MISASA VIII

International Symposium on Future Planetary Exploration: Understanding of Planetary Surface Environment and Habitability

Abstract Volume

Misasa VIII organizing committee

Institute for Planetary Materials (IPM), Okayama University

Contents

Preface

Welcome to the international symposium of Misasa VIII on the "Future Planetary Exploration: Understanding of Planetary Surface Environments and Habitability" organized by the Institute for Planetary Materials (IPM), Okayama University.

IPM is located in Misasa town, Tottori Prefecture, which is a well-known hot spring resort. The Institute has a long tradition, originating from the Institute for Thermal Spring Research (1950-1985), which was reorganized into the Institute for Study of the Earth's Interior (ISEI) as a national collaborative research facility in 1985, and then into the current Institute for Planetary Materials in 2016. The mission of IPM is to study the origin, evolution and dynamics of the Earth and other planets and origin of life, and to promoting collaborative research and education in Earth and planetary material sciences by providing opportunities to access its broad spectrum of unique world-class analytical and experimental facilities to the domestic and international research community.

In April of this year, IPM established a new division on planetary surface environment research with the aim of contributing to human society through the social implementation of material science for planetary exploration and human space advancement. We welcomed new staff members so that we can grow into a leading research institute for this purpose. Coincidentally, Okayama University has been selected for the J-PEAKS program, and IPM belongs to the Institute for Advancing Cutting-Edge Research, playing a leading role in research as a research university. The introduction of the planetary surface environment simulator, hyperspectral camera, and low gravity device, which are the highlights of the new division, is progressing steadily with the support of the university. These will be open to a wide range of users regardless of field as new core facilities of the Joint Use and Research Center. We would be happy if this symposium could serve as a catalyst for new research fusion with IPM as a hub. We look forward to meeting you in March 2025 at the symposium, and wish you will have a great experience during your stay in Misasa.

Takashi Yoshino

Director of the Institute for Planetary Materials
Okayama University

Symposium Schedule

March 4 (Tue)

- 9:45 -9:50 Welcome note by IPM Director Takashi Yoshino

- The 1st session Chair by K. Kobayashi & K. Onodera (IPM)

09:50-10:15 Seiji Sugita (Univ. Tokyo)
What we learned from four way synergy among Hayabusa2 and OSIRIS-Rex, remote-sensing, and sample observations.
10:10-10:40 Zhiyong Xiao (Sun-Yet Sen Univ., China)
Past, future lunar exploration from the Chinese perspective.

10:40-10:55 Trishit Ruj (IPM)
Instruments to be installed and activities of the Institute.

- Coffee break

11:05-11:30 Makiko Ohtake (Univ. Aizu)
Goal and status of the lunar polar exploration (LUPEX) mission.

11:30-11:55 Hideaki Miyamoto (Univ. Tokyo)
Exploring lunar volatiles through electromagnetic studies.

- Lunch

- The 2nd session Chair by J. Kameda & T. Ruj (IPM)

14:00-14:35 Nicolas Mangold (Laboratory of Planetology and Geodynamics in Nantes, France)
The growing diversity of past Mars aqueous environments.

14:35-15:00 Yasushi Mori (Okayama Univ.)
Infiltration and evaporation of soil water caused by micro and low gravity environments.

15:00-15:25 Yasuhito Sekine (ELSI, Inst. Science. Tokyo)
Chemical diversity of icy ocean worlds.

- Coffee Break

15:35-16:00 Goro Komatsu (D'Annunzio Univ., Italy) (online)
Analog approach in planetary geology and geological reasoning.

16:00-16:25 Ikuo Katayama (Hiroshima Univ.)
Possible present-day liquid water in the Martian crust from seismic structure and rock physical model.

March 4 (Tue)

- The 3rd session

  16:30-18:15 Poster session Chair by T. Moriguti (IPM)

- 18:30-20:30 Banquet

March 5 (Wed)

- The 4th session Chair by R. Tanaka and C. Potiszil (IPM)

  9:00- 9:25 Tony Jia (ELSI, Science Tokyo) (online)
  TBD

  9:25- 9:50 Ken Takahashi (Okayama Univ.)
  What happens to the body in space?

  9:50-10:15 Christian Potiszil (IPM)
  Exploring small solar system bodies to understand the potential for the delivery of prebiotic organic molecules to early planetary surfaces.

  10:15-10:40 Yoko Kebukawa (Science Tokyo)
  Formation of organic matter in asteroids during aqueous alteration and implications for prebiotic chemical evolution in various solar system bodies.

- 11:00-12:00 Discussion (Moderator: Makiko Ohtake and Trishit Ruj)

- Lunch

- 13:30-15:00 IPM lab tour

Venue

Blanc Art Misasa
Zip code: 682-0123; 388-1, Misasa, Misasa-cho, Tottori-ken
〒 682-0123 鳥取県東伯郡三朝町三朝 388-1
℡ 0858-43-2211 https://www.blancart.jp/en/

Shuttle Bus (By Appointment Only)

A shuttle bus is provided between the main gate of the Tsushima Campus of Okayama University and the venue hotel at Misasa.

March 4 (Tue) 7:00 departure from Okayama University 9:00 arrival at Misasa Onsen

March 5 (Wed) 16:00 departure from Misasa Onsen 18:00 arrival at Okayama University

Links

Institute for Planetary Materials (IPM), Okayama University
Local Bus Schedule around Misasa and Kurayoshi (pdf in Japanese)
Misasa Onsen
Misasa Onsen Map (in Japanese)
Tsushima Campus of Okayama University (map)

Abstracts of Oral session

The “@” symbol in the email address is converted into “©”.

The first session

Seiji Sugita

Zhiyong Xiao

INSTRUMENTS TO BE INSTALLED AND ACTIVITIES OF THE INSTITUTE

T. Ruj[1], J. Kameda[1], M. Izawa[1]

[1] IPM, Okayama Univ. (trishitruj©okayama-u.ac.jp)

In April 2024, the Division of Planetary Surface Environment Science was established within the Institute for Planetary Materials, Okayama University. As one of the core instruments in the new division, we are currently developing a new pressure and temperature-controlled chamber to replicate Martian environmental conditions. The chamber, named MISASA (**M**art**I**an **S**imulator for **A**ssessing **S**urf**A**ce environments), has an interior space of approximately 1m x 1m and can reach a minimum temperature of -100°C, with pressure ranging from 3 to 5 millibars, and relative humidity (R_H) controlled between 0 to 100%. To further simulate surface geological processes, an adjustable stage inside the chamber allows for tilting up to 60°. The chamber is also designed for future upgrades, with flanges enabling modifications. Additionally, the atmospheric composition can be precisely regulated through controlled flows of CO_2, N_2, Ar, and O_2.

To enhance our research capabilities, we have equipped the chamber with two hyperspectral cameras, the VNIR-1800 and SWIR-640 from HySpex, covering a spectral range of 400 to 2500 nm with a spectral resolution of 5 nm. These cameras, mounted on the top of the chamber, will facilitate the study of mineralogical changes under Martian conditions. When not attached to the chamber, they will remain operational for other experimental applications.

Beyond the Martian simulator, we have also acquired a low-gravity simulator to replicate Lunar and Martian gravity conditions. These instruments will serve as core research facilities within the institute and will be made accessible to researchers worldwide on a collaborative basis, fostering international scientific cooperation.

GOAL AND STATUS OF THE LUNAR POLAR EXPLORATION (LUPEX) MISSION

M. Ohtake[1] and LUPEX project team

[1] The University of Aizu/ IPM, Okayama University

Multiple remote sensing dataset derived from recent lunar exploration missions suggested that water ice might be widely present in the lunar polar region [1]-[4]. Also, recent study of visible and near-infrared spectrometry observation reported possibility of active sublimation and condensation phenomena of water ice molecules identified as intermittent uplift of water ice/gas mixture at latitude higher than 85° in both poles at non-PSR [5]. As these reports indicate, the reported location and abundance of water in the lunar polar region varies among studies and even currently unknown process might be working at the polar region. Threfore, currently, the actual origin, abundance, condensation mechanism, and lateral and vertical distribution of water remain unclear because no landing mission and no in-situ measurements have been conducted at latitude higher than 85°.

To assess the abundance and distribution of water in the lunar polar region, the Japan Aerospace Exploration Agency (JAXA), in collaboration with the Indian Space Research Organisation (ISRO), is planning the lunar polar exploration mission (LUPEX). Objective of the LUPEX mission is to obtain information regarding water abundance, distribution, and condensation mechanism at the lunar polar region to evaluate possibility for utilizing water as a resource in the future missions. To attain this objective, we are going to land on the lunar surface at the polar region and directly measure water by conducting in-situ measurements. We are going to conduct measurements to know its quantity (how much), quality (content of other phases such as CO_2 and CH_4), and usability (how deep do we need to drill or how much energy is required for drilling the regolith to derive the water). In this mission, the ISRO and JAXA plan to develop a lander and a rover, respectively. Mass of the rover is around 350 kg (including payloads) and will carry multiple instruments (Table 1). The rover has capability of drilling the surface regolith up to 1.5 m depths, bringing up the regolith sample from the drilled depth, and transferring it to the instruments.

The rover is designed to move and carried out measurements at the shadowed area for a short period of time. Evaluation and validation of the rover design are underway in various test environments using engineering models. Resource Investigation Water Analyzer (REIWA) consist of four subunits, namely, lunar thermogravimetric analyzer (LTGA), triple-reflection reflectron (TRITON), aquatic detector using optical resonance (ADORE), and ISRO sample analysis package. Manufacturing EMs of REIWA system has finished and testing and evaluating them in the subsystem level has been underway and the REIWA system level test will start from January 2025. Manufacturing of Advanced Lunar Imaging Spectrometer (ALIS) EM was completed, and its functional performance test has started. A series of EM tests will continue to the end of February 2025.

Table 1 Mission Instruments on the LUPEX Rover

Mission Instruments	Observation Target
Resource Investigation Water Analyzer (REIWA)	
(1) Lunar Thermogravimetric Analyzer (LTGA)	Thermogravimetric analyses of the drilled samples for water contents
(2) Triple-Reflection Reflectron (TRITON)	Identification of chemical species of the volatile component based on mass spectrometry
(3) Aquatic Detector using Optical Resonance (ADORE)	Water content measurement in the drilled samples based on cavity ring down spectrometry
(4) ISRO's Sample Analysis Package (ISAP)	Mineralogical and elemental measurement of the drilled samples
Advanced Lunar Imaging Spectrometer (ALIS)	H_2O/OH observation of the lunar surface
Ground Penetrating Rader (GPR)	Underground radar observation up to 1.5 meter during rover traverse
Mid-Infrared Imaging Spectrometer (MIR)	Infrared spectral range observation of the lunar surface including 3 μm -H_2O/OH absorption band
Permittivity and Thermophysical Investigation for Moon's Aquatic Scout (PRATHIMA)	Detection and quantification of regolith bound water-ice in the lunar surface/sub-surface
Neutron Spectrometer (NS)	Underground neutron (hydrogen) observation up to 1 meter during rover traverse
Exospheric Mass Spectrometer for LUPEX (EMS-L)	Surface gas pressure and chemical species measurement

Reference: [1] Li S. et al. (2018) *Proc. Natl. Acad. Sci.*, 201802345. [2] Gladstone G. R. et al. (2012) *J. Geophys. Res. 117*, E00H04, doi:10.1029/2011JE003913. [3] Mitrofanov I. G. et al. (2010) *Science 330*, 483-486. [4] Sanin, A. B. et al. (2017) *Icarus 283*, 20-30. [5] Ohtake et al. (2024) *ApJ.*, 963, 124-147.

Exploring lunar volatiles through electromagnetic studies.

H. Miyamoto[1,2], M. Kobayashi[1], Y. Murakami[1], S. Takekura[1], A. Toida[1], Y. Shimizu[1], T. Takemura[1], T. Yoshimitsu3, N. Usami[3], M. Otsuki[3], Y. Kunii[4], T. Maeda[5], A. Kumamoto[6], Y. Nakauchi[7], T. Niihara[8], T. Usui[2], H. Nagaoka[7], K. Saiki[7], J. Culton[2], E. Asphaug[9], P. Michel[1,10], T. Himeno[1], M. Watanabe[11]

[1]University of Tokyo, [2]University of Adelaide, [3]JAXA, [4]Chuo University, [5]University of Tokyo Agricauture, [6]Tohoku University, [7]Ritsumeikan University, [8]Okayama University of Science, [9]University of Arizona, [10]Université Côte d’Azur, Observatoire de la Côte d'Azur, CNRS, [11]Gakushuin University

Recent lunar missions have significantly advanced our understanding of the potential presence of volatiles on the Moon. While trace amounts of water have been clearly detected, several studies suggest that peak concentrations could exceed 1 wt%. The scientific importance of determining the age, origin, and evolution of lunar volatiles has been emphasized in numerous research papers and community reports worldwide [1-2]. Additionally, interest in in-situ resource utilization (ISRU) has grown considerably, further underscoring the need for continued investigation to reach a scientific consensus.

We are conducting electromagnetic investigations of the Moon by utilizing data from past missions such as NASA’s LRO Mini-RF [3], ISRO’s Chandrayaan-1 Mini-SAR [4], and China’s Chang’E MRM [5], as well as upcoming missions, including LUPEX [6] and TSUKIMI (Lunar Terahertz Surveyor for Kilometer-scale Mapping). Electromagnetic methods offer distinct advantages over optical observations for probing the subsurface, which is critical because theoretical models predict that volatile concentrations are likely to occur at depths ranging from several to tens of centimeters, depending on soil packing conditions. TSUKIMI, currently under development with support from Japan’s Ministry of Internal Affairs and Communications and JAXA, will play a key role in investigating the Moon’s shallow subsurface (5–20 cm). By measuring the polarization ratio of brightness temperature across two frequency bands, it will derive the Apparent Bulk Permittivity (ABP). Also, its polar orbit enables repeated observations of the lunar poles, allowing for multiple measurements of the same area to determine averaged thermal diffusivities within a sub-kilometer field of view.

Proper interpretation of remote sensing data requires accurate estimates of the Moon’s surface permittivity. In other words, precise in-situ permittivity measurements are needed as ground truth for various radar data interpretation. While obtaining such measurements requires direct contact with undisturbed terrain, which is challenging for robotic missions, a trained crew can better identify pristine areas and ensure optimal sensor placement. For this reason, we are developing the Lunar Dielectric Analyzer (LDA) for deployment on the Artemis III mission. LDA is a simple, robust, and precise instrument designed to measure the permittivity of the lunar surface, providing critical insights into regolith properties such as density, composition, and volatile content. By operating across multiple frequencies and temperature conditions, LDA aims to characterize vertical density structures and detect potential ice deposits within the shallow subsurface. In this talk, I will present the current status of both LDA and TSUKIMI and outline our strategy for future lunar resource exploration.

Reference:

[1] Artemis III Science Definition Team. [2] National Academies of Sciences, Engineering, and Medicine (2022). Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023-2032. [3] Nozette, S. et al., T, *Space Sci Rev* 150, 285, 2010. [4] Spudis, P.D. et al., Geophys. Res. Lett., 37, 2010. [5] Zheng, Y.C. et al., Icarus, 219, 1, 2012. [6] Mizuno, H. et al. (2023) 74th IAC, IAC-23-A3. 2A.5.

The second session

THE GROWING DIVERSITY OF PAST MARS AQUEOUS ENVIRONMENTS

N. Mangold

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Mars is today a dry and cold planet, which displays a large diversity of water-related landforms, such as valleys, alluvial fans and deltas, which suggest the presence of liquid water. Orbital spectrometers have enabled the detection of huge areas of altered minerals such as phyllosilicates, especially within sediments that are record of past conditions. Their presence is limited to ancient Mars regions. However, the precise conditions behind the formation of these landforms and minerals are still debated, but this huge amount of orbital data helped to select landing sites for rover studies, which enable a more detailed analysis of past surface conditions.

During the years 2000s, the Mars Exploration Rover *Opportunity* analysed sulphate-rich deposits at Meridiani Planum. The environment deduced by Opportunity requires the formation of minerals such as jarosite, stable only in acidic waters, suggesting a low water:rock ratio in an overall groundwater-dominated environment. Based on the widespread detection of sulphates on Mars by orbiters, this local ground truth has created a paradigm in which Early Mars was an acidic world with limited water availability at the surface. Yet, the *Curiosity* rover landed in August 2012 in Gale crater, and since then observed more than 600 m thick strata, including lacustrine mudstones and fluvial sandstones and conglomerates. Clay minerals represent 30 % of the bulk composition in places, with a substantial degree of chemical alteration, highlighting a high water:rock ratio in their formation processes. The overlying sulphate-bearing unit is composed of various strata including fluvial deposits, but display no evidence for specifically acid conditions.

In February 2021, the *Perseverance* rover landed in Jezero crater, a location selected after the observation of both a large-scale fan and the detection of clay and carbonate minerals. Remote observations of the fan and its remnants allowed the identification of the sigmoidal structure of a deltaic architecture, typical of a perennial lake. The rover was also able to detect a whole series of hydrated minerals, clays, sulphates and carbonates, all indicating conditions linked to aqueous alteration either in the watershed or within the lake. Hence, sedimentary rocks analysed by *Curiosity* and *Perseverance* requires a strikingly different environment of formation than those observed by *Opportunity* rover. In addition, these rovers have explored mostly Late Noachian-Early Hesperian rocks. *Perseverance* has just started the exploration of the crater rim of Jezero entering into older Noachian rocks. In a few years, the European rover *Rosalind Franklin* of the ExoMars mission should explore widespread clay mineral signatures assumed to represent weathering conditions. More diversity is still expected! Hence, Early Mars should not be reduced to a single type of climate or environment. It should be recognized as a puzzle in which the climate is one piece of the puzzle, and parameters such as bedrock lithology, regional heat sources or local hydrology are other pieces of the puzzle that explain this diversity.

Infiltration and evaporation of soil water caused by micro and low gravity environments.

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In recent years, there has been a lot of research aimed at long-term stays in space. From a long-term perspective, it is necessary to cultivate plants and obtain food locally, but one issue is to understand the dynamics of water in soil in different gravitational environments. Therefore, in this study, we conducted research with the aim of clarifying the water infiltration and evaporation process in microgravity and low-gravity environments.

In order to create a microgravity environment, we used a 3D clinostat and conducted experiments under four conditions: 1G, 1/3G, 1/6G, and 0G. Infiltration and evaporation experiments were conducted using three types of soil: standard sand, clayey soil, and aggregate soil. In previous experiments, there was a problem where the soil would move due to the rotation of the clinostat, so we first constructed an experimental system where the soil would not move. The soil was placed in a centrifuge tube, and a nylon mesh that did not obstruct evaporation was placed over the soil surface, and the soil was fixed in place with an aluminum pipe. First, we investigated the effect of differences in soil on evaporation. Next, we prepared three types of soil structure: normal filling, with vertical pores, and with aggregate structure, and investigated the effect of differences in soil structure on evaporation. On the other hand, in the infiltration experiment, we created two structures: normal filling and with tubular macropores, and investigated the effect on infiltration.

In the experimental system we constructed, the soil did not spill out during rotation, and the evaporation experiment was able to continue. For all soil types, the smaller the gravity, the lower the evaporation rate, and we obtained a different finding than before. In microgravity and low-gravity environments, the buoyancy force acting on the evaporated water molecules becomes smaller, and convection does not occur. In other words, the evaporated water vapor does not move from the soil surface, and the relative humidity of the soil surface is maintained at a high level. We thought that this would make it difficult for subsequent evaporation to occur, and that the evaporation rate would consequently decrease. In addition, there was almost no difference in the amount of evaporation between different types of soil or soil structures over the 48-hour evaporation period. In the infiltration experiment, standard sand was the most affected by gravity. The effect of inertia was significant in the large pores between sand grains, and the difference in gravity would affected the depth of infiltration. In addition, the difference in depth of infiltration was greatest in clay soil when there were tubular macropores. For the same reason, the effect of inertia on infiltration in tubular macropore produced a large difference.

Unlike drop tests and flight tests, the 3D clinostat makes it possible to conduct long-term experiments, so we would like to develop experiments that make use of this characteristic.

Chemical diversity of icy ocean worlds.

Y. Sekine[1]

[1] Earth-Life Science Institute (ELSI), Institute of Science Tokyo (sekine©elsi.jp).

Geologically-active icy moons around Jupiter and Saturn, such as Europa and Enceladus, are known to possess subsurface oceans beneath the icy crust. According to the in-situ chemical analysis of plume materials erupting from Enceladus' subsurface ocean, the Cassini spacecraft has revealed water chemistry of the ocean – that is, seawater pH is alkaline (pH ~ 10) and Na-Cl-carbonate-rich composition. Planetary habitability can be defined as a planetary-scale system that can develop and sustain ingredients of life—liquid water, bioessential elements, and energy—over geological time. With this regard, Enceladus possesses a habitable world beneath the icy shell. This moon has a global subsurface interacting with a rocky core. A wide variety of organic matter and chemical energy supported by hydrothermal activities are also available. Among the major bioessential elements for Earth's life, phosphorus (P) is usually the least abundant in natural aqueous systems and has been a limiting nutrient of primary productivity over Earth's history. In icy ocean worlds, such as Enceladus, in the outer Solar System, there may be a more drastic depletion of P than Earth due to lack of surface lands, possibly limiting the emergence and activity of life similar to the form of Earth's life. Recently we discovered phosphate in ice grains emitted by Enceladus based on the analysis by Cassini's Cosmic Dust Analyser [1]. Our observational results are evidence that phosphorus is readily available in Enceladus' ocean, with anomalously high concentrations–at least 100 times higher than Earth's oceans [1]. On the other hand, abundance of sulfur (S)-bearing materials, such as sulfate, have been observed on the surface of Europa and Mars [2,3]. Although sulfates on Europa would have originated from volcanism on inner Jovian moon, Io, the occurrence of resurfacing of icy crust of Europa suggests that sulfate would have been supplied to its subsurface ocean.

What are geophysical and geochemical processes responsible for the diversity in ocean chemistry and availability of bioessential elements (such as P and S) in icy ocean worlds and terrestrial planets? Here we discuss the causative mechanism of the enrichment of phosphate in Enceladus' seawater based on our hydrothermal reaction experiments and geochemical modeling. We find that alkaline (pH ~10) and carbonate-rich aqueous environments are essential for the phosphate enrichment, where calcium phosphate minerals are thermodynamically unstable compared to calcium carbonate minerals, releasing phosphate into liquid phase. Such alkaline carbonate-rich aqueous environments are commonly achieved in icy ocean worlds beyond the CO_2/NH_3 snowline of the Solar System. Phosphate could have been also enriched in similar alkaline carbonate-rich aqueous environments on early Earth, where earliest life on Earth might have utilized phosphorus as components of its building materials. On the other hand, if icy moons formed within the CO_2/NH_3 snowline of the Solar System, the oceans within such icy moons should contain relatively high abundance of sulfur. Organic chemical evolution in such S-rich ocean worlds would be different from those possibly occurred in P-rich ocean worlds. The dichotomy in the ocean chemistry (P-rich and S-rich oceans) across the CO_2/NH_3 snowline should affect the potential of the emergence of life and habitability.

Reference: [1] Postberg, F. et al. (2023) Nature, 618, 489. [2] Fisher P. D. et al. (2015) ApJ, 150: 164. [3] Mangold, N. et al. (2005) Icarus, 194, 519.

GORO KOMATSU

POSSIBLE PRESENT-DAY LIQUID WATER IN THE MARTIAN CRUST FROM SEISMIC STRUCTURE AND ROCK PHYSICAL MODEL

I. Katayama[1] and Y. Akamatsu[2],

[1] Department of Earth and Planetary Systems Science, Hiroshima University (katayama©hiroshima-u.ac.jp), [2] Research Institute of Marine Geodynamics, Japan Agency for Marine-Earth Science and Technology

A variety of geomorphic features on Mars indicate the presence of a persistent ocean in its early history (e.g., Carr, 1987), which is consistent with the widespread occurrence of clay minerals in Noachian terrains (Ehlmann et al., 2011). Although there is little evidence for subsurface water on present-day Mars, water reservoirs may exist in the deep interior that could store a significant amount of ancient ocean. The Interior Exploration using Seismic Investigations, Geodesy and Heat Transport (InSight) mission, which landed on Mars in 2018, has deployed a seismometer and investigated the internal structure of Mars (e.g., Lognonné et al., 2020). The seismic structure of the Martian crust beneath the InSight landing site is characterized by three layers with seismic discontinuities at ~10 km and ~20 km depth (e.g., Kim et al., 2021; Knapmeyer-Endrun et al., 2021). The boundaries found in the crustal layer have been interpreted as distinct changes in porosity or chemical composition, since these factors have a strong influence on seismic velocity (e.g., Wieczorek et al., 2022; Kilburn et al., 2022). However, such a seismic discontinuity can be explained by a transition from a dry layer to a water-rich layer, because seismic velocity is strongly influenced by the presence of liquid water in the rock interstitial space.

We have tested this hypothesis by examining the seismic velocity of fractured crustal rocks under dry, water-saturated and frozen conditions. The P- and S-wave velocity is systematically different among the analyzed crack-filling phases, with the dry (gas-filled) samples yielding the slowest seismic velocity due to the different elastic moduli for gas, water, and ice. We applied the effective medium theory of Kuster and Toksöz (1974) to the experimental data, which indicate an average crack aspect ratio of $\alpha \sim 6\times10^{-3}$, nearly consistent with those inferred from terrestrial crustal rocks. Since the seismic velocities of the gas-, water-, and ice-filled cracks are significantly different, the seismic discontinuity may be caused by the transition from one crack-filling phase to another.

We have modeled seismic structure in the Martian crust from the effective medium theory with different crack-filling phases, where porosity is assumed to be constant down to the depth to ~20 km and pore closure occurs at greater depths due to viscous deformation at higher temperatures. Our calculations indicate that a significant increase in seismic velocity can occur when cracks are filled by liquid water in the middle crust at depth of ~10 km. Crack porosity can change continuously with depth due to compaction and precipitation, but the gradational change with depth does not provide the necessary impedance contrast across the boundary. Our calculations show increasing Vp/Vs in the water-rich layer, in agreement with joint inversion analyses of P- and S-wave velocities in the middle crust at ~10–20 km depth (Carrasco et al., 2023). Recently, Wright et al. (2024) suggested the presence of liquid water in the Martian middle crust based on Bayesian analysis, although their model requires round pores with a large aspect ratio ($\alpha = 0.19$), which cannot explain the high Vp/Vs observed in the middle crustal layer.

Based on these calculations, we propose that the seismic discontinuity detected at ~10 km depth at the InSight landing site may be caused by the presence of water-filled cracks, indicating the possible existence of subsurface water in the Martian middle crust. This may be due to increasing lithostatic pressure and temperature with depth, which could allow the presence of subsurface liquid water above the eutectic point. Since numerous microbes survive in the subsurface and receive nutrients through fluid-rock interactions on Earth, the presence of liquid water in the Martian crust could provide a habitable environment and support a microbial community.

Reference:

Carr (1987) *Nature*, v. 326, p. 30–35, https://doi.org/10.1038/35084172.
Carrasco et al. (2023) *Geophysical Research Letters*, v. 50, https://doi.org/10.1029/2023GL104816.
Ehlmann et al. (2011) *Nature*, v. 479, p. 53–60, https://doi.org/10.1038/nature10582.
Katayama and Akamatsu (2024) *Geology*, v. 52, p. 39–42, https://doi.org/10.1130/G52369.1.
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Lognonné et al. (2020) *Nature Geoscience*, v. 13, p. 213–220, https://doi.org/10.1038/s41561-020-0536-y.
Wieczorek et al. (2022) *Journal of Geophysical Research*, v. 127, https://doi.org/10.1029/2022JE007298.
Wright et al. (2024) *PNAS*, v. 121, https://doi.org/10.1073/pnas.2409983121

The fourth session

Tony Jia

What happens to the body in space?

Ken Takahashi[1]

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As space travel moves beyond professional astronauts to include researchers, tourists, and eventually settlers on the Moon and Mars, understanding how the human body adapts to space environments has never been more important. Whether for a short suborbital flight or a long-term mission to another planet, microgravity and space radiation pose unique challenges to human health. In weightlessness, bodily fluids shift upwards, causing swollen faces and sinus congestion, muscles weaken from disuse, bones lose density at an accelerated rate, and even vision can deteriorate. Over time, the heart and immune system also undergo significant changes, raising concerns for long-duration space habitation.

Why does this happen? Gravity is a fundamental force that has shaped human biology for millions of years. Without it, our cells, tissues, and organs behave differently—muscle fibers shrink, bone cells stop regenerating properly, and even gene expression is altered. Interestingly, many of these effects resemble aging on Earth, making space an extreme but valuable environment for studying human physiology.

This talk will explore how spaceflight affects the human body and what it means for the future of space exploration. As more people prepare to live and work beyond Earth, we must develop strategies to keep them healthy, from artificial gravity solutions to personalized countermeasures. Understanding how humans can thrive in space is not just a challenge for astronauts—it's a question that will define the future of human expansion beyond our planet.

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Exploring small solar system bodies to understand the potential for the delivery of prebiotic organic molecules to early planetary surfaces.

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Asteroids and comets represent the material that was left over after the formation of the planets. The planetesimal progenitor bodies, of asteroids and comets, would have initially formed from material within the protosolar nebular around the protosun, including ice, silicate dust and organic matter [1]. Shortly after the formation of such bodies radioactive decay of short-lived radionuclides, such as ^{26}Al, would have generated heat and melted the ice contained within them. In the several million years that followed, liquid water would have aqueously altered the interiors of these planetesimals and produced secondary mineral and organic products from the initially accreted materials.

How exactly this period of aqueous chemistry determined the final inventory of biologically important prebiotic organic molecules found within the remnants of these bodies remains a hotly debated topic. During analysis of two Ryugu particles returned from JAXA's Hayabusa2 mission, significant differences between the amino acid abundances between a particle from touchdown site (TD) 1 and TD 2 indicated that the amino acid abundances in Ryugu were heterogenous over a scale of ~870 m [2]. However, it remained unclear whether heterogeneity was present over smaller distances and if it was unique to Ryugu or common to other asteroidal fragments, such as carbonaceous chondrites. A subsequent study has indicated that carbonaceous chondrites do indeed demonstrate heterogeneity, at least at the mm-scale [3]. Therefore, understanding the processes responsible for determining this heterogeneity is important for revealing the processes and associated environments within the early Solar system and beyond that lead to the preservation and/or formation of biologically important organic molecules. This in turn will help us to better constrain the most likely places that could hold life within our Solar system and elsewhere within our universe. Such places would then be prime candidates for space exploration missions.

Among the processes proposed to be responsible for the generation of prebiotic molecules found within planetesimal fragments are photochemical processes within the interstellar medium, similar processes in the protosolar nebula (PSN), high temperature plasma-related processes within the PSN, aqueous alteration on planetesimals, impact related processes involving small bodies and surface irradiation processes on small bodies [1]. It is then possible that exogenous delivery of asteroidal and cometary fragments to planetary surfaces, including the Earth, could have delivered the building blocks of life and enabled an origin of life event. With this in mind, elucidating the particularly important processes for the generation of biologically important organic molecules is essential for understanding the potential habitability of bodies within our solar system and beyond.

Nevertheless, it is also important to further discuss and investigate the potential for planetary bodies themselves to generate biologically important prebiotic organic molecules as well. This is because it is not clear if asteroids and comets did in fact deliver the building blocks of life to planetary bodies throughout our solar system. Indeed, both the Hayabusa2 [4] and OSIRIS-REx [5] missions have reported racemic non-proteinogenic amino acids for their returned asteroid samples, which may suggest that potential enantiomer selective processes, such as the influence of circularly polarised light, may not be responsible for Terrestrial life's exclusive use of L-amino acids within its proteins. As such future exploration of both asteroids, comets and planetary bodies and their moons must prioritise deciphering the environments and processes responsible for the generation of biologically relevant prebiotic organic molecules and the pathway to the origin of life.

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Formation of organic matter in asteroids during aqueous alteration and implications for prebiotic chemical evolution in various solar system bodies.

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Parent bodies of carbonaceous chondrites which contain organic matter such as amino acids and sugars, experienced hydrothermal environments of at most several tens to 150°C during the early stages of solar system formation due to the melting of ice. In such environments, experimental studies have demonstrated that complex organic materials were formed by reactions starting from simple molecules such as formaldehyde [e.g., 1], which is an interesting process in terms of the chemical evolution of organic materials in small bodies. In hydrothermal experiments simulating meteorite parent bodies, we have shown that macromolecular solid organic matter and amino acids similar to those contained in meteorites are formed from simple molecules such as formaldehyde and ammonia [2-4]. Various other organic products, such as pyridines, are also known to be formed in such reactions [e.g., 5].

On the other hand, the heat source that produced warm water is considered to have been mainly the decay of radionuclides such as ^{26}Al. Using initial values of ^{26}Al estimated from meteorites [6], the total amount of energy released can be calculated to be as high as approximately 6.3 MGy [7]. Such non-equilibrium reactions due to radiation are expected to provide reaction processes different from those due to thermal reactions. However, previous studies have only considered the effect of heat and not the effect of radiation itself. We have therefore hypothesized that gamma rays emitted from the decay of radionuclides act directly on molecules to promote chemical reactions, and have experimentally shown the formation of amino acids by gamma rays [7-9]. Most recently we gamma-rays promote the formation of aldose sugars [10].

So far, we have demonstrated that the formation of precursor molecules for the origin of life in aqueous environments containing simple ubiquitous molecules such as formaldehyde and ammonia with some energy provided by heat or gamma rays. Such environments are found not only in meteorite parent bodies, but also in inner oceans of icy bodies such as Enceladus, Europa, and Pluto. In addition, comets contain abundant water, ammonia, and formaldehyde, and thus could provide temporary hydrothermal environments by hypervelocity impacts on the surfaces of various planetary bodies such as Mars and Titan [e.g., 11].

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Effect of iron content on the viscosity of ringwoodite: implication on the viscosity of Martian mantle

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Martian meteorites suggests that there is about twice as much iron in Mars' mantle (~18 wt% FeO) as on Earth (~8 wt% FeO)(Dreibus and Wänke, 1985;Wänke and Dreibus, 1988, 1994; Anderson, 1989; Rubie et al., 2004). And the viscosity of martian mantle is estimated to be ~10^{22} Pa·s from the tidal deformation by Phobbs, which is one order of magnitude higher than that of the Earth. The previous results of deformation of olivine show the viscosity of Fo_{90} is one order of magnitude larger than that of Fo_{75}. However, viscosities of high pressure polymorphs, wadslydite and ringwoodite, are not well-known. To discuss viscosity contrast between Earth and Mars, it is needed to determine the effect of iron on viscosity of high pressure mimerals. This study trys to design a series of high pressure experiments to test how iron content effect the viscosity of ringwoodite.

Specifically, this study use Kawai type multianvil apparatus to synthesis well-sintered ringwoodite with different iron content under 20 Gpa and 1200 ° C, and the starting materials as Fo_{60} + 3mol%Px and Fo_{90} + 3mol%Px. Then we make the ringwoodite samples deformed by D111-type high-pressure deformation apparatus which is capable of controlling the d-ram displacement of 300 μm and 600 μm at high pressure and high temperature. Then we measured the length of deformed samples and estimate the viscosity based on the following equations:

$$\epsilon = \frac{l_0 - l}{l_0} \qquad (1)$$

$$\dot{\boldsymbol{\epsilon}} = \frac{\boldsymbol{A}}{\eta}\boldsymbol{\sigma}^n \qquad (2)$$

where ϵ is strain, l_0 is the initial length of sample, l is the length after deformation,$\dot{\varepsilon}$ is strain rate, η is viscosity, A is constant, σ is stress, and n is stress exponent.

In conclusion, estimated from the strain rate between samples, viscosity of ringwoodite with Mg# 60 is 1.5 times larger than that with Mg# 90. This iron effect is much smaller than the effect on olivine (Zhao et al., 2009). Deformation mechanism in the present study may be dominated by diffusion creep because 1) no LPO was observed and 2) no recrystallization was observed. By understanding the difference of viscosity composed of different iron content, we can offer implications on the viscosity of Martian mantle.

Basanite in gypsum dunes on Mars? —New possibilities revealed by White Sands research

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Clarifying the mineral composition of Martian sulfate deposits plays an important role in reconstructing past aqueous environments and evaluating the habitability of Mars. Spectroscopic studies have revealed the presence of various types of hydrated minerals in deposits around the north polar cap of Mars. Previous studies have also shown that liquid brine may exist at high latitudes on Mars, suggesting that episodic saline activity may occur in these regions. Specifically, gypsum, a hydrated calcium sulfate ($CaSO_4$+$2H_2O$), has been detected around the sand dune-covered Olympia Planitia [1].

To investigate the geographic distribution and formation and accumulation process of these hydrated minerals in detail, we conducted field surveys at White Sands, New Mexico, USA, as a similar environment on Earth. Gypsum dunes have developed in White Sands, just like on Mars, and the topographical environment and depositional process by evaporites are similar, making it a suitable study target for gypsum dune analogues on Mars [2][3]. In this region, when Lake Lucero evaporates during the dry season, salt precipitates, which is then transported by the wind to form sand dunes. XRD analysis confirmed the presence of bassanite ($CaSO_4$+1/2 H2O) in samples from the evaporation site of Lake Lucero. Basanite has a higher solubility than gypsum, so bassanite is thought to have precipitated when the salt lake evaporated and the salinity increased. This transformation process suggests that metastable phases such as bassanite may form under certain evaporation conditions, which provides a clue to explain their presence in Martian sand dunes.

Based on this knowledge, in this study, we used remote sensing data to further analyze the seasonal variations in the mineral composition of sand dune fields around the north polar cap of Mars. These results suggest that both gypsum and bassanite vary seasonally on Mars and may be associated with episodic saline activity. However, further studies are needed to clarify the mechanisms that cause these mineralogical changes.

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The Li- and O-isotope composition of the proto-solar nebula determined from the chondrules of the Sahara 97103 (EH3).

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Enstatite chondrites are important as they are considered to be potential building blocks for terrestrial planets including Earth [1]. It has been suggested that the chondrules of unequilibrated enstatite chondrites (UEC) may have formed from similar precursor components to other chondrite groups, based on oxygen-isotope and major-element compositions [2-7]. The Mg/Si ratio of enstatite chondrites is smaller than that of ordinary and carbonaceous chondrites [8]. For enstatite to form from an olivine-rich precursor, the Mg/Si ratio would need to be lowered. This may occur by adding SiO_2 during the interaction of a Si-rich gas reservoir with melted or partially melted olivine [4,9]. To estimate the composition of the proto-Solar nebula (PSN), the Li- and O-isotope compositions of the chondrule constituents within the UEC Sahara 91703 (EH3) were determined.

The O-isotope compositions of the enstatite was close to the intersection of the terrestrial fractionation (TF) and primitive chondrule minerals (PCM) lines. However, the O-isotope composition of the olivine varied along the PCM line. This indicates the olivine is relict. Cristobalite was observed within the mesostasis or enclosed by enstatite, with no accompanying metal. This indicates it is the product of Si saturation, rather than the reduction of an FeO-rich silicate. Furthermore, chondrules with relict olivine lacked MgS, indicating that enstatite was not produced by sulfidation. This supports enstatite is produced by the addition of SiO_2 and is consistent with the Si-enrichment experienced by EH3 chondrites. The cristobalite was consistently enriched in ^{18}O relative to the enstatite. The O-isotope composition of the cristobalite is scattered along the TF line. This indicates that there were two generations of cristobalite. The first occurring during chondrule formation and the second formed in the parent asteroid. The O-isotope composition of the Si-rich reservoir was estimated from the values obtained for enstatite and relict olivine. Assuming the added SiO_2 and Si-rich reservoirs were in isotopic equilibrium, the O-isotope composition of the Si-reservoir was estimated to be ($\delta^{18}O$, $\delta^{17}O$, $\Delta^{17}O$)=(5.4, 3.7, 1.0‰). This differs from the O-isotope composition of the Si-rich reservoir for CR and CV chondrules, estimated to be ($\delta^{18}O$, $\delta^{17}O$, $\Delta^{17}O$)=(3.6, 1.8, -1.0‰) [9].

The Li-isotope composition and concentration of the enstatite was larger than that of the olivine. The Li-isotope composition of the Si-rich reservoir was estimated from the enstatite and relict olivine and was found to be 2‰. This is consistent with whole rock values for EH3 chondrites. However, this differs from the Li-composition of the Si-rich reservoir determined for the carbonaceous chondrule forming region (-11‰) [3]. Therefore, the Li-isotope composition of the Si-rich gas reservoirs were likely heterogenous throughout the Solar nebula. This indicates that there was heterogeneity between the nebula gas composition of the different chondrule forming regions throughout the Solar system. The Li-isotope heterogeneity is likely due to the production of light lithium by cosmic-rays in the interstellar medium and the incorporation of this signature into the Solar nebula. Therefore, it is likely that the Li-isotope composition of the outer Solar nebula, where carbonaceous chondrules formed, retained the interstellar medium contribution. Whereas the inner Solar nebula, where enstatite chondrules formed, lost this signature due to homogenisation associated with vaporisation. This may be due to the formation of the proto-Sun.

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Effect of Water on Martian Magma Ocean Evolution: Experimental Insights into dense silicate layer at the CMB

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Recent Insight seismic surveys of Mars have suggested a partial molten layer just above the Martian core, but the commonly proposed composition of the Martian mantle [1] makes it difficult to create such a molten zone at the base of the mantle [2,3,4]. The existence of such a melt zone throughout Mars' history would require the presence of dense, low-melting-point material that escaped convection. This study examines whether iron-rich hydrous melt could sink to the core-mantle boundary (CMB) and form a melt zone during differentiation of the early Martian magma ocean based on the melting relation of the Martian mantle with 2 wt.% H_2O at varying pressure and temperature by high-pressure and high-temperature experiments conducted in a Kawai-type multi-anvil apparatus. The results of these experiments reveal that at temperature above solidus the melt starts very enriched in Fe and high density as the temperature increases the Mg# of the melt increases by reducing the density of the melt. The effect of water in the system allow to decrease the temperature of the solidus readily move to the melt at higher temperatures. These experiments are to consider the validity of the formation of a hydrous melt layer, the melt density was calculated using the partial melt composition and compared with the density of the solid phase above the solidus both determined in this study. Below 15 GPa, the density of the hydrous melt does not exceed that of the solid phase. At 20 GPa, melt with a water content of at least 2.0 wt% can sink to the core-mantle boundary. The calculated melt density to exceed 4.0 g/cm³, which is consistent with that predicted from the latest InSight studies for a heterogeneous Martian mantle [2]. These findings provide strong evidence for the presence of a basal mantle layer (BML) [2,3] in the early Martian magma ocean, with water content being a key factor in its formation. Future research should focus on extending experimental conditions to deeper mantle regions, conducting more detailed quantitative analyses of Fe partitioning, and exploring comparative studies across different planetary bodies to enhance our understanding of planetary differentiation processes.

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SLIP SYSTEM TRANSITION OF BRISGMANITE

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Although the Earth's lower mantle globally appears nearly seismically isotropic for most of its depth, the regions in which oceanic lithosphere is subducting in the lower mantle show significant seismic anisotropy. Seismic anisotropy is often caused by lattice preferred orientation of constituting mineral, which is bridgmanite in the case of the lower mantle, formed mainly during plastic deformation in the dislocation creep regime but not in diffusion creep regime. The evolution of lattice preferred orientation of bridgmanite remains poorly constrained despite its key role to understand deformation mechanism and resultant mantle flow in the lower mantle because of experimental difficulties. In this study, we investigated the effect of temperature, to simulate the conditions of subducting lithosphere and surrounding mantle, on the evolution of lattice preferred orientation of iron-free and iron bearing bridgmanite during deformation by means of high-pressure experiments under the uppermost lower mantle conditions, 25 GPa and 1,700-2,100 K, using the D111-type apparatus. Observation of lattice preferred orientation across the temperature range showed the change of pattern of lattice preferred orientation and suggest that the transition of the dominant slip system from [010](100) below 1,800 K to [100](010) above 1,800 K, negligibly affected by Fe content. Calculated elastic anisotropy for lattice preferred orientation formed at high temperature is weaker, while lattice preferred orientation formed at lower temperature produces stronger, with the assumption of the dominant flow of horizontal shear in the uppermost lower mantle. These results reasonably explain the strong seismic anisotropy observed beneath subduction zones and the global nearly isotropic surroundings with single deformation mechanism of dislocation creep and hence viscosity in the lower mantle strongly depends on stress and is insensitive to grain size, providing critical insights into the viscosity structure and dynamics of the lower mantle.

Phase relations in the system CaAl2O4-MgAl2O4 up to top-lower-mantle conditions

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Many experimental studies have shown that under lower mantle conditions, Al-rich phases of hexagonal phase (NAL phase, with a chemical formula as $AB_2C_6O_{12}$) and calcium-ferrite phase (CF phase, AB_2O_4 or $XYZO_4$) are major phases in a subducted basaltic crust [1-2]. Although CF phase is considered to be stable down to the bottom of the lower mantle, the stability of NAL phase is still under debate. In addition, compositional changes of these phases under lower mantle conditions are not clear yet. In the system $CaAl_2O_4$-$MgAl_2O_4$, which are important endmembers for the Al-rich phases in a basaltic composition, at 1200 °C above 15 GPa [3-4], $CaAl_2O_4$-rich or $MgAl_2O_4$ CF phase and $CaAl_2O_4$-$MgAl_2O_4$ NAL phase are stable. The $MgAl_2O_4$ components in the $CaAl_2O_4$-rich CF phase and NAL phase increase with pressure. However, temperature dependence on chemical compositions and stabilities of these phases, which is important due to temperature variation in the mantle, has not been investigated yet. In this study, we conducted high-pressure phase-relation experiments in the system $CaAl_2O_4$-$MgAl_2O_4$ at 15-25 GPa and 1100-2000 °C using a multi-anvil press to understand compositional changes and stability of these phases in the mantle.

Our results showed that CF and NAL phases are stable in the present pressure-temperature range. As shown in the previous studies, the solubility of the $MgAl_2O_4$ component in the $CaAl_2O_4$-rich CF phase increased with increasing pressure in the temperature range of 1100-2000 °C. With increasing temperature, the $MgAl_2O_4$ component in the $CaAl_2O_4$-rich CF phase also increased. In the binary phase diagram, the $MgAl_2O_4$ compositional width of the stability field of the NAL phase expanded slightly from 3 mol% to 5 mol% with increasing temperature. Because the chemical composition of the $CaAl_2O_4$-rich CF phase systematically changes with pressure and temperature, we suggest that the compositional change can be used as a pressure calibrant at high temperatures under high pressure.

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Sound velocity measurements for the hydrous iron-rich HH1-phase: Implications for lower mantle seismic heterogeneity

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Water, which is heterogeneously distributed in the Earth's interior, is one of the most important volatiles of our planet. Incorporation of water into a multicomponent system of the Earth's lower mantle can dramatically alter its phase relations [1, 2]. In particular, changes in seismic velocity in the lower mantle could be caused by the formation of hydrous phases. Thus, knowledge of the sound velocity of hydrous minerals in the lower mantle can provide important insight into lower mantle seismic anomalies, although there is a lack of experimental data on the sound velocities of hydrous minerals in the lower mantle.

In this study, we performed inelastic x-ray scattering and x-ray diffraction experiments in diamond anvil cells and measured the compressional wave velocity (v_p) of HH1-phase ($Fe_{12.76}O_{18}H_x$, x~4.5), an iron-rich hydrous hexagonal phase that can be formed by reactions of basaltic or peridotitic compositions with water under the pressure and temperature conditions of the deep lower mantle [3]. The laser-heated diamond anvil cell technique was used to prepare samples of the HH1-phase, and the phase was then confirmed by x-ray diffraction. The v_p was measured by the inelastic x-ray scattering method at pressures between 64.7 and 79.6 GPa at the BL43LXU beamline of the RIKEN SPring-8 Center [4], and the shear wave velocity (v_s) was derived from the v_p and the equation of state of this phase. The results allowed us to investigate the changes in sound velocities (v_p and v_s) of the major lower mantle mineral, ferropericlase, before and after its reaction with water.

To discuss the differences in sound velocity between the hydrous and anhydrous phase assemblages in the mid-lower mantle, we have employed a simplified model. The results show that the hydrous assemblage, including the HH1 phase, has a higher v_s and a lower v_p/v_s ratio compared to its anhydrous counterpart. This suggests that the formation of mid-lower mantle seismic scatterers with high vs anomalies may be related to the heterogeneous distribution of water [5].

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Development of real-time measurement of sample thickness under high pressure by a GHz method

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The GHz-DAC ultrasonics is an experimental method to measure elasticity of the deep earth constituents. It is superior to other techniques to be able to measure simultaneously P and S wave velocities even on opaque specimens. It measures travel time of ultrasonic waves in a sample squeezed in diamond anvil cell (DAC). Thus it is needed to constrain the sample thickness in a separate procedure. For this purpose, we developed a real-time constrain of the sample thickness by combining (1) the newly devised instrument to measure distance between the rear surfaces of diamond anvils, (2) evaluation method of the load on diamond anvil through length change of disk springs, and (3) finite element method to examine elastic deformation of the diamond anvils. In this presentation, we show the P wave velocities of ferropericlase at 67 GPa by comparing with those reported in the previous studies.

Water in davemaoite: Implication for water cycle in the Earth's mantle

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Water is transported into the deep mantle by subducting slabs and can significantly affect chemical and physical properties of mantle minerals. Geochemical observations of ocean island basalts suggest water-rich sources in the lower mantle. Previous studies revealed that major lower-mantle minerals such as bridgmanite and ferropericlase have limited water contents up to 0.1 wt% [1,2]. However, water solubility of davemaoite, the third abundant mineral with the $CaSiO_3$ composition in the lower mantle, is still not clear yet. This is because of its unquenchability and therefore difficulty in estimating the water content in the crystal structure, preventing from making a precise model of water cycle in the mantle.

A recent experimental study investigated water contents in davemaoite based on its volume change under hydrous conditions compared with volumes under the dry condition using a laser-heated diamond anvil cell [3]. They observed volume reduction of davemaoite up to 3% under hydrous conditions up to 120 GPa and 2200 K. A theoretical study demonstrated the volume reduction is due to the substitution of Ca^{2+} to $2H^+$ [4]. I addition, their X-ray diffraction patterns showed the tetragonal symmetry of davemaoite under hydrous conditions at their experimental conditions, where devamaoite is cubic under the dry condition. They further obtained in-situ infrared spectra of davemaoite, showing a broad OH bands. These results suggested significant amounts of water in davemaoite up to 0.5-1 wt%. However, their study can have not been done under equilibrium conditions and hydrostatic conditions, resulting in possible metastable hydration and distortion of the crystal structure.

To precisely assess water incorporation into davemaoite, we conducted in-situ volume-measurements of davemaoite up to 30 GPa and 2100 K under hydrous conditions in a multi-anvil press and compared with volumes under the dry condition. In addition, we synthesized single crystals of $CaSiO_3$-$CaTiO_3$ perovskites as an analogue phase of davemaoite, which can be recovered into room pressure and temperature conditions, at conditions up to 25 GPa and 2300 K by means of multi-anvil press. Recovered crystals were analyzed by Fourier Transform Infrared Spectroscopy (FTIR) to estimate their water contents.

In-situ volume measurements of davemaoite showed volumes consistent with those under the dry condition, suggesting limited water contents in davemaoite. We also confirmed that davemaoite is cubic at high pressure-temperature conditions, supporting the conclusion. In the analogue experiments, we recovered single crystals of $CaTiO_3$-bearing $CaSiO_3$ perovskites with several compositions and dimensions up to several hundred microns together with hydrous silicate melt at 20-25 GPa and 1700-2300 K. Their single crystal X-ray diffraction data showed lattice volumes consistent with those in the dry $CaSiO_3$-$CaTiO_3$ perovskite join line. Their FTIR spectra also showed no detection of OH bands. Thus, $CaSiO_3$ davemaoite could be dry in mantle conditions, indicating that a peridotitic layer of a subducting slab has limited water contents in the lower mantle. Therefore, we suggest that water is cycled mainly by crustal materials such as basaltic crusts including hydrous aluminous silica minerals in the lower mantle [5].

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MODAL MINERALOGY OF BRECCIATED FELDSPATHIC LUNAR METEORITES

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Introduction: Knowledge of the identities and quantitative abundances of the constituent minerals is of fundamental importance to understanding the physical and spectral properties of planetary materials. Quantification of mineral abundances by Rietveld refinement of X-ray diffraction (XRD) data is a well-established and robust method that has been successfully applied, even to heterogeneous mixtures with multiple low-symmetry phases [1]. In this study, the modal mineralogy of Lunar meteorites Gadamis 004, Northwest Africa (NWA) 10401, NWA 11182, NWA 11788, NWA 12593, and NWA 13788 have been measured using Rietveld refinement of powder X-ray diffraction patterns.

Methods: Powder XRD patterns were measured with a Rigaku SmartLab diffractometer using Cu $K\alpha_1$ radiation (λ=1.54056 Å) operating at 40 kV accelerating voltage, 30 mA beam current. A curved Ge monochromator removed Cu $K\alpha_2$ radiation. Diffraction patterns were acquired in Bragg-Brentano geometry from 10° to 60° 2θ. To reduce the effects of Fe-fluorescence under Cu radiation, a Rigaku D/teX energy discriminating detector was used. The D/teX detector was calibrated using the (111) reflection of Si powder. Incident and receiving length limiting slits of 2/3 degrees and Soller slits of 5° were used. Meteorite aliquots of approximately 100 mg were ground with an agate mortar and pestle to a nominal grain size of <40 μm.

Rietveld refinement is a method for quantifying the crystal structural parameters and relative abundances of crystalline phases from powder diffraction patterns by fitting a simulated diffraction pattern to the observed data [2]. In this study, we have used Rietveld refinement primarily to quantify the proportions of the various minerals in each meteorite. Rietveld refinement was carried out using the General Structure Analysis System (GSAS) software [3]. Instrument parameters were obtained by refinement of the diffraction pattern of Al_2O_3 obtained under identical instrument conditions as the meteorite data.

Results: The modal mineralogy of each meteorite is reported in Table 1. Volume fractions have been calculated from the refined phase densities.

Meteorite	Rw	An	olv	cpx	opx	pig
Gadamis 004	10.295	0.93	0.02	0.00	0.00	0.05
NWA 10401	13.648	0.34	0.30	0.20	0.16	0.00
NWA 11182a	11.442	0.83	0.03	0.06	0.00	0.08
NWA 11182b	19.954	0.78	0.02	0.08	0.00	0.10
NWA 11788	13.037	0.91	0.03	0.05	0.00	0.00
NWA 12593	19.636	0.74	0.05	0.21	0.00	0.00
NWA 13788	18.898	0.85	0.06	0.05	0.04	0.10

Table 1: Refined mineral abundances for the Lunar meteorites in this study. Rw is a measure of the goodness-of-fit of the refinement.

Discussion: All the Lunar meteorites investigated here are dominated by anorthitic plagioclase, consistent with available semi-quantitative information for these samples. For NWA 11182, we have compared wire-saw cuttings with a crushed aliquot. The mineral modes in each are similar, and no trace of wire-saw contamination was detected. The consistency of our results even in the presence of multiple structurally-similar pyroxenes, low-symmetry anorthite, and in some cases, amorphous materials demonstrates the great potential for XRD-Rietveld quantification even for challenging materials.

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Disproportionation of wadsleyite splits the 520-km seismic discontinuity

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The seismic discontinuities, which define the layered structure of the solid Earth, are the most important features in the deep interior and play a critical role in geodynamics[1]. They are generally caused either by compositional jumps (such as the Moho and Gutenberg discontinuities defining the Earth's mantle)[2] or by mineral phase transformations (e.g., the discontinuities at 410 and 660-km depths defining the mantle transition zone)[3]. In contrast, the 520-km discontinuity, separating the upper and lower parts of the mantle transition zone caused by the wadsleyite to ringwoodite phase transition[4], shows a splitting at around 500 and 560 km depths[5], while the origin of the splitting is unclear because a simple wadsleyite to ringwoodite transition should produce a single seismic discontinuity. Here, based on high-pressure and high-temperature experiments under mantle transition zone conditions, we found the disproportionation of wadsleyite to $(Mg_{0.92}Fe_{0.08})_2SiO_4$ and $(Mg_{0.89}Fe_{0.11})_2SiO_4$ compositions. Since iron affects the phase transition pressure between wadsleyite and ringwoodite strongly[6], the two types of wadsleyite should transfer to ringwoodite at different depths, leading to the splitting of the 520-km discontinuity. The disproportionation of wadsleyite may also account for the seismic anisotropy observed in the upper part of the mantle transition zone[7] and the relatively weak seismic velocity jump of the 520-km discontinuity compared to that interpreted from mineral physics data[8].

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ANCIENT MARTIAN HYDROLOGY REVEALED BY DELTA MORPHOLOGY AND TANK EXPERIMENTS

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Several evidence of ancient aqueous environments has been found on the Martian surfaces such as outflow channels and valley networks and delta landforms. However, there is debate as to what environment these landforms represent. The two main hypotheses are that (1) ancient Mars had vast oceans in the northern hemisphere, and after the disappearance of the oceans, local lacustrine environments existed until the Amazonian period (after 3.0 Ga) [1-3] and (2) There were no oceans and localized lacustrine environments existed from the beginning [4-8]. In this study, we investigate Martian delta morphology using tank experiments and remote sensing analysis to verify these unsolved questions.

First, we conducted tank experiments to clarify the evolution of delta morphology under changing sea levels. We identified two distinct key delta types, such as "lobe-extruding deltas (having elongated lobes) " formed by falling water levels and "deltaic steps (having terraced topography)" formed by rising water levels.

Next, we analyzed Martian satellite images to identify the same type of delta as that formed in our tank experiments, and examined these distribution, elevation and morphology. Formation ages were estimated using crater size-frequency distribution (CSFD) and considered potential uncertainties such as resurfacing effects. Lobe-extruding deltas are located in plains and open basins at -2077 to -3122 m, and are concentrated near the inferred coastlines [9, 10]. Formation ages of these are indicated during 3.8–3.2 Ga. These results suggest lobe-extruding deltas were developed during ocean regression. On the other hand, deltaic steps are located in open basins and closed basins at wide elevation range (-5000 to +1950 m). Formation ages of these are indicated during 3.7–0.5 Ga and peak during 1.6-0.5 Ga. These results suggest deltaic steps were developed during more recent localized water activity. formed in localized lacustrine setting during 1.6–0.5 Ga. These findings suggest global ocean regression occurred between 3.6–3.3 Ga followed by the localized water flows likely induced by volcanic activity at 1.6–0.5 Ga. In addition, the orientation of river inflow that forms lobe-extruding deltas predominantly exhibit eastward to northward to flow. This is consistent with drainage into a northern ocean. In contrast, the orientation of river inflow that forms deltaic steps exhibit various directions, often trending southward. This supports localized hydrological processes.

Based on these results, it is considered that the lobe-extruding deltas were formed at coastlines during the period when the ancient ocean existed and formed due to sea-level fall in the range of -2077m to -2760m at around 3.6-3.3 Ga. On the other hand, deltaic steps were formed by rising water levels in the basin or crater during 1.6-0.5 Ga. In addition, we did not find any delta aged between 3.2 and 1.6 Ga, suggesting that fluvial processes were not active on surface and the oceans most probably did not exist during this period. This hypothesis is consistent with the age when volcanic and fluvial activity was relatively low [11, 12]. Therefore, our study revealed ocean disappearance at 3.6-3.3 Ga and localized lacustrine environments at 1.6-0.5 Ga.

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Partitioning of highly siderophile elements between metal and silicate liquids: Challenging to the Late Veneer hypothesis

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The highly siderophile elements (HSE), which comprise platinum-group elements along with Re and Au, are known for their strong affinities to Fe-metal rather than coexisting silicates. Geochemical and experimental investigation on the HSE composition of the bulk silicate Earth (BSE) have provided a long-standing issue known as the “excess HSE problem”. One important feature of the “excess HSE problem” is that the HSE concentrations in the primitive upper mantle (PUM) are higher than the HSE concentrations in the silicate portion after core-mantle differentiation, which were predicted from experimentally determined partition coefficients. In addition, the relative HSE abundances of the PUM are broadly chondritic, despite that the experimental data showed largely different affinities of the HSE to Fe-metal. To reconcile the “excess HSE problem”, the Late Veneer hypothesis, which propose addition of a small amount of chondritic material after core-mantle differentiation, has been argued.

On the other hand, previously determined metal-silicate partition coefficients of the HSEs themselves contain uncertainties. The HSE partitioning can be affected by HSE contents in the starting material, whereas most previous studies have conducted partitioning experiments with starting materials of excessively high HSE contents (wt.% order). In order to assess the effect of HSE contents on the HSE partitioning and to obtain HSE partition coefficients more appropriate to estimate HSE composition of the BSE, we conducted partitioning experiments of HSEs (Re, Os, Ir, Ru, Pt, Pd) between metal and silicate liquids up to lower mantle pressures with starting materials of various HSE contents.

As a result, partitioning experiments from 6 to 23 GPa with the starting Fe-HSE alloy of low HSE content (in this alloy, each HSE content is around 1000 ppm) demonstrated lower metal/silicate partition coefficients than that in Mann et al. (2012)[1], and the HSEs showed similar affinities to Fe-metal. By using the revised HSE partition coefficients, the relative HSE abundances in the silicate portion after core-mantle differentiation are predicted to be broadly chondritic, and the estimated HSE concentrations in the BSE get closer to the HSE concentrations of the PUM. From these results, we discuss the necessity of the Late Veneer in the early Earth.

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Reference: [1] Mann et al. (2012), *Geochimica et Cosmochimica Acta*, 84, 593-613

Development of a technique to identify µm-sized organic matter in asteroidal material: An approach using machine learning.

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Carbonaceous chondrites (CC) contain abundant organic matter (OM), the formation of which has been posited to occur via multiple mechanisms, including on the progenitor planetesimals of asteroid bodies, within the protosolar nebula of the early solar system, and within diffuse and molecular clouds in the interstellar medium. Meteoritic OM would have been delivered to the early Earth, with the potential to facilitate the origin of life. Therefore, OM from meteorite provides a record of early solar system processes and an inventory of compounds that could have been essential for the origin of life on Earth. In prior studies the OM was located by analyzing many 10x10 µm^2 regions using a secondary ion mass spectrometer (SIMS)[1,2]. A few OM were then characterized by transmission electron microscopy[3–5].

CC contain numerous µm-sized OM (µOM) and diffuse organic matter (DOM) within their matrix, which are randomly distributed. The µOM was identified as a C-rich object characterized by a dark coloration in BSE image, which is surrounded by matrix components. DOM is characterized by its C-rich composition, brighter coloration (compared with µOM) and is intermixed with the matrix components. The matrix components are predominantly phyllosilicate with minor Fe-sulfide and carbonate minerals. Previous studies have characterized µOM as IOM and DOM as diffuse carbon, occurring as many nanoscale objects[3–5].This study utilizes a microscale scanning electron microscopy-energy dispersive spectrometry (SEM-EDS) approach to locate numerous OM on the sample. The generation of an OM map involved scanning the whole area of a sample. The BSE and element maps were obtained from this process. Image processing of the element maps was then performed to obtain the OM map. An OM map is thus represented by a boolean array of pixels with true connected components being designated as instances. The instances were then manually classified into one of four categories such as µOM, DOM, a hole, or noise.

In this study, a method to classify OM using machine learning technique was developed. The method utilizes mosaic backscatter electron (BSE) images, element maps, and OM maps of the mm-sized CC samples for the reference surface (Orgueil) and a new surface (Murray). The two-dimensional properties of µOM and DOM, such as geometry and chemistry were estimated from the BSE image, element maps, and OM map. The performance of five different classification algorithms were compared, and these were logistic regression, Gaussian-naïve Bayes, k-nearest neighbor, support vector machine and random forest. The algorithms were trained on the instances from the reference surface. Certainty parameters such as accuracy (A_0), precision (A_1), recall (A_2), F1-score (Z_{F1}), and Kappa-score (Z_k) were estimated for the algorithms. Among the algorithms, the random forest certainty parameters were the highest in the majority of cases and were A_0 (0.9), A_1 (0.9), A_2 (0.90), Z_{F1} (0.87), and Z_k (0.50). Thus, random forest was selected as the algorithm to classify the instances. As such, the instances in the OM maps of Murray were classified using the random forest algorithm.

The resulting OM maps with their classified instances, enabled many µOM and DOM objects to be identified and located. These OM objects had a size ranging from 1 to 15 µm. The spatial occurrence of these objects exhibit heterogeneity, and their orientation is random, suggesting that unidirectional physical forces did not influence their accretion or formation during aqueous alteration. Therefore the OM maps with their classified OM can be utilized to select regions of interest for further detailed spatial analyses, such as transmission electron microscopy (TEM), secondary ion mass spectrometry (SIMS), Raman spectroscopy, and Fourier transform infrared spectroscopy (FTIR).

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The Role of Hydrogen and Thermal Inertia in the Formation Processes of Slope Streaks on the Medusae Fossae Formation, Mars

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A slope streak is a thin, dark, or light-toned feature on a steep slope, typically found in dusty regions of Martian slopes, primarily in dust-rich regions [1]. Their formation mechanisms remain debated with competing hypotheses suggesting dry granular flows, dust avalanches [1-3], or possibly transient briny water activity [4-6]. In this study, we investigated 91 areas from the Medusae Fossae Formation and its surrounding areas. Using slope streak concentration, we compare their distribution using hydrogen abundance and thermal inertia values.

Our analysis identifies a thermal inertia threshold of 160 $\mathrm{J\ m^{-2}\ K^{-1}\ s^{-0.5}}$, above which the frequency of slope streak occurrence abruptly shifts to a lower value. This suggests intergranular cohesion, rather than gravity alone, governs slope streak initiation, because finer-grained, low-thermal inertia materials exhibit lower shear resistance and are prone to mass movement [7]. Furthermore, a strong negative correlation between slope streak density and water-equivalent hydrogen abundance is identified in regions with thermal inertia below the threshold of 160 $\mathrm{J\ m^{-2}\ K^{-1}\ s^{-0.5}}$ (Fig. 1), implying that moisture enhances particle cohesion [8], thereby suppressing the downslope movement.

This study challenges previous interpretations that associate slope streaks with briny water activity and instead support a dry, cohesion-driven mechanism (Fig. 2). Our results highlight the role of particle cohesion in shaping Martian slopes, refining our understanding of mass movements and dust dynamics. These insights are critical for planetary protection strategies and future Mars exploration.

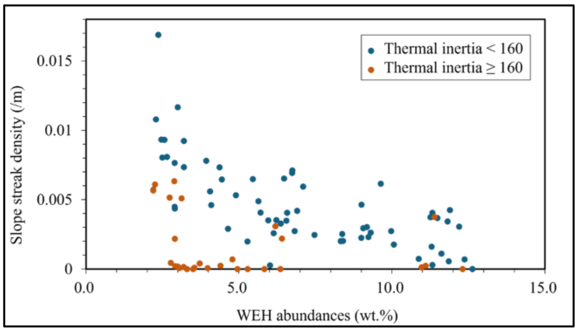

Fig. 1 The relationship between slope streak density and Water Equivalent Hydrogen abundances.

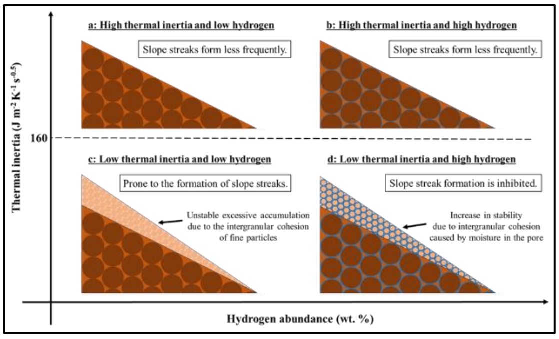

Fig. 2 Schematic diagram illustrating the effects of thermal inertia and hydrogen abundance on slope streak formation.

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Light Element Distribution in the Early Solar System: An Investigation of the Beryllium and Boron Carriers in Ryugu Samples

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Samples returned by the Hayabusa2 mission from the asteroid Ryugu show a genetic link to CI chondrites [1,2], meaning they represent the most chemically primitive materials from the formation of the solar system. Comprehensive analysis revealed a negative correlation in the bulk compositions of Be and B within the particles from the second sampling location, TD2 [1]. The correlation could not be attributed to volatility- or solubility-dependent fractionation processes, as no fractionations were observed in similar elements. The various B/Be ratios of the TD2 particles should therefore be caused by incorporation of at least two chemically distinct components that have experienced minimal thermal processing. To understand the origin of these components, the elemental distributions of Be and B were determined using ion mapping. Combined with petrographic observation, the major host of Be was found to be Cr-rich oxide located in the rims of phyllosilicate nodules, and B was found to be hosted by the phyllosilicate matrix. The phyllosilicate nodules were classified into 5 groups based on internal distribution of Be and B that may reflect variation of Be and B in the asteroid Ryugu, spatially and/or temporally. Nano structure of a typical Cr-rich oxide was examined using TEM and revealed genetic link between phyllosilicate nodules and matrix. Based on the nodule's relationship of FeS and Cr-rich oxides in the rim with its phyllosilicate core, we conclude phyllosilicate nodules formed after the matrix. Accordingly, we conclude Be is concentrated in a late-stage product on Ryugu.

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High-pressure and high-temperature experimental approaches for the understanding of the carbon cycle in the Earth's Interior

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The 'Global warming anthropogenic theory,' which states that the earth is warming due to greenhouse gases such as carbon dioxide emitted by humans, is one of our most interesting topics. However, to quantitatively evaluate the relationship between global warming and anthropogenic activities, it is also indispensable to understand the long-term influence of the secular variation of CO_2 content in the atmosphere on global climate change through understanding the carbon cycle in Earth's interior.

In our previous work [1] to understand slab decarbonation and CO_2 recycling in the arc system, we investigated the contribution of subducted carbonate sediments to the genesis of the Southwestern Colombian arc magmas using comprehensive petrography and geochemical analysis including determination of major and trace element contents and Sr, Nd, Hf and Pb isotope compositions. Through this work, we elucidated the relationship between the degree of decarbonation and the degree of dehydration with increasing pressure and temperature in the arc system.

On the other hand, the stability fields of carbonates such as $MgCO_3$, which is a CO_2 reservoir in the mantle (e.g. [2]), have been determined empirically. Melting and subsolidus phase relations in the $MgCO_3$ - $MgSiO_3$ system were investigated at 4 to 26 GPa under 'dry' conditions [2, 3]. However, the mantle is not dry in actual. For example, the isotope and trace element systematics applied to island arc volcanics showed that the slab-derived fluids, originally from seawater, were transported to the mantle wedge from subduction zones (e.g. [4, 5]). High-temperature and high-pressure experiments showed some of the hydrous phases (e.g., phengite and lawsonite) in the subducting slab can be decomposed at sub-arc conditions with water release (e.g. [6, 7]). On the other hand, a hydrous phase, Al-rich phase H, can be stable at 25–26 GPa [8]. This indicates that water can be transported to lower mantle regions. In addition, hydrous phases (Phase Egg and hydrous-wadsleyite and -ringwoodite) were found in diamonds as mineral inclusions derived from the transition zone [9, 10]. Thus, investigations of the stability fields of carbonates under water-bearing mantle conditions are indispensable to quantitative understandings of the conditions under which CO_2 reservation is capable in the mantle.

Maeda et al. (2017) [11] showed the possibility of diamond formation in a high-pressure reaction of $MgCO_3$ and SiO_2 at the core-mantle boundary in the lower mantle by high-pressure and high-temperature experiments. On the other hand, determinations of not only the conditions of diamond formation reactions but also the state of carbon in the mantle are indispensable to understanding the physicochemical conditions of the mantle. As shown above, the high-pressure hydrous phases were found in diamonds as inclusions [9, 10]. This reflects the state of carbon at the transition zone and the upper region of the lower mantle. Based on the occurrence of the high-pressure hydrous phases, we will try to reevaluate the state of carbon at around the transition zone and the lower mantle through high-pressure and high-temperature experiments.

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UPDATED LUNAR SEISMICITY THROUGH ANALYSES OF NEWLY DISCOVERED SHALLOW MOONQUAKES

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The first lunar seismic observation was conducted during the Apollo missions (11, 12, 14, 15, 16, and 17), opening the studies on seismicity and internal structure of the Moon (e.g., [1]-[3]). In the missions, two types of seismometers were installed on the surface of the Moon: a tri-axial long-period (LP) seismometer and a short-period (SP) seismometer with a vertical component (e.g., [1]). In previous studies, the LP seismic data were mainly used, whereas most of the SP data remained unanalyzed until today because the data were highly contaminated with electronic noises.

Recently, Onodera (2024) [4] cleaned all the SP data and performed automatic event detection, resulting in the discovery of more than 22,000 seismic events, increasing the number of identified events by three times than before. The new dataset includes impact-induced events, thermal moonquakes, and shallow moonquakes. Among these, shallow moonquakes are considered to be of tectonic origin, therefore reflecting the current geological/geodynamical activity of the Moon. In addition, unlike other types of lunar seismic events, shallow moonquakes typically record body-wave magnitude 4 – 6 ([4]-[6]), which can be one of the prime natural disasters affecting future manned missions. Thus, it is paramount to understand the occurrence rate, regionality, and source mechanism of shallow moonquakes from the aspects of science and disaster prevention.

One of the important implications by Onodera (2024)[4] can be found in Figure 1, where shallow moonquake waveforms recorded at the Apollo 14, 15, and 16 sites are aligned with S-P time. Interestingly, the highest detection number was observed at the Apollo 15 site, implying that the northern hemisphere of the Moon is more seismically active than the southern hemisphere. Other than that, analyses of newly discovered moonquakes provided us with new insights into lunar seismicity (therefore, current geological state in the lunar crust). In the presentation, I will give a review of the discovery of Onodera (2024) [4] and share new views of lunar seismicity.

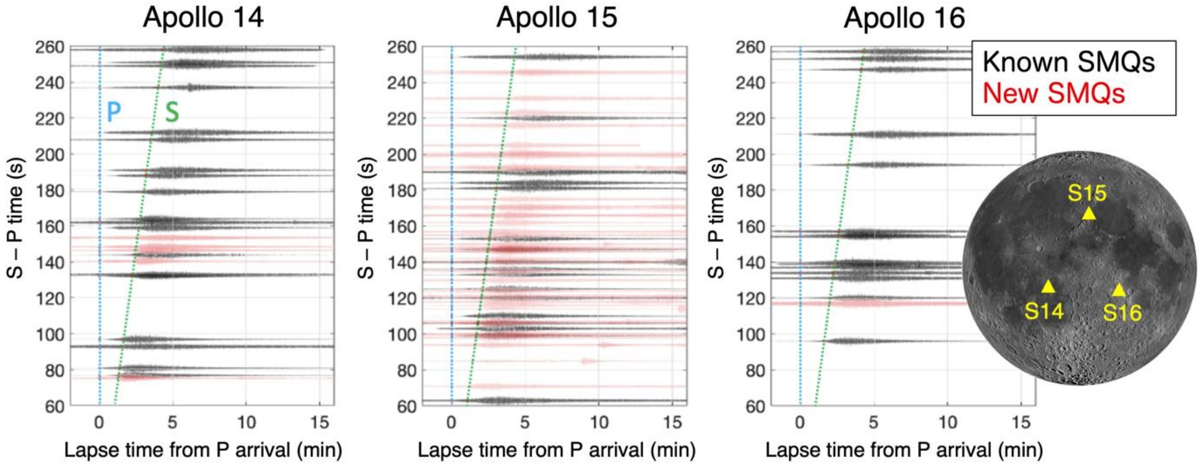

Figure 1. Shallow moonquake waveforms identified at the Apollo 14, 15, and 16 landing sites, respectively. The horizontal axis shows the lapse time from the P wave arrival, and the vertical axis shows the time difference between S-wave and P-wave arrivals. The black signals are for known shallow moonquakes before, and the red ones are newly discovered events by Onodera (2024) [4]. SMQ stands for shallow moonquake.

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THE WATER SOLUBILITY IN CA-PEROVSKITE

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Ca-perovskite is an abundant mineral in basaltic compositions at lower mantle conditions and comprises up 25 Volume % of such compositions. It is also present, though less abundantly so, in pyrolitic compositions at lower mantle conditions. While the solubility of water in most other lower mantle mineral phases is constrained for at least certain compositions and conditions, the same is not true for Ca-perovskite. This is due to the unquenchability of the phase to atmospheric conditions. The recovered amorphous material has been probed for its water content [1]. However, the effect of the amorphization on the phases water solubility remains unconstrained and the water content of the crystalline mineral phase can not be studied conventionally by methods like SIMS or FTIR on recovery.

Nevertheless, the solubility of water in Ca-perovskite has significant implications for the overall volatile budget and evolution of the Earth, including the Earth's deep water cycle, making it a crucial question of lower mantle mineralogy and Earth's volatile evolution.

We explore the solubility of water in Ca-perovskite for a range of pressures. Additionally, we probe the effect of amorphization on the OH-incorporation mechanism for the pure $CaSiO_3$ endmember upon decompression. To probe this behavior we synthesize Ca-perovskite in diamond anvil cells and study them in situ by FTIR and by X-ray diffraction. Our results suggest significant water solubility in $CaSiO_3$-perovskite, with symmetric OH stretching vibrations similar to those observed for natural $CaTiO_3$-perovskite [2]. Based on our results, previous in situ measurements [3] may be better explained by Ice VII, rather than a $CaSiO_3$-perovskite phase.

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Geomorphological evidence of liquid water on Mars: Insights from Terrestrial Polygonal Landforms in the USA

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The existence of liquid water on Mars is a key topic in planetary science, influencing our understanding of past and present Martian hydrology. In low-latitude regions, recurring slope lineae (RSL) have been studied as possible evidence of transient liquid water [1]. However, despite theoretical and observational evidence suggesting the possibility of liquid water, mid-to-high latitude regions of Mars remain underexplored. Features such as polygonal terrains [2], similar to those in terrestrial salt lakes, and dark dune spots (DDS) may indicate past or present liquid water activity [3]. Observations from the Phoenix Mars Lander, including temperature and humidity measurements and the detection of perchlorates, suggest that stable liquid brines could persist near the surface even in cold high-latitude environments [4].

To better understand Mars’ liquid environment, this study focuses on polygonal terrains that may form due to liquid evaporation. Desiccation polygons are landforms created by the evaporation of liquid water. The supply and circulation of water from the subsurface contribute to the formation of these polygonal patterns on the surface [5]. We conducted field investigations in the southwestern United States, where similar landforms on Mars exist. We studied by drone surveys, digital elevation models (DEM), Sentinel and ASTER remote sensing data, and distribution mapping. We analyzed polygon formation processes and their relationship with environmental factors.

We identified four types of polygons: Raised rim polygons (**Fig.1A)**, Sinuous Depression polygons (**Fig.1B)**, Low rim polygons (**Fig.1C)**, and Mix polygons (**Fig.1D)**. Raised rim polygons (~10 m) have zigzagging edges, while Sinuous Depression polygons consist of circular pit-like structures. Low-rim polygons (30~50 m) have sunken boundaries, and Mix polygons combine both large and small raised-rim structures. Sentinel imagery of Winnemucca Lake, Nevada, where three of these types coexist, revealed that Raised rim and Sinuous Depression polygons currently interact with surface water, whereas Low rim polygons have remained dry for at least five years, suggesting they are relict features formed under past conditions. ASTER analysis showed high concentrations of halite and gypsum in polygons interacting with surface water, indicating that salt accumulation influences their development.

These findings suggest that polygon formation is strongly influenced by water availability and salt accumulation, suggesting that similar processes may be active on Mars. If similar relationships can be applied to Martian desiccation polygon distributions, they could provide evidence for the presence of liquid water in Mars’ high-latitude regions today.

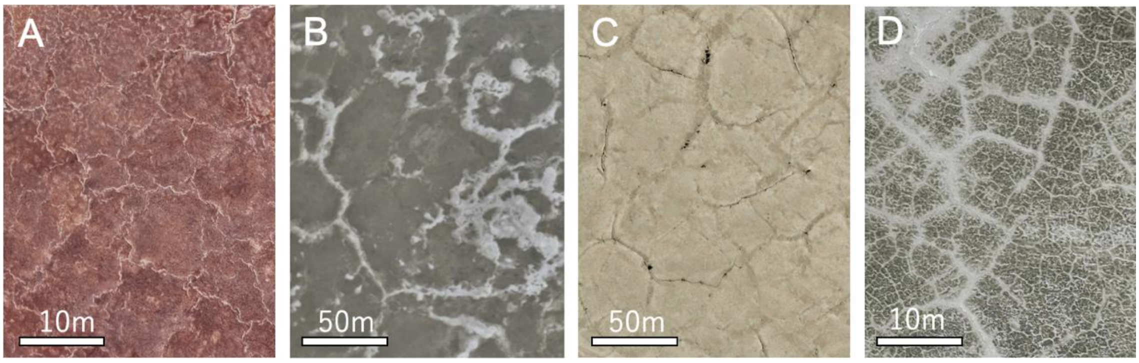

Fig. 1. Drone images of four types of polygonal terrain identified in the U.S. **A)** Raised rim polygons in Winnemucca Lake. **B)** Transition polygons in Winnemucca Lake. **C)** Low rim polygons in Lucerne Lake **D)** Mix polygons in Linda Lake.

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THE ORIGIN AND DEVELOPMENT OF SINUOUS RIDGES IN ARGYRE PLANITIA AND IMPLICATIONS FOR ITS HYDROLOGY

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The Argyre basin, located on the southern highlands, spans over 1500 km wide and is one of the largest impact basins on Mars. Three large valleys drain into Argyre from the southern circumpolar region, whereas the basin is breached at the north and perhaps connected to the Ladon-Morava-Ares outflow system draining into Chryse Planitia. Given its volume and valley connections, this basin played a key role in the global hydrology of early Mars. (e.g., [1], [2]). Several morphological features indicate that the basin may have contained a lake and/or ice sheet, which could have been fed with meltwater from an ancient south polar ice sheet through the three inlet valleys in the past (e.g., [3], [4]). A suite of sinuous ridges in the southern Argyre basin has been interpreted as evidence that an ice sheet once occupied the basin. (e.g., [5], [6]). However, the formation mechanisms for the Argyre sinuous ridges (ASRs) remain a topic of debate. (e.g., [7], [8]). Among the formation mechanisms that have already been proposed, the most; plausible interpretations are eskers and inverted fluvial channels. Nevertheless, both remain inconclusive.

Here, we have undertaken detailed morphometric measurements of Argyre ASRs and compared them to other glacial and fluvial ridge features on Earth and Mars, to reveal their origin. We mapped cross-sectional profiles at 1 km intervals along crestlines of ASRs using Context Camera (CTX) images and digital elevation models (DEM) [9]. We fitted power-law relationships to those ridge geometries, including width (W) and cross-sectional area (A_{CS}). This power law is expected because a scaling relationship between channel width and bank-full discharge is commonly applied to fluvial and subglacial systems. We use A_{CS} as a proxy for bank-full discharge (e.g., [10]). We also measured dip and azimuths of layering observed within ridge stratigraphy and surrounding terrains, to understand the stratigraphic relationship between ASRs and surrounding layered terrains. Last, we performed crater counts using the buffer crater counting technique on the ASR to determine their ages (e.g., [11]).

Two distinct populations of sinuous ASRs can be distinguished stratigraphically: NE-oriented ridges in the eastern population (upper) and NW-oriented ridges in the western population (lower). The power-law relationship for ASRs geometry shows a strong correlation between log-width and log-cross-sectional area, which is consistent with martian inverted fluvial channels in Aeolis Dorsa region, though the power-law exponents for ASRs are smaller than, yet still comparable to, the subglacial range. The measurement of layering structures revealed that the layers in ASRs are extremely horizontal (~0.07–<0.3°). These horizontal layers are consistently observed both in ASRs and the surrounding terrains, highlighting their shared sedimentological characteristics. This characteristic are inconsistent with the hypothesis of an eskers previously proposed, but consistent with inverted fluvial channels [8]. Thus, we conclude that the origin of ASRs is inverted fluvial channels, and the surrounding layered terrains are lacustrine deposits. Some of the ASRs lack fluvial capping rock because the floor units in which the ridges lie are strongly degraded [12].

We identified equivalent layered terrains in other regions of the Agyre basin, justifying an extrapolation of the horizontal layers to the entire basin. Given that the Argyre impact age is ~3.9 Ga and the exhumed age of the ASRs is ~3.7 Ga, the basin may have hosted a lake at approximately the same time (~3.8 Ga) as the ages of valley networks in the southern highlands [13]. Sediment constructing the layered terrain could have been transported by meltwater from an ancient ice sheet in the south. The two distinct populations of ASRs could provides possible evidence for ancient multiple ancient flood episodes. The Argyre basin served as an impoundment for meltwater from the southern circumpolar region.

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Rampart Crater Analysis Using Machine Learning for Spatiotemporal Distribution of Martian Cryosphere

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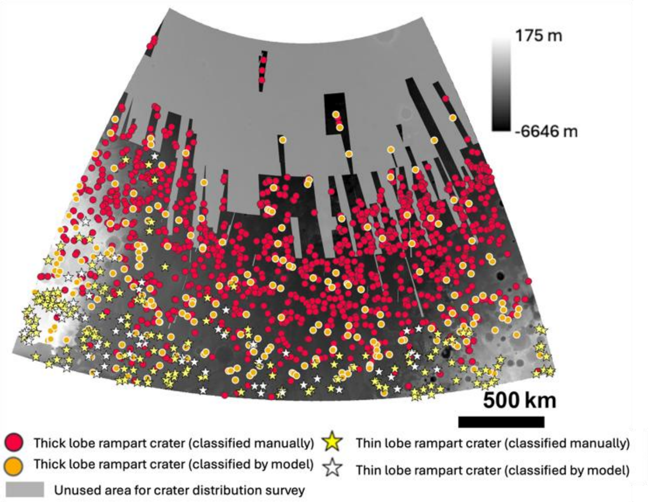
One of the conditions necessary for the birth and evolution of life is the long-term presence of liquid water on a planet's surface, which depends on complex surface evolution. It is believed that liquid water once existed on Mars' surface but dissipated into space through the Martian history. Therefore, understanding the evolution of Mars' water environment is essential for understanding its surface evolution. Current evidence suggests that some of the past surface liquid water on Mars is preserved as subsurface ice. In this study, the aim is to estimate the depth and investigate the changes of the subsurface ice, focusing on the landform known as rampart craters, which are considered indicators of subsurface ice. Using machine learning methods, morphological classification of rampart craters was conducted in Acidalia Planitia of Mars' northern lowlands. Based on this classification, a distribution survey was conducted and the distribution characteristics based on the morphology was investigated for estimation of the subsurface ice depth. Additionally, this study also examined the historical changes in the subsurface ice depth.

Figure 1 shows the distribution of rampart craters with thick and thin lobes. It was found that thick lobe type are concentrated in lowland areas, while thin lobe type are concentrated in highland areas. When examining the distribution ratio of thick and thin lobe type in the range of -500 m to -5500 m, it was observed that around -1500 m and -4000 m, a boundary exists, with thick lobes predominantly found in the lowland areas. Three shorelines have been suggested to exist on Mars [1, 2]. The boundary at -1500 m is close to the average elevation of Contact 1, one of these shorelines, which is -1680 m [1]. On the other hand, -4000 m is close to the elevation of the boundary of the Vastitas Borealis Formation, which is -3903 m [3]. This indicates that thick lobes are primarily distributed in regions near the boundary of Contact 1 and the Vastitas Borealis Formation.

Furthermore, from the relationship between crater diameter and excavation depth, the excavation depth of rampart craters was calculated. It was found that the excavation depth decreases with increasing latitude. This is consistent with the results of previous studies and suggests that the depth of the subsurface ice is shallower with increasing latitude.

To investigate the changes in subsurface ice depth, Acidalia Planitia was divided into seven different geological ages and regions, and the minimum excavation depth of rampart craters and the average elevation of each unit were examined. As a result, the average elevation varied on the order of 10^3 m between units, while the minimum excavation depth changed on the order of 10 m. The change in minimum excavation depth is much smaller compared to the change in average elevation. This suggests that the depth to the subsurface ice layer is not correlated with elevation, geological age, or region. Since the formation of rampart craters occurred after 3.7 Ga [e.g., 4], the depth of the subsurface ice revealed in this study is likely to represent a relatively recent depth.

From the morphological and distribution survey of rampart craters in Acidalia Planitia, it was found that the spatial distribution of martian cryosphere depends on the geology, while the depth of the cryosphere is independent of geological age and region.



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GHz-DAC ultrasonics: Current status and characteristics of the ZnO piezoelectric oscillator

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We have developed a GHz ultrasonic technique to measure elastic velocities of thin samples (a few dozen mm) squeezed in a diamond anvil cell (DAC) up to ~67 GPa. We have devised (1) to construct GHz buffer rods, (2) to improve acoustic coupling between buffer rod and diamond anvil, (3) to improve SN ratio in measurement, and (4) to estimate the most probable travel time. We conducted a preliminary test with polycrystalline MgO; the consistency with previous studies suggests future potentiality of the GHz-DAC ultrasonics. Followingly, we succeeded to measure P wave travel time of e iron and S wave travel time of ferropericlase over 30 GPa pressure range. We succeeded to extend the pressure range to 67 GPa in ferropericlase measurement.

On the other hand, we examined the ZnO piezoelectric transducer between YAG crystal and an electrode. We learned that the ideal electrode should have twice the acoustic impedance of current electrode of indium.

Detection of water in the Martian mantle by conductivity measurement

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Water in the Martian mantle has had profound effects on its geological history, volcanic activity, and potential habitability. Although Martian meteorites contain hydrous minerals and suggest the mantle may hold 50–300 ppm H_2O, similar to Earth's upper mantle, little is known about how water is distributed throughout the Martian mantle. Estimating the water content of the Martian mantle provides important constraints on the water inventory to understand its sources, sinks, and secular variation.

Electrical conductivity is useful in studying the composition, mineralogy and temperature of the planetary deep interior, if electrical conductivity is well constrained. The electrical conductivity of the mantle constituent minerals is mostly influenced by proton (H) and small polaron conduction (electron holes hopping between ferrous and ferric iron) mechanisms. In other words, conductivity is sensitive to small amounts of hydrogen and iron [1]. Since the Martian mantle has FeO-rich composition compared to the Earth's mantle, the effect of proton conduction may be masked by small polaron conduction. Therefore, to estimate the water content of the Martian mantle, the contributions of small polaron must be considered to separately determined to reach a full understanding of the electrical conductivity of olivine and its high-pressure polymorphs.

In this study, we measured electrical conductivity of hydrous olivine and ringwoodite aggregates at high pressure to constrain the water content in the FeO-rich Martian mantle. The contributions of proton conduction significantly raise the conductivity against those of small polaron conduction, and ringwoodite conductivity is considerably higher than that of olivine. Water is expected to exist in the lithosphere shallower than 200 km. On the other hand, at depths of more than 200 km, the dry model can explain well the currently available conductivity–depth profile predicted from electromagnetic studies [2].

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MAGNESIUM ISOTOPE COMPOSITIONS OF VOLCANIC ROCKS FROM COLD AND WARM SUBDUCTION ZONES: IMPLICATIONS FOR RECYCLING OF SUBDUCTED SERPENTINITES AND CARBONATES

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Magnesium (Mg) isotopes are regarded as a sensitive tracer to the contribution from subducted serpentinites and carbonates [1]. However, the source, distribution, and controlling factors of the Mg isotope composition of arc magmas remain unclear. In this study, we investigated the intra-arc and inter-arc variations in Mg isotope compositions of volcanic rocks from two typical cold subduction zones [NE Japan (NEJ) and Izu arcs] and a typical hot subduction zone [SW Japan (SWJ) arc] to address the question. The volcanic rocks from the frontal-arc regions of NEJ and Izu have isotopically heavy Mg (δ^{26}Mg = –0.20 to –0.08 ‰) compared to the mantle-like δ^{26}Mg values of most of volcanic rocks from SWJ and the rear regions of NEJ and Izu arcs (–0.28 to –0.17 ‰). It is also worth noting that NEJ arc includes samples with δ^{26}Mg values (–0.61 to –0.39 ‰) significantly lower than the mantle, but similar to the < 110 Ma intra-continental basalts from eastern China [2], which is the first observation in modern arc rocks. No obvious effects of post-eruptive alteration, fractional crystallization, partial melting, or the addition of silicate-rich sediment and oceanic crust components could be identified in the Mg isotope compositions of these volcanic rocks. By contrast, the correlations between the δ^{26}Mg values and the proxy for serpentinite component (i.e., ^{11}B/^{10}B and Nb/B ratios) indicate that the component exerts a strong control on the Mg-isotopic signature of these arc rocks. Considering metamorphic reactions in subduction lithologies under *P*-*T* conditions postulated for these arcs [3], the variations in δ^{26}Mg values of these arc magmas are unlikely to have been controlled by dehydration of serpentinites in subducted oceanic lithosphere (slab serpentinite). Instead, the high-δ^{26}Mg values of frontal-arc rocks are delivered by the fluids from serpentinite formed in the lowermost part of the sub-arc mantle (mantle wedge serpentinite) in channelized flow. Comparatively, such a high-δ^{26}Mg signature is invisible in volcanic rocks from rear-arc regions of NEJ and Izu, and the entire SWJ, suggesting that the major Mg carriers in subducted serpentinites (e.g., talc, chlorite, and serpentine) were broken down completely before subducted slabs reached the depth beneath these volcanoes. Moreover, the volcanic rocks with low δ^{26}Mg values from the rear arc of NEJ are characterized by high La/Yb and U/Nb ratios as well as low Ti/Eu, Ti/Ti*, and Hf/Hf* ratios, suggesting the involvements of carbonates in their magma sources. The quantitative modeling suggests that <20 % of sedimentary carbonate (dolomite) was recycled into their mantle source, revealing that Mg-rich carbonate could be incorporated into a deep mantle wedge at rear-arc depths of 150–400 km in subduction zones.

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Stability of hydrous minerals in hydrous pyrolite system at high pressure: implication for water transportation into the deep mantle

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Water in the nominally anhydrous minerals (NAMs) and hydrous minerals transported into the deep mantle by subducting peridotite is of great significance in the geochemical and dynamical processes in the mantle. The stability of hydrous minerals and water solubility in NAMs control the deep water cycling and slab dynamics. Along a cold slab geotherm, hydrous minerals form as main water hosts while NAMs (e.g. olivine and its high-pressure polymorphs) remain dry [1]. NAMs can accommodate weight precent levels of water after the dehydration of hydrous minerals [2]. Water contents of NAMs control slab deformation, thus stability of hydrous minerals plays an important role on mantle dynamics and water distribution in the deep mantle. Considering limited water transported into the deep mantle, phase relations of hydrous minerals coexisting with NAMs could be applied for a realistic slab condition. However, most previous studies investigated phase relations in MgO-SiO_2-H_2O systems with high water content (5-20 wt% H_2O) where hydrous minerals often coexist with hydrous fluid or melt [3-4].

We previously have determined the stability of hydrous minerals in MgO-SiO_2-H_2O system with 2 wt% H_2O up to 28 GPa and we revealed that the phase relations in MgO-SiO_2-H_2O systems depends on water content and Mg/Si ratio in the starting materials. The stability of hydrous minerals changes when NAMs coexist [5]. In this study, we further explored the phase relations in more complicated systems to study the effect of other major components (e.g. Al_2O_3, FeO, CaO) in subducting peridotite on stability of hydrous minerals when they coexist with NAMs using a multi-anvil press up to 22 GPa and 1400 °C. Two starting materials, FeO-MgO-Al_2O_3-SiO_2 +2wt% H_2O (FMASH) and pyrolite + 2wt% H_2O controlled by Ni-NiO buffer were prepared to assess the phase relations of hydrous simplified pyrolite and realistic pyrolite, respectively.

In FMASH system, at 16 GPa and 900 °C, super-hydrous phase B and phase D were observed coexisting with ringwoodite, stishovite and majorite. Above 1000 °C, hydrous minerals decomposed to form an assemblage of wadsleyite + clinoenstatite + majorite. Above 18 GPa at 1200 °C, phase D + ringwoodite + stishovite + majorite were stable.

In hydrous pyrolite system, the thermal stability of hydrous minerals decreased compared to that in FMASH system. At 18-20 GPa, super hydrous phase B and phase D were stable along with ringwoodite, stishovite, majorite and davemaoite below 1100 °C. At 22 GPa and 1200 °C, phase D was found to coexist with ringwoodite, stishovite majorite and davemaoite. When the temperature exceeded 1200 °C, phase D dehydrated. Compared to our previous phase relations in a simplified pyrolite system ($Mg_{1.3}SiO_{3.3}$ + 2 wt% H_2O) [5], thermal stability of super hydrous phase B is largely decreased while phase D has enlarged P-T stability. The dehydration temperature of hydrous minerals in FMASH systems was nearly consistent with that in $Mg_{1.3}SiO_{3.3}$ + 2 wt% H_2O, but ~ 100 °C lower in hydrous pyrolite system. We proposed that phase relation and stability of hydrous minerals in hydrous slabs are largely depends on the water content, Mg/Si ratio and the major component like CaO and Al_2O_3. The major water carrier in the cold subducting peridotite is phase D to the depth of uppermost lower mantle.

[1] Ohtani and Ishii, Prog. Earth Planet. Sci. 2024. 11: 1-20.
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[3] Frost, The Geochemical Society. 1999.
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[5] Zhu et al., 2024, AGU2024 abstract.

Affiliation Index

Abbreviations

ELSI: Earth-Life Science Institute
IPM: Institute of Planetary Materials
ISAS: Institute of Space and Astronautical Science
JAMSTEC: Japan Agency for Marine-Earth Science and Technology
JAXA: Japan Aerospace Exploration Agency

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2 Mar. 2025 a