Solar System. Deuterium enrichment in interstellar molecules has been attributed to the D enrichment in H$_3^+$ through exothermic reactions (endothermic reactions would not occur at low temperatures such as 10–100 K), followed by ion–molecule reactions to form a variety of D-enriched molecules (e.g., Delgarno and Lepp 1984). The fractionation of nitrogen isotopes in interstellar molecules has been observationally confirmed, and $^{15}$N enrichment has also been found in cometary molecules (e.g., Füri and Marty 2015 and references therein). Such nitrogen isotope fractionation can be caused by ion–molecule reactions and/or photo dissociation (e.g., Füri and Marty 2015). The correlation between $^{15}$N/$^{14}$N and N concentration of bulk Ryugu grains suggests the presence of two distinct nitrogen sources ($^{15}$N-rich and $^{15}$N-poor sources) in Ryugu samples at milligram scale (Okazaki et al. 2022). The large isotope anomalies of H and N in the Ryugu samples suggest that the earliest generation of organic matter has been preserved in Ryugu. We also note that presolar carbonaceous materials with a wide range of $^{13}$C/$^{12}$C ratios, distinct from the solar ratio, are also present in the Ryugu samples. These are the circumstellar condensates that formed around carbon-rich stars (Barosch et al. 2022).
The N/C ratios of Ryugu's macromolecular organic matter range from 0.01 to 0.035 (Yabuta et al. 2023) and are within the range of N/C ratios of IOM in carbonaceous chondrites and those of organic particles from comet 67P/Churyumov–Gerasimenko (e.g., Yabuta et al. 2017; Fray et al. 2017; Fig. 4). Organic matter from particles from comet 81P/Wild2, interplanetary dust particles (IDPs), and an ultracarbonaceous Antarctic micrometeorite (UCAMM) shows a wide range of N/C ratios. Specifically, the ratios are higher than those found in IOMs in carbonaceous chondrites and even partially exceed the solar ratio (Fig. 4). The N/C ratios of Ryugu's macromolecular organic matter are consistent with the lower end of the N/C ranges of Wild2, IDPs, and an UCAMM (Fig. 4). Yabuta et al. (2023) argued that the N/C ratio of Ryugu's macromolecular organics should reflect the composition of macromolecular organics formed prior to the formation of Ryugu's parent planetesimal because the N/C ratio of the macromolecular organic matter is not largely affected by aqueous alteration on the parent bodies. Thus, the macromolecular organics with a N/C ratio lower than the solar N/C ratio were present together with those having the high N/C ratios in the Sun's protoplanetary disk, but the organic matter with the lower N/C ratio may have been preferentially incorporated into Ryugu's parent body and comet 67P/Churyumov–Gerasimenko. The selective incorporation of organic matter with lower N/C into Ryugu and the comet should be clarified in future studies.

**Solvent-Soluble Organic Molecules**

Solvent-soluble organic molecules were extracted from the Ryugu samples using different solvents (hexane, dichloromethane, methanol, and water) (Naraoka et al. 2023). Hundreds of thousands of ion signals with a mass-to-charge ratio of 150–700 were obtained from a methanol extract by Fourier transform–ion cyclotron resonance mass spectrometry (Naraoka et al. 2023). Chemical formulas containing C, H, N, O, and/or S were successfully assigned to about 20,000 ion signals (Naraoka et al. 2023). Their abundance patterns show repetitive mass differences, suggesting that there were various molecular evolution paths that added unit components to form large organic molecules (Naraoka et al. 2023). Such various evolutionary pathways indicate that these organic molecules formed abiotically because biotically formed organic molecules should show a more limited abundance pattern of essential molecules (Naraoka et al. 2023).

Polycyclic aromatic hydrocarbons (PAHs) and alkylbenzenes such as naphthalene, phenanthrene, anthracene, fluoranthene, pyrene, methylfluoranthenes, and methylpyrenes were detected from the Ryugu samples. These molecules could be the products of hydrothermal processes on Ryugu's parent body, but could also be interstellar in origin (Naraoka et al. 2023). If the latter is the case, PAHs should also record the chemical processes that were active prior to the formation of the Solar System. Indeed, gaseous aromatic rings of hydrocarbons were recently detected in a star-forming cloud (e.g., Guélin and Cernicharo 2022). Volatile aliphatic amines were also identified (methylamine, ethylamine, isopropylamine, and n-propylamine; Naraoka et al. 2023). These amines were probably present as amine/ammonia salts in the Ryugu grains.

Magnesium-bearing organic molecules, which have been observed in carbonaceous chondrites, were not detected in the Ryugu samples, implying that the aqueous alteration on Ryugu's parent body occurred at a relatively low temperature (∼150 °C; Naraoka et al. 2023). On the other hand, hexamethylenetetramine (HMT) \((C_6H_{12}N_4)\) that could be formed in a molecular cloud was not detected in the Ryugu samples (Naraoka et al. 2023). This implies that Ryugu's parent body did experience ∼150 °C, above which HMT is decomposed into formaldehyde and ammonia. Although the amount of sample used to analyze the Mg-bearing organic molecules and HMT was limited and further investigation is needed, the maximum temperature that Ryugu's parent body experienced during aqueous alteration could have been ∼150 °C.

Astrobiologically important molecules were also detected in the Ryugu samples. Twenty-three amino acids, both proteinogenic and non-proteinogenic, have so far been identified. Some of these are present as racemic mixtures, suggesting that they were indigenous to the Ryugu sample and are not terrestrial contaminants (Naraoka et al. 2023). One of the nucleobases constituting RNA, uracil, was found with its structural isomers in the acid hydrolysates of the Ryugu samples (Oba et al. 2023). In the search for nitrogen heterocyclic molecules, nicotinic acid (8-aminopyrrol) was also found with its derivatives (Oba et al. 2023). The detection of these molecules implies that molecules essential for terrestrial life were synthesized on small planetesimals like Ryugu and/or before planetesimal formation, and could have been delivered during and/or after the formation of the Earth and other Solar System bodies.
The growing number of observations of protostars with ALMA has shown that 58% of 50 embedded protostars in the Perseus molecular cloud are hot corinos (Yang et al. 2021). They also show a large diversity of COM (e.g., CH$_3$OH, CH$_3$CN, CH$_3$OCHO, and CH$_3$OCH$_3$) abundances over more than two orders of magnitude among the sources. Large diversity was also found in a different cloud, the Orion A molecular cloud (Bouvier et al. 2022), in which 26% of 19 protostars were found to be hot corinos. Although the statistics need to be improved, the difference in the proportion of hot corino objects between the Perseus and Orion molecular clouds implies that the molecular evolution of protostars is controlled by the star-forming environment; the former cloud forms only low-mass stars, while the latter forms massive stars as well.

The high spatial resolution and high sensitivity of ALMA observations have enabled astronomers to study the chemistry of protoplanetary disk–forming regions. The protoplanetary disks inherit the characteristics of molecular diversity from the envelopes of protostars (e.g., Sakai et al. 2014; Oya et al. 2016). The chemistry of protoplanetary disks should therefore be similarly diverse, reflecting the observed diversity of the envelopes of protostars. The Solar System formed 4.567 billion years ago as one of such chemically diverse protoplanetary systems. The Solar System’s small bodies, such as comets and asteroids including Ryugu, are expected to record the initial chemical environment of the Solar System.

The Rosetta spacecraft detected numerous molecules, such as H$_2$O, CO$_2$, CO, O$_2$, NH$_3$, HCN, HCONO, CH$_3$NO, CH$_3$CN, HC$_3$N, H$_2$S, SO, and their isotopologues, from 67P/Churyumov–Gerasimenko (e.g., Altwegg et al. 2019). The presence of highly volatile species and the deuterium enrichment in H$_2$O, H$_2$S, and methanol (e.g., Altwegg et al. 2019) suggest that the cometary volatiles are inherited (at least partly) from the Sun’s parent molecular cloud. Drozdovskaya et al. (2019) compared the relative abundances of various cometary molecules in 67P/Churyumov–Gerasimenko with those in the protostar IRAS 16293-2422, which is known as a hot corino object (e.g. Caselli and Ceccarelli 2012). They showed that the abundances of CHO-, N-, and S-bearing molecules relative to molecules such as CH$_3$OH, CH$_3$CN+CH$_3$NC, and CH$_3$SH in the comet and protostar show a correlation with some scatter. If the correlation is confirmed in further investigations, we may be able to say that the Sun’s parent molecular cloud evolved like a hot corino.

The Ryugu sample is the chemically most pristine material in the Solar System with no terrestrial alteration, and is currently the best material to study the organic evolution from the birth environment of the Solar System to planetesimal aqueous alteration. As mentioned, the Ryugu samples contain a variety of organic matter from macromolecular organic matter with morphological and structural variations (Yabuta et al. 2023) to more than 20,000 soluble organic molecules including pre-biotic molecules (Naraoka et al. 2023; Oba et al. 2023). Because Ryugu underwent aqueous alteration, the initial characteristics of organic matter in the Sun’s protoplanetary disk and parent molecular cloud have largely been erased through polymerization of COMs into larger molecules.

In spite of the overprint of aqueous alteration, Ryugu’s organic matter still records organic evolution before planetesimal formation. The D- and/or $^{15}$N-rich macromolecular organic matter in Ryugu (Yabuta et al. 2023) should have inherited the heavy isotope enrichment in organic molecules observed in molecular clouds, followed by isotope dilution on the parent body to some extent. Some volatile species, such as formic acid, acetic acid, methylamine, and PAHs (Naraoka et al. 2023), could also be a molecular heritage from the Sun’s parent molecular cloud, although further investigation, especially isotope analysis, is required to determine their origins.

Fluid inclusions found within a pyrrhotite grain in the Ryugu sample contained CO$_2$ ice, implying that Ryugu’s parent planetesimal contained CO$_2$ ice (Nakamura et al. 2023). The recent infrared observations with JWST have confirmed CO$_2$-bearing H$_2$O ice and CO$_2$ ice in protostars Cha MMS1 and IRAS 15398–3359 (Yang et al. 2022; McClure et al. 2023). The CO$_2$-bearing ices contain organic molecules as well, and hence, such ices could have been one of the original ingredients of Ryugu and 67P/Churyumov–Gerasimenko (e.g., Altwegg et al. 2019). After formation in the early Solar System, these two objects experienced
different evolutionary pathways; Ryugu underwent aqueous alteration via chemical reactions with liquid water, of which the heat source was probably the short-lived radionuclide $^{26}$Al (Nakamura et al. 2023), while 67P/Churyumov–Gerasimenko has been mostly frozen since its formation and is thus expected to preserve the original ice component of the Solar System.

To explain the lower than solar N/C ratios found in macromolecular organic matter in comets, IDPs, Ryugu, and carbonaceous chondrites, it is necessary to study the molecular evolution pathway from interstellar ice to the macromolecular organics through COM. The evolution would have taken place before planetesimal formation in the protoplanetary disk and/or in the molecular cloud, as discussed by Yabuta et al. (2023) (Fig. 4). The lower abundance of volatiles in Ryugu samples compared with comets also suggests that Ryugu’s parent planetesimal incorporated volatiles less efficiently than comets, indicating regional chemical variation (likely along the radial direction) in the Sun’s protoplanetary disk.

It is therefore essential to make an effort to trace molecular evolution back to the origin of the Solar System from the Ryugu samples by unveiling the overprint of asteroidal and disk processes. Ongoing and future Solar-System exploration missions to primitive small bodies, such as OSIRIS-REx, Lucy, and comet nucleus sample return missions, will also provide materials that record evolutionary evidence from the prebirth environment of the Solar System to the aqueous environment on planetesimals. The samples from B-type asteroid (101955) Bennu, returned by OSIRIS-REx, will tell us about the origin and evolution of another hydrated carbonaceous small body in the context of the Solar System evolution. The Lucy spacecraft will show us Jupiter’s Trojan asteroids for the first time. Some of the target bodies are D- and P-type asteroids, which could be remnant materials that formed the outer planets and differ from Ryugu and Bennu. Samples from comet nuclei that escaped significant chemical reactions after their formation will allow us to directly compare Solar System volatiles with the ices and molecules observed by telescopes. Further astronomical observations of gaseous molecules and ices in protostars and protoplanetary disks will tell us about the details of the diversity of molecular evolution in the early epoch of star and planetary system formation. By comparing the evidence from Solar System materials with the observations, we can comprehend the origins of the Solar System and the stars and planets in the Galaxy. We also emphasize that it is important to understand the fundamentals of elementary processes (e.g., reaction mechanisms, activation energy barriers for reactions, branching ratios of reactions; Fig. 5) experimentally and theoretically to form organic matter in the gas phase, on grain surfaces, and in the icy grain mantle with changing physical and chemical environments during star and planet formation for better understanding our origins.

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References
Analytical Techniques for Identification and Characterization of Extraterrestrial Organic Matter

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INTRODUCTION

Organic matter in meteorites has been analyzed since the 1800s, while modern techniques have been applied since the 1960s' Apollo era. The Murchison meteorite fell in 1969 and extraterrestrial amino acids were detected in a well-equipped laboratory designed for analyses of Apollo samples (Kvenvolden et al. 1970). Since then, the Murchison meteorite has been the meteorite most intensively analyzed for organic matter and has witnessed substantial developments of analytical techniques over decades as a kind of “standard” sample. Briefly, organic compounds in chondritic meteorites are analyzed by solvent extractions and acid demineralization. The former are called soluble organic matter (SOM) and the latter are called insoluble organic matter (IOM). IOM is ~2 wt.% of a typical unheated carbonaceous chondrite, but SOM ranges from ppb to ppm levels (depending on the compounds and meteorite classes). The relationship between SOM and IOM is currently unclear. The whole analytical process includes hot water extraction (for amino acids, amines, carboxyl acids etc.), methanol and dichloromethane extraction (for less-polar and non-polar compounds), followed by HCl and HF or CsF treatments to dissolve inorganic materials to finally obtain the acid residual IOM. These procedures can be varied depending on the purpose. More recently, microscopic techniques have often been used for direct analyses of organic matter without such extractions. Direct two-dimensional analyses (there are even three-dimensional techniques) allow researchers to obtain the spatial contexts that are lost by the extraction procedures. Such direct analyses are suitable for small samples such as interplanetary dust particles (IDPs), micrometeorites, and mission-retumed samples. Analytical instruments developed for in-situ or remote investigations during planetary exploration missions have also provided opportunities for direct analyses of organic matter on Mars, moons, and small bodies in the Solar System.

MASS SPECTROMETRY

Mass spectrometry (MS) is widely used for analyses of extraterrestrial organic matter in various ways. This technique has been used for over 50 years and has improved significantly in accuracy and precision over time. There are large variations in ionization and mass separation techniques that allow us to obtain different kinds of invaluable information. The most common ionization techniques are electron ionization (EI) and electrospray ionization (ESI). The former is a hard ionization that breaks a molecule into fragment ions that give a specific fragmentation pattern in the mass spectra, providing information about its molecular structure. The latter is a soft ionization that results in very little fragmentation and, thus, is typically used to determine molecular weights. The most common mass spectrometers are the magnetic sector mass spectrometer, time-of-flight mass spectrometer (TOF-MS), and quadrupole mass spectrometer (Q-MS). Chromatographic separations such as gas chromatography (GC) and liquid chromatography (LC) are often used before introducing samples to a mass spectrometer for better identification of the compounds.

Elemental and Isotopic Analysis

Elemental and isotopic analyses that provide the basic characteristics of IOM are performed using MS analysis combined with sample processing (pyrolysis or combustion) and GC separation (Alexander et al. 2007). Analyses of N and C are typically conducted by heating samples in a high-temperature (~1000 °C) oven and combusting with O₂ and a catalyst. The resulting CO₂ and N₂ gases are then...
separated by GC and introduced to a mass spectrometer to obtain $^{12}\text{C}$, $^{13}\text{C}$, $^{14}\text{N}$, and $^{15}\text{N}$ abundances by comparing them to standard gases. H and O in samples are converted to H$_2$ and CO by high-temperature pyrolysis ($\sim$1500 °C), then separated by GC before being introduced to a mass spectrometer to obtain $^1\text{H}$, $^2\text{H}$ (D), $^{16}\text{O}$, $^{17}\text{O}$, and $^{18}\text{O}$ abundances. The H/C, N/C, and O/C atomic ratios (i.e., Murchison IOM has a composition of C$_{1000}$H$_{389}$N$_{25}$O$_{158}$S$_{18}$, with the abundance of S estimated using H, C, N, and ash weight fractions) and D, $^{15}\text{N}$, and $^{13}\text{C}$ values are often used to infer the origin and degree of alteration of IOM from chondrites (Alexander et al. 2007).

**GC/MS and LC/MS**

For targeted analyses of compounds including amino acids, carboxylic acids, amines etc., GC/MS and LC/MS are often used after solvent extractions. The main reason for combining GC or LC with MS is the identification and quantification of the targeted compounds by comparison with their standards. Complicated laboratory workups are usually required before GC/MS or LC/MS analysis. Amino acids (and their precursors) are extracted from a powdered meteorite sample by hot water, hydrolyzed by HCl, desalted by an ion exchange resin to avoid damage to the GC or LC columns, and then derivatized (chemical modification of targeted compounds into suitable structures for analysis) before introducing samples to GC/MS or LC/MS (Simkus et al. 2019). For both GC/MS and LC/MS, the derivatization is mandatory in many cases. For GC/MS, various derivatization methods allow separation of enantiomers (D or L amino acids) with the use of a chiral column, e.g., trifluoroacetic acid (TFA) or trifluoroacetic anhydride (TFAA) derivatization is typically used. For LC/MS, o-phthalaldehyde and N-acetyl-L-cysteine (OPA/NAC) derivatization is often used, which allows chiral separation without the use of a chiral column. OPA/NAC derivatization is also suitable for UV fluorescence detection combined with MS that allows highly sensitive quantitative analysis with precise molecular identifications. Moreover, gas chromatography coupled with mass spectrometry and isotope ratio mass spectrometry (GC-MS/IRMS) allows compound-specific stable isotopic measurements.

**High-Resolution MS (FTICR and Orbitrap)**

For non-targeted analyses with mass spectrometry, a high mass resolution (the ability to separate ions with very similar, but different masses) is required. Accurate masses provide specific elemental compositions, e.g., the integral mass of N$_2$ and CO is 28 u, but their precise monoisotopic masses are 28.006148 u and 27.994915 u, respectively, which can be separated with a mass resolution of $R = 28/\left(28.006148 - 27.994915\right) \approx 2500$. ESI Fourier transform ion cyclotron resonance/mass spectrometry (FTICR/MS) has the highest mass resolution $R$ of 900,000 (see Fig. 1), allowing the detection of tens of thousands of different molecular compositions without GC or LC separations from solvent extracted organic compounds in the Murchison meteorite (Schmitt-Kopplin et al. 2010). This method includes both ultra-high-resolution MS using FTICR, and also ESI, which enables direct ionization of each compound without fragmentation. Because of the complexity of the detected compounds, the H/C, O/C, and N/C ratios and mass defect analysis are useful for the purpose of constraining the molecular diversity and genetic relationships among the detected compounds. Orbitrap MS (a type of ion trap MS) also allows high-mass-resolution analyses and can be combined with LC or GC for both targeted and non-targeted analyses.

**Imaging Mass Spectrometry**

Mass spectrometry is often used for imaging analyses. The most common method for organic analysis using MS imaging is probably nanoscale secondary ion mass spectrometry (NanoSIMS), which is used for stable isotopic measurements with a spatial resolution of a few tens of nanometers (see Fig. 1). Local concentrations of D and $^{15}\text{N}$, so-called “isotopic hot-spots”, have been found in organic matter in meteorites, IDPs, micrometeorites, cometary, and asteroidal samples (e.g., Messenger 2000). Microprobe two-step laser mass spectrometry (μL2MS) is used for the in-situ analysis of polycyclic aromatic hydrocarbons (PAHs) and related compounds with 40 × 40 μm spatial resolution by vaporizing and ionizing with two independent laser sources (e.g., Clemett and Zare 1997). Desorption electrospray ionization (DESI) combined with high-resolution MS allows soluble organic compound analysis with a typical surface spatial resolution of 50–100 μm using a spray of electrically charged solvent, such as methanol, to visualize the heterogeneous distributions of soluble organic compounds in meteorites (e.g., Naraoka and Hashiguchi 2018).

**Mass Spectrometry for Space Exploration**

Mass spectrometry is also used for in-situ analyses by space exploration missions. The _Cassini_ orbiter at Saturn and its moons had two mass spectrometers onboard—the Cosmic Dust Analyzer (CDA) and the Ion and Neutral Mass Spectrometer (INMS). The INMS detected H$_2$O, CO$_2$, CO/N$_2$ (m/z 28, cannot be separated), CH$_4$, C$_2$H$_2$ (acetylene), C$_2$H$_4$ (propane), and NH$_3$ in the Enceladus plume (Waite et al. 2006). Complex macromolecular organic material with molecular masses above 200 atomic mass units was also detected in ice grains from the Enceladus plume (Postberg et al. 2018). The _Rosetta_ spacecraft had four mass spectrometers, two in the orbiter—the
the presence of more than $2 \times 10^{19}$ free radicals/gram was conducted by Schulz and Elofson (1965) who reported  

... radicals, ions, and molecules having an odd number of electrons; thus, information on their molecular structures can be obtained via ESR spectroscopy.  

... and dynamics, such as electronic distribution, molecular orientations, and nature of the molecular environment, and better constraining its formation and evolution in space, although we review only a few of them here.

**SPECTROSCOPY**

Spectroscopy is the interaction between electromagnetic radiation and matter as a function of the wavelength of the radiation. Detailed chemical, molecular, structural, and compositional information can be obtained from extraterrestrial samples depending on the spectroscopic technique applied. There are many kinds of spectroscopic techniques (Fig. 2) for studying complex extraterrestrial organic matter and better constraining its formation and evolution in space, although we review only a few of them here.

**ESR Spectroscopy**

Electron spin resonance (ESR) spectroscopy is based on the interaction between an external magnetic field and the spins of unpaired electrons (radicals) in molecules. It is, in many ways, similar to nuclear magnetic resonance (NMR) spectroscopy, as discussed in the following section. The theoretical difference mainly lies in the excited spin under an externally applied magnetic field. In NMR spectroscopy, nuclei spins are excited, whereas in ESR spectroscopy, the electron spins are excited. ESR spectroscopy measures the energy difference of spin states that are aligned either parallel or antiparallel in an external magnetic field. Many species contain one or more unpaired electrons (including free radicals, ions, and molecules having an odd number of electrons); thus, information on their molecular structures and dynamics, such as electronic distribution, molecular orientations, and nature of the molecular environment, can be obtained via ESR spectroscopy.

One of the first ESR studies on extraterrestrial organic matter was conducted by Schulz and Elofson (1965) who reported the presence of more than $2 \times 10^{19}$ free radicals/gram in the IOM of the Orgueil meteorite. The IOM isolated from Murchison and Orgueil contains highly localized radical-rich ($3-4 \times 10^{19}$ spins/g, corresponding to 5%-20% of the IOM) organic molecules, as determined via ESR spectroscopy (Binet et al. 2002). Radicals in the IOM of meteorites are likely bonded to other radical moieties. The investigation by Alexander et al. (2022) on the IOM of a suite of carbonaceous chondrites provides the largest available ESR dataset to date.

**NMR Spectroscopy**

NMR spectroscopy measures the interaction of an oscillating electromagnetic field with the nuclei (with an integral or a fractional spin) of atoms that are in a static magnetic field, providing a spectrum that is characteristic to that specific nucleus of the atom. By probing variations in the resonant frequency caused by the position of the atom within a molecule, precise structural and proximity information can be obtained down to each atom and bond. Atoms with a non-zero nuclear spin, e.g., $^1$H, $^{13}$C, and $^{15}$N, can be detected using NMR. While requiring larger amounts (tens of mg of IOM) of sample for experiments compared with other spectroscopic methods, NMR enables better quantitative analysis. In the case of samples with abundant Fe-bearing molecules, measurements need to be made on the extracted organic matter rather than the whole samples. Solid-state $^{13}$C-NMR spectroscopic investigations by Cody et al. (2002) showed that ~60% of the total carbon present in the Murchison meteorite is aromatic, which is linked with oxygen-containing organic functional groups and highly branched aliphatic moieties. Solid-state $^{13}$C-NMR spectra quantitatively describe changes in the molecular structures by alteration, as seen in the IOM from several different lithologies in the Tagish Lake meteorites (Alexander et al. 2014; Fig. 3a). Most solid-state NMR studies on meteorites focus on the macromolecular IOM fraction, although a new generation of spectrometers with better detectors has made the detection of soluble organics possible using solution-state NMR. Thousands of individual NMR resonances were detected in the solution-state $^1$H-NMR spectra of soluble organics extracted from Murchison, which contains a wide range of aliphatic and aromatic chemical environments with substantial variability in the aliphatic branching (Schmitt-Kopplin et al. 2010).

**Infrared Spectroscopy**

Infrared (IR) spectroscopy is based on the absorption, transmission, reflection, or emission of light in the infrared region of the spectrum. It can be used to detect and characterize numerous chemical functional groups, including organic compounds, through their characteristic molecular vibrations. Generally, molecular vibrations that cause a change in the dipole moment are allowed in IR and forbidden in Raman (i.e., C–O, C=O, and C–N are weak Raman scatterers but strong IR absorbers), or vice versa. Thus, IR and Raman spectroscopies are complementary to each other. The IR region of the electromagnetic spectrum is divided into multiple parts; however, the mid-IR (~400–4000 cm$^{-1}$; 2.5–25 μm) is the most frequently chosen region for studying extraterrestrial organic matter because spectral intensities of organic matter in this range are often better resolved than in the near-IR (~14,000–4000 cm$^{-1}$; 0.7–2.5 μm) and far-IR (~400–10 cm$^{-1}$; 25–1000 μm) regions. Space telescopes such as the Kuiper Airborne Observatory, Spitzer Space Telescope, the Stratospheric Observatory for IR Astronomy, the Infrared Space Observatory, and the James Webb Space Telescope have detected signatures of many organic molecules in different astronomical regions. Ground-based IR observations and laboratory spectroscopic analysis of meteorites, IDPs, cometary dust, and
asteroid particles provide additional insights into many aspects of extraterrestrial organic matter and expand our understanding of carbon in the cosmos. Indeed, IR spectra of galactic center sources and meteoritic organic matter are remarkably similar near the 3.4 μm (~2950 cm⁻¹) region, where aliphatic C–H stretching vibrations occur (Ehrenfreund and Charnley 2000). A unique perspective on the complexity and heterogeneity of organic matter, and how it evolves through post-accretionary hydrothermal processes, can be obtained from the IR spectroscopic analysis of IOM in chondrites. Similar to NMR, molecular evolution in different lithologies of the Tagish Lake meteorite was detected by IR spectroscopy using functional group chemistry (Alexander et al. 2014; Fig. 3b). Studies on organic–mineral relations significantly improve our understanding of the evolution of organic matter, which is still not fully known. IR spectroscopy can also unravel organic–mineral relations in situ in extraterrestrial samples by interrogating organic matter within the local mineralogy of a sample. IR efforts for such a task include 2D IR imaging spectroscopy at micro- and nano-scales, and micro-scale 3D IR tomography, which have the capability to unravel spatially resolved and statistically significant organic–mineral relations with the goal of understanding the formation pathways of organics.

**Raman Spectroscopy**

Raman spectroscopy is based on the inelastic scattering of incident light from molecules. A portion of the incident photon energy is used to excite vibrations at frequencies characteristic to the molecules, which provides detailed chemical and molecular information. With the integration of microscopes to Raman spectrometers, studying structural and chemical properties of organics in situ within its local mineralogy both on the surface (via 2D mapping) and inside the samples (via 3D tomography; Fig. 4) has become possible. Organic matter in extraterrestrial samples has been the subject of a wide range of Raman spectroscopic studies. Raman spectroscopic investigations of the structural order of polyaromatic organic matter have attracted much attention because Raman spectroscopy is highly sensitive to even small amounts of structural ordering of carbon due to thermal annealing. This is a significant advantage because Raman spectra of extraterrestrial organic matter can be used as a geothermometer to reveal the peak metamorphic temperatures of chondritic meteorites and shed light on the thermal history of parent asteroids (e.g., Quirico et al. 2003). Busemann et al. (2007) compared the Raman spectral parameters of the carbon bands near 1350 cm⁻¹ (D-band) and 1580 cm⁻¹ (G-band) and observed that some primitive meteorites exhibit structural ordering in their polyaromatic organic matter that is similar to those seen in IDPs and comet Wild 2 particles, supporting the idea that the meteorite parent bodies may have accreted a similar precursor organic material as the parent bodies of the IDPs. This idea is supported by Raman observations of highly disordered carbon in IDPs and their similarity to meteoritic carbon (Starkey et al. 2013). Raman spectroscopy is also well suited for planetary exploration. In pursuit of the search for life (or extinct life) on Mars, Raman instruments have been developed for the NASA **Perseverance** rover mission, which has detected organics at Jezero crater (Scheller et al. 2022), and the upcoming **ESA ExoMars** rover mission, the primary goal of which is to detect organic compounds on the Martian surface.

**MICROSCOPY**

Microscopes and microscopic analysis techniques have significantly developed over the last couple of decades and now provide high-resolution access to molecular components, down to the atomic level. There are many different light, electron, and X-ray microscopy techniques. We review some of them below in the context of organic materials in extraterrestrial samples.

**Electron Microscopy**

Electron microscopes utilize a beam of accelerated electrons to illuminate the sample of interest. Compared with light microscopes, electron microscopes have much higher spatial resolution (nano to picometer) and resolving power, hence allowing the investigation of much smaller molecular, or even atomic components. As a result of the interactions between the electrons and the sample, different signals (i.e., secondary electrons (SE) and backscattered electrons (BSE)) are obtained. Characteristic X-rays can also be used to map the elemental composition of the sample surface (energy dispersive X-ray spectroscopy (EDS)). Thus, detailed compositional and morphological information can be easily determined. Scanning electron microscopy (SEM) is one of the most popular microscopic techniques, although only surface features are accessible via SEM. A focused, low-power electron beam (e.g., ~5–20 kV) raster scans an area of interest on the surface of a sample to produce SE, BSE, or element distribution images. Transmission electron microscopy (TEM), on the other hand, is based on the transmission of a beam of high-energy electrons (e.g., 200 kV) through sufficiently thin samples to reveal the structure and composition at the atomic level. Like many other fields, investigations of organic matter in meteorites, micrometeorites, IDPs, and asteroidal and cometary particles significantly benefit from SEM and TEM analyses, especially when coupled...
to energy dispersive X-ray spectroscopy (EDS) detectors, which enable semi-quantitative elemental analysis and compositional imaging or wavelength dispersive X-ray spectroscopy (WDS) detectors, which enable quantitative elemental analysis and compositional mapping. Extraterrestrial materials contain many kinds of organics, including nanoglobules (nanoscale carbonaceous particles) and carbon-rich clasts. SEM and TEM investigations of their forms, sizes, external structures, and morphologies provide a window into the evolution of materials in the early Solar System. Figure 5A–5C shows extraterrestrial carbonaceous nanoglobules observed with a range of forms and structures in primitive carbonaceous chondrites, as revealed by SEM and TEM imaging (Garvie et al. 2008; De Gregorio et al. 2013). Electron energy-loss spectroscopy (EELS) is often combined with TEM imaging to obtain molecular structure information and provide information similar to X-ray absorption near edge structure (XANES, see next section) spectra using electrons instead of X-rays.

**Figure 4** (A) Raman map of a region in the Didim meteorite (ordinary chondrite) containing both “disordered” (red) as well as “graphitic” (blue) carbonaceous materials. (B) Corresponding Raman spectra presenting the first- and second-order carbon bands, which indicate that the carbonaceous matter is less disordered than amorphous carbon, and aromatic units are large (but still far from graphite). (C) Raman map of a thin channel of carbonaceous matter (blue) separating olivine (green) structures in Didim. (D) 3D Raman tomographic distribution of the blue and green components. This dataset, collected from a 40 × 40 × 15 µm³ region and containing a total of 24,000 spectra, clearly shows that the carbonaceous matter extends underneath olivine and goes further down toward the interior. Modified from Yesiltas et al. (2020).

**Scanning Transmission X-Ray Microscopy**

X-ray microscopy has often been the method of choice for investigations focusing on extraterrestrial organic matter. Improvements in X-ray methodologies, bright light sources using synchrotrons, and detectors have given rise to one of the most advantageous X-ray methods: scanning transmission X-ray microscopy (STXM). For a STXM measurement, an X-ray image is collected by raster-scanning the surface of a sample while detecting the transmission intensity of focused X-rays for every pixel. This produces molecular/elemental abundance and distribution maps with ~30 nm resolution. As such, it is an extremely powerful analytical method. XANES analyses can be performed on X-ray spectra collected at each pixel, providing element-specific and local bonding information for molecules. STXM images and C- and N-XANES analyses therefore have this unique potential to unravel the complex organic chemistry and functional groups in a variety of objects, including primitive meteorites, micrometeorites, IDPs, and asteroidal and cometary particles (Fig. 5D).
Atomic Force Microscopy Coupled with IR Spectroscopy

Atomic force microscopy (AFM) allows investigation of material surfaces with unprecedented spatial resolution. Unlike traditional microscopes, AFM measurements use a sharp conductive probe at the end of a cantilever that physically interacts with surface features and generates a map of the surface topography and sample physical/mechanical properties. AFM can be combined with spectroscopy to obtain spectroscopic data with nm-scale resolution. Scattering-type scanning near-field optical microscopy (s-SNOM) coupled with nanoscale Fourier transform infrared (nano-FTIR) spectroscopy is a particularly exciting development because it overcomes the theoretical spatial resolution limits of conventional IR spectroscopy and allows AFM images with ~10 nm resolution, as well as IR spectra of molecular compounds that are otherwise inaccessible to be obtained via conventional IR methods.

In s-SNOM, the incident light (i.e., IR laser or synchrotron beam) is focused on a metallic AFM tip and the scattered light is measured to form an optical image with nanometer spatial resolution while collecting IR spectra of each pixel. Using s-SNOM, Dominguez et al. (2014) demonstrated the potential of nano-FTIR spectroscopy for extraterrestrial material by conducting a mineralogical investigation on Carbonaceous nanoglobules observed in theTagish Lake meteorite via SEM. Modified from Garvie et al. (2008). (C, D) TEM image and XANES spectra of nanoglobules in Murchison IOM. Modified from De Gregorio et al. (2013).
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a meteorite and a cometary dust grain. Alternatively, AFM can also be combined with a tunable infrared laser to detect photo-thermal expansion of samples via the opto-mechanical response of the AFM tip, which allows a few tens of nanometer spatial resolution and attributes similar to IR absorption spectra (Mathurin et al. 2019). This technique was used to reveal organic–mineral interactions (~30 nm spatial scale) that occurred during aqueous alteration of the parent asteroid of the Murchison and Bells meteorites (Kebukawa et al. 2019). Recently, s-SNOM nano-FTIR spectroscopy with ~20 nm spatial scales was also utilized to detect nano-sized prebiotic carboxyl compounds in a primitive meteorite (Yesiltas et al. 2021; Fig. S5, SF).

**PERSPECTIVES**

Recent advances in our understanding of the Solar System’s formation and evolution would not be possible without developments of advanced analytical techniques. In particular, the developments are remarkable since late 1960s—the Apollo era. It should be noted, however, that there are limits to the information that can be obtained from a single analytical technique. Coordinated analyses—including various analytical instruments for both organic and inorganic materials—would maximize the obtained information as well as the scientific output. Such techniques have been applied to meteorites and are especially useful for valuable samples from past and future return missions, including cometary dust; asteroids Itokawa, Ryugu, and Bennu; that occurred during aqueous alteration of the parent asteroid of the Murchison and Bells meteorites (Kebukawa et al. 2019). Finally, in addition to sample analysis, observations, experimental and numerical simulations should be combined to provide a complete picture of Solar System history.

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- 15 March 2024: Grant Application Deadline
- 29 March 2024: Abstract Submission Deadline
- 1 July 2024: Early Registration Deadline
CHANGES TO THE EAG COUNCIL

The Council elections took place last autumn and we are delighted to announce that Julie Prytulak (Durham University, UK) and Paolo Sossi (ETH Zürich, Switzerland) were elected. We are very grateful to all EAG members who voted and to all candidates who agreed to stand for election. The EAG Council also elected Pallavi Anand (Open University, UK), Baptiste Debret (IPGP, France) as Early Career Councillor, and Béatrice Luais (CRPG Nancy, France) as Treasurer.

The EAG could not function without all the scientists who volunteer for the association, and we take this opportunity to thank those who departed the Council at the end of 2023 for their immense contributions to the EAG during their respective terms: Treasurer, Estelle Rose Koga; Early Career Councillor, Janne Koorneef; and Councillors, Susan Little, Olivier Namur, and Carmen Sanchez-Valle.

A SPOTLIGHT ON EAG ACTIVITIES

Community and Communications

Connecting geochemists around the world to build a thriving and inclusive community forms the foundation of all EAG activities. Through day-to-day communications via newsletters and publication e-alerts, the EAG website, blogosphere, and social media channels, EAG news on activities and opportunities reaches thousands of geochemists around the world.

A number of activities were driven by the EAG’s Communication and Diversity, Equity, and Inclusion (DEI) Committees in 2023. Highlights included:

- articles and interviews on the EAG blogosphere and in Elements Society News (check out the ongoing blog series People’s Profiles and Careers outside Academia)
- EAG crosswords
- DEI events, sessions and initiatives at Goldschmidt2023, led by the EAG and Geochemical Society (GS) DEI committees
- publication of the results of the EAG-GS Global Geochemistry Survey (read more at https://www.eag.eu.com/about/dei/survey-report-and-questionnaire/)

In 2024, we also look forward to the launch of EAG Reactions, a series of informal online discussions—open to all and free to register—led by guest speakers on diverse topics. The first Reactions, on the topic of Carbon Dioxide Capture and Removal, will take place early this year. Find out more at https://www.eag.eu.com/events/reactions/

Supporting training opportunities for geochemists in the early stages of their careers, as well as those from under-represented regions, is core to the EAG. The Student Sponsorship and Early Career Science Ambassador Programs have provided funding for over 60 student and early career members to attend conferences, workshops, and other events over the past 5 years, and you can read about many of their experiences on the EAG blog. The Student Sponsorship Program has been expanded for 2024, and successful applicants can now
receive up to 1000€ to attend events in Europe (including short research stays at host institutes). Visit https://www.eag.eu.com/early-career/ for more information, and don’t miss the next application deadlines on 1 March (Ambassador Program) and 1 May (Student Sponsorship Program).

The EAG also organizes outreach initiatives in Eastern Europe through the EAG Distinguished Lecture Program (DLP), and in Africa through the EAG-GS Outreach Program. Recordings of Sandra Arndt’s 2023 DLP lectures can be watched on the EAG YouTube Channel. EAG-GS Outreach lecturer Sebastian Doetterl continues on his tour in 2024 with visits to Kenya, Uganda, and Malawi in January. Find out more at https://www.eag.eu.com/outreach/outreach-program/.

The EAG Short Course and Conference Sponsorship program supports student attendance at member-led events. We are proud to be co-sponsoring the following events in 2024:

<table>
<thead>
<tr>
<th>Event</th>
<th>Location</th>
<th>Dates</th>
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<tr>
<td>Tropical Resources Summer School</td>
<td>Fort Portal, Uganda</td>
<td>19–24 August 2024</td>
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<tr>
<td>Granulite &amp; Granulites 2024</td>
<td>Verbania, Italy</td>
<td>3–6 September 2024</td>
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<tr>
<td>5th SerpentineDays</td>
<td>Granada, Spain</td>
<td>23–25 September 2024</td>
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<tr>
<td>iGEO2024 Early Career Research Symposium</td>
<td>Galway, Ireland</td>
<td>25–28 October 2024</td>
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EAG Publications

The EAG publishes two open access society journals, created by and for the geochemistry community. Geochemical Perspectives publishes invited contributions by leading scientists and everyone now has access to 27 issues. Geochemical Perspectives Letters is EAG’s letters journal to which anyone can submit short articles of up to 3000 words. It is fully open access and has no page charges!

EAG Awards

Each year, the EAG presents a number of awards to recognize scientific excellence at various stages of a scientist’s career. The recipients of the 2024 EAG Awards will be announced in the coming weeks, and we encourage the whole community to consider submitting a nomination next autumn to ensure the recognition of deserving scientists.

Goldschmidt Conference

The Goldschmidt Conference, co-organized by the EAG and GS, is the world’s largest annual geochemistry conference, providing outstanding science as well as numerous networking and training opportunities through science and early career workshops, social events, and the Mentor Program, which in 2023 matched over 400 mentees to mentors in their fields. Crucial financial support for early career delegates from low and lower-middle income economy countries to attend is provided through the Goldschmidt Grant Program.

The GS and EAG look forward to welcoming delegates to Goldschmidt2024 in Chicago, USA, next August (note the upcoming deadlines: grant applications – 15 March; abstract submission: 29 March), and the Goldschmidt2025 Organizing and Science Committees are now hard at work in their preparations for Goldschmidt2025, which will take place in Prague, Czech Republic, on 6–11 July 2025.

Your EAG membership directly supports all of these activities and much more!

To find out more about the benefits of becoming an EAG member, visit https://eag.eu.com/membership or scan the QR code below!

How to:

- Publicize your new research article? Send us your press releases to include them in the newsletter. https://www.eag.eu.com/submit-a-press-release/.
- Propose a contribution for the EAG blog? Write to us at office@eag.eu.com.
- Promote an event? Add it to the EAG events calendar at https://www.eag.eu.com/events/conferences/.
- Connect with other EAG members? Log in to the EAG membership platform and post in the newsfeed and forums at https://members.eag.eu.com/.
- Meet the EAG? Visit us at EGU24 in April, Goldschmidt2024 in August, or attend the AGM online next autumn!
HAPPY 2024 TO ALL!

Best New Year wishes to all our members and Elements readers. It’s going to be a busy year at the Mineralogical Society.

New journal

This year marks the first of our new journal, Geo-Bio Interfaces. Check out the first content at www.cambridge.org/gbi. Be sure to set up a TOC (table of contents) alert so you can be informed when new content is published.

EMC 2024

Also this year, of course, we are hosting the fourth European Mineralogical Conference. If you haven’t already done so, go to www.emc-2024.org to see our proposed sessions list, keynote speakers, and to register. This event promises to be one of the best EMCs yet and we guarantee a warm Irish welcome in Dublin.

MINERALOGY AND MUSEUMS 10

The 10th Mineralogy & Museums conference will be held at Amgueddfa Cymru – Museum Wales, Cardiff, Wales, 12-14 August 2024, with an option of pre- and post-conference trips. M&M10 has been timed to allow participants to travel on to EMC³, in Dublin (18th-23rd August 2024).

This conference will focus on Collections, Research, Care, and how to make them accessible to the widest range of users and relevant to society. We aim to bring those with these common interests together to share ideas, knowledge, and experience, and to strengthen international links. This is the 10th meeting in the international conference series organized by the Commission on Museums of the International Mineralogical Association. To make the meeting as accessible as possible, the two-day program will include both in-person and remote talks, lightning talks, and poster presentations.

Go to www.mm-10.org for details and to register.

Special Interest Groups

By the time this issue reaches you, one of our Special Interest Groups (Volcanic and Magmatic Studies Group) will already have held its annual conference.

In April, we will have the 2024 renewal of the Geochemistry Group’s Research in Progress meeting, which will be held on 9-11 April 2024 at Durham University. For more details and to register, go to https://geochemistry.group/research-in-progress-meeting/.

The Metamorphic Studies Group will meet at the University of Bristol on 27-28 March 2024. Details are available at https://metamorphicstudiesgroup.wordpress.com/msg-rip-2024/.
Our other special interest groups will also hold their Research in Progress meetings during 2024. The Environmental Mineralogy Group has already agreed to join forces with a Royal Society of Chemistry Special Interest group for a meeting on a topic of mutual interest. The Clay Minerals Group will hold its annual RiP meeting at the University of Edinburgh (date to be confirmed). The Mineral Physics Group plans to follow up its most successful RiP ever (U. Bristol, 2023) with another well-attended event. The Applied Mineralogy Group will focus its efforts on sessions being held during the European Mineralogical Conference, mentioned above. The Geomicrobiology Network has yet to announce its plans.

If all of this wasn’t enough, each of the Special Interest Groups offers funding for students to attend conferences, do fieldwork, etc. Check this at https://www.minersoc.org/bursaries.html. The Geochemistry Group also runs an extensive programme of online events and a mentorship scheme: https://geochemistry.group/.

Website

Have you visited our website recently? It’s had a revamp and looks fresh and new. As our EDI changes come into force, we will also be updating many of the pages related to our membership, awards, meetings/events, and publications.

EDI

As mentioned above, our hard-working EDI committee will soon bring final versions of proposals regarding membership, awards, conferences, and more to Council for debate and approval. These actions will mark a significant change in how we do business and signals our approach to the business end (the application of new policies) of several years of work at our EDI committee. Our committee will continue, however, and it is our intention to ensure that it operates across all areas of our ‘business’.

Recent content in our journals

Guangyuanite, Pb₂Cl₃(Se⁴⁺O₃)(OH), a new lead-chloride-selenite mineral from the El Dragón mine, Potosí, Bolivia. Hexiong Yang, Xiangping Gu, James A. McGlasson, Ronald B. Gibbs, Robert T. Downs

Evidence of fluid-induced myrmekite formation after alkali-feldspar megacryst: example from a metaporphyritic granitoid in Makrohar, Madhya Pradesh, India. Arimita Chakrabarty, Shreyo Karmakar, Upama Dutta, Sanjoy Sanyal, Pulak Sengupta

IMA Commission on New Minerals, Nomenclature and Classification (CMNMC) Ferdinandino Bosi, Frédéric Hatert, Marco Pasero, Stuart J. Mills

Characterization, axial anisotropy and formation conditions of celestine from the Jabal Eghei (Nuqay) late Neogene – Pleistocene volcanic province, southern Libya: Constraints on the mineralogical geothermometer. Pavle Tančić, Maja Milošević, Darko Spahić, Bojan Kostić, Aleksandar Kremenović, Maja Poznanović-Spahić, Jovan Kovačević

Bimbrowrieite, NaMgFe³⁺₅(PO₄)₄(OH)₆·2H₂O, a new dufrénite-group mineral from the White Rock No.2 quarry, South Australia, Australia. Peter Elliott, Anthony R. Kampf

A new mineral cuprodobrovolskyite Na₄Cu(SO₄)₃ from the Tolbachik volcano (Kamchatka, Russia) and the relations in the family of natural anhydrous Na–Cu sulfates. Nadezhdà V. Shchipalkina, Igor V. Pekov, Natalia N. Koshlyakova, Dmitry I. Belakovskiy, Natalia V. Zubkova, Atali A. Agakhanov, Sergey N. Britvin, Maria A. Nazarova

Characterization of refractory bricks from selected Cameroonian kaolinites. Pountouenchí Amadou, Njóya André, Mbéy Jean Aimé, Mache Jacqué Richard, Njóya Dayirou, Yongue Fouateu Rose, Njopwouo Daniel, Nathalie Fagel, Pascal Pilate, Laurent Van Parys

Characterization of the clayey sediments in the environment of exposed mudflats on the western Dead Sea shore. Shlomo Shoval

The implications of Fe speciation for the humic substance stability of ternary Fe(III)–montmorillonite–humic substance systems. Qinlai Lei, Yahui Lv, Chengshuai Liu, Wenpo Xu, Shujie Hu, Manjia Chen, Hongliang Bu, Junhui Li

Preparation of phase-change microcapsules with illite as a filler and their applications in foaming materials. Ming Li, Shuhua Zhang, Weijun Liu, Binyan Liu, Yu Wang

Differential dissolution of interlayer, octahedral and tetrahedral cations of vermiculite in oxalic acid. Yu Zhang, Hongjuan Sun, Tongjiang Peng, Liming Luo, Li Zeng

Changes in the basic structure and strength deterioration of clay minerals with different hydration degrees. Jiyu Lin, Daoyong Wu, Jiwei Jia, Jing Yan, Lingtong Cai

Microstructural observations of clay-hosted pores in black shales: implications for porosity preservation and petrophysical variability. Hongjian Zhu, Shuangjian Li, Zongquan Hu, Yiwen Ju, Yanyan Pan, Manping Yang, Yanjun Lu, Mingbo Wei, Weidong Qian

FROM THE PRESIDENT

Dear members and friends,

At the end of 2023, a number of people concluded their service on the steering committee of the DMG and the recent elections have successfully helped to fill those positions. I would like to thank in particular two members, Gerhard Franz and Klaus-Dieter Grevel, who have served on the committee for the past nine years (2015–2023) as treasurer and secretary, respectively. Their experience in running the DMG’s business was invaluable for me and my predecessor chairmen, and the constructive collaboration and strong support in all our meetings and conferences over the past years have been very much appreciated. Klaus-Dieter Grevel continues to be part of the DMG steering committee as the newly elected treasurer. His previous job as the society’s secretary was taken over by Ina Alt. The fourth member of the steering committee, past-president Friedhelm von Blanckenburg, has left the inner circle and his place is now filled by newly elected Frank Schilling, designated chairman for 2025–2026. I want to thank Friedhelm for his years of service for the DMG and the many ideas and initiatives he has brought about. I also want to thank all the newly elected members of the board and the steering committee for running for all the various offices that carry the DMG and for accepting the appointment. I am looking forward to working with the new team in 2024.

Yours sincerely,
Horst Marschall

DMG YOUNG SCIENTIST AWARDS

Call for Applications 2024

At the annual meeting of the German Mineralogical Society (DMG) the Paul Ramdohr Award is given for the best oral and poster presentations by a student. Student DMG members may apply when submitting an abstract for the 102nd annual DMG meeting in 2024, which is enclosed in the 4th European Mineralogical Conference emc2 (https://emc-2024.org/). The application form can be downloaded from https://www.dmg-home.org/fileadmin/user_upload/Form-Paul-Ramdohr-Preis_v2024.pdf.

The Beate Mocck Prize of the DMG is intended to promote female scientists in an early stage of their career in the field of mineralogy, specifically in the areas of petrology and geochemistry. This award was created in memory of the geochemist and petrologist Beate Mocck by her family in 2013. Female undergraduate or PhD students who are also DMG members are eligible to apply. Please submit your application to Horst Marschall (marschall@em.uni-frankfurt.de).

Awardees 2023

Last year’s Beate Mocck Prize was awarded to Victoria Kohn (University Vienna) for her part of the international FWF-ARRS-funded (a joint project of the Austrian research fund and the Slovenian Research Agency) research project “Mineral Inclusions in Garnet: Correlating Shape and Crystallographic Orientation Relationships with Compositional and Interface Characteristics to Infer Inclusion Origins” at the Department of Lithosphere Research. As part of her dissertation, she investigated the controlling factors of mineral phase relationships between rutile inclusions and the garnet as host mineral. Victoria Kohn used various analytical methods, both 2D and 3D, providing valuable new insights into these relationships between crystallographic and chemical intergranular processes. Her dedicated and independent work and her well-founded scientific contribution are therefore honored with the Beate-Mocck Prize. The award was used by Victoria to attend the “Fluid and Melt Inclusions Protagonists in Palermo” workshop, which allowed her to deepen her knowledge concerning the identification, characterization, and use of fluid and melt inclusions, both in science and industry, in addition to new analytical methods.

The Paul Ramdohr Award 2023 was given to Rebecca Volkmann (GFZ Potsdam) for her presentation “Tracking Transformation Processes in the Mg-Phosphate Mineral System – A Mineralogical Study for Environmental Applications”, which was presented at MinWien2023 in Vienna. This study investigated the transformation and decomposition of struvite at different temperatures in both closed and open systems over a period of nearly a whole year. Ms. Volkmann showed that in the open system at room temperature, a slow transformation to newberryite was observed, while at higher temperatures of up to 60 °C, it transformed at a higher rate into dittmarite. In closed systems, struvite remained stable. This is an important finding because agricultural struvite fertilizer can lose up to 15% of its ammonia content after 10 months of open storage at 22 °C. Therefore, Ms. Volkmann recommends storing struvite fertilizer only in closed containers. This is crucial as today’s society must act more resource-conscious and environmentally friendly than ever before.

Andreas Wittke, Mannheim
The global demand for resources, especially for metals required within our highly technological society and for metals necessary for the current development of CO₂-neutral economic cycles, is already leading to the search for new metallic deposits. Central to this search is the development of new exploration concepts and methods based on an improved understanding of ore-forming processes. The necessity of such efforts is widely known within the field of mineralogy and has been excellently illustrated, e.g., by publications on the criticality of various metals (see e.g., *Elements* past issues “Mineral Resources and Sustainability” (vol. 13, no. 5) and “Geometallurgy” (vol. 19, no. 6)). In addition to increased research on and re-evaluation of already-known ore deposits at various institutes within Germany, e.g., by programs funded by the Federal Ministry of Education and Research in the last decade, basic research on ore-forming processes has also been significantly funded by the German Research Foundation (DFG) since 2020 through the Priority Programme 2238 (DOME). This SPP will now enter its second funding phase in 2023 for another three years.

DOME – Dynamic of Ore Metal Enrichment – was initiated by a Germany-wide interdisciplinary group of experts and is coordinated by scientists from the University of Potsdam, University of Münster, University of Freiburg, and the German Research Centre for Geosciences (GFZ). In the first phase, the funding comprised 26 projects on different topics of metal enrichment. In addition to newly gained research knowledge, the SPP will create a new generation of geoscientists with cutting-edge expertise in the field of ore geology research within Germany. In the first phase, 18 doctoral and 8 post-doctoral positions were created. The same number of projects will also be funded in the next three years. The well over 50 publications and numerous more still to come out of the first phase demonstrate the successful execution and complexity of the research projects in DOME, which also strives to intersect the focal points of the individual projects. Over the entire DOME funding period, almost all possibilities for evaluating ore-forming processes are used (e.g. fieldwork, geochemistry, experimental approaches, numerical modelling).

The projects of the two funding periods are distributed among numerous German universities and research institutes in 17 German cities. There is great value in the methodological and disciplinary diversity of the research projects, as a broad exchange takes place in the jointly organised DOME workshops and meetings. Young scientists not only present their research, but are also encouraged to engage in interdisciplinary exchange and learn new methods. The workshops organised for all DOME young researchers are intended to provide SPP members with an overview of ore-forming systems and processes, as well as common and newly developed methods. Further, they also enable contact with leading scientists from Germany and abroad. The workshops include field trips and introductions to modelling and experimental and analytical methods. These meetings are also open to interested (young) scientists who are not directly funded by the DOME SPP. All information on approved projects, research highlights, and meeting/workshop announcements can be found on the DOME website (www.uni-potsdam.de/en/spp2238/). If you have any questions, please contact us at spp2238@geo.uni-potsdam.de.

Maximilian Korges, University Potsdam

DMG SHORT COURSES 2024
As before, DMG will support several short courses next year. All courses will be aimed primarily at advanced-level undergraduate and graduate students but, as always, are open to more senior researchers as well. Nonlocal student members of DMG will be eligible for travel support to the amount of € 100. Further information can be found at https://www.dmg-home.org/aktuelles/doktorandenkurse/.

1) **Metal Stable Isotopes as Fingerprints in the Earth and the Environment**, GFZ Potsdam and FU Berlin, Geosciences, Friedhelm von Blanckenburg, Patrick Frings, 8–13 April 2024 (patrick.frings@gfz-potsdam.de, f.v.b@fu-berlin.de)

2) **Solid-state NMR Spectroscopy**, Institute for Geology, Mineralogy and Geophysics, Ruhr University Bochum, Michael Fechtelkord, 21–24 May 2024 (michael.fechtelkord@rub.de)

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

4) **Application of Diffusion Studies to the Determination of Timescales in Geochemistry and Petrology**, Institute for Geology, Mineralogy and Geophysics, Ruhr University Bochum, Sumit Chakraborty, Ralf Dohmen, TBA Summer/Fall 2024 (sumit.chakraborty@rub.de)
PRESIDENT’S LETTER

New ideas for connecting with the public about minerals and mineral sciences

Many MSA members interact creatively and effectively about mineral-related topics with non-scientists in their communities or more broadly via social media and other web-based forms of communications. MSA as a Society also has various ways in which it communicates beyond MSA. For example, MSA has a booth at the Tucson Gem and Mineral Show that is held annually in Arizona in February and uses this venue to interact with mineral enthusiasts. At the show, former Executive Director Alex Speer and current Executive Director Ann Benbow and others spend considerable time at an MSA booth that has informative displays about minerals used in green technology and other essential aspects of modern life. At the show, MSA also co-sponsors events with the Friends of Mineralogy organization and the Tucson Gem and Mineral Society. This year, the theme of the Tucson show is “Pegmatites—Crystals Big and Beautiful”—clearly well aligned with the interests of MSA, which has a pegmatite special interest group, as well as a listserv for pegmatite enthusiasts.

At the 2024 show, MSA will also for the first time host “mini-workshops” on topics such as Minerals in Car Batteries, Cobalt, Garnet, Topaz, Pencils and Minerals, Mineral Density, and Trinitite. This is a 90-minute event involving displays at which MSA members interact with any show participants who want to stop by. Based on experiences this year, MSA will evaluate whether this program is effective and should be continued in future years.

According to our mission statement, “The Mineralogical Society of America (MSA) is dedicated to promoting the study of minerals and advancing mineral-based sciences. Our mission is to foster scientific research, education, and collaboration among professionals, students, and mineral enthusiasts.” Increased participation in gem and mineral shows may be a good way to accomplish part of this mission. In addition, one stated aim in MSA’s new strategic plan, which is currently being implemented, is for MSA to grow and diversify the organization and its membership, so we are actively seeking new and creative ways to do so while also maintaining and strengthening support for our current members.

We welcome feedback and ideas from the mineral sciences community about these efforts.

Donna Whitney
2024 MSA President

NOTES FROM CHANTILLY

Renewal Season! It is time to renew your memberships for 2024, as well as subscriptions to MSA’s publications. Member dues are: Regular Members and Fellows ($85); Early Career Members ($45); Student Members ($20); Senior Members ($0); Sustaining Members ($235 – membership plus a $150 contribution to support MSA’s many activities). You can renew via the home page of MSA’s website: www.msaweb.org. At that time, we hope that you will also make a contribution to one or more of MSA’s funds. These funds support our student research grants, lecture series, websites, education and outreach activities, awards, and much more.

EVENTS

42nd FM-TGMS-MSA Tucson Mineral Symposium: The symposium is held in conjunction with the Tucson Gem and Mineral Show®, and will take place on Saturday, February 10, 2024. The symposium is co-sponsored by the Tucson Gem and Mineral Society, the Friends of Mineralogy, and the Mineralogical Society of America. The symposium theme is: “Pegmatites: Crystals Big & Beautiful.” An audience of avocational and professional mineralogists and geologists is expected. Further details are on the Friends of Mineralogy website.

NEW VIEWS OF THE MOON 2

MSA is delighted to announce the publication of Reviews in Mineralogy & Geochemistry Volume 89: New Views of the Moon 2. Volume editors are Clive R. Neal, Lisa R. Gaddis, Bradley L. Jolliff, Samuel J. Lawrence, Stephen J. Mackwell, Charles K. Shearer, Sarah N. Valencia. The series editor is Ian P. Swainson, and American Mineralogist Managing Editor Rachel Russell is responsible for production. The volume is available in both hard copy and online via a subscription to the Reviews series. For more information, visit the Publications section of the MSA website: www.msaweb.org. While there, you can also view the list of MSA’s other publications.
2024 RESEARCH GRANTS

March 1, 2024 is the deadline to submit proposals for the Edward H. Kraus Crystallography Research Grant and the Mineralogy/Petrology Research Grant. There is one Kraus grant of $5,000 awarded each year, two $5,000 Mineralogy/Petrology grants for graduate-level research, and one $2,000 grant for undergraduate research. For more information about the proposal format and how to submit, visit https://msaweb.org/awards-grants/. For any questions, please contact Ann Benbow at abenbow@minsocam.org.

CONTRIBUTIONS

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

DID YOU KNOW?

If you haven’t yet done so, please take some time to explore MSA’s YouTube Channel. There, you will find videos on a variety of mineralogical topics, such as gemology, mineral photography, mineralogy and cultural heritage, mineral museum curation, diamonds, mineral collecting, space mineralogy and much more. There is also a series of videos on careers that use mineralogy, including forensics, environmental science, materials science, jobs in federal science agencies, and a number of others. The link to the MSA YouTube Channel is: https://www.youtube.com/@mineralogicalsocietyofamer6947.
Wager & Brown Layered Intrusion Workshop

the complete compilation of the extended allogically related geological delights, and include our normal cornucopia of miner-definitely by the time you read this), will able online at the time of this writing (but

of

IOS Services Géoscientifiques. He joined the associate editorial team home to Canada, where he is currently employed as a metallogenist for

professor in the China University of Geosciences. He recently returned research on Yanshanian and Tibetan porphyries/skarns, serving as a term professor at the University of

are broad and include experimental and igneous petrology, mantle and crustal evolution, geothermobarometry, and deeper Earth geochemical cycles. His most recent publications involve arc-crustal sections, mantle xenoliths, and intraplate lavas (from the
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SOCIETY NEWS

Mineralogical Association of Canada

www.mineralogicalassociation.ca

THE CANADIAN JOURNAL OF MINERALOGY AND PETROLOGY NEWS

Highlights

The November issue of CJMP, not yet available online at the time of this writing (but definitely by the time you read this), will include our normal cornucopia of mineralogically related geological delights, and the complete compilation of the extended abstracts from the 2023 meetings of the Wager & Brown Layered Intrusion Workshop and the 14th International Platinum Symposium. These insights into the most recent thought innovations on the world of magmatic-hosted PGE deposits and their settings will be available for your holiday seasonal viewing pleasure.

Our Associate Editors

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

Dante Canil

Prof. Canil has been employed in the School of Earth and Ocean Sciences at the University of Victoria (Canada) since 1994. Prior to that, he was a research scientist at the Bayerisches Geoinstitut in Bayreuth (Germany), after having acquired his PhD at the University of Alberta (Canada, where he was a contemporary and colleague of this editor). His fields of interest are broad and include experimental and igneous petrology, mantle and crustal evolution, geothermobarometry, and deeper Earth geochemical cycles. His most recent publications involve arc-crustal sections, mantle xenoliths, and intraplate lavas (from the Canadian Cordillera), and CO₂ sources in arc magmas. His most cited works concern mantle redox over time and the calibration of various thermometers and barometers. Prof. Canil has served as an associate editor of CJMP since 2022 and is also Co-Editor in Chief for Contributions to Mineralogy and Petrology.

Olivier Nadeau

Olivier obtained his PhD from McGill University (Canada), studying Merapi Volcano in Indonesia, and then completed a postdoctoral fellowship at Université du Québec à Montréal (Canada), investigating the Montvieil carbonatite-hosted REE-Nb deposit and intrusion-related/orogenic Au deposits, Abitibi. He subsequently developed Li isotopes as a tool to study hydrothermal alteration and mineralization, by observing a variety of different geological systems, as a term professor at the University of Ottawa (Canada). He then moved to Wuhan, China, where he conducted research on Yanshanian and Tibetan porphyries/skarns, serving as a professor in the China University of Geosciences. He recently returned home to Canada, where he is currently employed as a metallurgist for IOS Services Géoscientifiques. He joined the associate editorial team of CJMP in 2023.

CALL FOR PAPERS – INVITATION REMINDERS

The Canadian Journal of Mineralogy and Petrology (CJMP), formerly The Canadian Mineralogist, covers a variety of topics including petrology, crystal chemistry, ore deposits, and applied mineralogy.

Thematic Issue on Critical Minerals

The Canadian Journal of Mineralogy and Petrology (CJMP) is announcing a second volume of a Thematic Issue on Critical Minerals. The last volume was released in November 2022 and covered a variety of mineral commodities with V, Li, PGEs, and REEs occurring in a multitude of petrogenetic environments.

The editorial team will be led by Dr. Tania Martins from the Manitoba Geological Survey (Canada), who has worked extensively on Li-Cs-Ta-Sn-bearing pegmatites in Portugal, as well as in central Canada. She will be joined by Dr. Anton Chakhmouradian from the University of Manitoba (Canada), whose focus is on carbonatites and associated rocks; Dr. Marc Rinne from the Manitoba Geological Survey (Canada) with expertise in magmatic nickel, volcanogenic, and intrusion-related sulfide deposits; and Dr. Jon Erradonea from the University of the Basque Country (Spain) with expertise in Variscan peraluminous granite magmatism of the Iberian Massif and Li mineralization in pegmatites and evolved granites.

Submissions are invited on any topic involving the mineralogy or petrogenesis of any critical minerals (not limited to those mentioned above). The deadline for submissions is March 31, 2024 (with a target date for publication six months from then). Potential contributors should contact Tania Martins at Tania.Martins@gov.mb.ca. Thematic Issue in honour of Jim Franklin

Jim has influenced so very many, near and wide, with his ideas on the formation of massive sulfide and many other ore deposit types, his dedication to the Earth sciences covers the gamut of mentoring, researching, managing, and outreach. To recognize the impact he has had and continues to have on our science, a special issue of The Canadian Journal of Mineralogy and Petrology (CJMP) is being developed in his honour.

Jim is retired as Chief Geoscientist at the Geological Survey of Canada and he continues as a consultant and principal for several companies. He has always had a passion for ore deposits research. He also delved into many aspects of ore deposits, ranging from their geochemistry, mineralogy, geological setting, isotopic signatures, etc., so a contribution that falls into any of these related areas would be welcomed. Our goal is to showcase research that highlights Jim’s long-term contributions.

The plan right now is to have contributions submitted by March 2024, followed by reviews being conducted shortly thereafter, with a target date for publication later in 2024. Another goal that we are working on is to be able to provide partial or complete open access for the articles published in this issue.

If you are interested in providing a submission, please send an email to one of the guest editors, Dan Marshall: marshall@gsfc.ca, Steve Piercey: spiercey@mun.ca, or Lyn Anglin: anglin.cd@gmail.com with an idea of what your paper will involve.

We personally invite you to be part of these initiatives and to consider submitting a paper to one of these very special issues. If you are unable to contribute, you may be willing to serve as a reviewer for the contributions received and we would equally welcome hearing from you.
BRANDON GAC-MAC-PEG 2024 JOINT ANNUAL MEETING

May 19–22, 2024
Brandon University, in Brandon, Manitoba, Canada
At the Heart of the Continent – Au Cœur du Continent

The 2024 Joint Annual Meeting of the Geological Association of Canada (GAC) and the Mineralogical Association of Canada (MAC) will be held on May 19–22, 2024, at Brandon University, Manitoba, Canada. This meeting will include all the expected GAC and MAC programming, as well the 10th International Symposium on Granitic Pegmatites with field trips and special sessions.

Registration is open: lower registration fees will be applied to those who register before April 7, 2024.

Below are just a few of the events that will potentially take place.

PLENARY LECTURES

MAC Peacock and Young Scientist Medalists
Sponsored by MAC
Professor Robert F. Martin, MAC Special Publications Editors, and The Canadian Mineralogist Former Editor.
Sponsored by PEG 2024 – the 10th International Symposium on Granitic Pegmatites

SYMPOSIA

10th International Symposium on Granitic Pegmatites dedicated to Professor Robert F. Martin
Sponsored by PEG 2024 – the 10th International Symposium on Granitic Pegmatites
CHAIRS: Tania Martins (Manitoba Geological Survey, Canada), Lee Groat (University of British Columbia, Canada), Encarnacion Roda-Robles (University of Basque Country, Spain), Alexandre Lima (University of Porto, Portugal)
DURATION: Three days of technical talks and posters
The symposium will have an emphasis on “The Origin of Pegmatite Melts”, “Pegmatite Minerals and Gems”, “Secondary Processes in Pegmatites”, “Host Rock-Pegmatite Interaction”; and “Recent Advances in Geochronology of Pegmatites” to cite a few thematic sessions.

“Pegmatite Minerals and Gems”
CHAIR(s): Dan Marshall and Lee Groat
Gems are generated in a variety of geological environments. The most common environment for their genesis generally involves proximity to or interaction with pegmatites. The various modes of gem formation have been studied for decades and formational models are continually being proposed and modified as new discoveries are developed. In this session, we welcome presentations on geological environments, geochemistry, petrology, fluid and melt inclusion studies, as well as gem enhancement processes for gems associated with pegmatites and associated rocks.

SPECIAL SESSIONS

Mineralogy

Precious and Semi-Precious Gems and Earth Materials
Sponsor: MAC – Mineralogical Association of Canada
ORGANIZERS: Lee Groat, Dan Marshall
DURATION: One day of oral and poster presentations
An open session discussing the occurrence, geology, mineralogy, and geochemistry of all types of precious and semi-precious minerals and Earth materials including jade, turquoise, quartz varieties, diamonds, biogenic materials, and “ordinary minerals” with “extraordinary qualities”.

GENERAL SESSION

Mineralogy and Crystallography
DURATION: One day of oral and poster presentations
For this session, we welcome abstracts describing recent advances in mineralogy, crystallography, and related fields.

FIELD TRIPS

Pegmatites of the Winnipeg River-Cat Lake pegmatite field (MB) and Separation Rapids (ON)
Sponsored by PEG 2024 – the 10th International Symposium on Granitic Pegmatites
ORGANIZER: PEG, main contact: Tania Martins
DATE and TIME: Post-conference, May 23 AM to May 26 PM
DEPARTURE and DESTINATION: Round trip out of Winnipeg
During this four-day field trip, we will visit lithium pegmatites in Manitoba (Cat Lake-Winnipeg River pegmatite field) and northwestern Ontario (Separation Rapids pegmatite field). Visits will focus on different aspects of the pegmatites including mineralogy, emplacement controls, and regional geology. Examples of pegmatites we will visit include the Eagle, FD no.5, Tanco, Big Mack, and Big Whopper. The Tanco portion of the trip is expected to include visits to the underground workings and the spodumene mill and viewing of drill core. We are also planning to view the paragenetic collection of the Tanco pegmatite organized by Petr Černý and located at the University of Manitoba.

2024 TUCSON GEM & MINERAL SHOW®

PEGMATITES – Crystals Big and Beautiful
February 8–11, 2024
Tucson Convention Center
42nd FM-TGMS-MSA Tucson Symposium February 10, 2024
10:55 AM Michael Menzies, Gem Pegmatites
1:30 PM Robert F. Martin, Cleavelandite: Only Crystals Small and Beautiful

THE TUCSON GEM AND MINERAL SHOW BOOK SIGNING EVENT

Friday, February 9
1pm - 3pm
Tucson Convention Center Booth #1226
Don’t miss the 8P15 book signing event with Michael Menzies, Jeffrey Scisl and Robert F. Martin.
International Association on the Genesis of Ore Deposits

www.iagod.org

MEET THE NEW IAGOD COUNCIL

The general assembly of IAGOD in London (August 2023) elected a new council that will serve during the period of 2024–2028 and deliver the 2026 Quadrennial Symposium in Porto, Portugal. With a focus on the energy transition, we’re looking forward to welcoming you to an excellent meeting that aims to address opportunities, as well as challenges, in this pivotal moment for our civilization. The new council includes:

Executive Councillors

President Dr Tânia Martins
Tânia Martins (PhD 2009, University of Porto, Portugal) is Chief Geologist for the Precambrian Geoscience section of the Manitoba Geological Survey, Winnipeg, Canada. Her research interests are in Li-Cs-Sn-Nb-Ta mineralization in granitic pegmatites, critical mineral systems, and how these fit in the tectonic evolution of the Precambrian terrains in Manitoba.

Executive Secretary Dr Wei Jian
Wei Jian (PhD 2015, Technische Universität Clausthal, Germany) is an associate researcher at the China University of Geosciences, Beijing, China. His principal research interests are in the mineralogy, fluid inclusion, and ore-forming process of hydrothermal gold deposits.

Chief Treasurer Dr Alla Dolgopolova
Alla Dolgopolova (PhD 2005, Royal School of Mines, Imperial College London, UK) is a principal researcher at the Natural History Museum, London, United Kingdom and Co-Leader of CERCAMS (Centre for Russian and Central Eurasian Mineral Studies). She researches the behaviour of metals critical for our modern economy in Earth systems.

Promotions Manager Prof David Lentz
David Lentz (PhD 1992, University of Ottawa, Canada) is the research chair in economic geology at the University of New Brunswick, Canada. His principal research interests include magmatic–hydrothermal processes associated with the formation of massive sulphide deposits, porphyry Cu-Mo-Au systems, and granite-related Sn-W-Mo-Au skarn, IOA (iron oxide apatite) and IOCG (iron oxide copper-gold, REY, U) systems.

Publications Manager and Webmaster Prof Jens Andersen
Jens Andersen (PhD 1996, University of Copenhagen, Denmark) is an associate professor of economic geology at Camborne School of Mines, University of Exeter, United Kingdom. His principal research focus is to develop our understanding of metals associated with igneous rocks, including PGEs, Ni, Co, V, and Ti in mafic-ultramafic layered intrusions; and Li, In, Sn and W in granite-related magmatic-hydrothermal systems.

Regional Councillors

Africa Prof Thierry Olivier Bineli-Betsi, Botswana International University of Science and Technology, Palapye, Botswana
Asia Prof Batkhishig Bayaraa, Mongolian University of Science and Technology, Ulan Bator, Mongolia
Australasia Prof Nigel Cook, University of Adelaide, Australia
China Dr Xiaobo Zhao, China University of Geosciences, Beijing, China
Europe Dr Thomas Belgrano, University College Dublin, Ireland
North America Dr Nadia Mohammadi, Natural Resources Canada, Ottawa, Canada
South America Dr Andreas Dietrich, Dietrich Consulting, Santiago, Chile

Other Councillors and Officers

Past President Dr Sean McClanaghan, Trinity College Dublin, Ireland
First Vice President Dr Helena Sant’Ovaia, University of Porto, Portugal
Second Vice President Dr Junfeng Xiang, Chinese Academy of Geological Sciences, Beijing, China
First Vice President at Large Dr Olena Ganzha, National Academy of Sciences, Ukraine
Second Vice President at Large Ms Mary Barton, Namibia
Ex-officio officers Prof David Banks, Dr Jan Pašava for SGA, and Dr Andreas Nägele for Schweizerbart

IN MEMORIAM: MIROSLAV ŠTEMPROK (1933–2023)

Professor Miroslav Štemprok (Mirek), former research scientist at the Czech Geological Survey and emeritus professor at the Charles University in Prague, sadly passed away on November 15, 2023. He was an internationally renowned expert on highly evolved granitic rocks and associated mineralization, particularly Sn-W greisen deposits. Mirek graduated with a MSc (1955) from Charles University (Czech Republic) and PhD (1962) on the Cínovec (Zinnwald) deposit in the Eastern Erzgebirge, followed by postdoctoral fellowships at Penn State, USA (with Hubert L. Barnes), the Geophysical Laboratory, USA (with Gunnar Kullerud), and the University of Heidelberg, Germany (with Günter Moh). Upon his return, he established the first experimental geochemistry laboratory in the former Czechoslovakia and was promoted to associate professor in 1969. He became a pioneer in the experimental studies of Sn, W, and Mo solubility in silicate melts and the complex interaction between granitic rocks and highly saline fluids. His field-based projects on Sn-W-Mo greisens,

Cont’d on page 57
IN LOVING MEMORY OF STEVEN BANWART

Our hearts are heavy as we come together to honor the memory of our cherished friend and colleague, Steven Banwart, affectionately known as “Barney” to many of us. It is with deep sorrow that we share the heartbreaking news of his passing on December 30, 2023 due to a massive cerebral hemorrhage stroke. Steve’s departure has left an irreplaceable void in our lives, but as we gather to celebrate his extraordinary life, let us also reflect on the enduring legacy he leaves behind.

Steve was not just a scientist; he was a beacon of inspiration in the world of scientific discovery. He dedicated nearly three decades of his life to the development of the “critical zone” concept, leaving an indelible mark on the British, European, and global critical zone communities. His roles as Dean for Global Development, Director of the Global Food and Environment Institute, and Leadership Chair in Integrating Soil/Agriculture/Water Research at the University of Leeds underscore his commitment to groundbreaking research.

Among his many accomplishments, Steve’s leadership as the Principal Investigator of the European SoilTrec project from 2009 to 2014 stands as a testament to his visionary spirit. This project played a pivotal role in uniting the European critical zone community and set the stage for similar initiatives worldwide. Steve’s unwavering dedication and passionate advocacy for an integrative scientific vision enriched our understanding of the critical zone.

Yet, Steve’s greatness extended far beyond his scientific achievements. He was a compassionate and empathetic human being, always lending a listening ear to his colleagues. His authentic concern for others, coupled with his unwavering belief in the significance of critical zone research, made him a beloved figure in our scientific community.

Steve’s commitment transcended the confines of the laboratory. He actively contributed to the IAGC community as the Chair of the GES working group and served on the council since 2012. His tireless efforts in promoting our association’s mission exemplified his dedication to advancing our shared goals.

For many of us, our connection with Steve extended beyond the boundaries of science. His infectious spirit and camaraderie endeared him to us as not just a colleague but a cherished friend. Steve was not only a friend but a guiding light who helped us navigate the complexities of life and science. Though his absence leaves a void that cannot be filled, his legacy will forever inspire us. In his memory, we pledge to carry forward his important research and uphold the values he cherished. While we mourn his passing, we find solace in knowing that his spirit lives on in the hearts and minds of all who had the privilege of knowing him.

As we grieve the loss of this exceptional individual, our hearts reach out to his family during this difficult time. We share in their sorrow and offer our deepest sympathies.

To Steve’s family, we extend our heartfelt condolences. Rest in peace, dear friend.

Cont’d from page S6


Mirek was a founding member, general secretary, and honorary life member of IAGOD. He was president of the Czech Geological Society (1990–1994), served on the board of directors of the Geologische Vereinigung (1992–1996), and was president of the Czech national geological commission (1996–2000). After political changes in Eastern Europe, Charles University promoted him to full professor (1993), and he became director of the geoscience analytical facilities (1994–1998). He taught economic geology and phase equilibria for nearly 50 years until his retirement as emeritus professor in 2010. He received the Cyril Purkyňě award from the Czech Geological Survey and the Kutina-Smirnov medal from IAGOD in 2018.

Mirek was a remarkable international scientist with many worldwide collaborations. Those who met him admired and sought his insight and perspective, rational advice, and generous encouragement. We have lost an excellent scientist, a modest colleague, and first and foremost, a friend. He will be missed by many.

By Prof David Dolejš, University of Freiburg, Germany
We appreciate that we are able to celebrate the scientific contributions of Zhang, Ke Zhu, Allan Treiman, Tomo Usui, Lionel Vacher, Maria Valdes, Toru Yada, Bidong Angel Mojarro, Andrea Patzer, Nicolas Randazzo, Philip Reger, Alex Ruzicka, Mizuho Koike, Nan Liu, Rhiannon Mayne, Kaitlyn McCain, Jennifer Mitchell, Hanna, Natasha Johnson, Jim Karner, Gunther Kletetschka, Piers Koefoed, Erickson, Tim Fagan, Ryota Fukai, Matt Genge, Sammy Griffin, Romy Hanna, Natasha Johnson, Jim Karner, Gunther Kletetschka, Piers Koefoed, Mizuho Koike, Nan Liu, Rhiannon Mayne, Kaitlyn McCain, Jennifer Mitchell, Angel Mojarro, Andrea Patzer, Nicolas Randazzo, Philip Reger, Alex Ruzicka, Elizabeth Silber, Justin Simon, Robert Steele, Melissa Strait, François Tisot, Allan Treiman, Tomo Usui, Lionel Vacher, Maria Valdes, Toru Yada, Bidong Zhang, Ke Zhu.

We appreciate that we are able to celebrate the scientific contributions of these 41 individuals for their judging reports: for chairing the committee and for the presentations “Direct U-Pb measurements of reidite from Rochechouart chondrites”; and (Arizona State University, USA) for the presentation “The Qingzhen reaction – a fine-grained mineral assemblage associated with djerfisherite in some EH chondrites”; and (University of Manchester, UK), for the presentation “Sector-zoned pyroxenes in young lunar mare basalt Northwest Africa (NWA) 8632: Insights into crystallization kinetics during late-stage volcanism on the Moon”; Peter Mc Ardle (University of Manchester, UK) for the presentation “The Qingzhon reaction – a fine-grained mineral assemblage associated with djerfisherite in some EH chondrites”; and Leah Shteynman (Arizona State University, USA) for the presentation “Direct U-Pb measurements of reidite from Rochechouart impact structure”.

The WILEY-BLACKWELL AWARD is presented for outstanding presentations by students at the annual meeting of the society. Wiley-Blackwell are the publishers of Meteoritics and Planetary Science and, for the 84th Annual Meeting in Los Angeles, they sponsored five awards of US $500 each. The winners for 2023 include Sophie Benaroya (University of Alberta, Canada) for the presentation “Unraveling the crystallization history of poikilitic shergottite Northwest Africa 12002”; Catherine Harrison, (Natural History Museum, London; University of Manchester, UK), for the presentation “Fe-sulfides in experimentally and naturally heated CM chondrites”; Alissa Madera (Rutgers University, USA) for the presentation “Sector-zoned pyroxenes in young lunar mare basalt Northwest Africa (NWA) 8632: Insights into crystallization kinetics during late-stage volcanism on the Moon”; Peter Mc Ardle (University of Manchester, UK) for the presentation “The Qingzhon reaction – a fine-grained mineral assemblage associated with djerfisherite in some EH chondrites”; and Leah Shteynman (Arizona State University, USA) for the presentation “Direct U-Pb measurements of reidite from Rochechouart impact structure”.

CONGRATULATIONS TO THE WINNERS! We would like to congratulate all of the students who submitted presentations for the 84th Annual Meeting of the Meteoritical Society in Los Angeles for their oral presentations and for the outstanding quality of the work presented. The winners of the WILEY-BLACKWELL AWARD are the following:

- Sophie Benaroya, University of Alberta, Canada
- Catherine Harrison, Natural History Museum, London
- Alissa Madera, Rutgers University, USA
- Peter Mc Ardle, University of Manchester, UK
- Leah Shteynman, Arizona State University, USA

Congratulations to the awardees for outstanding presentations! Additionally, thank you to Alex Ruzicka for chairing the committee and to 41 individuals for their judging reports: Jen Barosch, Helena Bates, Enrica Bonato, Aaron Cavosie, Hasnua Chennaoui Aoudjehane, Cari Corrigan, Gerardo Dominguez, Emile Dunham, Scott Eckley, Timmons Erickson, Tim Faugn, Ryota Fukai, Matt Genge, Sammy Griffin, Romy Hanna, Natasha Johnson, Jim Karner, Gunther Kletetschka, Piers Koefoed, Mizuho Koike, Nan Liu, Rhiannon Mayne, Kaitlyn McCain, Jennifer Mitchell, Angel Mojarro, Andrea Patzer, Nicolas Randazzo, Philip Reger, Alex Ruzicka, Elizabeth Silber, Justin Simon, Robert Steele, Melissa Strait, François Tisot, Allan Treiman, Tomo Usui, Lionel Vacher, Maria Valdes, Toru Yada, Bidong Zhang, Ke Zhu.

The Barringer Crater Company has established a special fund to support field work by eligible students interested in the study of impact cratering processes. The Barringer Family Fund for Meteorite Impact Research will provide a number of competitive grants in the range of $2,500 to $5,000 for support of field research at known or suspected impact sites worldwide. Grant funds may be used to assist with travel and subsistence costs, as well as laboratory and computer analysis of research samples and findings. Masters, doctoral, and post-doctoral students enrolled in formal university programs are eligible. Application to the fund will be due by 5 April 2024, with notification of grant awards by 7 June 2024.

Additional details about the fund and its application process can be found at: http://www.lpi.usra.edu/science/kring/Awards/Barringer_Fund.

RENEW YOUR MEMBERSHIP NOW!

Please renew by 31 March 2024; after that date, a $15 late fee will be assessed. You can easily renew online at https://meteoritical.org/news/hiroshi-takeda-1934-2023.

THE BARRINGER FAMILY FUND FOR METEORITE IMPACT RESEARCH

HIROSHI TAKEDA

Hiroshi Takeda, an emeritus professor at the University of Tokyo, Japan passed away on September 11, 2023, just one day short of his 89th birthday. Globally recognized for his groundbreaking work in mineralogy and crystallography for solid Earth and planetary material science, Takeda’s accolades are numerous. Notably, he received the Leonard Medal from the society in 2010. Back home in Japan, he was honored with the Special Award during the Japan Mineralogical Society’s 50th anniversary in 2002 and the esteemed 26th Manjiro Watanabe Award in 2009. His legacy was further cemented when a new Ca borate mineral was named “Takedaite” in his honor in 1995, and asteroid (4965) was dubbed “Takeda” in 2001. For his invaluable contributions to lunar sample studies and his research on meteorites for NASA, he was awarded NASA’s Public Service Medal in 1996. Takeda was a highly accomplished researcher, studying many types of planetary materials, in particular, lunar rocks, HEDs, and ureilites. He was also a critical player in the Japanese lunar exploration program.

Takeda was active in academic organizations both in Japan and abroad, continuously showcasing the strength of Japan’s solid planetary material science on the international stage. For our society, he was active in roles such as a council member (1981–1986) and associate editor of Meteoritics (1988–1992). He was a chair for the Cosmic Mineralogy Working Group of the International Mineralogical Association (IMA) (1991–1995). In Japan, he served as vice-president during the founding of the Japanese Society for Planetary Science (1992–1996) and as a councilor of the Japan Mineralogical Society for two decades.

This is just a short list of Takeda’s accomplishments, contributions, and accolades. Please see the full citation written by Takashi Mikouchi, Akira Yamaguchi, and Larry Nittler, at the Meteoritical Society website (https://meteoritical.org/news/hiroshi-takeda-1934-2023).
SFMC HAÜY-LACROIX 2023 PRIZE

Congratulations to Clément Herviou and Rémy Pierru who jointly received the SFMC Haüy-Lacroix 2023 prize.

Clément Herviou completed his PhD thesis entitled “Fluid circulation and deformation mechanisms in the Schistes Lustrés of the Liguro-Piedmont domain: Implications for the functioning of subduction zones” at the Institut des Sciences de la Terre de Paris (Sorbonne University) under the supervision of Philippe Agard and Anne Verlaguet. The aim of his thesis was to gain a better understanding of the composition of fluids and how they migrate through the crust in the context of oceanic subduction.

Rémy Pierru will receive his prize shortly. His PhD thesis is entitled “High-pressure and high-temperature mantle melting: Application to the dynamics of the early Earth”. He completed his PhD at the Magmas and Volcanoes Laboratory (University of Clermont-Auvergne) under the supervision of Denis Andrault and Geeth Manthilake. The aim of his thesis was to experimentally constrain the conditions under which the Earth’s mantle melts.

A SCIENTIFIC LIFE UNDER ULTRA-HIGH PRESSURE


Around 60 international scientists from all generations gathered to celebrate Christian Chopin’s retirement after an exemplary career dedicated to metamorphic petrology. Lectures followed by lively discussions covered the main topics that were deeply impacted by the discovery of coesite in Alpine metamorphic units in 1984 by Christian Chopin. This includes Alpine geology, continental subduction, metamorphic petrology (experimental and computational), fluid–rock interactions, as well as the crystal chemistry of exotic minerals found in UHP metamorphic rocks (phosphates, but not only...), which is still occupying Christian’s time!

Science, friendship, and emotion were present all along these two days. Each participant also went home with a bottle of Morgon wine offered by Christian (Beaujolais wine from his family’s home region). Interested participants were able to visit the exhibition “Eclogites” at the Société Géologique de France.

The organizing committee
(O. Beyssac, F. Brunet, L. Labrousse, B. Goffé, A. Schubnel)
Every three years, the IAG has the pleasure of convening an international meeting devoted specifically to developments in analytical geochemistry and their application. In doing so, we aim to support the professional needs of those involved in the analysis of geological and environmental materials to enable them to share experiences in this fundamental area of geochemical research. The Geoanalysis series of conferences started in Canada in 1990, and since then they have been held all over the world, from Brazil to Australia. For our 12th conference this year, we return to China and move to the city of Wuhan.

For Geoanalysis 2024, we are fortunate to be able to call upon the resources of the China University of Geosciences (CUG), one of the leading universities in Earth Sciences in the world, with very well-equipped analytical facilities. Geoanalysis 2024 will be held at the East Lake Hotel, which has a shoreline of over 3 km, so there will be plenty of room to stretch your legs with a walk or jog by the lakeside!

**Conference Programme**

Several short courses will take place in advance of the main conference. These will include one on quality assurance lead by Prof Thomas Meisel (Leoben University, Austria) with interactive sessions on measurement uncertainty estimations, terminology and definitions, and the proper use of reference materials.

During the conference, there will be a mixture of oral and poster presentations, with plenty of opportunity to view the posters and chat with their authors. Session topics will include:

- Preparation and characterisation of reference materials
- Developments in laboratory and field instrumentation
- Sample preparation and bulk analysis
- Microanalysis, mapping, and imaging by a variety of techniques
- Measurement of isotope ratios and their applications
- Mineral identification and characterisation

There will also be an instrument manufacturers’ exhibition so that you can view the latest equipment on sale and discuss their merits with the company representatives.

The IAG is offering several student bursaries that cover the registration fee and accommodation costs. Information on how to apply for one of these grants will be available on the conference website.

The deadline for submitting abstracts is 1 May 2024 and potential participants will receive an acceptance letter before the beginning of June. Early bird registration will be open until 1 July.

For more information, please see the conference website: https://geoanalysis2024.aconf.org.

The philosophy of Geoanalysis conferences is to provide an intimate gathering of about 200 delegates with an all-inclusive programme of scientific and cultural activities, with accommodation situated close to the conference centre so that opportunities for networking are maximised. We would be delighted if you could join us in Wuhan in September for what we are sure will be a memorable gathering of geoanalysts!
MEETING OF THE MINERALOGICAL SOCIETY OF POLAND, BIELAWA 2023

The 9th Meeting of the Mineralogical Society of Poland (PTMin) and 28th Meeting of the Petrology Group of the PTMin (https://ptmin2023.ing.pan.pl/home.html) were chaired on 19–22 October 2023 by Jakub Ciążela and his team from the Wrocław centers of the Instytut Nauk Geologicznych PAN in cooperation with the other centers, as well as Adam Mickiewicz University in Poznań, Polish Geological Institute - National Research Institute, and Wrocław University. The conference was held in Hotel Dębowy Biowellness & SPA (hoteldebowy.pl), in the picturesque park and palace complex in Bielawa near Wrocław, a town located between different units of the Central Sudetic Ophiolite.

For the first time in a long time, the conference gathered more than 100 participants, including numerous international researchers from Italy, Germany, Great Britain, South Africa, Spain, Belgium, and Hungary. The conference, with this year’s topic “Oceanic lithosphere: rocks, minerals, and critical resources”, focused on the oceanic lithosphere and ophiolites, crucial for Poland due to the ongoing Polish sulfide exploration in the contract area of the International Seabed Authority on the Mid-Atlantic Ridge (2018–2033). The first four of eight thematic sessions were dedicated to this topic, with one on the oceanic lithosphere and its vital resources, two on ophiolites, and one on subduction zones, all held on Friday. We also had the pleasure of hosting renowned keynote speakers. Francisco Javier González Sanz from the Geological Survey of Spain summarized the challenges of deep-sea mining for polymetallic nodules and polymetallic sulfides, focused on the oceanic lithosphere and ophiolites, crucial for Poland due to the ongoing Polish sulfide exploration in the contract area of the International Seabed Authority on the Mid-Atlantic Ridge (2018–2033). The first four of eight thematic sessions were dedicated to this topic, with one on the oceanic lithosphere and its vital resources, two on ophiolites, and one on subduction zones, all held on Friday. We also had the pleasure of hosting renowned keynote speakers. Francisco Javier González Sanz from the Geological Survey of Spain summarized the challenges of deep-sea mining for polymetallic nodules and polymetallic sulfides. Jürgen Koepe of the Leibniz Universität Hannover (Germany) discussed fast-spreading-type ophiolites in the context of the Oman Drilling Project of the International Continental Scientific Drilling Program. Riccardo Tribuzio of the Department of Earth and Environmental Sciences, University of Pavia (Italy) discussed ophiolites’ origin and tectonic position in the Alpine–Apennine complex. The topic of the oceanic lithosphere was further exploited during the field trip on Sunday, which allowed the participants to see exposures of rocks representing various parts of the Central Sudetic Ophiolite, including the upper mantle and the Moho transition zone at the Tapadla Pass; gabbro, diabase dikes, and basalts at Góra Kunowska; and metamorphosed oceanic sediments with metamanganolites representing former Fe–Mn crusts of the ocean floor in the Kamionki Hill near Pustków Wilczkowski.

During the Saturday ore geology session, Frédéric Hatert of the Laboratory of Mineralogy, University of Liège (Belgium) explained how to link the Fe–Mn-rich crusts to metamanganolite rocks such as those present, for example, in Pustków Wilczkowski or the famous manganese coticules of the Stavelot massif, Belgium. In addition to ore geology, Saturday’s second set of sessions included environmental geology, mineralogy and petrology, and planetary geology. In his keynote talk, Krzysztof Woźniak of the Chemistry Department, University of Warsaw (Poland), invited us into the fascinating world of high-pressure quantum crystallography of minerals. In an electrifying talk, Stephen Mojzsis (Research Centre for Astronomy and Earth Sciences, MTA Centre for Excellence, Budapest / Hungarian Academy of Sciences, Hungary) took us to extraterrestrial environments, including those beyond the Solar System, which is particularly timely, when the need of human space expansion is inevitable.
Clay minerals are fascinating materials to study, both from a fundamental point of view and because they have applications in many fields. Transport of clays, soil physics and clay geophysics, biogeochemistry and environmental geochemistry, soil science and soil chemistry, remediation and carbon removal, microscopies and molecular modeling, planetary science and astrobiology, and applications of clays as nanomaterials or building materials are some topics that illustrate the diverse application fields and importance of clay minerals for environmental purposes. These topics correspond to the technical sessions proposed for the annual meeting, which will be held in Hawaii in June.

Co-organized by the Clay Minerals Society, the Clay Science Society of Japan, and the Chinese Association for the Study of Clays, this meeting will not only be an exciting opportunity to learn more about our favorite minerals and their applications, but also to share knowledge with other communities. During the conference, mentoring for students and young scholars will be organized. They will have the opportunity to have dedicated time to meet with matched professors and professionals to discuss about science and career. Expanding clay science over the Pacific and beyond is an ambitious objective we actually aim to attain. Deadline for abstract submission and early registration is March 1st 2024. Follow the link for details: CMS ANNUAL CONFERENCES (clayconferences.org).

This time of the year is also the time when the composition of the Council and committees of The Clay Minerals Society is renewed. Many thanks to the new volunteers who have responded favorably to our requests for service.

All ideas to increase membership in our society and appeal for new members are more relevant than ever.

Sabine Petit, CMS President

THE PRESIDENT’S CORNER

JOURNAL’S UPDATE: CLAYS AND CLAY MINERALS

From 2024, Clays and Clay Minerals will be published in conjunction with our new partners, Cambridge University Press. All of the journal content is available at https://www.cambridge.org/core/journals/clays-and-clay-minerals and members can access it without additional charge at https://www.clays.org/ccm_online_access. Members will need to login using their member credentials.

The editors and council of The Clay Minerals Society thank Springer and, in particular, their representative Ron Doering, for their hard work and support during the past five-year contract and for their cooperation during this transition to a new partner.

We look forward to an exciting new partnership with Cambridge University Press.

IMPORTANT ANNOUNCEMENT

Join CMS

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

Deadline to Remember

The student research grant deadline is March 1, 2024.

Save the Date!

The 61st Annual Meeting of The Clay Minerals Society and the 5th Asian Clay Conference
Location: Honolulu, Hawaii
Time: June 3-6, 2024

RECENT CONTENT

- Insights into Glyphosate Adsorption in Aqueous Solutions Using Zn–Al Layered Double Oxide, by Emanoel Hottes, Glauco Favilla Bauerfeldt, Marcelo Hawrylak Herbst
- From Coupling Second-Order Stresses to Understanding and Predicting the Structural Response of a Dioctahedral Smectite, by Chadhia Mejri, Walid Oueslati, Abdesslem Ben Haj Amara
- Influence of pH on the Hydrothermal Synthesis of Al-Substituted Smectites (Saponite, Beidellite, and Nontronite), by I. Criouet, J. C. Viennet, S. Bernard
- Antibacterial Finishing of Textile Materials using Modified Bentonite, by Ljiljana Topalić-Trivunović, Aleksandar Savić, Mugdin Imamović
- Determination of Sulfide Consumption by Fe-bearing Components of Bentonites, by Jebri Hadi, Jean-Marc Greneche, Barbara Pastina
- Development of a Nanostructured Film Containing Palygorskite and Dermaseptin 01 Peptide for Biotechnological Applications, by Karla Costa Bezerra Fontenele Oliveira, Emanuil Airton de Oliveira Farias, Carla Eiras
- Raw Materials Used in Traditional Pottery from Northern Morocco: Possible Alternative Material for a Sustainable Future in the Frane Area, by Fatima Hilali, Younes El Kharim, Mohamed Ahniche
- A New Preparation Method for cis-1,4-polysisoprene/Na-montmorillonite Latex Composites by in situ Solution Emulsification, by Liyun Guo, Haichang Zhang, Danfeng Liu
- Determination of Hansen Solubility Parameters of Raw Muscovite, by Ming Weng, Xiuhua Wang
- Mineralogy, Chemistry, and Thermal and Surface Properties of Various Technological Types of K-Bentonite from the Dolná Ves Deposit (Kremnické vrchy Mts., Western Carpathians, Slovakia), by M. Osacký, Y. Bai, M. Čaplovičová
The annual JAMS meeting was held face-to-face at Osaka Metropolitan University in September. Many members joined there, and lively discussions took place. The number of student members has also increased noticeably in recent years. This phenomenon is expected to revitalize the activity of JAMS. The members of JAMS have examined the description of mineralogical sciences in junior high school textbooks and made recommendations to ensure that they reflect more appropriate content.

Through these activities, the JAMS would like to continue to contribute to the development of mineralogical sciences.

JAMS President
Prof. Masaaki Owada

INVITATION TO THE JAPAN GEOSCIENCE UNION MEETING 2024

We are pleased to inform you that the Japan Geoscience Union (JpGU) meeting will be held on 26–31 May 2024 at Makuhari Messe in Chiba, Japan. The JpGU is an organization of about 10,000 individual members and about 50 domestic society members related to Earth and planetary sciences. The 2024 JpGU meeting will be held in a hybrid format, as was the case in the previous two meetings. While retaining the advantages of the hybrid format, including the ability to allow participation from remote locations, we will be able to hold more full-fledged, face-to-face discussion. We encourage you to apply, regardless of the form of participation, and look forward to lively discussions both onsite and online. More information is available at www.jspgu.org/meeting_e2024.

JOURNAL OF MINERALOGICAL AND PETROLOGICAL SCIENCES

Vol. 118, Issue 1, 2023

Original Articles
Pressure-tuned correlation field splitting in phase A [Mg$_7$Si$_2$O$_8$(OH)$_6$]. Masami KANZAKI.

New approach to obtain the correct chemical compositions by absorption correction using analytical transmission electron microscopy. Kiyoshi FUJINO, Naotaka TOMIOKA, Hiroaki OHFUJI.

Experimental synthesis of Fe-bearing olivine at near-solidus temperatures and its decomposition during longtime heating. Naoki HIRAKAWA, Yoko KEBUKAWA, Takazo SHIBUYA, HisahiroUEDA, Kensei KOBAYASHI.

Zircon U-Pb ages of the Cretaceous gabbroic and granitic rocks from the Najd Complex, East Antarctica. Sato SUZUKI, Tomokazu HOKADA, Masahiro ISHIKAWA, Takaji HAMAMOTO.

Letter
Rutile exsolution lamellae of garnet in quartz eclogite from the Sanbagawa Belt, Mt. Gongen, central Shikoku, Japan. Tomohiro TAKEBAYASHI, Yui KOUKETSU, Katuyoshi MIYAMOTO.
The “First Italian Workshop on Fluid and Melt Inclusions” took place in the beautiful location of the Botanical Garden of Palermo, Sicily, Italy, on May 10–11, 2023. The workshop was organized by Dr. Francesco Maria Lo Forte and Prof. Alessandro Aiuppa of the University of Palermo (Italy), and Dr. Simone Costa of the University of Pisa (Italy). The Department of Earth and Marine Sciences at the University of Palermo (DiSteM) acted as the main sponsor for the event. The workshop received significant financial support and sponsorship from several organizations, including the Italian Society of Mineralogy and Petrography (SIMP), the Italian Association of Volcanology (AIV), the Italian Geochemical Society (So.Ge.I.), and the Italian Gemological Review (IGR). These organizations also served as media partners and sponsors. The workshop attracted a diverse range of participants, including researchers; PhD, master’s, and bachelor’s students; as well as individuals from national and international universities and research institutions, including the National Research Council (IGG-CNR) and the National Institute of Geophysics and Volcanology (INGV). The main objective of the workshop was to explore the identification, characterization, and application of fluid and melt inclusions in the field of Earth sciences. Additionally, it aimed to facilitate communication between academic researchers, young researchers, and the national and international business community. Notably, the workshop integrated the expertise of gemologists who approached the study of fluid and melt inclusions from a commercial standpoint, bridging the gap between academia and industry.

Spanning two days, the workshop comprised four thematic sessions, each featuring keynote speeches by experts in the field. Following the keynotes, participants had the opportunity to present their research through oral presentations. Lively and insightful scientific discussions took place during the various coffee breaks and the two lunches. The workshop commenced with a warm welcome from the Head of the DiSteM and the organizers, followed by a pleasant ice-breaker activity.

The first day of the workshop focused on two scientific themes, one in the morning and another in the afternoon after lunch. The morning theme, titled “Fluid inclusions, tracers of petrological and geodynamic processes”, featured keynote speeches on “Carbon fluxes in the lithospheric mantle recorded by fluid inclusions” by Prof. Maria Luce Frezzotti (University of Milan Bicocca, Italy) and “Noble gases isotopes in fluid inclusions: methods and applications to Geosciences” by Dr. Andrea Rizzo (INGV section of Milan). The afternoon theme, titled “Resources and reserves, fluid inclusions as a survey method for prospecting”, began with a plenary lecture by Giovanni Ruggieri (National Research Council, IGG-CNR, Italy) on the “Application of the synthetic fluid inclusion method for temperature measurements in super-hot geothermal reservoirs”.

The second day of the workshop focused on the third scientific theme, titled “Melt inclusions as tracers of deep and superficial magmatic processes”, in the morning. The keynote speech during this session was delivered by Dr. Rosario Esposito (University of Milan Bicocca) on “Selecting melt inclusions associated with volcanic systems and interpreting their volatile records: an integrated approach”. The closing scientific session of the workshop was titled “Fluid inclusions in materials of gemological interest” and was introduced by Dr. Maya Musa (University of Milan Bicocca and University of Pavia, Italy) with a presentation entitled “Fluid inclusions in gemstones: what information can they provide for gem lab applications?” The workshop concluded with an interesting and captivating guided tour of the Botanical Garden, which hosts more than 12,000 different plant species from all continents. This pioneering event in the Italian community generated interest and enthusiasm among the participants, with hopes of continuity for future years.

The organizers, Francesco Maria Lo Forte, Alessandro Aiuppa, and Simone Costa
CALENDAR

2024

February 20–23 Integrating Ocean Drilling and NASA Science: A Workshop to Explore Missions to Planet Earth, Washington DC, USA and virtual. Web page: www.hou.usra.edu/meetings/oceandrilling2024/.


March 1–3 Serpentinefinite, Fluids and Plate Boundary Deformation in Subduction Zones, McGill University, Quebec, Canada. Web page: sites.google.com/view/2024subductionfluidsworkshop/home.


March 27–28 Metamorphic Studies Group Research in Progress (RIP), Bristol, UK. Web page: events.minesoc.org/Event-Registration/EventId/43.


May 23–24 10th International Geosciences Conference of Young Researchers, Kyiv, Ukraine. Web page: gc.igi-nas.u.ua.


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


August 12–14 Museums & Mineralogy 10, Cardiff, Wales. Web page: mm-10.org/.

August 18–22 American Chemical Society Fall Meeting, Denver, CO, USA. Web page: forthcoming.


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

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


September 12–14 2024 Annual Meeting of the Japan Society of Mineralogical Sciences, Nagoya University, Japan. Web page: forthcoming.


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


November 9–11 New Mexico Mineral Symposium, Socorro, NM, USA. Web page: geoinfo.nmt.edu/museum/minsymp/home.cfm#.


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


2025


2026


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


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

To obtain the listed meeting information, please contact her at akoziol1@du.edu

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