

MARTIAN MOONS EXPLORATION: PHOBOS SAMPLE RETURN FOR UNDERSTANDING THE MARS-MOON SYSTEM. T. Usui¹, K. Bajo², W. Fujiya³, Y. Furukawa⁴, M. Koike¹, Y. N. Miura⁵, H. Sugahara¹, S. Tachibana^{1,6}, Y. Takano⁷, M. Zolenski⁸, K. Kuramoto^{1,2}. ¹Institute of Space and Astronautical Science, JAXA, 3-1-1 Yoshinodai, Sagami-hara, Kanagawa 252-5210, Japan (usui.tomohiro@jaxa.jp), ²Dept Earth Planet Sci, Hokkaido University, ³ Faculty of Science, Ibaraki University, ⁴Dept Earth Sci, Tohoku University, ⁵ERI, University of Tokyo, ⁶UTOPS, University of Tokyo, ⁷Biogeochem. Program, JAMSTEC, ⁸ARES, JSC/NASA.

Introduction: Japan Aerospace Exploration Agency (JAXA) plans a Martian moon's sample return mission (MMX: Martian Moons eXploration) [1]. The origin(s) of the Martian moons (Phobos and Deimos) is still a matter of significant debate: i) capture of asteroids [e.g., 2] or ii) *in-situ* formation by co-accretion [3] or a giant impact [e.g., 4] on Mars (Table 1). In either case, samples from a Martian moon returned by MMX will provide the necessary ground truth to test these theories and to offer an opportunity to directly explore the building blocks or juvenile crust/mantle components of Mars. This new knowledge of Phobos/Deimos and Mars will be further leveraged by constraining the initial condition of the Mars-moon system and have the potential for offering vital insights regarding the sources and delivery process of volatiles including water and organics into the inner rocky planets. This paper summarizes the recent update on our study [5] for the expected characteristics of the returned samples and the prospective scientific outcomes from their laboratory analyses (Table 1).

Sampling System: The MMX spacecraft is scheduled to be launched in 2024, orbit Phobos and Deimos (performing multiple flybys), and retrieve and return >10 g of Phobos regolith back to Earth in 2029. To fulfill the mission goals [6], MMX should collect both endogenous and exogenous samples from the regolith covering the Phobos surface. The former represents Phobos building blocks that record information of the moon's origin, while the latter is expected to contain solar system projectiles and ejecta derived from Mars and Deimos [7, 8]. Although the depth profile of Phobos regolith regarding material distribution is unknown, a ratio of [exogenous /endogenous] abundances is expected to be highest at the top-most regolith layer which is where sampling will occur.

MMX plans to employ a double sampling approach: (C) coring and (P) pneumatic. The C-sampler, a core soil tube deployed by a robotic arm, would provide access to Phobos' building blocks beneath the surface (>2 cm), but would collect a mixture of surface and sub-surface materials. The P-sampler, on the other hand, selectively samples the surface veneer and provides a reference of surface component for the C-sampler. The P-sampler will also increase the chance of retrieving invaluable Martian and Deimos materials.

Thus, the C- and P-samplers would provide a complementary approach to addressing the MMX mission goals [6].

The double sampling system not only enhances the scientific merits of MMX, but also reduces risks associated with the coring system. The nominal landing operation will execute both C- and P-sampling at each landing site. However, lacking knowledge of physical and chemical properties and conditions of the surface of Phobos (e.g., compositions, temperature gradient/variation, porosity, grain size distribution), we will prepare for scenarios in which the C-sampler cannot penetrate deep enough into a thin regolith layer covering a rigid basement and/or that it cannot be extracted once it penetrates. Under any conceivable surface conditions, the P-sampler will work effectively and independently to collect fine-grained regolith particles.

Expected Characteristics of Returned Samples:

The characteristics of the returned endogenous samples depend on Phobos' origin (Table 1). In the case of the captured asteroid origin [e.g., 2], the returned samples would be analogous to a certain type of chondrites, IDPs (interplanetary dust particles), or even comets, depending on where these moons originally formed in the early solar system. If they formed in the outer solar system (beyond the snow line), they could potentially contain abundant hydrous secondary phases and organic molecules. Such phases could have formed by water-rock-organic interaction under low-temperature conditions in the parent asteroid of Phobos, resulting in H-, C-, and N-rich bulk chemistry [9]. Alternatively, outer solar system formation could be indicated by unreacted ice and crystalline/amorphous silicate dust mixtures, as found with the comet Wild-2 samples returned by the Stardust Spacecraft [10]. On the other hand, if the Martian moons formed in the inner solar system (inside of the snow line), they probably consist mostly of anhydrous phases with lower bulk volatile contents and characteristic isotopic differences. These two extreme cases for the captured model may be tested on the basis of the heliocentric gradients of volatile isotopes and abundances (e.g., CO₂/H₂O, D/H, ¹⁵N/¹⁴N and noble gases) and the isotopes of rock-forming elements of O, Cr, Ti in the solar system [11-13].

In contrast to the captured asteroid scenario, if Phobos and Deimos formed *in-situ* by a giant impact

(like the Earth's moon) [e.g., 4, 14], the returned samples would be characterized by high- T and possibly high- P glassy or recrystallized igneous phases. Due to the high- T impact process (e.g., ~ 2000 K)[14], endogenous organic materials would be unlikely to be present to a significant degree in the regolith. The bulk chemistry could range from a mafic to ultramafic composition with high abundances of highly siderophile elements, representing a mixture of Martian silicate portions (crust/mantle) and the impactor [14]. The bulk-silicate Mars is characterized by elevated volatile (e.g., Na and K) and siderophile (e.g., Mn, Cr, and W) elements and depletions in chalcophile elements (e.g., Cu), relative to the bulk silicate Earth. Such a volatile-rich nature relative to the Earth and Moon is evident in ratios of K/Th and K/U (volatile/refractory incompatible element); the K/Th ratio of Phobos surface will be measured by MEGANE [15].

Under the condition that the representativeness of the sampling site(s) is guaranteed by remote sensing observations in the geologic context of Phobos, laboratory analysis (e.g., mineralogy, bulk composition, O-Cr-Ti isotopic systematics, and radiometric dating) of the returned sample will provide definitive information about the moon's origin. Stable isotopic systematics of O, Cr, Ti, and Mo clearly differentiate the carbonaceous and non-carbonaceous reservoirs, which are currently proposed to have been spatially separated by Jupiter [e.g., 13, 16, 17]. A suite of these isotope analyses, except for Mo, can be carried out using a <100

mg fraction of the returned samples. These comprehensive isotopic data will be carefully examined petrographic and mineralogical observations to help discriminate the exogenous materials. For example, major element mineral chemistry of olivine and pyroxene, phases that are common in planetary materials, is distinct between asteroids (chondrite/achondrite parent bodies) and Mars. Other lines of evidence for Phobos' origin would also come from the presence/lack of refractory inclusions, amorphous silicates, presolar grains, organic materials with anomalous H, C, and N isotopic compositions.

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Table 1: Expected characteristics of endogenous returned samples

	Moon origin			
	capture of asteroid		In-situ formation	
	Outer solar system body	Inner solar system body	Co-accretion	Giant impact
Petrology	Analogous to carbonaceous chondrite, IDP, or cometary material	Analogous to ordinary chondrite	?	Glassy or recrystallized igneous texture
Mineralogy	Rich in oxidized and hydrous alteration phases (e.g. phyllosilicate, carbonates), amorphous silicate	Reduced and mostly anhydrous phases (e.g., pyroxene, olivine, metal, sulfides)	Un-equilibrated mixture of chondritic minerals?	High- T igneous phases (e.g., pyroxene, olivine), Martian crustal (evolved igneous) & mantle (high- P) phases
Bulk chemistry	Chondritic, volatile-rich (e.g. high C and high H)	Chondritic, volatile poor	Chondritic (= \sim bulk Mars?) with nebula-derived volatile?	Mixture of Martian crustal (mafic) and mantle-like (ultramafic) composition possibly with impactor material (high HSE?). Degree of volatile depletion varies due to impact regime
Isotopes	Carbonaceous chondrite signature (e.g., $\Delta 17\text{O}$, $\epsilon 54\text{Cr}$, $\epsilon 50\text{Ti}$, ϵMo , noble gases), primitive solar-system volatile signature (e.g., D/H, $15\text{N}/14\text{N}$)	Non-carbonaceous chondrite signature (e.g., $\Delta 17\text{O}$, $\epsilon 54\text{Cr}$, $\epsilon 50\text{Ti}$, ϵMo , noble gases), primitive (e.g., chondritic D/H, $15\text{N}/14\text{N}$)?	Bulk-Mars (?) signature (e.g., $\Delta 17\text{O}$, $\epsilon 54\text{Cr}$, $\epsilon 50\text{Ti}$, ϵMo), planetary volatile (e.g., intermediate D/H, low $15\text{N}/14\text{N}$)?	Mixture of Martian and impactor (carbonaceous or non-carbonaceous) composition, highly mass fractionated planetary volatile (e.g., low D/H, low $15\text{N}/14\text{N}$)?
Organics	Primitive organic matter, volatile & semi-volatile organics, soluble organics?	Non-carbonaceous signature?	?	?