The 2016 Mars Water In-Situ Resource Utilization (ISRU) Planning (M-WIP) Study

General Introduction

Space Resources Roundtable, Golden, CO

June 7, 2016

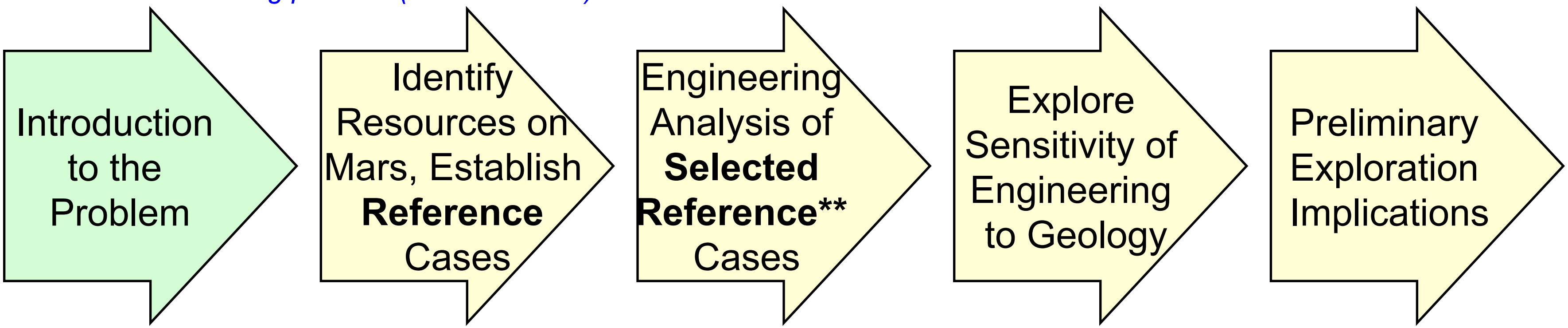
David Beaty, Angel Abbud-Madrid, Dale Boucher, Ben Bussey, Richard Davis, Leslie Gertsch, Lindsay Hays, Julie Kleinhenz, Michael Meyer, Michael Moats, Robert Mueller, Aaron Paz, Nantel Suzuki, Paul van Susante, Charles Whetsel, and Elizabeth Zbinden

For further information, see the full M-WIP report: http://mepag.nasa.gov/reports.cfm.

Objectives of This Study

1. Prepare an initial description of hypothetical "reserves" (identified, usable resource deposits*) that may exist on Mars. Assume that these reserves are the output of an exploration program, and the input to an overall engineering system. Specify all relevant parameters.
2. Estimate the rough order-of-magnitude mass/power/complexity of the ISRU engineered system (mining/acquisition, extraction, transportation, processing and storage) needed to produce a given quantity of water from each of several categories of potential water "ore" deposits.
3. Prepare a sensitivity analysis of the major inter-relationships between geological attributes of the water deposits (Task #1 above), and the engineering attributes of the production and processing systems (Task #2 above), in order to propose preliminary minimum acceptable thresholds for "reserves".
4. Prepare an initial description of the preliminary implications for exploration for the different reserves.

** The adjective "hypothetical" is assumed throughout these slides, modifying "reserves" from its legal meaning in terrestrial mining practice (see* **Slide #10***).*



**Primary focus was on water-bearing surface materials for a variety of reasons - Availability of scientific & engineering data, initial survey of prior efforts, and others. *Engineering evaluation of mid-latitude subsurface ice at the same level of detail is a key next step.*

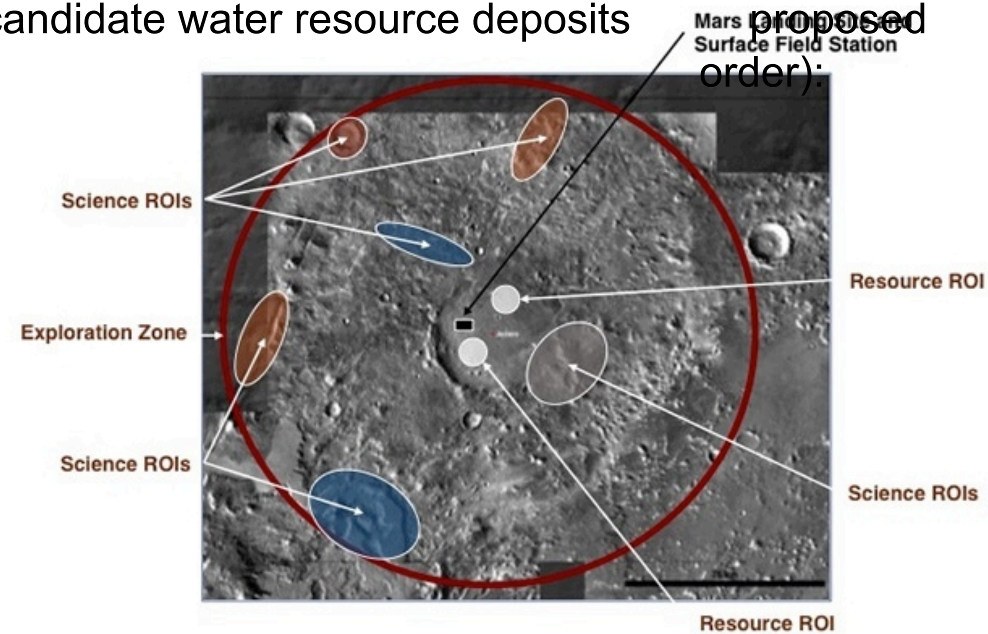
Key Antecedent #2: HLS^2

- Human Landing Site Selection (HLS^2): October 2015 workshop on Mars Exploration Zones.
- In addition to science regions of interest, all site proposers were asked to identify one or more candidate water resource deposits within their Exploration Zone that have the potential to produce 5 metric tons of water per year.
- 47 candidate sites proposed by the world's leading experts in ISRU and Mars geology. The four most common candidate water resource deposits proposed include (not in priority order):

1. Mid-latitude ice
2. Concentrations of poly-hydrated sulfate minerals
3. Concentrations of phyllosilicate minerals
4. Regolith.

See also ICE-WG (2015; Hoffman and Mueller, co-chairs)

http://www.nasa.gov/journeytomars/mars-exploration-zones



Possible configuration of an Exploration Zone. Note hypothetical "Resource ROIs" in gray.

DESCRIPTION OF WATER RESOURCES ON MARS THAT HAVE THE POTENTIAL TO BECOME RESERVES AS PART OF A HUMAN EXPLORATION ZONE:

THE M-WIP STUDY, PART 1

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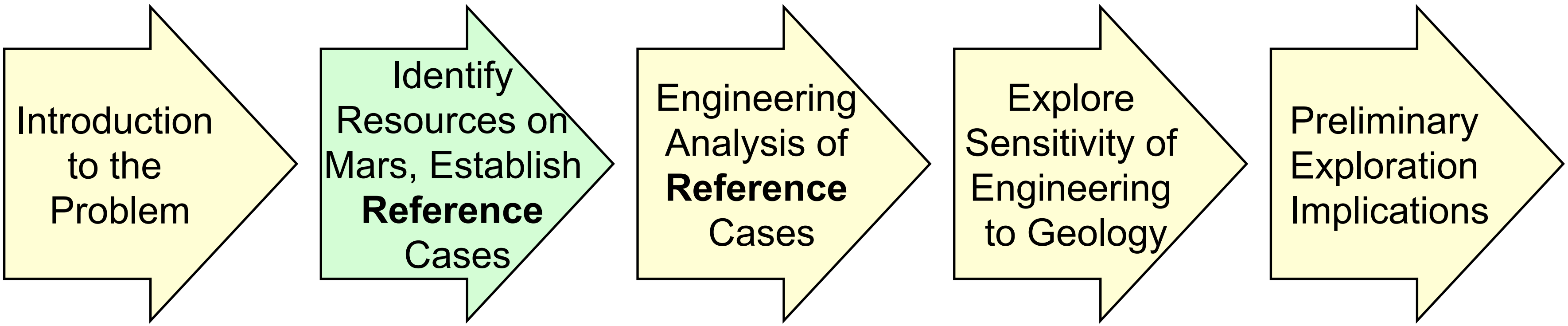
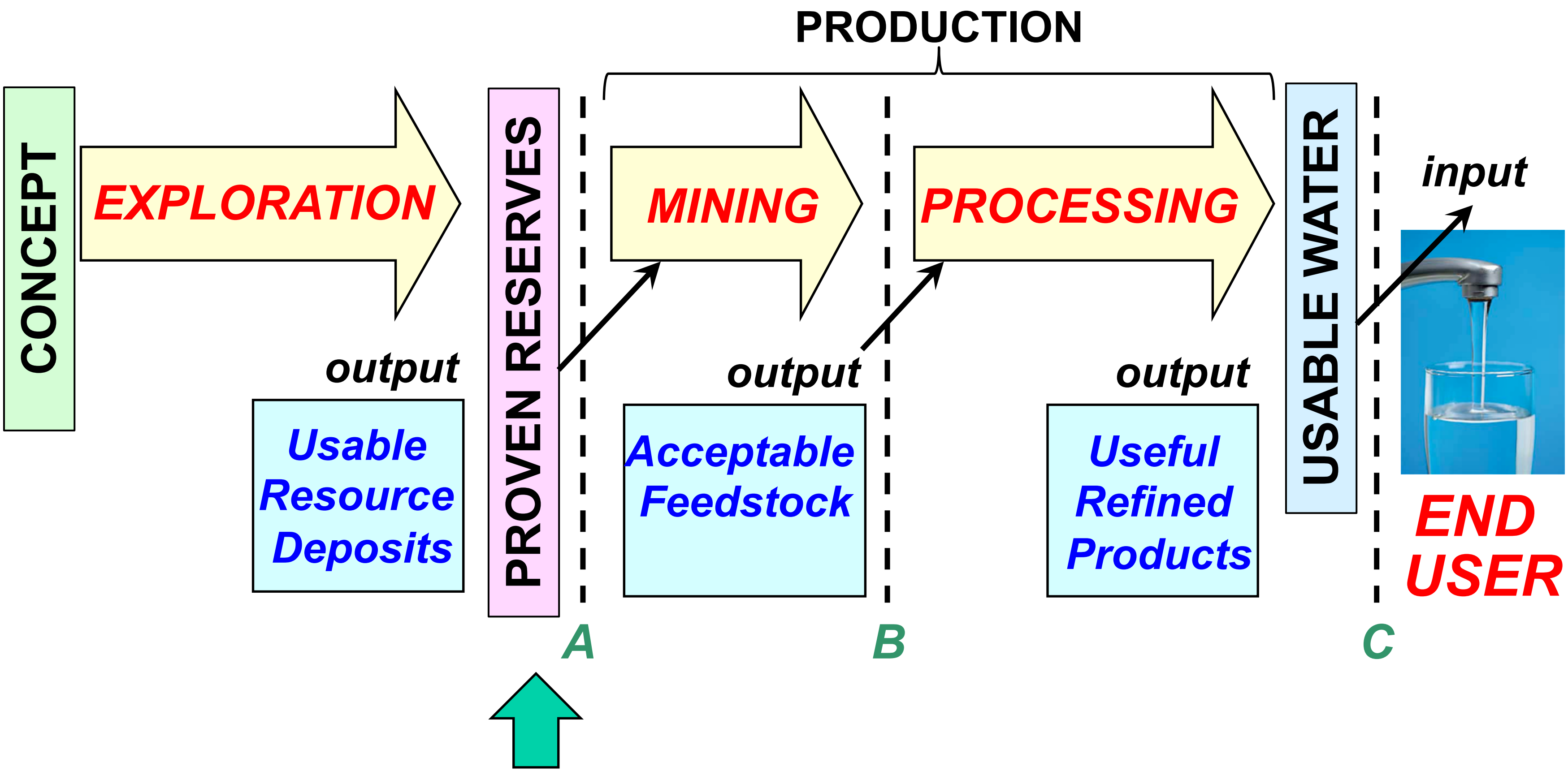
Task #2

Estimate the basic engineering attributes of the potential production and processing ISRU systems



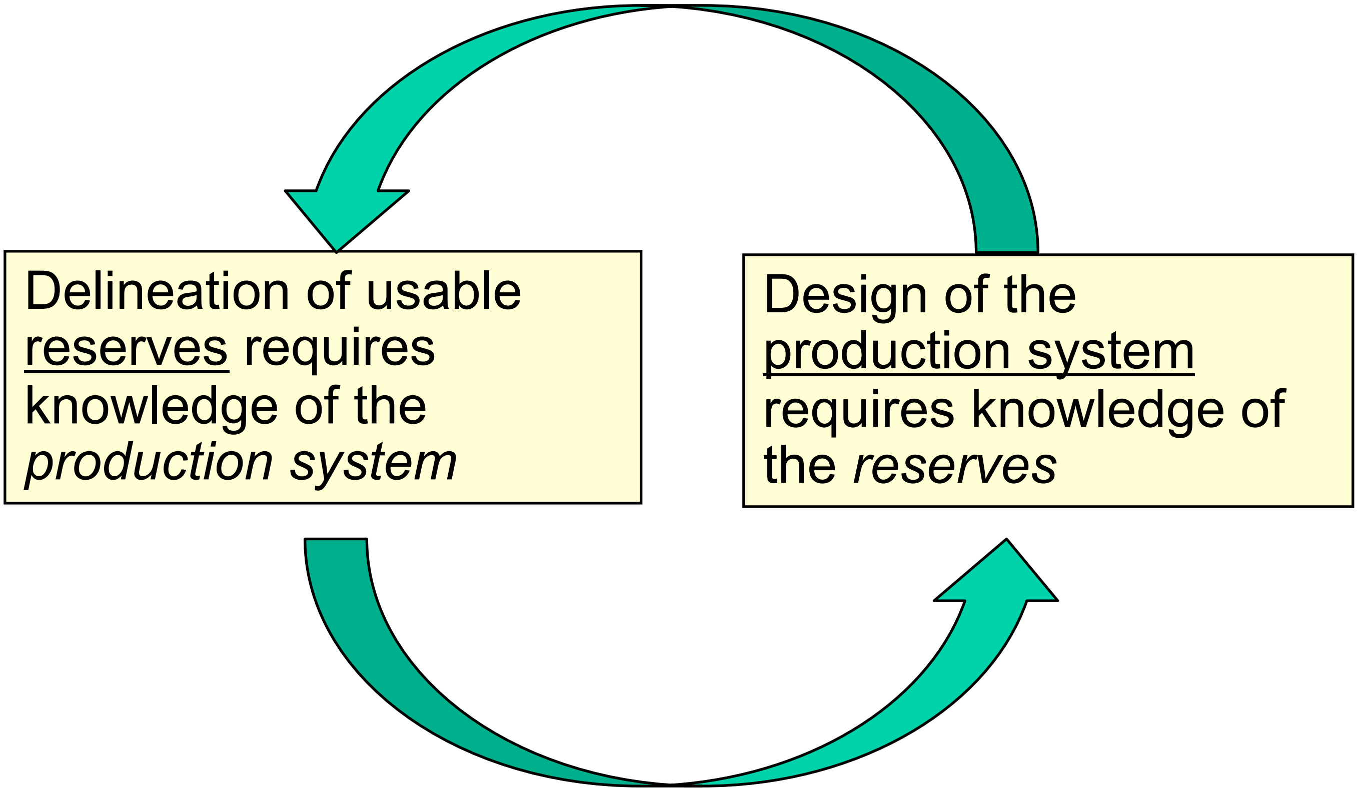
The Exploration-Production Flow



"Reserves" are the essential interface between "exploration" and "production"

From Beaty et al. (2016); discussion with the Geological Society of Nevada acknowledged

A Chicken-Egg Issue

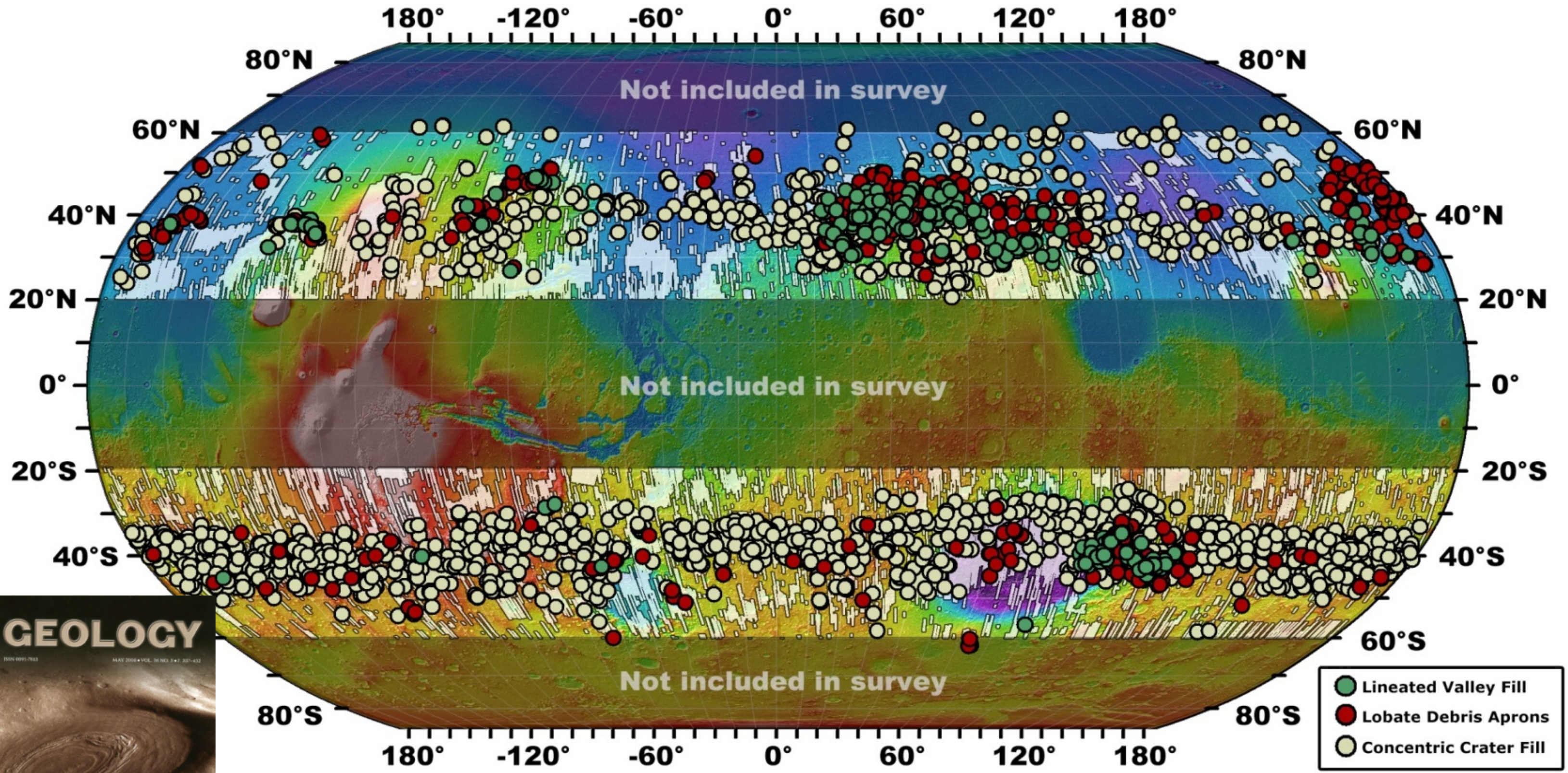


Because of this chicken-egg relationship, both exploration and engineering need to advance together.

From Beaty et al. (2016)

Basis for Case A

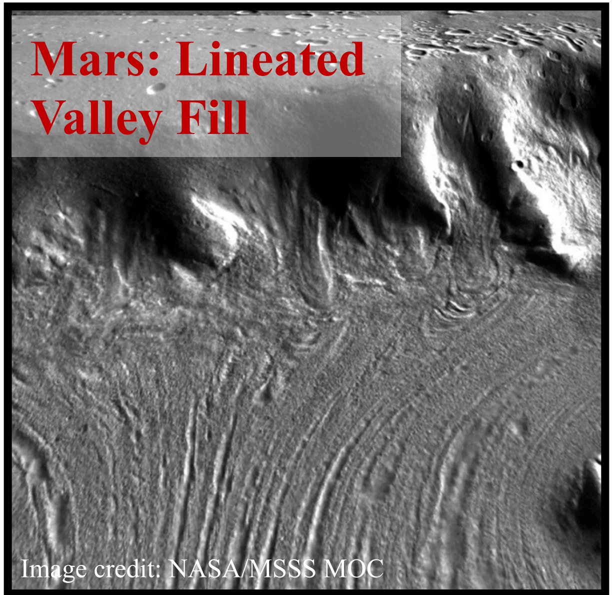
Map of Mars Glacial Features

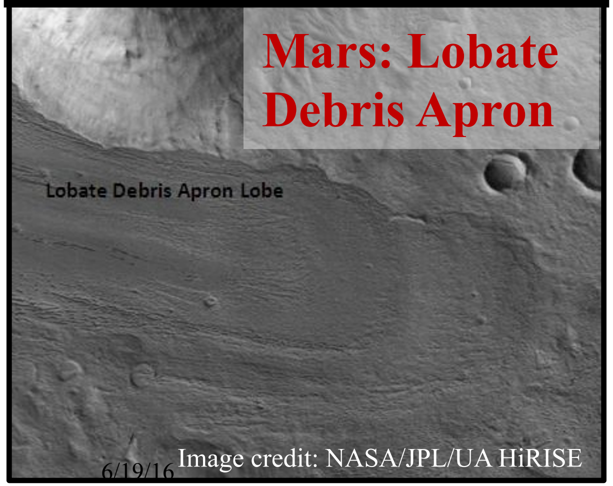


With many of these glacier-related geomorphic features, we have no information about whether residual ice remains, and if so, at what depth. Note that some lobate debris aprons have been confirmed to contain ice by radar investigations.

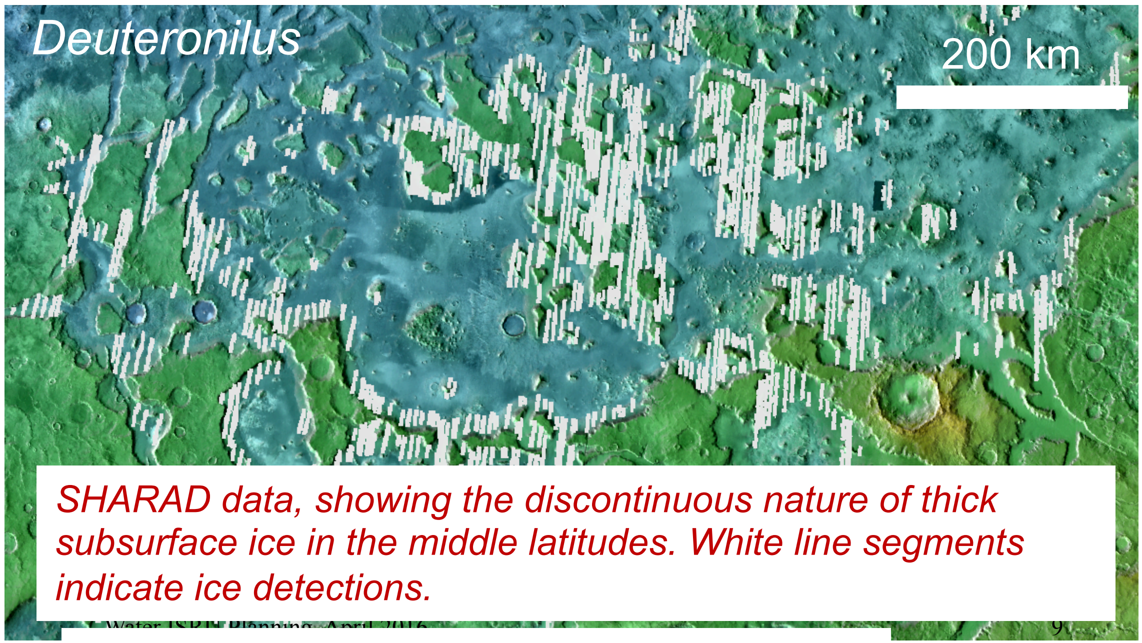
From Dickson et al., 2012; discussion with Jim Head acknowledged

Glacial Deposits on Mars: More Detail





- Mars glaciers are covered with a combination of sublimation till (the residue left as a result of ice sublimation) and rubble from nearby exposed outcrops.
- SHARAD data show a single, discrete surface echo over glaciers, implying that the thickness of the protective debris/ dust cover is on order of the SHARAD vertical resolution (~10m) or less.
  - Could be between 1-10 m thick
- Glacial ice is 100s of meters thick.

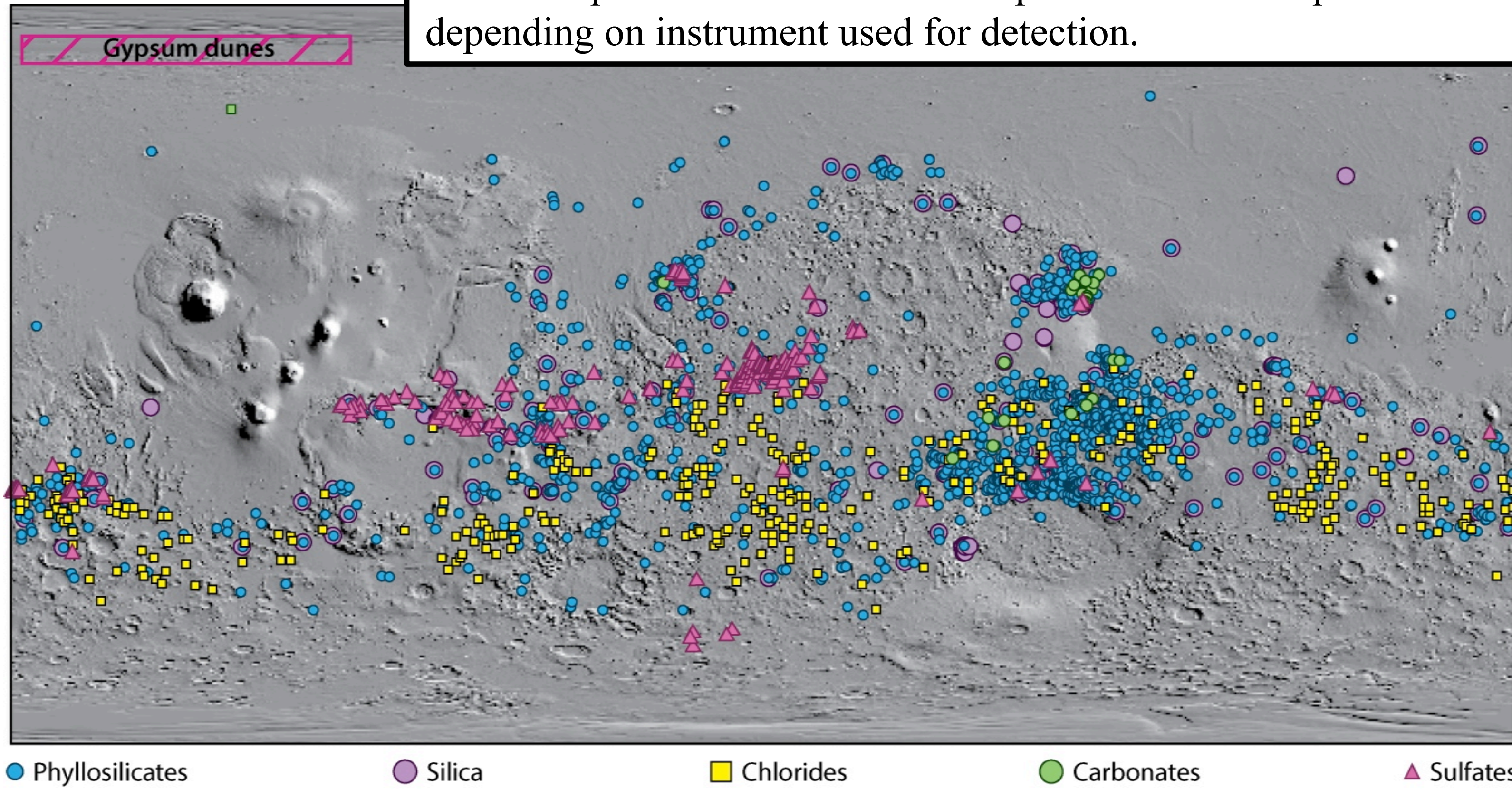


SHARAD data, showing the discontinuous nature of thick subsurface ice in the middle latitudes. White line segments indicate ice detections.

Rummel et al. (2014) and Plaut (2016, Pers. Comm.)

Basis for Cases B, C
Map of aqueous mineral detections

Note: footprint size is from 3x6km spots to 18-2000m/pixel depending on instrument used for detection.

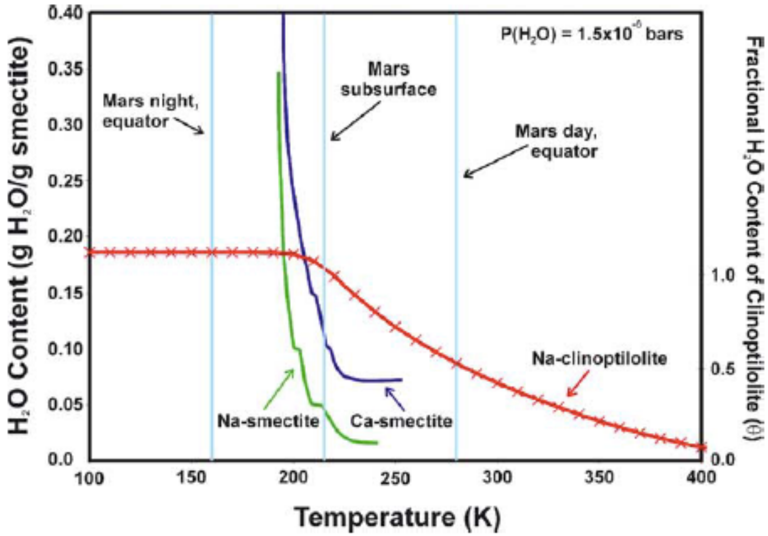


A master compilation of all mineral detections for Mars. Of relevance to this study are the phyllosilicate and sulfate detections.

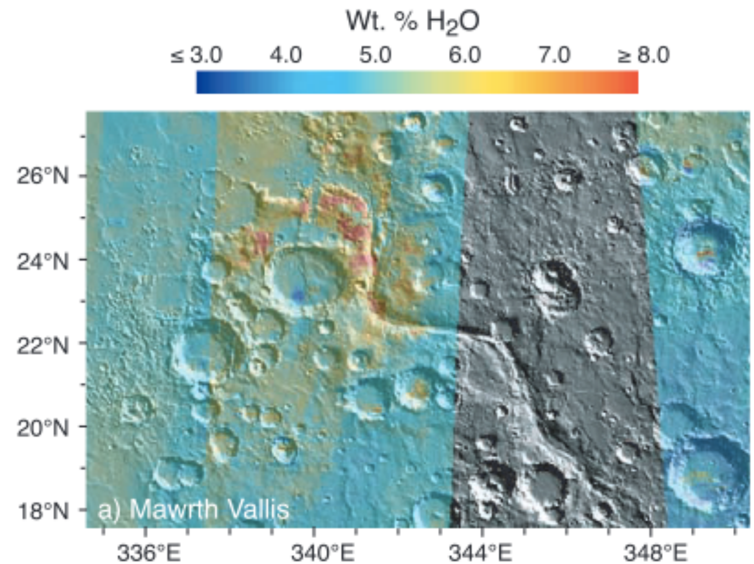
From Ehlmann and Edwards (2014)

Basis for Case C
Phyllosilicate Water Content

- For the purpose of this analysis, we assume a deposit consisting of smectite with an average of 4 wt% water content – note that this is lower than would be expected for terrestrial samples. It is also possible that phyllosilicate deposits with higher water contents could be identified.



Equilibrium hydration state of Na- and Ca-smectites (left axis) and of Na-clinoptilolite (right axis) as a function of T at a P (H_2O) of $1.5x10^{-6}$ bars. Note that at Mars surface conditions, Na-smectite has ~2 wt% water, and Ca-smectite has ~7 wt% water.



Modeled hydration maps for phyllosilicates in the Mawrth Vallis region. These regions exhibit water contents 2–3 times higher than surrounding terrains with similar albedo values, approaching values of 6–9 wt.% H_2O.

From Bish et al (2003) (left), Milliken et al (2007) (right), and discussion with Dave Bish and Ron Peterson

Basis for Case D (1 of 3)
Introduction to the Martian Regolith

- The broadest definition of "regolith", as it is used in a planetary sense, is: "The entire layer or mantle of fragmental and loose, incoherent, or unconsolidated rock material, of whatever origin (residual or transported) that nearly everywhere forms the surface, and that overlies more coherent bedrock." As such, this term as applied to Mars encompasses "soil", dunes, talus, ejecta, rubble, airfall dust, etc.

JPL/NASA

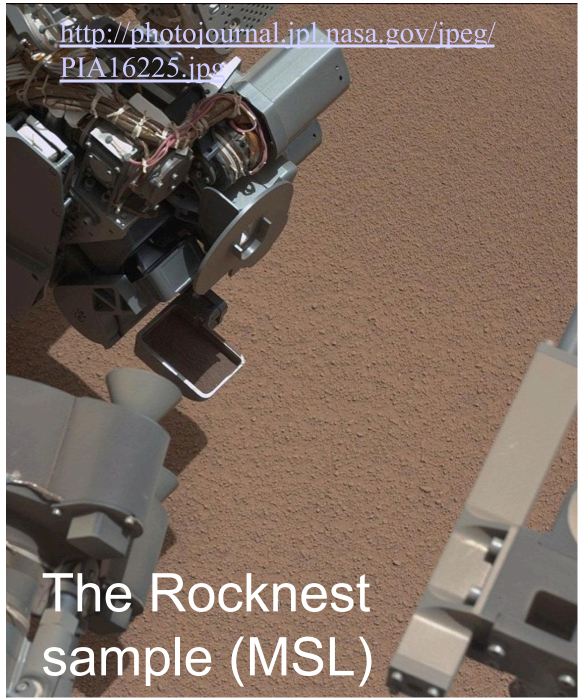
Although regolith, in the strictest sense, is present essentially everywhere on Mars, it is not all equally amenable to ISRU operations. Note significant differences in mechanical properties.

Basis for Case D (2 of 3)
What is the Regolith Made of? (Data from MSL)

- Mineralogy and total weight percent water used for reference Case D are based on data from MSL instruments: CheMin, SAM, and DAN.
- Case D mineralogy was based primarily on Rocknest, with additional minor components from John Klein and Cumberland to match the 1.5 wt% water indicated by the more conservative DAN results.

Mineral	Rocknest	John Klein	Cumberland
Plagioclase	29.8	22.4	22.2
Fe-forsterite	16.4	2.8	0.9
Augite	10.7	3.8	4.1
Pigeonite	10.1	5.6	8.0
Orthopyroxene		3.0	4.1
Magnetite	1.5	3.8	4.4
Anhydrite	1.1	2.6	0.8
Bassanite		1.0	0.7
Quartz	1.0	0.4*	0.1*
Sanidine	0.9*	1.2	1.6
Hematite	0.8*	0.6*	0.7
Ilmenite	0.7*		0.5*
Akaganeite		1.1	1.7
Halite		0.1*	0.1*
Pyrite		0.3*	
Pyrrhotite		1.0	1.0
Smectite		22	18
Amorphous	27	28	31

Crystalline and amorphous components (wt%) of the John Klein and Cumberland drill powders, compared with the Rocknest scooped eolian deposit. From plagioclase to pyrrhotite the estimated errors are ~6% of the amount shown for abundances of >20%, ~15% for abundances of 10 to 20%, ~25% for abundances of 2 to 10%, and ~50% for abundances of <2% but above detection limit. Phases marked with an asterisk are at or near detection limit. Relative 2σ errors are ~50% of the amount shown for smectite and ~60% for the amorphous component. [*Data primarily from CheMin, with smectite information from SAM.*]

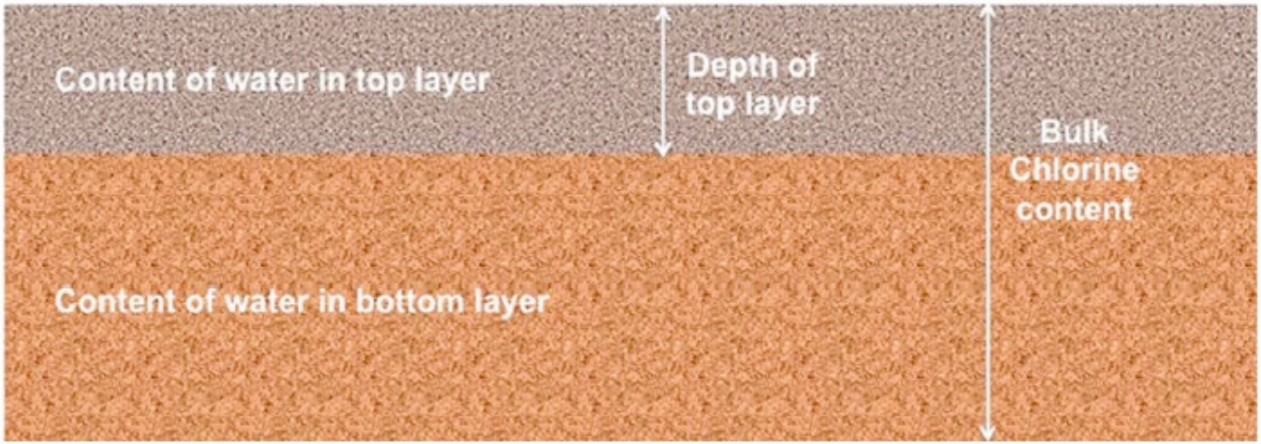


This material was analyzed in detail by MSL.

From Vaniman et al. (2014)

Basis for Case D (3 of 3)
DAN Measurements of Water Equivalent Hydrogen

- DAN measures total hydrogen over a footprint 3m wide and down to a depth of ~60 cm.
- Data from DAN are best modeled by a 2-layer structure
  - Upper layer has less H (average 1.5-1.7% WEH) than the lower layer (average 2.2-3.3% WEH).
  - Local anomalies as high as 6% WEH were measured in the first 361 martian sols; in later sols contents up to 10% WEH were measured.



Data from MSL's DAN instrument are best modelled using a two-layer subsurface structure. The top layer ranges between 10-30 cm thick. Water concentrations are in table below.

Note that the DAN instrument detects H, not water. The H could be present in hydrous minerals or as OH—it is almost certainly not present as liquid water. The "water-equivalent hydrogen" or WEH measured by DAN, is used to calculated the potential amount of "water" present using the models.

Table 3. Average Parameters of Soil for Four Different Ranges of the Curiosity Odometry

Odometry Ranges	0–455 m	455–638 m	638–876 m	876–1900 m
(1)	(2)	(3)	(4)	(5)
Top water (wt %)	1.68 ± 0.08	2.17 ± 0.12	1.50 ± 0.04	1.48 ± 0.03
Bottom water (wt %)	2.23 ± 0.08	1.41 ± 0.04	2.64 ± 0.06	3.33 ± 0.07
Vertical-average water (wt %)	2.07 ± 0.05	1.47 ± 0.03	2.31 ± 0.04	2.65 ± 0.04
Thickness of thetop layer (cm)	13 ± 1	6 ± 2	16 ± 1	22 ± 1
Content of absorption equivalent chlorine (wt %)	1.07 ± 0.02	1.14 ± 0.02	1.19 ± 0.01	1.17 ± 0.01

From Litvak et al. (2014) (top) and Mitrofanov et al. (2014) (bottom).

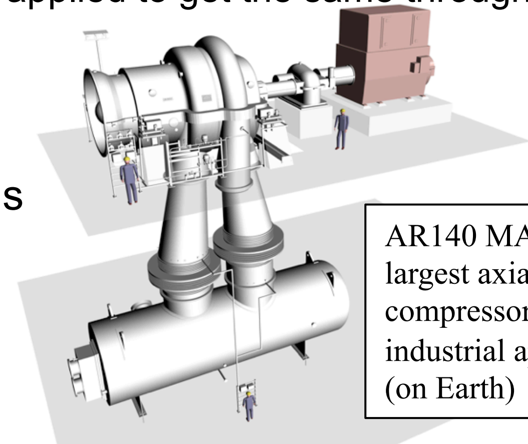
Other Options Considered and Ruled Out: Extraction of Water from the Atmosphere

Some general facts and calculations:

1. At Mars surface pressure = ~6 mbar; atm density averages ~0.020 kg/m^3, water ~210 ppm = 0.0042 g(water)/m^3
2. 1 kg water is contained in 250,000 m^3 of atmosphere
3. To produce 5 mt water per yr, 0.57 kg would have to be produced per hour, which means 2400 m^3 (~1 Olympic sized swimming pool) of atmosphere would have to be handled per minute, assuming 100% recovery. This is equivalent to 84,000 CFM.
4. Martian atmosphere is at 1% of the pressure of the inlet pressure for compressors on Earth, thus an additional compression factor of 10^2 would have to be applied to get the same throughput.

→ We have not seen a credible method proposed for separating the water from an airstream of this scale, so we cannot estimate recovery efficiency.

→ The air-handling system implied by these calculations would be on the same order of magnitude as the largest air compressors known on Earth: ~600,000 CFM, requiring 65 megawatts to run, and roughly 5x5x10m in size.



AR140 MAN1 – the largest axial flow compressor for use in industrial applications (on Earth)

CONCLUSION: The mass, power, volume, and mechanical complexity of the system needed for this approach are far outside of what is practical for deployment to Mars.

Other Options Considered and Ruled Out: RSL, Permafrost, High Latitude Ice

Recurring Slope Lineae (RSL)

- Only occur on steep slopes – very difficult for mining/transport operations.
- By definition, RSL are transient (seasonal). If liquid water is present, it may be only temporary.
- Hydrated minerals likely present, but are not necessarily more concentrated than in our other cases.

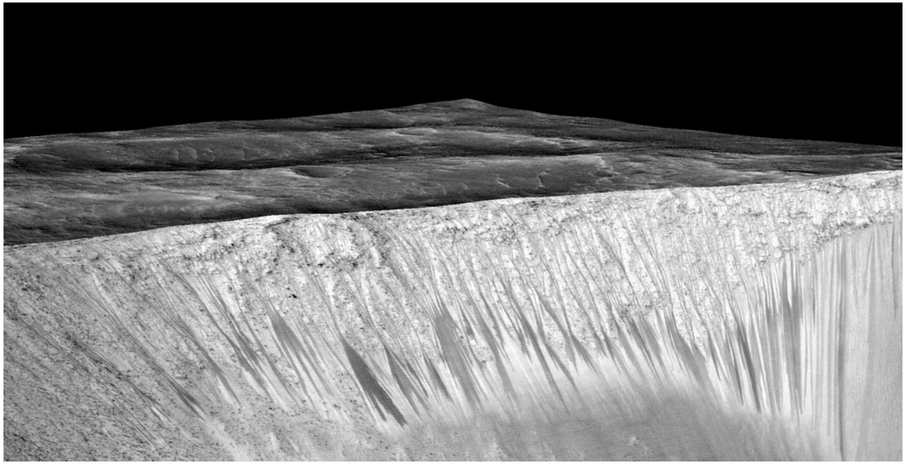


Image of a set of RSL (dark streaks) on a crater wall. Image credit JPL/NASA/Univ. Arizona

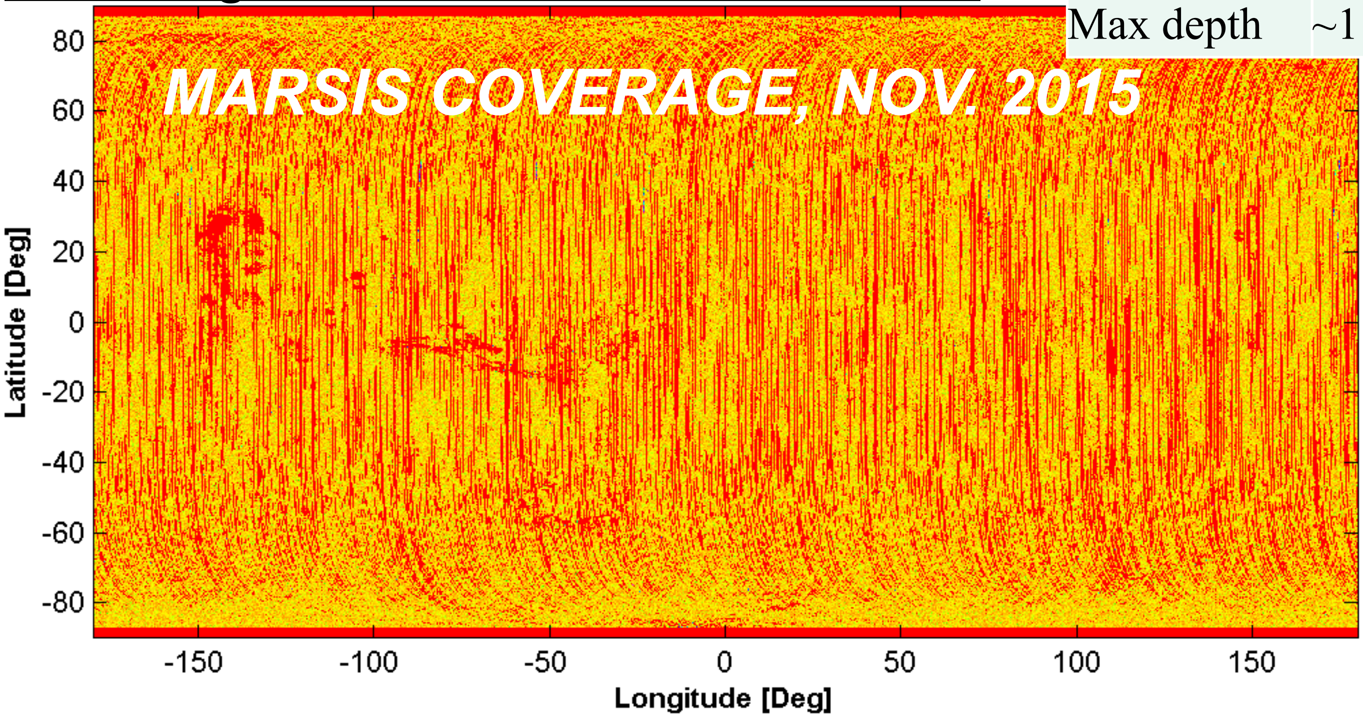
Permafrost: Although this exists (at high latitudes) on Mars, permafrost represents the existence of ice in the pore space of rock or soil, which is a low-grade variant of Case A (glacial ice). Since this will be less productive than glacial ice, we evaluate the latter here.

High Latitude Ice: Although large deposits of ice exist on Mars above 60° latitude, these exceed the latitudes set by our ground rules and assumptions (see **Slide #8**).

Other Options Considered and Ruled Out: Deep Groundwater (1 of 2)

- MARSIS and SHARAD (radars) would be able to detect Mars groundwater (liquid water or brine in Mars bedrock) if it were present within the depths cited.
- ***<u>No such groundwater has been detected</u>*****.**

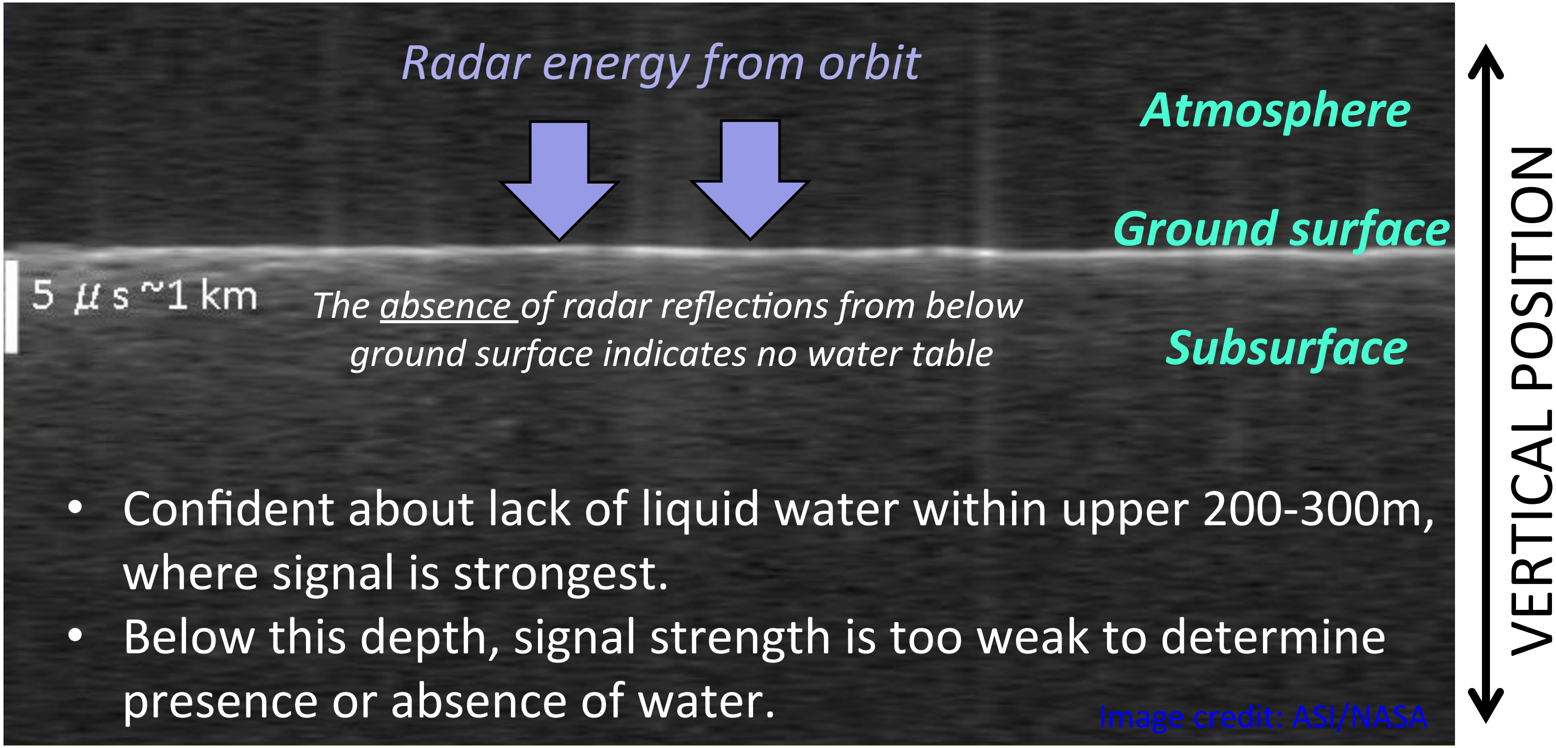
	MARSIS	SHARAD
Coverage	~69%	~31%
Spatial res.	~10 km	~0.5 km
Depth res.	~100 m	~10 m
Max depth	~1 km	~ 300 m



Map of Mars showing MARSIS data coverage as of Nov. 2015.
- *Yellow: Survey completed and no water detected (evidence of absence).*
- *Red: No data or SNR too low (absence of evidence)*

Contribution from Jeff Plaut; discussion with Rich Zurek, Serina Diniega

Other Options Considered and Ruled Out: Deep Groundwater (2 of 2)



MARSIS 5-MHz, radargram of the Athabasca region of Mars (4-7N, 149E). Images are taken along the track of the orbiter, using radar to detect subsurface features like water, which would show up as a reflective surface.

- Given the absence of detections, and the fact that the coverage map is rapidly filling in → *unlikely that there is groundwater at a depth shallower than ~200-300 m anywhere on the planet.*

Contributions from Jeff Plaut; Rummel et al. 2014

Definition of Reference Reserve Cases

Four reference cases were chosen to represent the output of HLS[2] (See **Slide #7**)

Essential Attribute	Deposit Type: A. Ice	B. Poly-hydrated Sulfate	C. Clay	D. Typical Regolith (Gale)
Depth to top of deposit (stripping ratio)	variable (1-10m)	0 m	0 m	0 m
Deposit geometry, size	bulk	bulk	bulk	bulk
Mechanical character of overburden	sand	NA	NA	NA
Concentration and state of water-bearing phase within the minable volume				
–Phase 1	90% ice	40% gypsum[1]	40% smectite[2]	23.5% basaltic glass[3]
–Phase 2	--	3.0% allophane[4]	3.0% allophane[4]	3.0% allophane[4]
–Phase 3	--	3.0% akaganeite[5]	3.0% akaganeite[5]	3.0% akaganeite[5]
–Phase 4	--	3.0% smectite[2]	3.0% bassanite[6]	3.0% bassanite[6]
–Phase 5	--	--	--	3.0% smectite[2]
Geotechnical properties				
–large-scale properties (“minability”), e.g. competence, hardness	competent--hard	sand--easy	sand--easy	sand--easy
–fine-scale properties (“processability”) , e.g. competence, mineralogy	no crushing needed	no crushing needed	no crushing needed	no crushing needed
The nature and scale of heterogeneity	variation in impurities	±30% in concentration	±30% in concentration	±30% in concentration
Distance to power source	1 km	1 km	1 km	100 m
Distance to processing plant	1 km	1 km	1 km	100 m
Amenability of the terrain for transportation	flat terrain	flat terrain	flat terrain	flat terrain
Presence/absence of deleterious impurities	dissolved salts	none	none	perchlorate?
First order power requirements	TBD	TBD	TBD	TBD
Not Considered				
Planetary Protection implications	TBD	TBD	TBD	TBD

1. ~20 wt% water, 100-150°C
2. ~4 wt% water, 300°C
3. ~1 wt% water, >500°C
4. ~20 wt% water, 90°C
5. ~12 wt% water, 250°C
6. ~6 wt% water, 150°C

Note: Planetary Protection implications are addressed on **Slide #86**