




# The Importance of Phobos Sample Return for Understanding the Mars-Moon System

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**Abstract** Phobos and Deimos occupy unique positions both scientifically and programmatically on the road to the exploration of the solar system. Japan Aerospace Exploration Agency (JAXA) plans a Phobos sample return mission (MMX: Martian Moons eXploration). The MMX spacecraft is scheduled to be launched in 2024, orbit both Phobos and Deimos (multiple flybys), and retrieve and return >10 g of Phobos regolith back to Earth in 2029. The Phobos regolith represents a mixture of endogenous Phobos building blocks and exogenous materials that contain solar system projectiles (e.g., interplanetary dust particles and coarser materials) and ejecta from Mars and Deimos. 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 crucial information

Role of Sample Return in Addressing Major Questions in Planetary Sciences

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about the moon's origin: capture of an asteroid or in-situ formation by a giant impact. If Phobos proves to be a captured object, isotopic compositions of volatile elements (e.g., D/H,  $^{13}\text{C}/^{12}\text{C}$ ,  $^{15}\text{N}/^{14}\text{N}$ ) in inorganic and organic materials will shed light on both organic-mineral-water/ice interactions in a primitive rocky body originally formed in the outer solar system and the delivery process of water and organics into the inner rocky planets.

**Keywords** Phobos sample return · Origin of Martian moons · Martian Moons eXploration · Endogenous Phobos material · Mars-originating materials

## 1 Introduction

The Mars-moon system is a most promising target for exploration in the broad field of planetary science: e.g., geology, geochemistry, astrobiology, and comparative planetology. The international Mars science community has set a long-term goal toward achieving Mars sample return (MSR) and human exploration (Banfield 2018). MSR will address questions on the origin (e.g., source of building blocks), interior evolution (e.g., crust-mantle differentiation and mantle dynamics), the potential biological history (e.g., nature and extent of habitability and preservation of biosignature), and geologic history of Mars with an emphasis on the role of water (Beaty et al. 2019). Previous Mars exploration missions have provided compelling evidence for the presence of liquid water during the earliest geologic era (Noachian:  $>\sim 3.9$  Ga) of Mars. Observations of dense valley networks, evaporites (e.g., gypsum) and hydrous minerals (e.g., clays) that are commonly formed by aqueous processes imply that, at some time in the past, Mars had an Earth-like active hydrological cycle with lakes, oceans, possibly also aquifers and groundwater, and had the potential for life (Carr 2006; Ehlmann et al. 2016; Usui 2019).

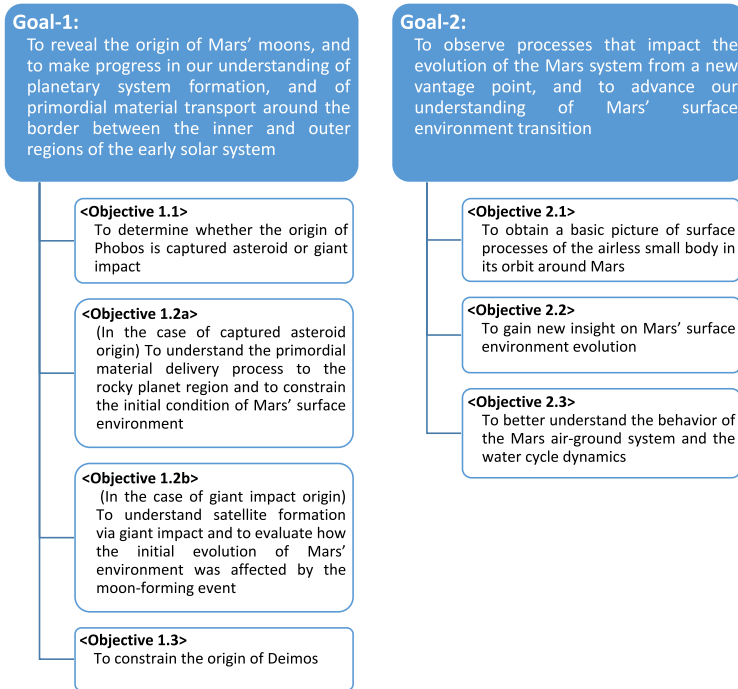
Along with the geological similarities, Earth and Mars are the only terrestrial planets in the inner solar system that have moons. The moons are witness plates for planet formation processes. Lunar exploration and studies of lunar samples (Apollo and meteorites) in the lab provided significant knowledge of the formation and co-evolution of the Earth-Moon system: e.g., the giant impact and magma ocean hypotheses for terrestrial planet formation, and the late veneer hypothesis for the delivery of water into the inner solar system (e.g., Taylor et al. 2006; Day et al. 2016). These hypotheses may also be tested for the Mars system by virtue of studying Phobos and Deimos. However, our understanding of Phobos and Deimos is sparse mainly due to the complete lack of successful missions dedicated to the exploration of Phobos/Deimos as well as the lack of meteorites from these bodies. The Soviet Union's Phobos 2 spacecraft acquired television images and infrared spectra at  $\sim 700$  m/pixel resolution (Avanesov et al. 1989; Bibring et al. 1990). Subsequent observations have been made by Earth-based telescopes and Mars orbiters/landers reporting a surface spectral similarity to D-type asteroid (e.g., Murchie and Erard 1996; Simonelli et al. 1998; Cantor et al. 1999; Thomas et al. 2011; Fraeman et al. 2012; Fraeman et al. 2014). Therefore, Phobos and Deimos occupy unique positions both scientifically and programmatically on the road to the exploration of the solar system (Murchie et al. 2014).

The Japan Aerospace Exploration Agency (JAXA) plans a Martian moons' sample return mission (MMX: Martian Moons eXploration) (Kuramoto et al. 2018; Usui et al. 2018); MMX is the 3rd Japanese sample return mission, following Hayabusa (Fujiwara et al. 2006) and Hayabusa2 (Watanabe et al. 2019). The origin(s) of Phobos and Deimos is still a matter of significant debate, with the most likely candidates being: 1) the capture of asteroids (e.g.,

**Table 1** Expected characteristics of endogenous returned samples

	Moon origin		In-situ formation	
	capture of asteroid			
	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- <i>T</i> igneous phases (e.g., pyroxene, olivine), Martian crustal (evolved igneous) & mantle (high- <i>P</i> ) 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., $\Delta^{17}\text{O}$ , $\epsilon^{54}\text{Cr}$ , $\epsilon^{50}\text{Ti}$ , $\epsilon\text{Mo}$ , noble gases), primitive solar-system volatile signature (e.g., D/H, $^{15}\text{N}/^{14}\text{N}$ )	Non-carbonaceous chondrite signature (e.g., $\Delta^{17}\text{O}$ , $\epsilon^{54}\text{Cr}$ , $\epsilon^{50}\text{Ti}$ , $\epsilon\text{Mo}$ , noble gases), primitive (e.g., chondritic D/H, $^{15}\text{N}/^{14}\text{N}$ )?	Bulk-Mars (?) signature (e.g., $\Delta^{17}\text{O}$ , $\epsilon^{54}\text{Cr}$ , $\epsilon^{50}\text{Ti}$ , $\epsilon\text{Mo}$ ), 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 ?	?	?

Hartmann 1990; Higuchi et al. 2017) or 2) in-situ formation by either co-accretion (Safronov et al. 1986) or by a giant impact (e.g., Rosenblatt et al. 2016; Hesselbrock and Minton 2017; Hyodo et al. 2017) 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 has potential for offering vital insights regarding the sources and delivery process of volatiles including water and organics to the inner rocky planets. This paper describes the science goals, mission profile and science payload of the MMX mission (Sect. 2), summarizes the expected characteristics of the returned samples and the prospective scientific outcome from the laboratory analysis (Sects. 3–5), and describes an assessment of contamination control issues (Sect. 6).



**Fig. 1** Mission goals and objectives of MMX

## 2 Mission Overview

### 2.1 Mission Goals and Objectives

MMX has two main science goals: Goal-1) to reveal the origin of the Martian moons and make progress in the understanding of planetary system formation and material transport in the solar system, and Goal-2) to observe processes that impact the circumplanetary and surface environments of Mars (Fig. 1). These mission goals lead to the five mission objectives (MO): MO-1.1) to determine whether the origin of Phobos was by capture of an asteroid or by in-situ formation following a giant impact on Mars; MO-1.2) to understand material transport within the Mars-system during the moon formation stage; MO-1.3) to constrain the origin of Deimos; MO-2.1) to obtain a basic picture of surface processes acting on airless small bodies in orbit around Mars; MO-2.2) to gain critical new insight on Mars surface environment evolution; and MO2.3) to better understand the behavior of the Mars atmosphere-surface system and water cycle dynamics. To accomplish the science goals and objectives, the MMX team has defined a mission profile, has selected a comprehensive suite of remote-sensing and in-situ instruments, designed the Phobos regolith sampling system, and will conduct laboratory analyses of returned samples. Analyses of endogenous Phobos constituent materials and exogenous late accreted materials would specifically achieve the mission goals-1 and -2, respectively (Sect. 3).

## 2.2 Mission Profile and Science Payload

The MMX spacecraft is scheduled to be launched in 2024, orbit Phobos and Deimos, perform multiple flybys, and retrieve and return >10 g of Phobos regolith back to Earth in 2029 (Kawakatsu et al. 2017). The spacecraft will consist of propulsion, exploration, and return modules (total launch mass = ~4,000 kg). The chemical propulsion system is utilized for Mars orbit injection and an escape maneuver. The outward interplanetary flights will take ~1 year by the most efficient Hohmann-like transfer. The spacecraft will remain in circum-Mars orbits for approximately 3 years for survey and exploration, followed by the ~1 year homeward interplanetary journey to Earth. The Phobos exploration phase will include multiple landing/sampling operations, each taking ~2.5 hours. To prevent sample contamination from thruster plume products and regolith particles that could be ejected from the surface during a thrust descent, the spacecraft will employ ballistic descent to reach a point directly above a landing site before a final free-fall descent without a thruster jet (Kawakatsu et al. 2017; Kawakatsu et al. 2019).

Seven nominal science instruments comprise several payloads for the remote sensing observations (Kuramoto et al. 2018): 1) a narrow-angle camera (TElescopic Nadir imager for GeOmOrphology, TENG00) (JAXA) (Kameda et al. 2019), 2) a wide-angle multi-spectral camera (Optical RadiOMeter composed of CHromatic Imagers, OROCHI) (JAXA) (Kameda et al. 2019), 3) a near-infrared spectrometer (0.9–3.6  $\mu\text{m}$ ) MMX Infrared Spectrometer, MIRS (CNES), 4) a light detection and ranging instrument (LIDAR) (JAXA), 5) a dust instrument for particle sizes >10  $\mu\text{m}$  (Circum-Martian Dust Monitor, CMDM) (JAXA) (Kobayashi et al. 2018), 6) a gamma-ray and neutron instrument (Mars-moon Exploration with GAMMA rays and Neutrons, MEGANE) (NASA) (Lawrence et al. 2019), and 7) an ion mass spectrometer (Mass Spectrum Analyzer, MSA) (JAXA). Along with these seven instruments, the MMX spacecraft will carry and deploy a Rover (CNES/DLR) for in-situ surface exploration (Ulamec et al. 2019). The rover will carry several instruments for in-situ observations, including a Raman spectrometer, radiometer as well as navigation and wheel cameras.

## 2.3 Sampling System

Samples collected by MMX are expected to represent a mixture of endogenous and exogenous materials in Phobos' regolith. 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 (Ramsley and Head 2013; Nayak et al. 2016; Hyodo et al. 2019). Although the depth profile of Phobos regolith regarding material distribution is unknown, the 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 has more than two core soil tubes deployed by a robotic arm; each core has a volume large enough to collect >10 g regolith. The cores would provide access to material 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 components for the C-sampler. The P-sampler will also increase the chance of retrieving invaluable Martian and Deimos materials. Each core sample retrieved by the C-sampler and surface materials collected by the P-sampler will be separately stored in different canisters and returned to Earth. Thus, the C- and P-samplers would constitute complementary approaches to addressing the MMX mission goals.

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 has penetrated. Under any conceivable surface conditions, the P-sampler will work effectively and independently to collect fine-grained regolith particles.

### 3 Expected Characteristics of Returned Samples

#### 3.1 Phobos' Original Building Blocks

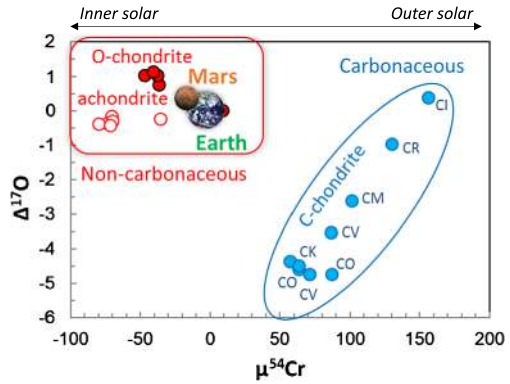
##### 3.1.1 A Case of the Captured Asteroid Hypothesis

The characteristics of the returned endogenous samples depend on Phobos' origin (Table 1). In the case of captured asteroid origin (e.g., Hartmann 1990; Higuchi et al. 2017), 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, represented by H-, C-, and N-rich bulk chemistry (Alexander et al. 2012; Krot et al. 2015). Outer solar system formation could be also indicated by crystalline/amorphous silicate dust mixtures with a solar nebular origin, as found with the comet Wild-2 samples returned by the Stardust spacecraft (Brownlee et al. 2006). 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., CO<sub>2</sub>/H<sub>2</sub>O, D/H, <sup>15</sup>N/<sup>14</sup>N and noble gases) and the isotopes of rock-forming elements of O, Cr, and Ti in the solar system (Figs. 2, 3, and 4) (Trinquier et al. 2007; Trinquier et al. 2009; Qin et al. 2010; Warren 2011; Marty 2012; Fujiya et al. 2019).

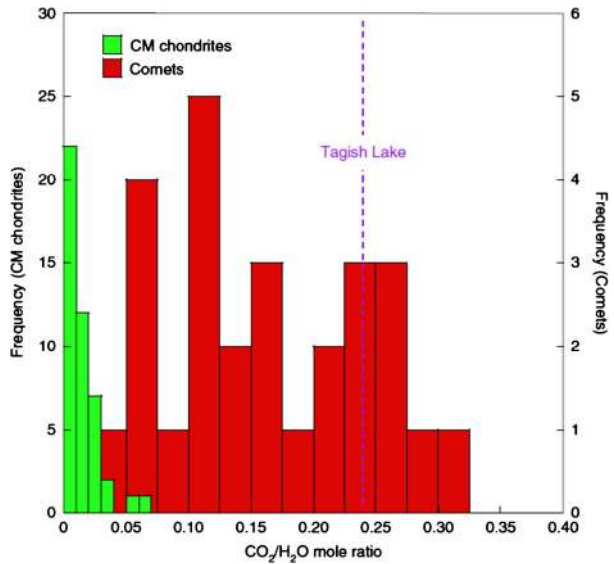
##### 3.1.2 A Case of In-Situ Formation

If Phobos and Deimos formed in-situ by a giant impact (like the Earth's moon) (e.g., Rosenblatt et al. 2016; Hesselbrock and Minton 2017; Hyodo et al. 2017), the returned samples would be characterized by high-temperature and possibly high-pressure shocked phases and/or glassy/recrystallized phases. Due to the high-temperature impact process (e.g., ~2000 K, Hyodo et al. 2017), 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, possibly representing a mixture of Martian silicate portions (crust/mantle) and the impactor (Hyodo et al. 2017). 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 (Dreibus and Wanke 1985;

**Fig. 2**  $\mu^{54}\text{Cr}$  vs.  $\Delta^{17}\text{O}$  isotope diagram of planetary materials. Data compilation by Ryota Fukai



**Fig. 3** Histogram of the  $\text{CO}_2/\text{H}_2\text{O}$  mole ratios of ice in CM chondrites and comets. The  $\text{CO}_2/\text{H}_2\text{O}$  ratios of ice in CM chondrites are calculated from carbonate abundances and hydrogen contents. Modified after Fujiya et al. (2019)

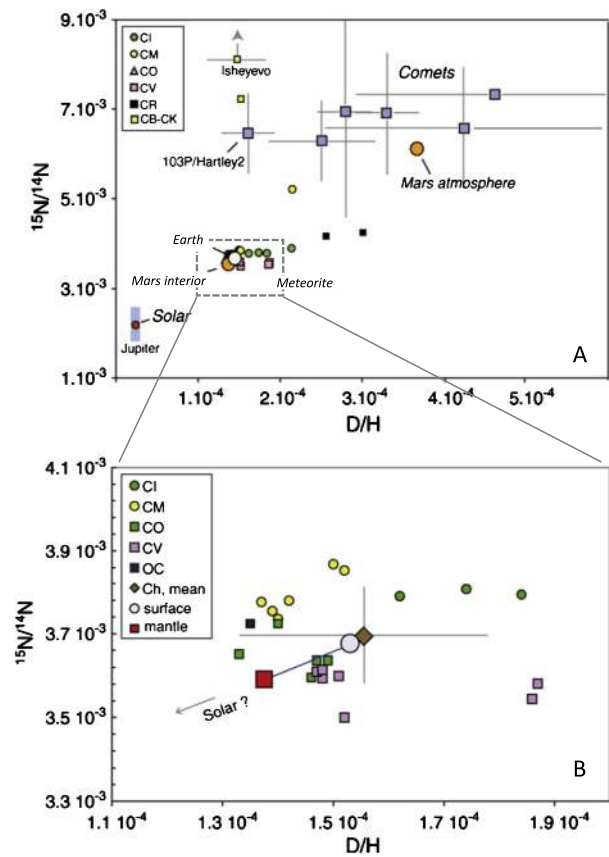


Taylor 2013). Such a volatile-rich nature relative to the Earth and Moon is evident in ratios of K/Th and K/U (volatile/refractory incompatible element) (Fig. 5) and the K/Th ratio of Phobos surface will be measured by MEGANE (Lawrence et al. 2019). On the other hand, in-situ formation by co-accretion with Mars would provide a bulk chemistry represented by the chondritic bulk Mars.

### 3.2 Late Accreted Materials

The regolith of Phobos is likely to contain ejecta derived from Mars and Deimos due to Phobos' location in Mars' orbit (Ramsley and Head 2013; Nayak et al. 2016; Hyodo et al. 2019). Though the exact nature of Deimos-originating material is unknown, the spectral similarity between Deimos and the dominant red unit of Phobos suggests that Deimos-originating materials resemble the endogenous Phobos materials (Fraeman et al. 2012); note that Phobos' surface shows two distinct units named "blue unit" and "red unit" after the relative slopes of their reflectance spectra (Murchie and Erard 1996). We may have diffi-

**Fig. 4** D/H and  $^{15}\text{N}/^{14}\text{N}$  ratios among solar system reservoirs and objects. The hatched area in A is enlarged B. Modified after Marty (2012)

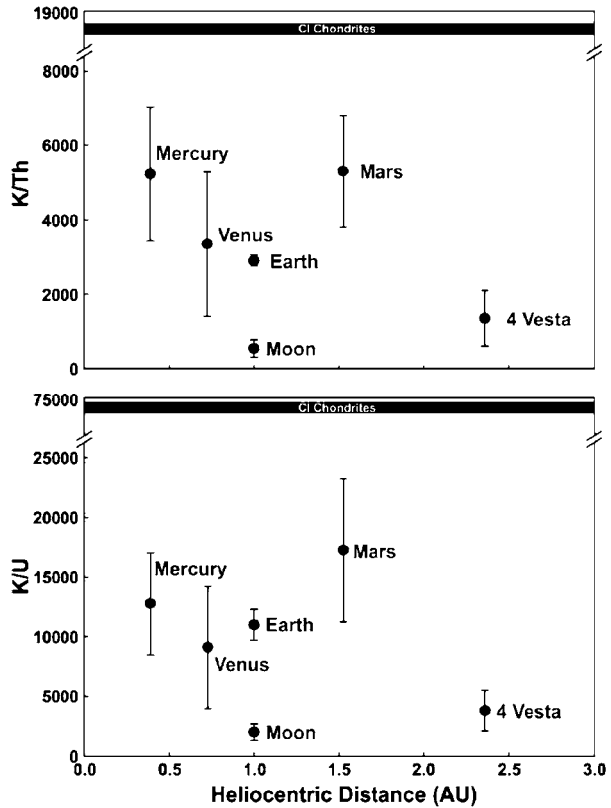


culty in discriminating Deimos-originating materials from the Phobos regolith unless detailed remote sensing observations by MMX clarify the distinction between the two moons. On the other hand, Mars-originating materials would differ from the endogenous Phobos materials even if Phobos was formed by a giant impact. The endogenous Phobos material formed by a giant impact should have sampled both crust and mantle reservoirs of Mars (Hyodo et al. 2017), whereas the later Mars-originating materials would have mostly derived from the near-surface of Mars (Hyodo et al. 2019). The Martian near-surface materials have oxygen ( $\Delta^{17}\text{O}$ ), hydrogen (D/H), and carbon ( $\delta^{13}\text{C}$ ) isotopic compositions that are distinct from those of the Martian crust and mantle reservoirs (Leshin et al. 1996; Farquhar and Thiemens 2000; Usui et al. 2012; Agee et al. 2013; Webster et al. 2013; Usui et al. 2015).

The surface of Mars is dominated by a basaltic crust mainly composed of olivine, pyroxene, and plagioclase (McSween et al. 2009) (Fig. 6). Although these igneous phases are common in chondrites and achondrites, their chemistries are distinct (e.g., Fe/Mg and Fe/Mn ratios, and anorthite component) (Karner et al. 2003; Karner et al. 2006). The Martian crust also contains a variety of sedimentary rocks, including both clastic rocks (sandstone and siltstone, shale and mudstone, and conglomerate) and chemically deposited rocks (mostly evaporitic sulfate, and some carbonate) (McSween 2015). Sedimentary rocks in ancient terranes potentially contain organic compounds (Eigenbrode et al. 2018). Global mapping of sedimentary rocks suggests the secular desiccation and acidification of the near-surface en-



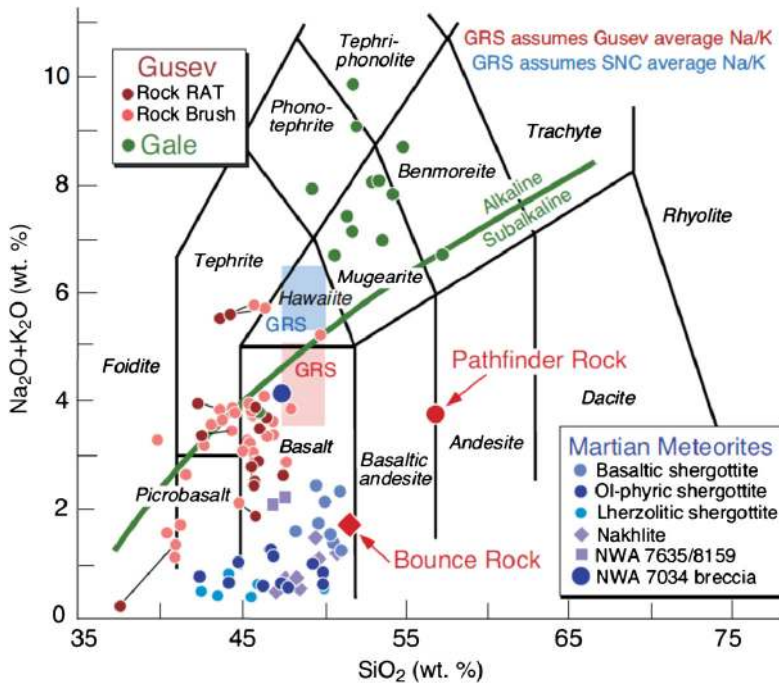
**Fig. 5** K/Th and K/U ratios of terrestrial bodies within the inner Solar System plotted as a function of heliocentric distance (McCubbin et al. 2012)



vironment (Bibring et al. 2006; Ehlmann and Edwards 2014) (Fig. 7). The surface mineralogy of early Noachian terranes is characterized by clay minerals such as Fe/Mg smectites, suggesting water-rich and near-neutral fluid conditions. The occurrence and distribution of carbonates and sulfates in the late Noachian to early Hesperian suggest a transition of fluid chemistry to more acidic conditions in this period. The young Amazonian terranes are dominated by anhydrous ferric oxides such as hematite, suggestive of acidic and drier conditions. Meteorite impacts would have randomly sampled these Martian surficial materials, some of which would have subsequently been deposited on the surface of Phobos as late accreting materials in the regolith (Hyodo et al. 2019).

#### 4 Key Analysis of Phobos Sample Return Mission

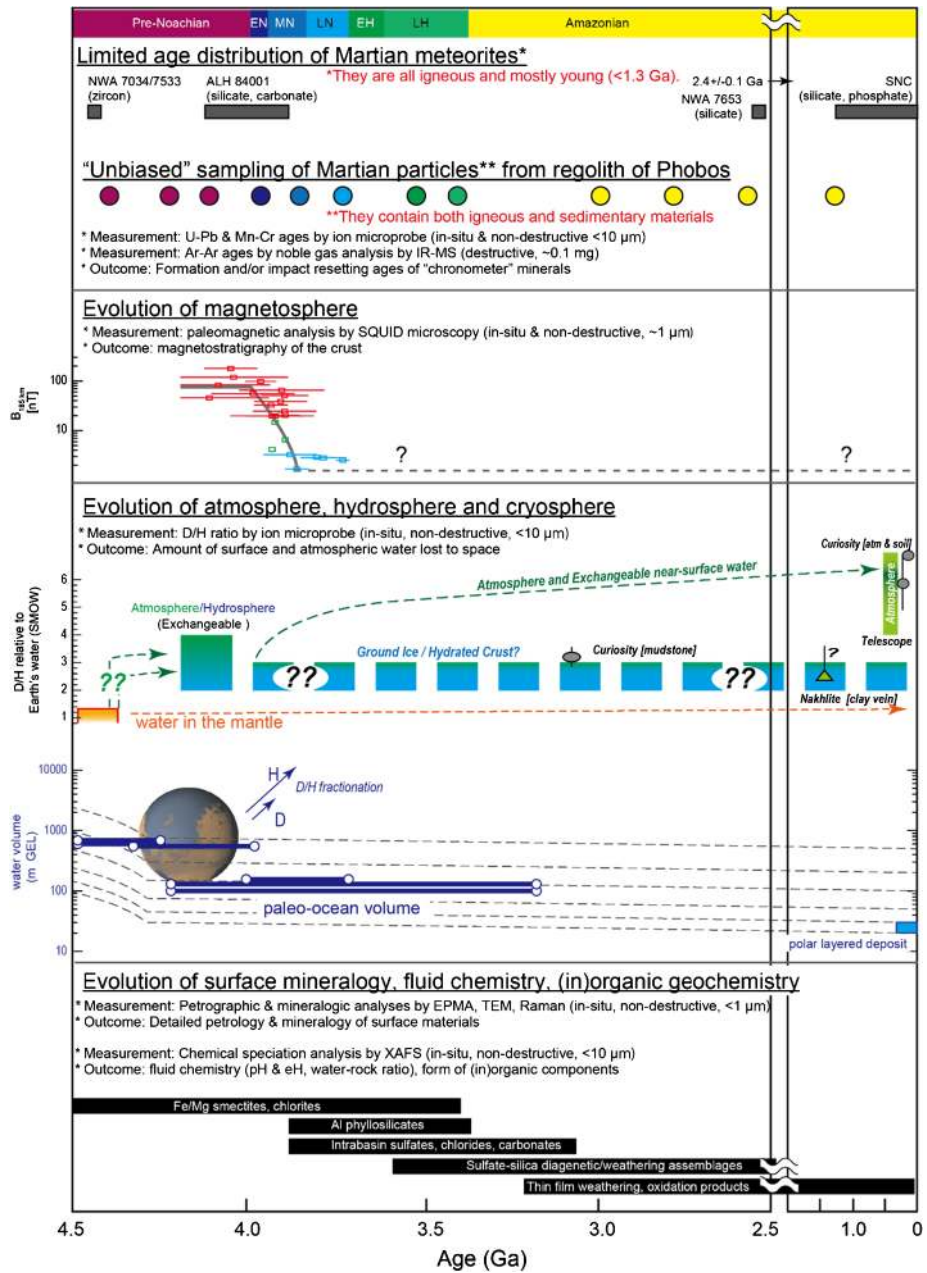
Compelling evidence for Phobos' origin will be provided by high precision isotopic analyses of lithophile elements. Stable isotopic systematics of O, Cr, Ti, and Mo clearly differentiate the carbonaceous and non-carbonaceous reservoirs (Fig. 2), which are proposed to be spatially distinguished either side of Jupiter's orbit (Trinquier et al. 2007; Trinquier et al. 2009; Qin et al. 2010; Warren 2011; Kruijer et al. 2017). A suite of these isotope analyses, except for Mo, can be carried out using a <100 mg fraction of the returned samples (Table 2). Secondary Ion Mass Spectrometry (SIMS) techniques further permit grain-by-grain characterization by high-spatial-resolution and high-precision O isotope analysis with a primary



**Fig. 6** Compositions of Martian igneous rocks (McSween 2015)

ion beam of  $\sim 15 \mu\text{m}$  in size and analytical uncertainties of  $\sim 0.5\text{‰}$  for  $\Delta^{17}\text{O}$  values (Kita et al. 2010; Yurimoto et al. 2011), potentially providing individual histories of each collected grain. Isotopic data will also be carefully examined alongside 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 (Brearley 1998; McSween and Treiman 1998; Mittlefehldt et al. 1998). Other lines of evidence for Phobos' origin would also come from the presence/lack of refractory inclusions, amorphous silicates, presolar grains, or organic materials with anomalous H, C, and N isotopic compositions.

Radiometric dating of the returned samples would provide chronological constraints on the origin of Phobos. Mineral isochrons of  $^{87}\text{Rb}$ - $^{87}\text{Sr}$ ,  $^{147,146}\text{Sm}$ - $^{143,142}\text{Nd}$ ,  $^{176}\text{Lu}$ - $^{176}\text{Hf}$ , and  $^{238,235}\text{U}$ - $^{206,207}\text{Pb}$  systems obtained by Thermal Ionization Mass Spectrometry (TIMS) and Inductively Coupled Plasma Mass Spectrometry (ICP-MS) could yield formation ages (e.g., timing of crystallization) of individual fragments in the returned regolith sample (e.g., Amelin et al. 2002; Borg et al. 2005; Lapen et al. 2010). Bulk isochron defined by co-genetic fragments in the regolith sample could yield a formation age of the source (e.g., timing of the giant impact). Chronological study of short-lived nuclides (e.g.,  $^{146}\text{Sm}$ - $^{142}\text{Nd}$ ,  $^{182}\text{Hf}$ - $^{182}\text{W}$ ,  $^{53}\text{Mn}$ - $^{53}\text{Cr}$ ) would provide more precise knowledge of formation ages (e.g., Kleine et al. 2002; Trinquier et al. 2008; Kruijer et al. 2014). The  $^{40}\text{K}$ ( $^{39}\text{Ar}$ )- $^{40}\text{Ar}$  age could represent the timing of a secondary impact on Phobos. Should a statistically meaningful number of  $^{40}\text{K}$ ( $^{39}\text{Ar}$ )- $^{40}\text{Ar}$  ages be obtained, they would provide the chronometric ground truth for the crater density distribution obtained by MMX's remote sensing observations. Furthermore, in-situ dating of secondary phases (e.g.,  $^{53}\text{Mn}$ - $^{53}\text{Cr}$  age of carbonate) would provide the



**Fig. 7** Timeline of the evolution of magnetosphere, atmosphere, hydrosphere, cryosphere, and surface mineralogy of Mars. Age distribution of Martian meteorites are also plotted (Hyodo et al. 2019)

timing of secondary aqueous alteration events (Fujiya et al. 2012). Temperature of aqueous alteration would be estimated by C-O clumped isotope thermometry (e.g., Halevy et al. 2011).

Organic analysis plays an essential role in the Phobos sample return mission because the regolith of Phobos is expected to contain mature organics derived from the surface of Mars (Eigenbrode et al. 2018; Hyodo et al. 2019). If Phobos is a captured asteroid that formed in the outer solar system then the regolith could also contain a mixture of primitive compounds originating from its parent body (Table 1). In such a case, the MMX sample will expand knowledge about the primitive asteroids Ryugu and Bennu, the target bodies of Hayabusa 2 (Watanabe et al. 2019) and OSIRIS-REx (Lauretta et al. 2019) sample return missions, respectively. The MMX sample would be further important for organic astrochemistry, because Phobos has stayed in Mars' orbit ( $\sim 1.5$  AU), maintaining average surface temperatures lower than those of near-Earth asteroids Ryugu and Bennu.

Considering our experience with these sample return missions, Phobos sample return requires a comprehensive framework to maximize the scientific harvest through a seamless pathway from non-destructive to semi-destructive and destructive analysis (Table 2). In this workflow, bulk chemical analysis and molecular-based organic analysis will contribute to the careful documentation of volatile organic gas, soluble organic matter, insoluble organic matter, and remaining organic chemistry. For example, compound-specific isotope analyses of hydrogen (D/H), carbon ( $^{13}\text{C}/^{12}\text{C}$ ), and nitrogen ( $^{15}\text{N}/^{14}\text{N}$ ) by destructive (e.g., gas chromatography/isotope ratio mass spectrometry) and non-destructive (e.g., cavity ring-down spectroscopy) techniques would provide quantitative estimates of the low-temperature reactions between inorganic phases and organic molecules, many of which occur during aqueous alteration of anhydrous phases (Pizzarello et al. 2001; Kminek et al. 2002). The behavior of elements, isotopes, and molecules in micron-scale regions of interest can be measured by two dimensional-liquid chromatography/fluorescence detector system (2D-LC/FLD) and gas chromatography mass spectrometry (2D-GC/MS) in order to monitor these small-scale organic-mineral-water/ice interactions. These mass spectrometry analyses will complement spectroscopic analytical techniques of scanning transmission x-ray microscopy (STXM), and micro-Raman and infrared (IR) spectroscopy (e.g., Yabuta et al. 2014; Kitajima et al. 2015).

## 5 Sample Representativeness

To reveal the origin of the Martian moons (Goal-1, Fig. 1), one should evaluate the representativeness of the returned sample in the geologic context of Phobos understood from remote sensing observations; otherwise, the origin of individual grains analyzed by detailed laboratory analyses cannot directly reveal the moon's origin. The surface of Phobos is geologically diverse, which is evident in the spectral difference between the blue unit located around Stickney crater and the red unit found on the remainder of Phobos' surface (Murchie and Erard 1996). Basilevsky et al. (2014) suggest that the red and blue materials might have formed from large blocks originating in the interior of Phobos, although the actual cause of the spectral difference between the red and blue units is still unclear. A comprehensive and high spatial resolution analysis of reflectance spectra obtained by OROCHI and MIRS will document the distribution and mutual relations of the red and blue units in detail. Furthermore, subsurface ( $<1$  m) chemical information of Phobos' surface obtained by MEGANE and in-situ surface observations to be provided by the rover in the vicinity of the landing site will establish the representativeness of the returned sample.

**Table 2** List of key analysis for returned sample

Method	Data type	sample amount	Notes
<b>Inorganic</b>			
SIMS	O, H, (C, S, etc.) isotopes	~10 $\mu\text{m}$ dia.	in-situ, destructive but limited to meas. spot
IRMS	O (C, S, N) isotopes	<1 mg	Bulk, destructive
TIMS, ICP-MS	Cr, Ti isotope	<10 mg	Bulk, destructive
TIMS, ICP-MS	Rb-Sr, Sm-Nd, Pb-Pb age	~10 mg	Bulk, destructive
SIMS	Mn-Cr age	~10 $\mu\text{m}$ dia.	in-situ, destructive but limited to meas. spot
NG/IRMS	Ar-Ar age	<0.1 mg	Bulk, destructive, neutron irradiated
NG/IRMS	Noble gas isotopes	<1 mg	Bulk, destructive
PGA/NAA	Bulk chemistry	~1 g	Bulk, non-destructive
ICP-MS	Bulk chemistry	~10 mg	Bulk, destructive
EPMA/TEM/ Raman	Mineral chemistry, crystallography	<3 $\mu\text{m}$ dia.	in-situ, non-destructive
XAFS	Chemical speciation	~1-10 $\mu\text{m}$ dia.	in-situ, non-destructive
SQUID spectroscopy	Magnetic field	~1 $\mu\text{m}$ dia.	in-situ, non-destructive
<b>Organic</b>			
CRDS	Individual gas molecules with H, C, N, O, (S) isotopes	~ 1 ppb	Molecular level, non-destructive
HS-GC/MS	Individual volatile molecules	< 1 mg	Molecular level, destructive
LC/MS	Individual molecules	< 10 mg	Molecular level, destructive
(2D)-LC/FLD	Individual amino acids with enantiomer ratio	< 1 mg	Molecular level (including D/L ratio), destructive
(2D)-GC/MS	Individual molecules	< 10 mg	Molecular level, destructive
GC/IRMS	Individual molecules with H, C, N, (S) isotopes	< 10 mg	Molecular level, destructive
DESI/MS	Molecular imaging	~5 $\mu\text{m}$ dia.	in-situ, destructive but limited to meas. spot
MALDI/TOF- MS	Molecular imaging with accurate mass	~5 $\mu\text{m}$ dia.	in-situ, destructive but limited to meas. spot
EA/IRMS	Bulk composition with H, C, N, O, (S) isotopes	< 1 mg	Bulk, destructive
XAFS	Chemical speciation of organic molecules	~1-10 $\mu\text{m}$ dia.	in-situ, non-destructive
NMR	Molecular structure, chemical speciation	~ 1 mg	Bulk & Molecular level, non-destructive
FT-ICRMS	Comprehensive individual molecules	< 10 mg	Molecular level, destructive

Abbreviations: SIMS, Secondary Ion Mass Spectrometry; IRMS, Isotope Ratio Mass Spectrometry; TIMS, Thermal Ionization Mass Spectrometry; ICP-MS, Inductively Coupled Plasma Mass Spectrometry; NG, Noble Gas; EPMA, Electron Probe Micro Analyzer; TEM, Transmission Electron Microprobe; XAFS, X-ray Absorption Fine Structure; SQUID, Superconducting Quantum Interference Device; CRDS, Cavity Ring-Down spectroscopy; HS-GCMS, Head Space Gas Chromatography Mass Spectrometry; LC/MS, Liquid Chromatography Mass Spectrometry; (2D)-LC/FLD, 2 dimensional LC fluorescence detector; (2D)-GC/MS, 2 dimensional GC/MS; GC/IRMS, GC isotope ratio MS; DESI/MS, Desorption electrospray ionization MS; MALDI/TOF-MS, matrix-assisted laser desorption/ionization/ time-of-flight MS; EA/IRMS, Elemental analyzer/IRMS; NMR, Nuclear Magnetic Resonance. FT-ICRMS, Fourier transform ion cyclotron resonance mass spectrometry

## 6 Sample Assessment for Martian Moon Sample Return

Sample return missions offer sample analysis potential that is not otherwise achievable in-situ via the present generation of robotic planetary exploration missions. Nonetheless, preserving the integrity of returned samples to produce meaningful results requires that terrestrial contamination is understood, controlled, and minimized. Planetary protection regulations also serve to prevent the returned samples from contaminating the Earth. Thus, any sample return mission must take into account contamination assessment through design, manufacture, construction, testing, launch, flight and recovery.

MMX will be the first mission to return Phobos regolith to Earth. Sample return of Phobos regolith was classified as an unrestricted Earth-return mission by the Committee on Space Research (COSPAR) (Fujita et al. 2019; Kurosawa et al. 2019). Although MMX is unrestricted, the Phobos regolith is expected to contain a variety of volatile-bearing phases and organics, similar to the C-class asteroid target for the Hayabusa2 mission (Table 1). Thus, MMX has inherited the contamination assessment, control procedures, and practical knowledge of Hayabusa2 (Tachibana et al. 2014; Okazaki et al. 2017; Sawada et al. 2017).

Hayabusa2 is an unrestricted Earth-return mission from the carbonaceous asteroid 162173 Ryugu (Watanabe et al. 2019). The sample catcher and container of Hayabusa2 are designed to avoid terrestrial contamination of volatile and non-volatile organic and inorganic materials into the returned sample container (Okazaki et al. 2017; Sawada et al. 2017). To maintain the interior pressure and the chemical information of the initial gas components originating from the Ryugu sample, the maximum leak rate permitted to mitigate the atmospheric contamination is  $<1$  Pa for 100 hours at one atmosphere. These conditions will preserve the isotope analyses of highly volatile elements such as H, N, and noble gases. For the assembly, test, and launch operations (ATLO) for Hayabusa2, spacecraft cleanliness was carefully monitored. Immediately upon return to Earth, the Hayabusa2 sample container will be brought to the curation facility at ISAS/JAXA for the recovery and initial classification of the sample (Tachibana et al. 2014). The assessment of the organic terrestrial contamination in the curation facility was conducted by analyzing amino acids as an indicator molecule collected on witness coupons ( $\sim$  below the order of  $\text{pico mole cm}^{-2} \text{ day}^{-1}$ ) (Sugahara et al. 2018).

Each sample return mission has a different contamination control policy, as defined by the mission requirements. For MMX, accurate analyses of stable isotope ratios of O, Cr, and Ti in bulk samples are given the highest priority because these are the most important indicators of sample origin (Mission Goal-1) (Fig. 2). We must reduce possible contamination of these elements throughout the mission by  $<1/1000$  of the expected amounts in the samples so that we can distinguish isotopic signatures characterized by individual meteorite groups. Moreover, Mars-originating exogenous materials in the Phobos regolith are expected to contain sedimentary phases that would be rich in volatile elements. Their pristine geochemical information, such as water contents of clays and isotopic compositions of volatiles (H, C, N, O, and S), would also provide important clues for understanding the co-evolution of circum-Mars environments (Mission Goal-2) (Fig. 7).

We will leverage previously acquired knowledge from Hayabusa2 to optimize MMX's ATLO and curation protocols for the Phobos sample return. A critical difference in the sample assessment between MMX and Hayabusa2 is the returned sample mass; the expected minimum sample amounts are 0.1 g for Hayabusa2 and 10 g for MMX. The larger sample amount for MMX should reduce the relative degree of terrestrial contamination because the "cleanliness" is defined by a relative fraction of foreign material to the returned sample in

an amount that degrades the ability to analyze the chemistry and mineralogy of the sample. For example, NASA's OSIRIS-REx asteroid sample return mission set the contamination allowance level of the organic carbon contaminants to  $\pm 30\%$  precision and accuracy on measurements based on the National Research Council's recommendation (Dworkin et al. 2018).

## 7 Conclusions

MMX has two mission goals: 1) to reveal the origin of the Martian moons and 2) to observe processes that impact on the evolution of the circum-Mars environment (Fig. 1). These mission goals will be achieved by comprehensive remote sensing observations of Phobos and Deimos and by laboratory analyses of a regolith sample returned from Phobos. Operation of C- and P-samplers will provide access to both Phobos' subsurface building blocks ( $> 2$  cm deep) and the top-most regolith layer, resulting in a total of  $> 10$  g of Phobos regolith returned to Earth. The regolith of Phobos likely represents a mixture of endogenous Phobos materials and exogenous materials that accumulated after the moon's formation. Laboratory analyses of these two kinds of materials would allow successful achievement of the critical mission goals.

The characteristics of the endogenous Phobos materials depend on the moon's origin. In the case of the captured asteroid scenario, they would be analogous to a certain type of chondrites. On the other hand, if Phobos formed in-situ by a giant impact, the endogenous Phobos materials should contain high-temperature phases with the bulk chemistry possibly representing a mixture of Martian silicate reservoirs (crust and mantle) and the impactor. In addition to such contrasting characteristics of the endogenous Phobos materials, stable isotopic systematics of O, Cr, and Ti will further differentiate the source of Phobos' building blocks. The exogenous late accreted materials are expected to contain Mars-originating materials. Because the Mars-originating materials could be derived from several geologic units on the surface of Mars by random samplings through impacts, which could be potentially corroborated by radiometric dating of the returned samples, they would provide valuable information about the change in surface environments through the history of Mars.

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