MARTIAN MOONS EXPLORATION: THE IMPORTANCE OF PHOBOS SAMPLE RETURN FOR UNDERSTANDING THE MARS-MOON SYSTEM.

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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, the returned samples will definitely provide clues about their origin(s) and offer an opportunity to directly explore the satellite building blocks or juvenile crust/mantle components of Mars. The new knowledge of Phobos/Deimos and Mars will be further leveraged by constraining the initial condition of the Mars-moon system and offering vital insights regarding the sources and delivery process of water (and organics) into the inner rocky planets. This paper summarizes the expected characteristics of the returned samples and the prospective scientific outcomes from their laboratory analyses (Table 1).

Mission Overview: The MMX spacecraft is scheduled to be launched in 2024, orbit Phobos and Deimos (multi-flyby), and retrieve and return >10 g of Phobos regolith back to Earth in 2029. The chemical propulsion system is utilized for Mars orbit injection and an escape maneuver. The outward interplanetary flights take ~1 year by the most efficient Hohmann-like transfer. The spacecraft stays at circum-Mars orbits ~3 years for exploration followed by the ~1 year homeward interplanetary flight to Earth. The Phobos exploration includes multiple landing/sampling operations; each takes ~2.5 hours. The spacecraft employs ballistic descent to reach the space right above a landing site before the final free-fall descent without a thruster jet to prevent whirling wind from blowing regolith particles. For the remote sensing science payloads, see[5] in detail.

Sampling System: To fulfill the mission goals [5], 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 [6, 7]. 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.

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 "involuntarily" collects 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 should cooperate to address the MMX mission goals [5].

The double sampling system not only enhances the scientific merits of MMX, but also reduces risks associated with the coring system. Without enough knowledge of physical and chemical properties and conditions of the surface of Phobos (e.g., compositions, temperature gradient/variation, porosity, grain size distribution), we should prepare for cases in which the C-sampler cannot penetrate deep enough into a thin regolith layer covering the rigid basement and/or that it cannot be extracted once it penetrates. Under any 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 the moon's origin (Table 1). In the case of the captured asteroid origin [e.g., 2], the returned samples would be analogous to different types of chondrites, IDPs, or even comets, depending on where these moons originally formed in the early solar system. If they formed in the outer solar, they will potentially contain abundant hydrous alteration phases (or unreacted ice and silicate dust mixture) including organic molecules, resulting in volatile-rich bulk chemistry. On the other hand, if they formed in the inner solar (inside of the snow line), they will consist mostly of anhydrous phases. These two extreme cases for the captured model may be tested on the basis of the heliocentric gradients of volatile isotopes (e.g., D/H, $^{15}N/^{14}N$ and noble gases) in the solar system[8].

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], the returned samples would be characterized by high-*T* (and possibly high-*P*) glassy or recrystallized igneous phases. Their bulk chemistry could range from a mafic to ultramafic composition with high abundances of highly siderophile elements (HSEs), representing a mixture of Martian silicate portions (crust/mantle) and the impactor [9]. Instead, the *in-situ* formation by co-accretion with Mars would provide the bulk chemistry similar to the bulk Mars.

Compelling evidence for Phobos' origin will be provided by high precision isotopic analyses of lithophile elements. Stable isotopic systematics of O, Cr, Ti, and Mo clearly differentiate the carbonaceous (outer solar) and non-carbonaceous (inner solar) reservoirs [e.g., 10, 11] (Fig. 1). A suite of these comprehensive 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 in accordance with the petrographic and mineralogical observations that would help discriminate the exogenous materials. Moreover, the representativeness of the returned samples will be examined by remote sensing observations in advance of the sample analyses.

References: [1] Usui, T. et al. (2018) *42nd COSPAR Scientific Assembly*. Abstract# B4.2-7-18.[2] Hartmann, W.K. (1990) *Icarus*, *87*, 236-240. [3] Safronov, V. et al. (1986) in *Satellites*, 89-116. [4] Rosenblatt, P. et al. (2016) *Nat. Geosci.*, *9*, 581-583. [5] Kuramoto, K. et al. (2018) *LPS XLIX*. Abstract #2143. [6] Ramsley, K.R. and J.W. Head (2013) *Planet. Space Sci.*, *87*, 115-129. [7] Nayak, M. et al. (2016) *Icarus*, *267*, 220-231. [8] Marty, B. (2012) *EPSL*, *313–314*, 56-66. [9] Hyodo, R. et al. (2017) *ApJ*, *845*, 125. [10] Kruijer, T.S. et al. (2017) *PNAS*, *114*, 6712-6716. [11] Warren, P.H. (2011) *EPSL*, *311*, 93-100.

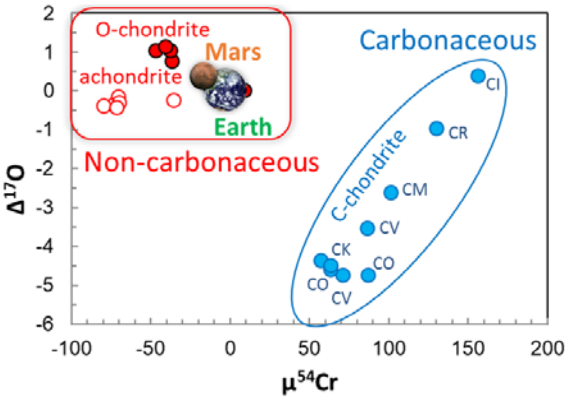

Fig. 1: *μ^{54}Cr vs. Δ^{17}O isotope diagram of planetary material*s. *Data compilation by R. Fukai.*

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 (= ~ 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., Δ^{17}O, ε^{54}Cr, ε^{50}Ti, εMo, noble gases), primitive solar-system volatile signature (e.g., D/H, ^{15}N/^{14}N)	Non-carbonaceous chondrite signature (e.g., Δ^{17}O, ε^{54}Cr, ε^{50}Ti, εMo, noble gases), primitive chondritic signature (e.g., D/H, ^{15}N/^{14}N)?	Bulk-Mars (?) signature (e.g., Δ^{17}O, ε^{54}Cr, ε^{50}Ti, εMo), planetary volatile (e.g., intermediate D/H, low ^{15}N/^{14}N)?	Mixture of Martian and impactor (carbonaceous or non-carbonaceous) composition, highly mass fractionated planetary volatile (e.g., low D/H, low ^{15}N/^{14}N)?
Organics	Primitive organic matter, volatile & semi-volatile organics, soluble organics ?	Non-carbonaceous signature ?	?	?