月，そして火星へ繋がる水探査の科学意義

臼井寛裕（JAXA 宇宙科学研究所）

海をたたえる地球，海の消失により表層の乾燥化が進行した火星，氷が表層を覆う木星衛星ガニメデ・エウロパに見られるように，太陽系天体は様々な表層環境を保持している．一方，多様な表層環境を保持する太陽系天体においても，その本質は「水素の宇宙空間への散逸に伴う不可逆的な酸化過程」と，「水-岩石反応の結果生じる還元過程」で規定される．これら酸化還元過程において，水は反応物・生成物としての役割に加え，化学反応の媒体であり，化学反応に伴う物質とエネルギーの循環促進剤としての役割を担う．つまり，一見すると多様な惑星表層環境の底流にある科学的本質，すなわち汎惑星表層環境進化の理解には，異なる天体における水環境システムの解明が必要不可欠であり，その解明こそが戦略的惑星探査プログラムの研究意義となる．また，水環境システムの解明は，太陽系天体の水の起源・化学進化・分布を明らかにすることと同値であり，日本の目指す戦略的惑星探査プログラムが解くべき課題となる．

水環境システムの観点で太陽系天体を俯瞰し，水の起源・化学進化・分布を明らかにしようとした際, 火星は戦略的惑星探査プログラムの中核をなす（臼井, 2018）．火星は，水環境システムを安定的に保持し，水の「化学進化」および「分布」に関する情報を提供する唯一の内惑星であり，また地球との比較対象として，汎惑星表層進化解明の鍵を握る．一方，水環境システムの初期条件である「水の起源」は，太陽系全体での物質循環過程の結果を反映するため，複数の太陽系天体をシステム的に探査することでのみ正確な描像を得ることが可能となる．つまり，水の“受け手”である内惑星天体（水・金・地・火・月）と，外惑星領域を起源とする水の“送り手”である小天体（小惑星・彗星）の両者からの知見を総合することが必須となる．小天体に関しては，はやぶさ，はやぶさ２，MMX（Martian Moons eXploration）につながる強力な探査戦略が検討・実施されている．そこで，汎惑星表層環境進化の解明を科学目標とした戦略的な惑星探査プログラムでは，これら小天体探査と相補的なプログラムとして，火星を軸とした重力天体探査プログラムの実施が必須となる．

JAXA 国際宇宙探査専門委員会に設置された火星探査検討タスクフォースでは、2030 年代の「火星地下水圏・生命圏探査火星着陸探査」を今後 20 年のマイルストーンと見据えた, 戦略的火星探査シリーズを提案している. このシリーズ探査では, 2020 年代の「MMX」および，それに続く「小型周回・探査技術実証機による火星宇宙天気・気候・水環境探査計画」を前段階として実施する．本発表では，最終ゴールを火星表層へのアクセスと火星地下水圏・生命圏の探査に求め，それらを火星地下圏探査を含む戦略的な惑星探査プログラムにより解明していく道筋を紹介する．

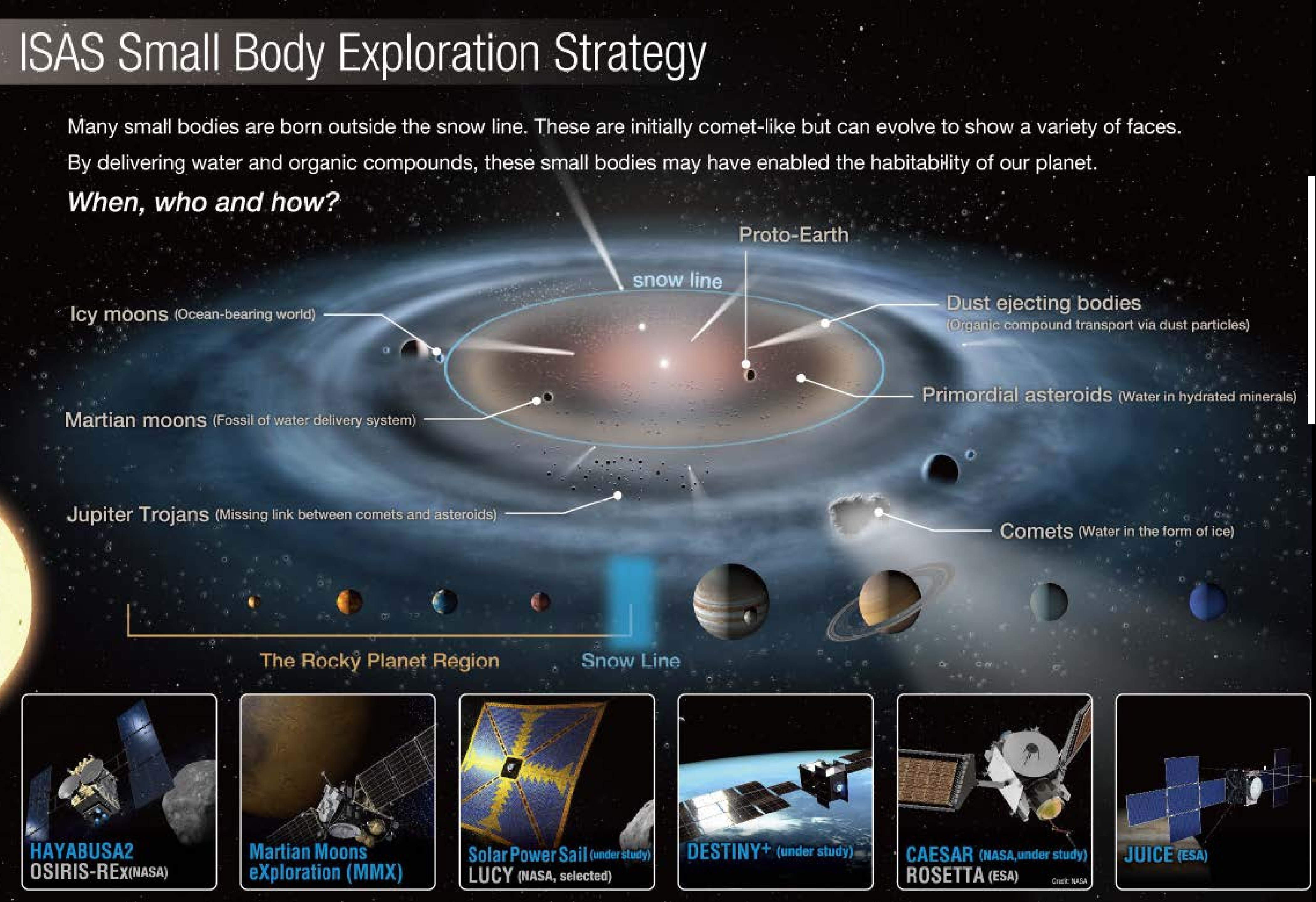
引用文献

臼井寛裕 (2018) 火星地下圏探査の科学的意義および戦略，*遊星人*, **27**, 296-301.

月，そして火星へ繋がる水探査の科学意義

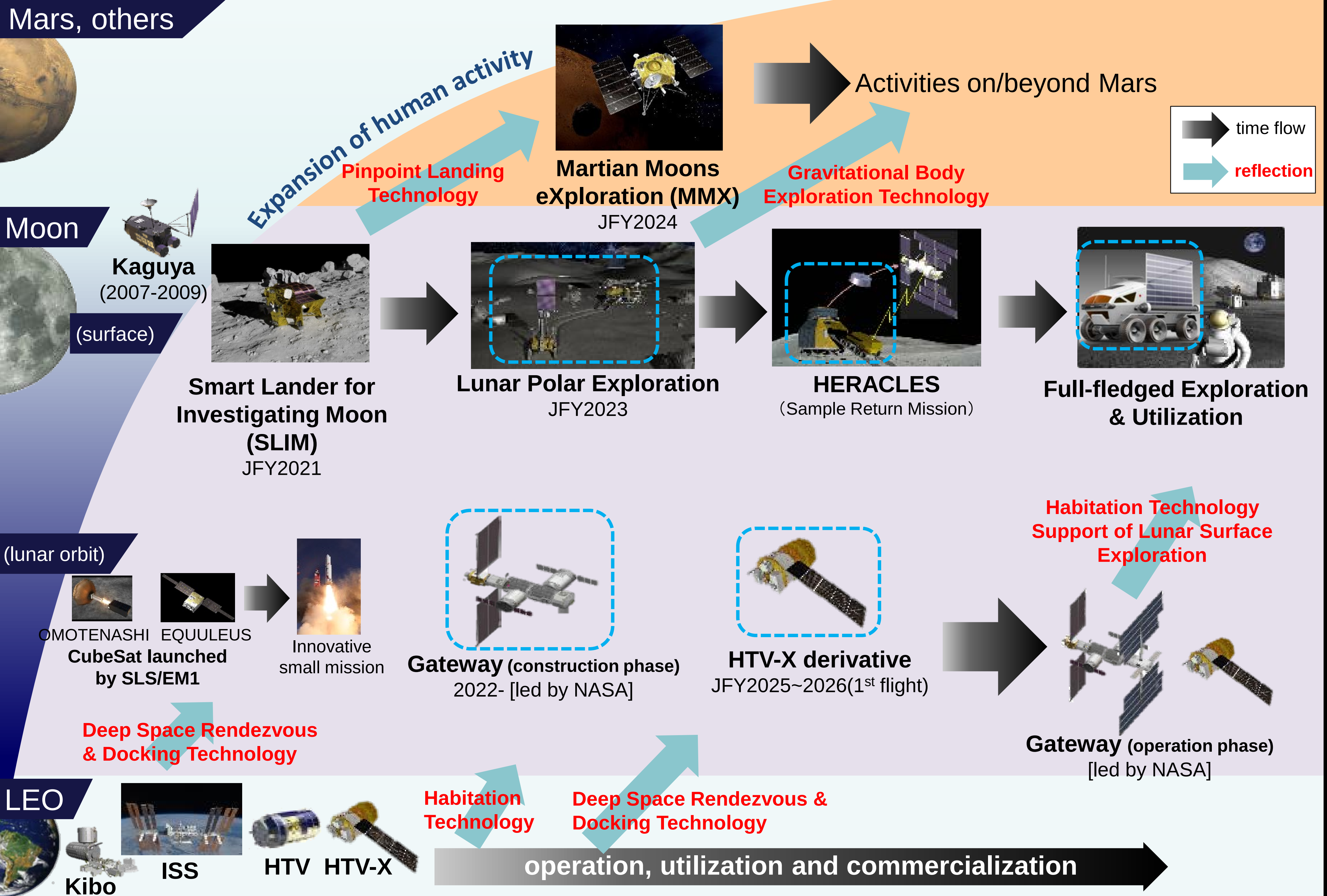
臼井寛裕（ISAS, JAXA）

伊豆大島での火星ローバー試験
写真提供：慶応大学（石上研究室）・立教大学（亀田研究室）



JAXA's strategic small body exploration stepping into Mars program through MMX

JAXA's Overall Scenario for International Space Exploration



Leverage small body and Lunar exploration to MMX and future Mars orbiter and rover missions

MMX:
Martian Moons eXploration

Martian Moons eXploration (MMX)

Japanese next-generation sample return mission

PHASE-B STARTS IN JANUARY 2020

- Launch in 2024 (TBD)
- Phobos: remote sensing & *in situ* observation
- Deimos: remote sensing observation (multi-flybys)
- Retrieve samples (>10 g) from Phobos/Deimos return to Earth in 2029 (TBD)

THE 1ST SAMPLE RETURN MISSION FROM THE MARTIAN SATELLITES!

Martian Moons eXploration (MMX)

Japanese next-generation sample return mission

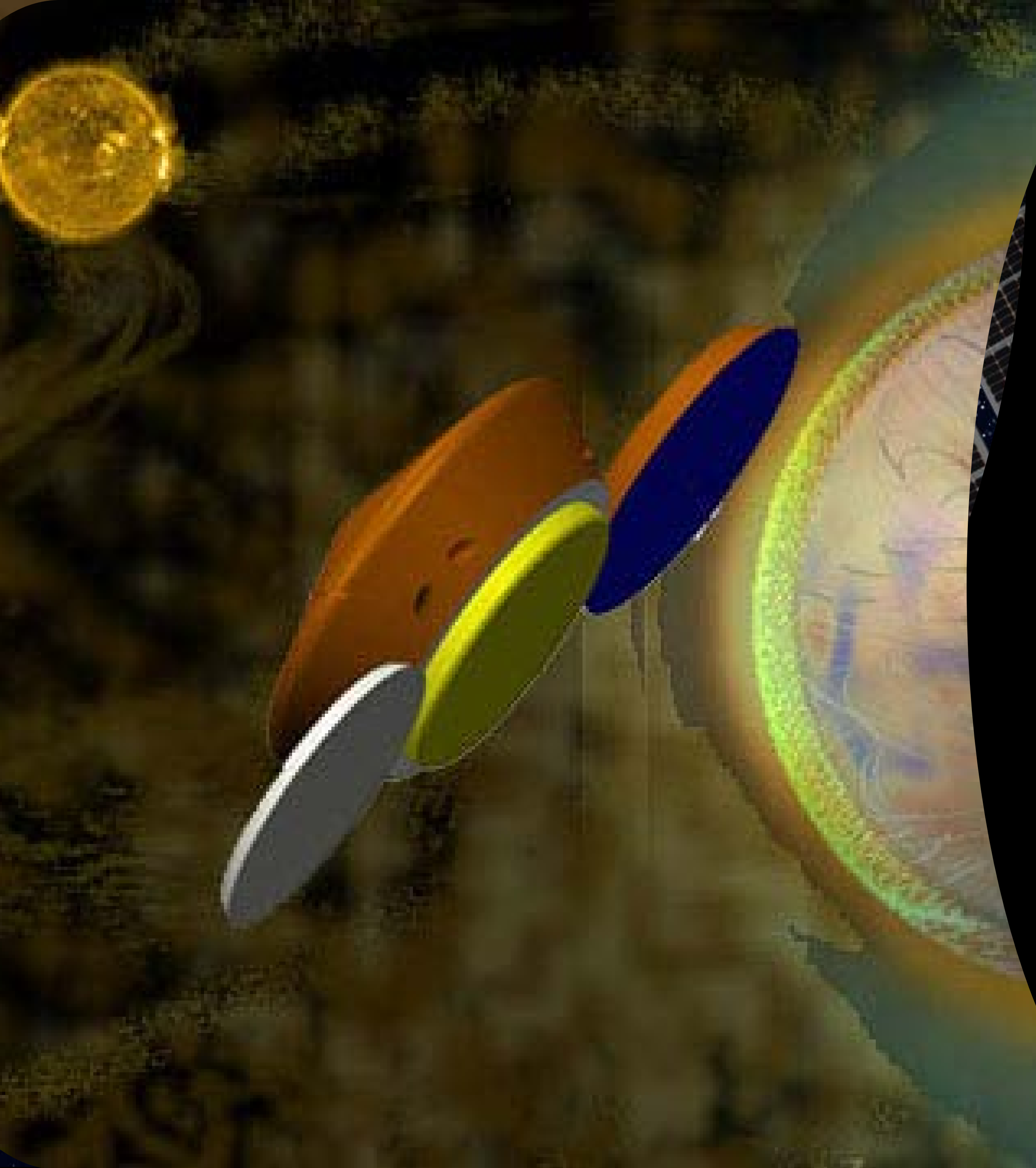
MMX COMPLEMENTS MSR

- Transportation to/from the Mars system
- Retrieve/Return samples of Phobos (moon) & Mars back to Earth

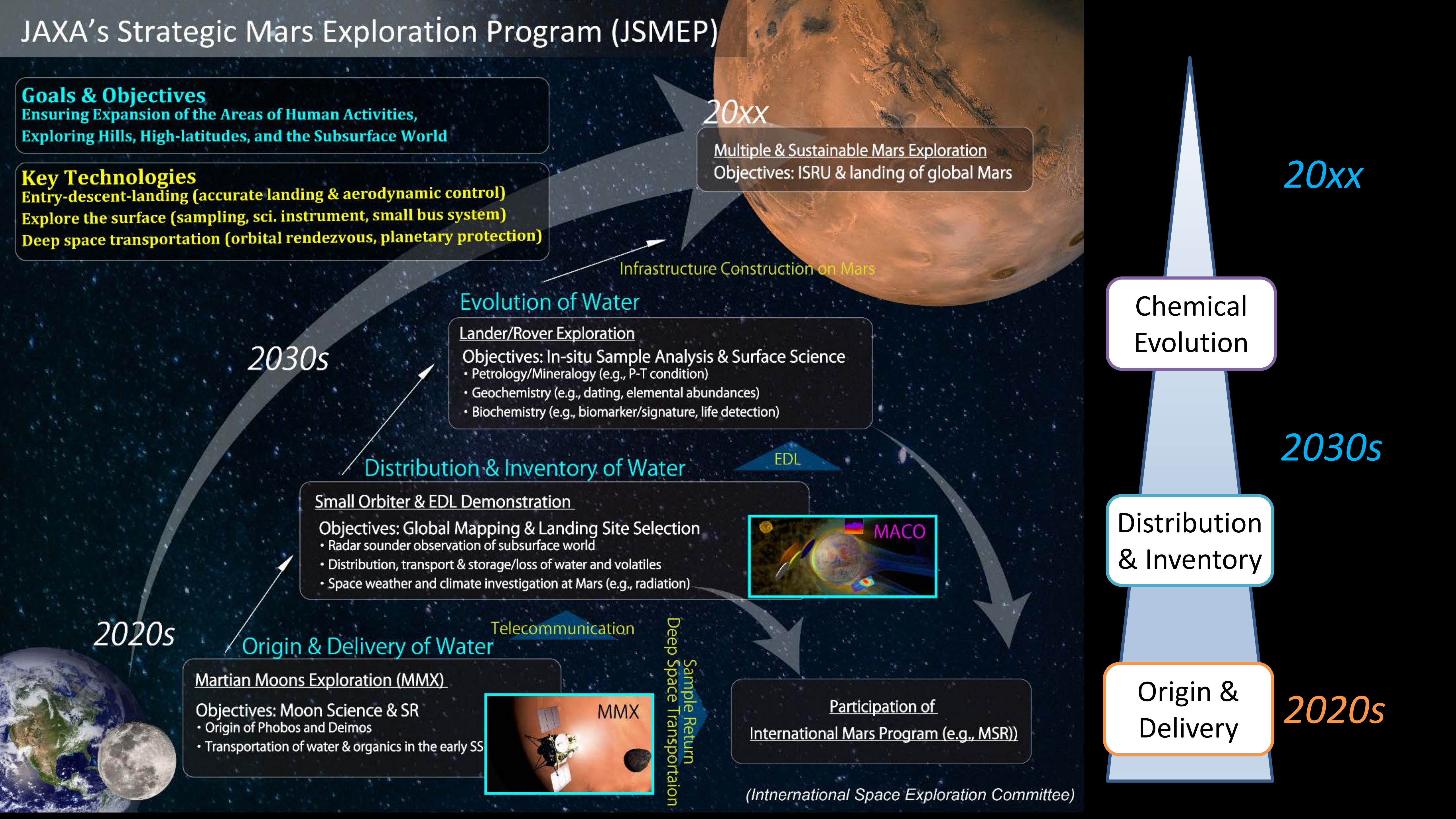
MMX IS AN INTERNATIONAL PROGRAM

- NASA/ESA/CNES/DLR/ASI are intensively involved
- Samples will be shared internationally (TBD)

PHASE B STARTS IN FEBRUARY 2020



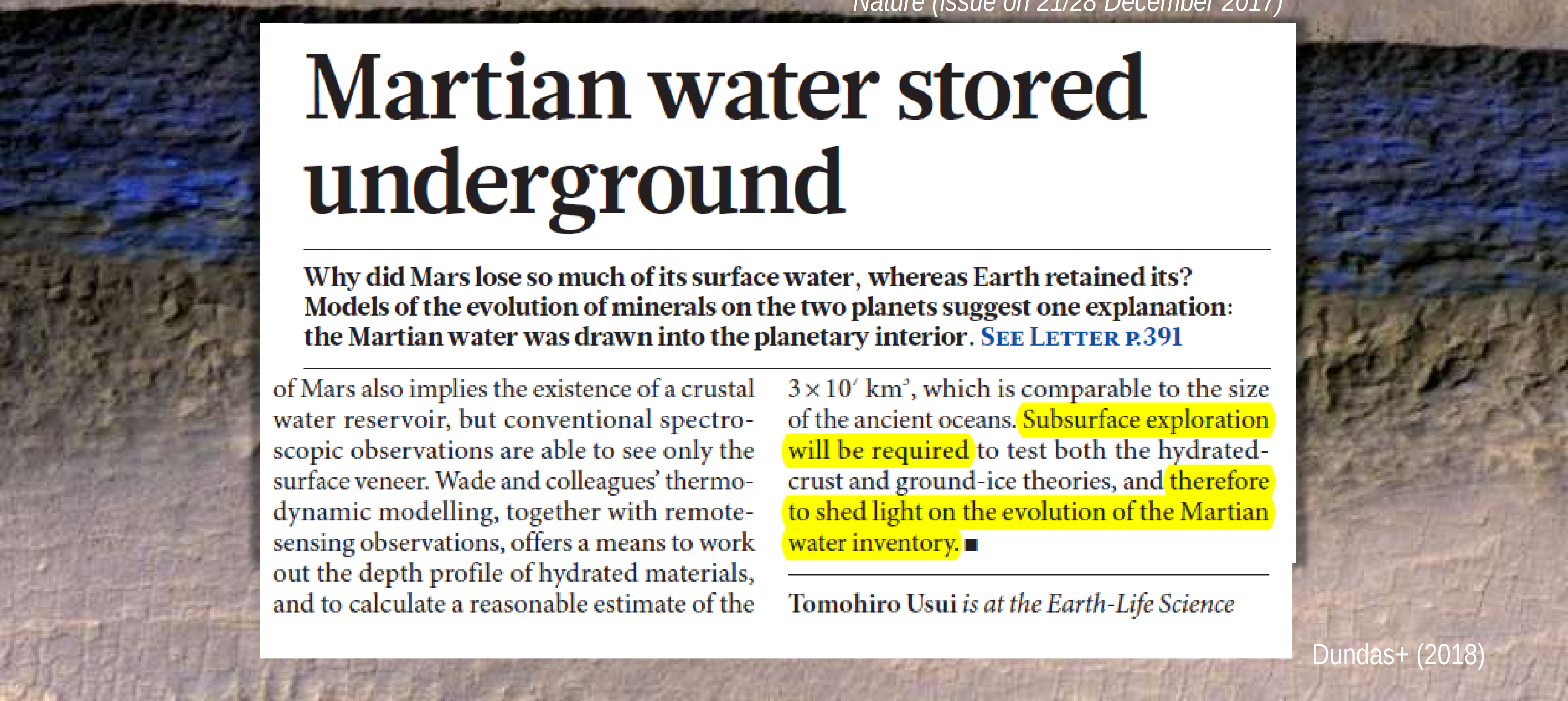
What’s next after MMX?


JAXA's Strategic Mars Exploration Program (JSMEP)
Goals & Objectives
Ensuring Expansion of the Areas of Human Activities,
Exploring Hills, High-latitudes, and the Subsurface World
Key Technologies
Entry-descent-landing (accurate landing & aerodynamic control)
Explore the surface (sampling, sci. instrument, small bus system)
Deep space transportation (orbital rendezvous, planetary protection)
20xx
Multiple & Sustainable Mars Exploration
Objectives: ISRU & landing of global Mars
Infrastructure Construction on Mars
2030s
Evolution of Water
Lander/Rover Exploration
Objectives: In-situ Sample Analysis & Surface Science
• Petrology/Mineralogy (e.g., P-T condition)
• Geochemistry (e.g., dating, elemental abundances)
• Biochemistry (e.g., biomarker/signature, life detection)
EDL
Distribution & Inventory of Water
Small Orbiter & EDL Demonstration
Objectives: Global Mapping & Landing Site Selection
• Radar sounder observation of subsurface world
• Distribution, transport & storage/loss of water and volatiles
• Space weather and climate investigation at Mars (e.g., radiation)
MACO
2020s
Telecommunication
Origin & Delivery of Water
Martian Moons Exploration (MMX)
Objectives: Moon Science & SR
• Origin of Phobos and Deimos
• Transportation of water & organics in the early SS
MMX
Deep Space Transportaion
Sample Return
Participation of
International Mars Program (e.g., MSR))
(Intnernational Space Exploration Committee)
20xx
Chemical Evolution
2030s
Distribution & Inventory
Origin & Delivery
2020s

SUBSURFACE IS OUR NEXT TARGET

Exposed subsurface ice sheets (~10s m thick) observed in the mid-latitudes

Nature (issue on 21/28 December 2017)



Martian water stored underground

Why did Mars lose so much of its surface water, whereas Earth retained its? Models of the evolution of minerals on the two planets suggest one explanation: the Martian water was drawn into the planetary interior. SEE LETTER P.391

of Mars also implies the existence of a crustal water reservoir, but conventional spectroscopic observations are able to see only the surface veneer. Wade and colleagues' thermodynamic modelling, together with remote-sensing observations, offers a means to work out the depth profile of hydrated materials, and to calculate a reasonable estimate of the 3×10^7 km^3, which is comparable to the size of the ancient oceans. Subsurface exploration will be required to test both the hydrated-crust and ground-ice theories, and therefore to shed light on the evolution of the Martian water inventory. ■

Tomohiro Usui *is at the Earth-Life Science*

Dundas+ (2018)


MARS MISSIONS
OPERATIONAL 2001–2019
2020 AND BEYOND
Mars Odyssey (2001)
Mars Express (ESA) (2003)
Mars Reconnaissance Orbiter (2005)
MAVEN (2013)
Mars Orbiter Mission (ISRO) (2013)
Trace Gas Orbiter (ESA/RSA) (2016)
HOPE (UAE)
Mars Orbiter (China)
MMX (JAXA)
Mars moon SR by Japan
MMX complements MSR
Mars Sample Return Orbiter
Mars Lander & Rover (China)
Mars Sample Return Lander
Mars 2020 Rover (NASA)
Mars Sample Return Lander
Curiosity Rover (2011)
InSight
Mars Sample Return (China)
ExoMars Rover (ESA/RSA)
Follow the Water
Explore Habitability
Seek Signs of Life
Prepare for Future Human Explorers
U.S. Missions
non-U.S. Missions
<NASA>

MSR Objectives

The Meteoritical Society

Meteoritics & Planetary Science 54, Nr S1, S3–S152 (2019)
doi: 10.1111/maps.13242

The potential science and engineering value of samples delivered to Earth by Mars sample return

International MSR Objectives and Samples Team (iMOST)

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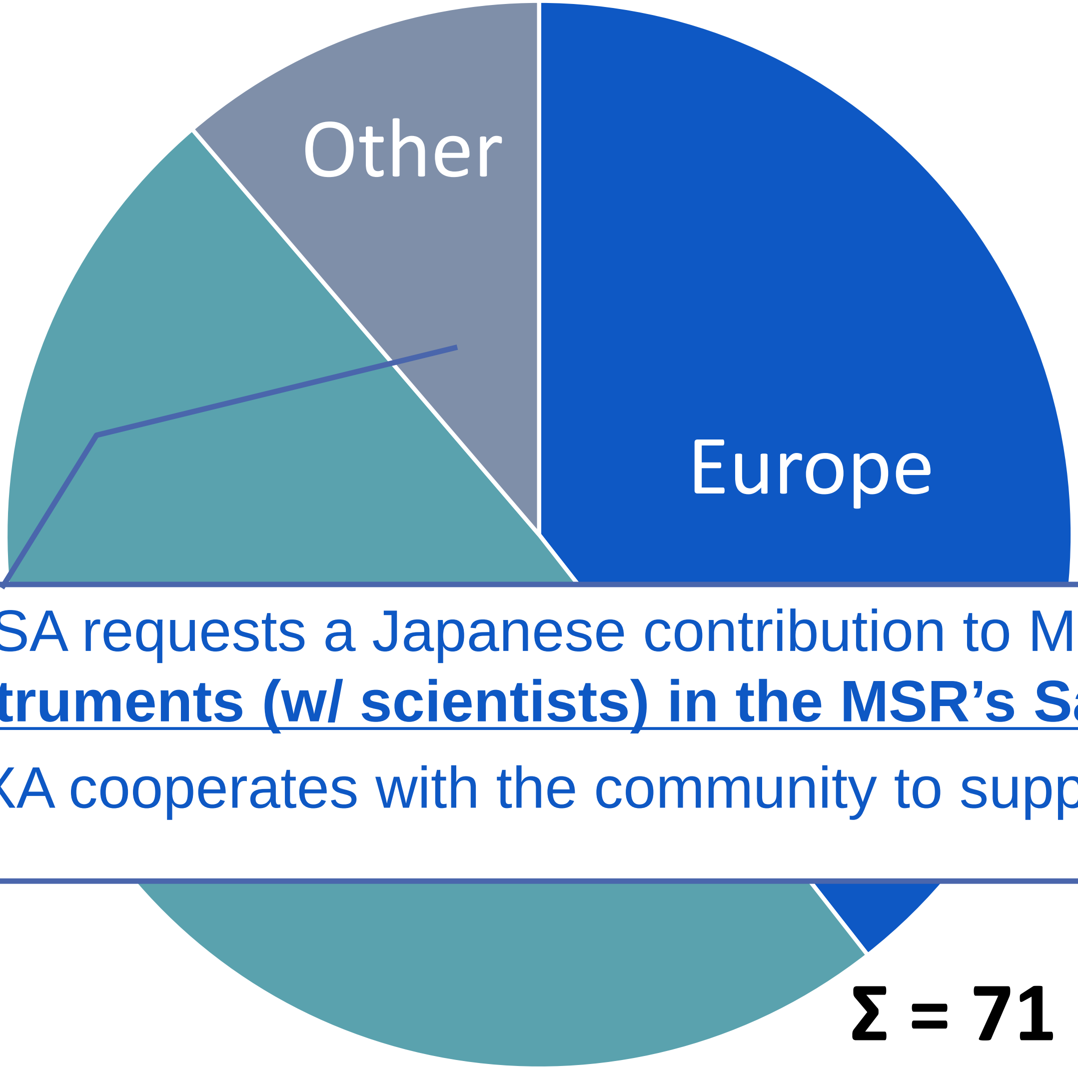
Proposed Sample-Related Objectives from the 2018 iMOST Study

	Objective
1	*Geological environment(s)*
2	*Life*
3	*Geochronology*
4	*Volatiles*
5	*Planetary-scale geology*
6	*Environmental hazards*
7	*ISRU*

Sub-Objective
Sedimentary System
Hydrothermal
Deep subsurface groundwater
Subaerial
Igneous terrane
Carbon chemistry
Biosignatures--ancient
Biosignatures--modern

(Objective 1 → Sedimentary System through Igneous terrane; Objective 2 → Carbon chemistry through Biosignatures--modern)

International Participation, iMOST Study



Countries Represented	
Australia	Netherlands
Belgium	Norway
Canada	Spain
France	Sweden
New Zealand	

Σ = 71

- NASA requests a Japanese contribution to MSR by **providing a suite of analytical instruments (w/ scientists) in the MSR's Sample Receiving Facility**
- JAXA cooperates with the community to support JP participating scientists

CONCLUSIONS

- JAXA Space Exploration Center sets a long-term strategic Moon-to-Mars exploration program including the JAXA's Strategic Mars Exploration Program (JSMEP)
- JSMEP endeavors to leverage small body and Lunar exploration to MMX and future Mars orbiter and rover missions
- MMX is not only a first stepping stone of the JSMEP but also complements Mars Sample Return
- NASA requests a Japanese contribution to MSR by providing a suite of analytical instruments (w/ scientists) in the MSR's Sample Receiving Facility