Gangotri mission concept on the glacial key to the Amazonian climate of Mars

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The wealth of geologic information bound in martian ice (Figs. 1, 2), including climate cycles, potential biomarkers, atmospheric particulates, and sources of H_2O that may drive alteration within the critical zone (CZ: zone of interaction between the atmosphere and the porous upper crust) has long been recognized (Figs. 6, 8). Much progress has been made in the last decade, in interpreting polar ice sheet [Bapst et al., 2019] and midlatitudinal ice [e.g., Dundas et al., 2018; Harish et al., 2020; Piqueux et al., 2019] processes.

Despite recent advances, outstanding questions remain at the forefront of exploration [cf., Bramson et al., 2021]. Martian midlatitudes provide a notable opportunity to explore these in the evolution of ice beyond the poles (Figs. 1, 2), as emphasized in the National Academies of Sciences 2023-2032 decadal survey's general Mars Life Explorer outline [2022]. Including the examples in Figs. 4 and 5, such glaciers are ablating as evident from scarps, boulder fields, and pits [Dundas et al., 2018]. Accordingly, our mission concept—aptly eponymous with the large and fast-receding Himalayan glacier, Gangotri—would investigate the geologic origins of midlatitudinal martian glaciers. Gangotri would help to characterize Amazonian climate evolution via Honeybee Robotics' hybrid thermo-mechanical drill [Mellerowicz et al., 2022] for deep and possibly multiple englacial sampling, including for in situ resource use (Fig. 7). Gangotri would use regolith compositional measurements to analyze ice-regolith interaction, and stable isotope measurements to characterize fundamental exchange processes (Fig. 8) of major ice reservoirs (Fig. 3). Meanwhile, geophysical observations would cross-calibrate composition, with sensitivity to the presence of brines or meltwater. Example platform and payload are shown in Figs. 9a-i, linked to the science traceability matrix (Table STM-A, B), and spacecraft architecture (Table SA).

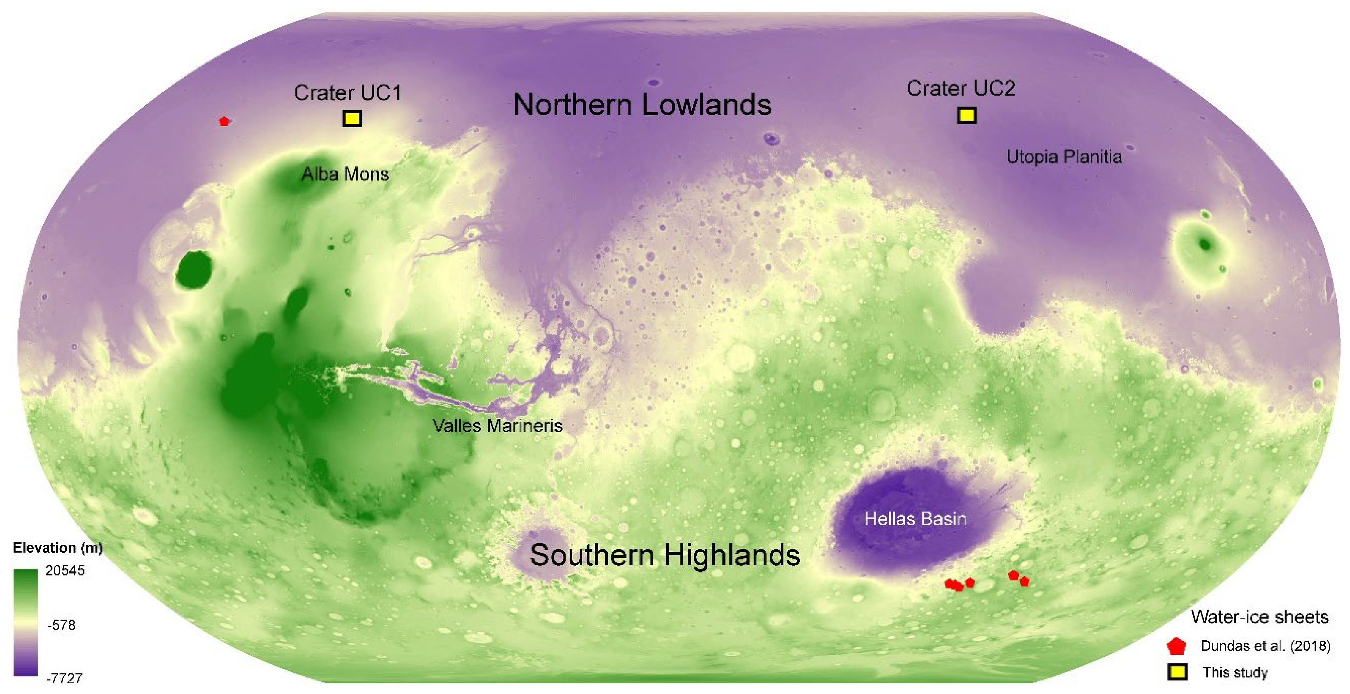


Figure 1. Sites of martian ground ice determined from satellite infrared spectroscopy (MRO-CRISM) and optical imagery (MRO-HiRISE). As in Figs. 4 and 5, ground ice occurs at hundreds of meter (intracrater: UC1, UC2) and up to tens of km (red icons) lateral scales. Some ice sheets likely **hundreds of meters thick**. From the work by Harish et al. [2020].

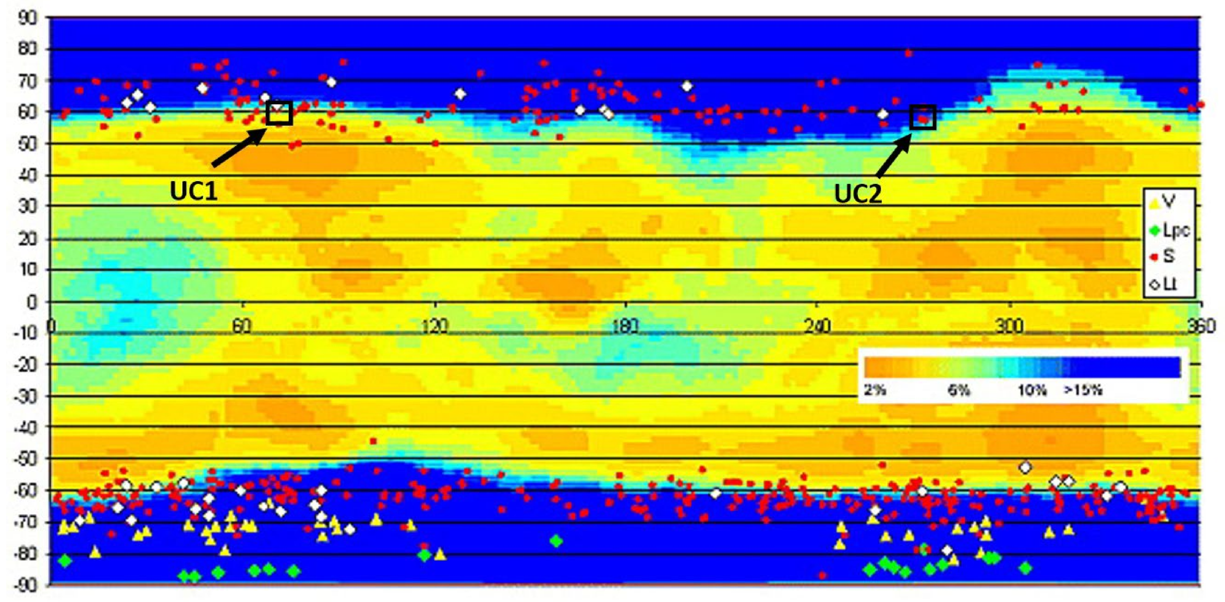


Figure 2. Distribution of ice-dominated landscapes (colored icons) and relative concentration of stoichiometric H_2O in bulk soil (mass fraction as %, color scale) from regional scale neutron spectroscopy representative of decimeter scale soil depths. [Harish et al., 2020]

Fig. 9 Example rover concept and payload

Fig 9a. Mars helicopter scout to survey the glacial landscape, extending to geologic mapping and site optimization for englacial sampling. Imaging of periglacial landscape and unstable zones. [Balaram, 2021]

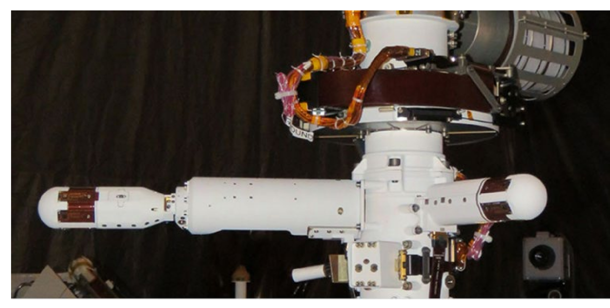
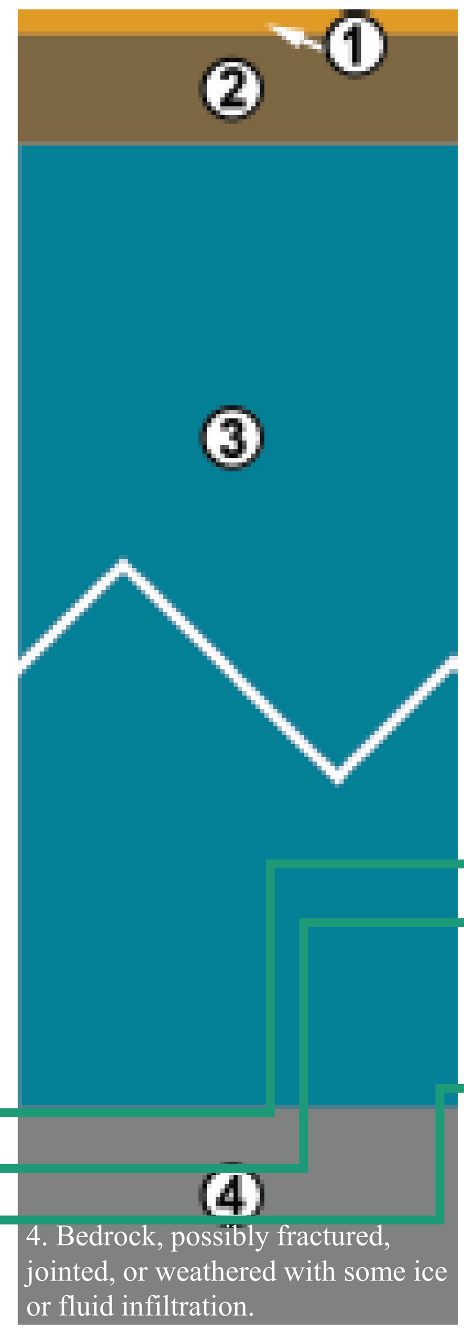


Fig 9b. Mars Environment Dynamic Analyzer (MEDA) to characterize glacial micro-climate. [Rodriguez-Manfredi, 2021]

Figure 3. Conceptual schematic of glacial profile for mission sampling



1. Dry soil, including tens of micron size dust grains, forming a mantling unit cm – m thick over ice sheets
2. Underlying perma-frost equivalent ice rich soil unit(s) of meter depth scales.
3. Ice layers, possibly containing unconformities, bedding, laminations and massive units. Primary archive of climatologic and geologic (e.g., globally dispersed volcanic ash columns) events. May reach 0.1 – 0.2 km depths in places (Fig. 4).
4. Bedrock, possibly fractured, jointed, or weathered with some ice or fluid infiltration.

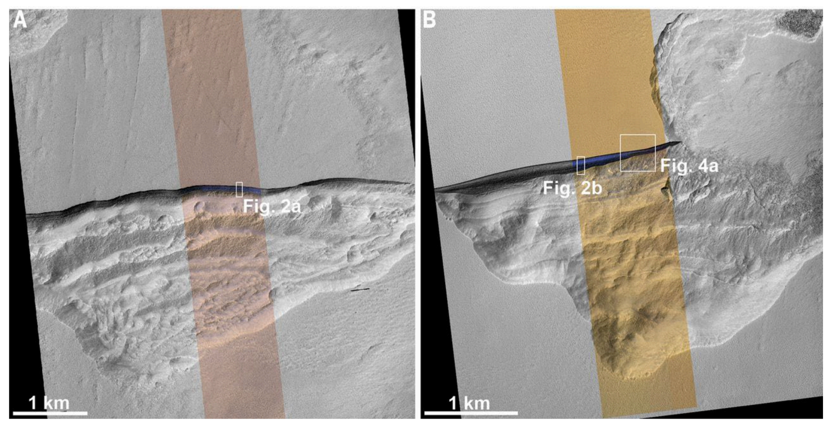


Figure 4. Example of southern mid-latitudinal ice sheet with collapse scarps and pitting (Geographic and geochemical context in Figures 1 and 2, respectively). By Dundas et al. [2018].

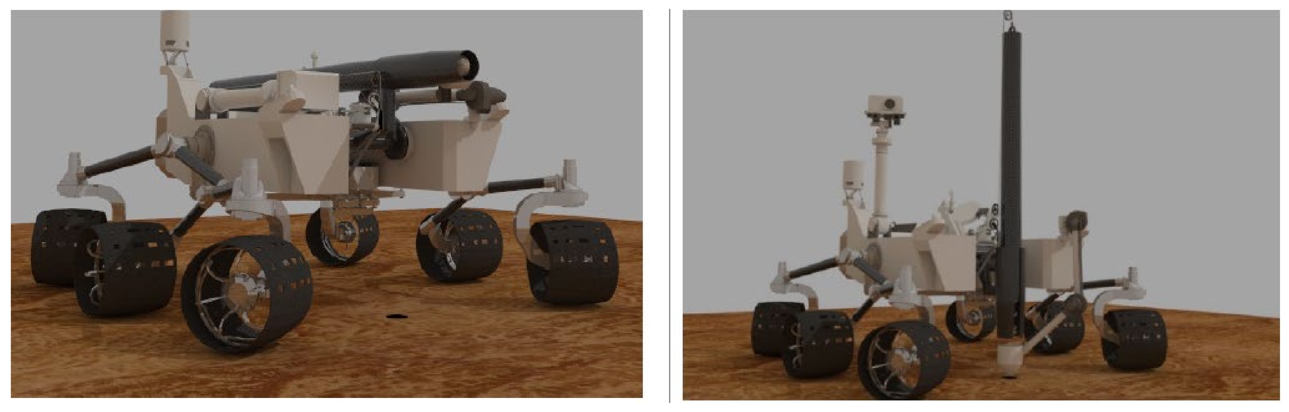


Fig 9c. Mobile to stationary rover-based platform to sample the glacial column at an optimal site for the science traceability matrix (Tables STM-A, B). Mobility will also enhance recoverability from unforeseeable drill obstructions by relocating to alternative sites.

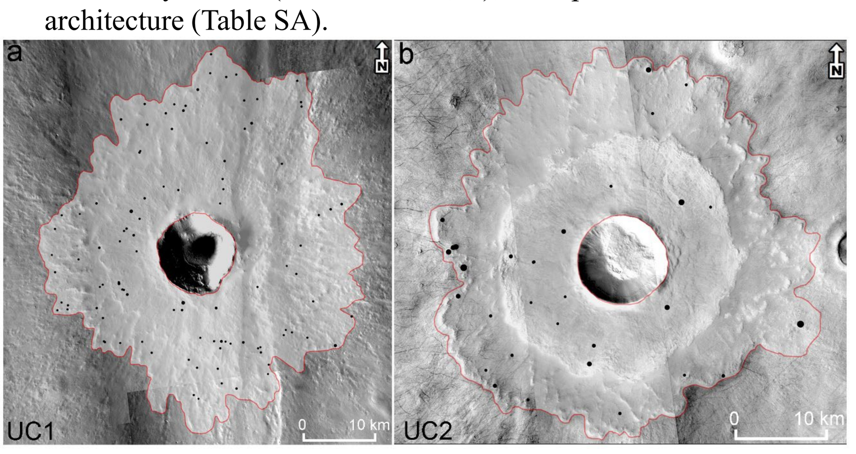


Figure 5a. Two mid-latitudinal craters in the northern hemisphere showing fluidized ejecta morphology and bearing ice within. Figures 1 and 2 show geographic and geochemical context. [Harish et al., 2020]

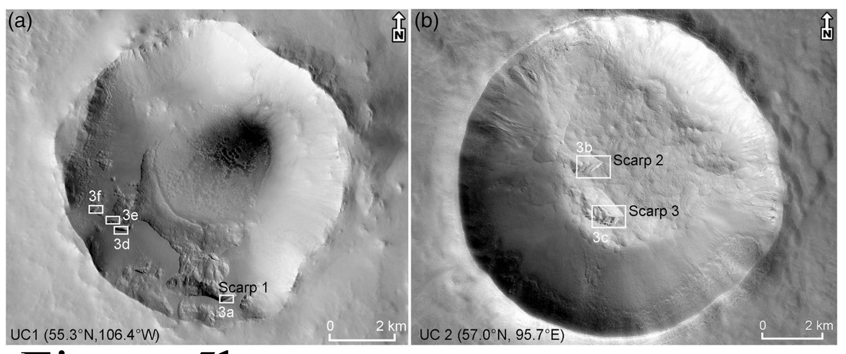


Figure 5b. Magnified view of the floor ground ice units for the crater shown in Figure 5a. [Harish et al., 2020]

Table STM-A. Science Traceability Matrix A (STM-A) for the GANGOTRI Mission Concept. For legibility and conceptual flow, STM is bifurcated, one relating mission goals and aims to NASA goals (Table STM-A); and the other associating mission aims with physical parameters, observables, and performance requirements (Table STM-B). For brevity, we only **excerpt** relevant text with ellipsis (…) of the NASA Visions and Voyages 2013 – 2022 decadal survey (DS) [NRC, 2011], mid-term review (MTR) [NAS, 2018] and NASA's science plan (SP) [2014]. The Committee on Astrobiology and Planetary Sciences (CAPS) report [*NAS*, 2017] identifies Mars as a key target for each DS goal excerpted.

Examples of NASA Goals	GANGOTRI Science & Human Exploration Goals	GANGOTRI Objectives (Aims)
DS: How do the climate, and especially the water cycle, vary with orbital and obliquity variations? ...more detailed examination of ... layered sedimentary rocks for the record of ... climate ... to improve the understanding of volatile budgets and cycles. **SP:** ...characterize and understand Mars as a system, including its current ... climate... **MTR:** ...(<3 Ga Age) Climate Change Amazonian...What processes formed shallow, excess ice? … How do those ... relate to obliquity variations...?	**SG.** Understanding climate-driven processes of mid-latitudinal glaciers as a key H2O reservoir within Mars's critical zone.	**SG1.** Test the latest H2O reservoir exchange model for Mars using D/H isotopic signatures. **SG2.** Resolve a paradoxical divergence between theoretical and observed atmospheric D/H variance for Mars. **SG3**. Determine the extent to which englacial siliciclastics and sulfate-rich aerosols undergoing low-pH alteration may yield Martian sulfate sedimentary strata.
DS: ...understanding of the astrobiological potential of the observable water-ice deposits... **SP:** ...characterize and understand Mars as a system, including its...biological potential...	**SB.** Determining the habitability and biomarker preservation potential of young Martian glaciations.	**SB1.** Determine the extent to which ancient organics and microorganisms can be deposited, immured, and preserved in young glaciers. **SB2.** Determine whether any presence of organics and microorganisms was driven by aeolian-deposited englacial dust.
DS: To reduce the cost and risk for future human exploration, robotic ... missions ... to acquire information concerning potential resources… **MTR:** ...investigating the distribution of shallow excess ice will quantify an important resource to provide astronauts with water and oxygen...	**HE.** Understanding the utility of glacial ice as an in situ resource (ISR) for humans.	**HE1.** Establish a ground-truth reference volume for H2O ice as a possible ISR. **HE2.** Identify which glacial H2O extraction and purification methods would be optimal for ISR use. **HE3.** Determine forward and backward biological contamination thresholds before using readily accessible Martian ice as an ISR.

Table STM-B.

Aims	Required physical parameters	Required observables	Platform and mission performance requirements
SG1	SR1. Englacial hydrogen isotopic abundance	SO1. Mass spectroscopy of D/H molar ratios	SP1. SAM specifications with δD resolution (2SD) of ±100‰
SG2	SR2.1 Englacial hydrogen isotopic variations	SO2.1 Same as SO1	SP2.1 Same as SP1
	SR2.2 Climate & weather governing glacial instability	SO2.2 Local temperature, pressure, wind velocity, and humidity over 1 Mars year	SP2.2 MEDA specifications, corrected for the spacecraft's thermal effects.
	SR2.3 Overnight energy exchange at glacial sites	SO2.3 Thermal characterization with infrared spectroscopy	SP2.3 MiniTES specifications
SG3	SR3.1 Extensiveness, composition, and layering of englacial siliciclastics, salts, and trapped gases, including dust-ash layers.	SO3.1.1 Relative englacial abundances of phyllosilicates, perchlorates, sulfates, and other mineralogic and amorphous components.	SP3.1.1 SAM evolved gas chromatography and mass spectroscopy operating up to 800 °C with 70 µg/kg sensitivity to evolved volatiles.
		SO3.1.2 Complementary isotopic measurements of H, C, O, S, and Cl	SP3.1.2 Same as SP3.1.1
		SO3.1.3 Optical scattering by englacial dust.	SP3.1.3 Dust logger with 405 nm laser to illuminate surrounding glacial ice in a horizontal fan (90° wide) at 1 - 2 mm vertical resolution in backscatter mode.
	SR3.2 Contextual surface geochemistry and mineralogy across overlying regolith and ground ice boundary	SO3.2.1 Bulk regolith concentration of major silicate forming elements (Fe, Si, Al, Ca, Mg), mobile elements significant for brine activity (Cl, S, H), and large ion lithophiles significant for distinguishing aqueous versus igneous processes (K, Th).	SP3.2.1 NGRS with better than 15% precision for targeted elements.
		SO3.2.2 Infrared spectroscopy of surficial minerals.	SP3.2.2 MiniTES infrared spectral resolution specification
		SO3.2.3 Compositional and physical stratification across the regolith-ice boundary layer.	SP3.2.3 Piezo-ceramic acoustic seismometer with 1 kHz bandwidth of finer than 10 cm vertical resolution, and SP3.2.1
SB1	Type abundance of aromatic organic molecules and microbial cell components.	SBO1.1 Evolved gas chromatograph mass spectrum	SBP1.1 SAM system using retention times on the gas chromatograph and full separation of isobaric interferences.
		SBO1.2 UV fluorometric detection of organics and microbial cells	SBP1.2 UV fluorometer with up to 4 excitation wavelengths, 16 emission channels, and mm-resolution sensitive to 50-100 cells/ml.
		SBO1.3 UV microscopic imaging of organics, microbial cell components, and granular material	SBP1.3.1 Sample staining sub-micron resolution UV microscope with 10, 1, and 0.1 µM sieves for melt slurry. SBP1.3.2 Darkfield imaging in four wavelengths and excitation fluorescence at four wavelengths, including D-UV.
SB2	Physical association between organic molecules, microbial cell components, and siliciclastics	Same as SBO1.2, SBO1.3	Same as SBP1.2, SBP1.3.1, SBP1.3.2
HE1	Depth, lateral extent, and concentration of H2O ice	HO1.1 Geologic mapping with optical imagery	HP1.1 MHS imaging at 10 - 30 cm / pixel resolution for km scale aerial surveying
		HO1.2 Same as SO3.1.3, SO3.2.1, & SO3.2.3	HP1.2 Same as SP3.1.3, SP3.2.1, SP3.2.3
HE2	Chemical (e.g., sulfates) and physical (e.g., siliciclastics) constituent abundance in ice	Same as SO3.1.1, SO3.1.2, SO3.1.3	Same as SP3.1.1, SP3.1.3
HE3	Microbial or biogenic material in ice	Same as SBO1.1, SBO1.2, SBO1.3	Same as SBP1.1, SBP1.2, SBP1.3.1, SBP1.3.2
All	All except SR2.2, SR2.3, SR3.2	All except SO2.2, SO2.3, SO3.2.1, SO3.2.2, SO3.2.3 and HO1.1	Hybrid thermo-mechanical drill penetrating 10 - 30 m depths. Sample preparation-delivery system from borehole to rover deck.

Table SA. Spacecraft architecture (SA) for the GANGOTRI mission concept

Component	Heritage or TRL	Details	Expected Mass (kg)
EDL Platform	M2020	EDL Platform and landing system based on the skycrane system adapted for the weight and momentum of the GANGOTRI rover.	2400 [NASA]
Rover	M2020	Rover chassis as the base design. Key enhancements include wheel design for enhanced excavating ability, Radioisotope Power System (RPS) optimization for the drill and rover, and acoustic seismometer integration into wheels.	900 [NASA]
Thermo-mechanical Drill	RedWater	Thermal source options, coiled tubing drill configuration, sample preparation, and sample delivery to the deck are key areas for development. Likewise, science payload consisting of dust logger, fluorometer, and microscope are to be incorporated.	75
MHS	M2020	MHS imaging systems will be modified for mapping.	1.81 [*Agle*, 2019]

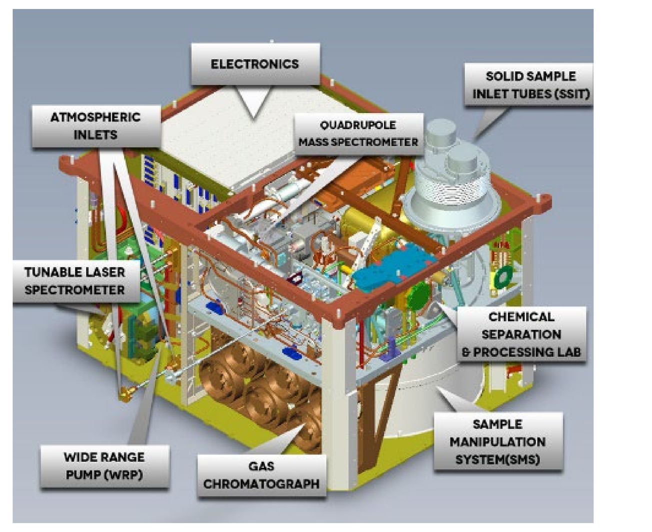


Fig 9d. Sample Analysis at Mars (SAM) module optimized for isotopic geochemistry of key elements (e.g., H, S). Mounted on-deck to analyze slurry (ice, fluid, silicate, salt mix) extracted during drilling. [cf., Franz et al., 2014, 2017; Mahaffy et al., 2012]

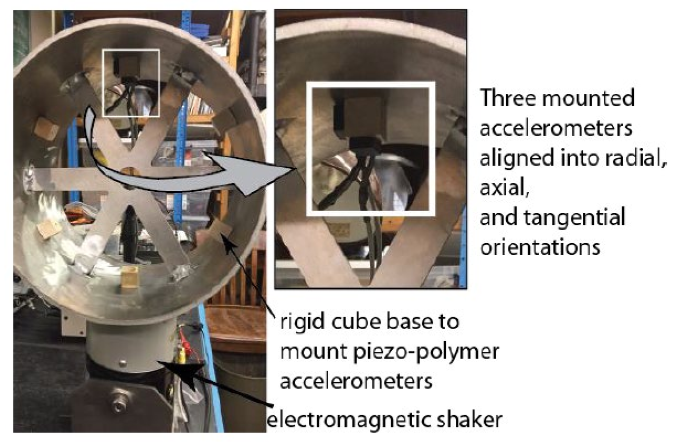


Fig 9e. Wheel-mounted low-resource seismometer at high (acoustic) frequency for soil-ice boundary layer insight at meter depth scales. [Lorenzo et al., 2022]

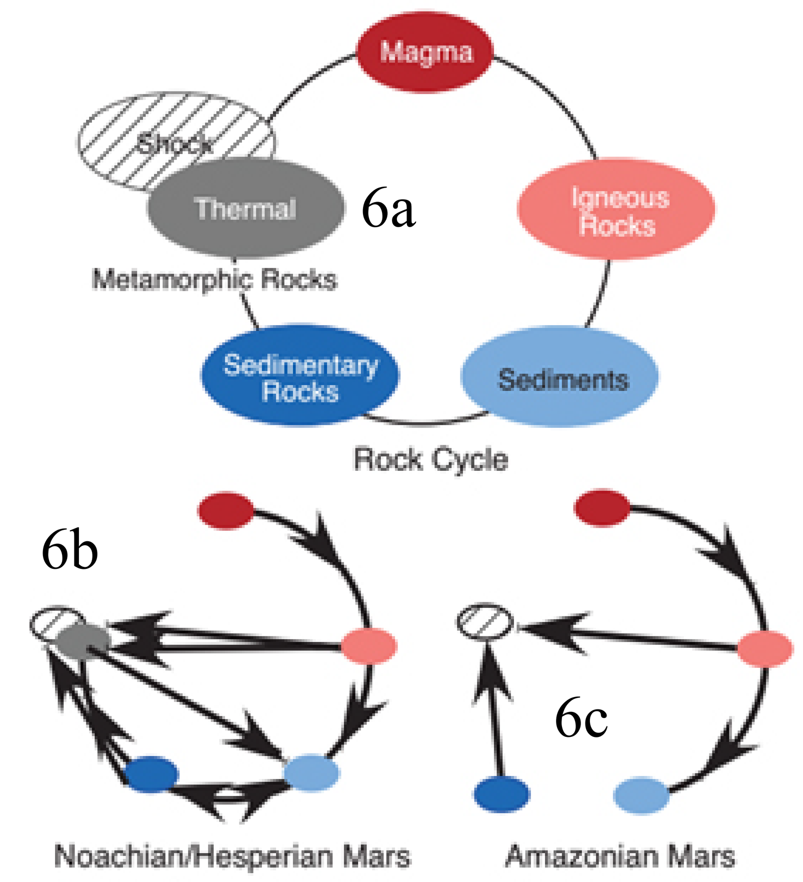


Figure 6. Unknowns in the martian rock cycle to be investigated with a mid-lat glacial mission. A: Earth's rock cycle, color-coded for reference. B: Ancient Mars, with the recycling of sedimentary rocks into magma poorly known. C: Additional gaps in modern Mars, particularly on sediment diagenesis or lithification. Weathering of englacial sediment by brines in ice, scavenging SO_2-phases, may be a possible pathway. [McSween, 2015]

Figure 7. Artist's rendering of in situ resource use for sustaining human habitats. Martian ice units could prove invaluable, but require assessment of forward-backward biologic contamination, construction of extraction facilities at supra- or peri- glacial landscapes, and mitigated toxicity risks of ice-entrained phases, such as sulfates, or particulates, such as volcanic ash.

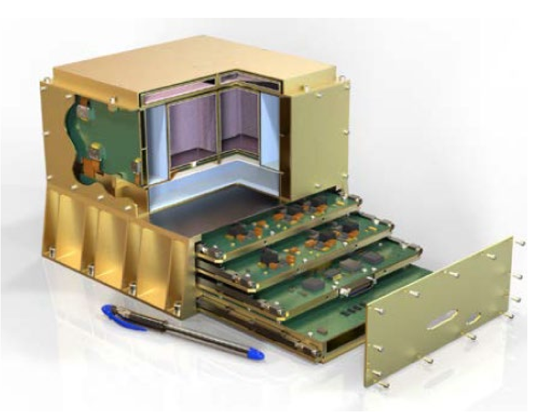


Fig 9f. Deck-mounted neutron-gamma spectrometer (NGRS) for geochemical characterization. Tables STM-A, B show key elements for geology and habitability characterizations. [Mesick et al., 2018]

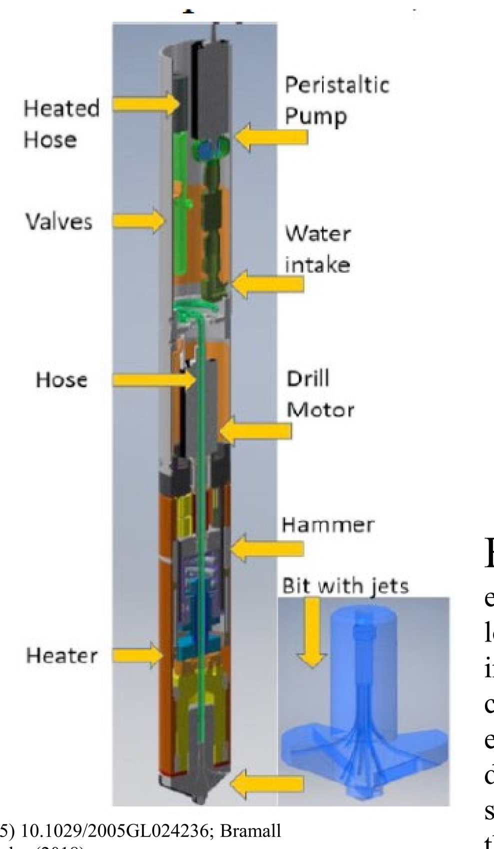


Fig 9g. Thermo-mechanical drill for tens of meter englacial sampling capability. Honeybee Robotics RedWater design shown as example. Ducts to extract sample slurry for analyses with deck-instruments, tether and emergency-jettison systems, as well as embedding analytical payload are needed. [Mellerowicz et al., 2022]

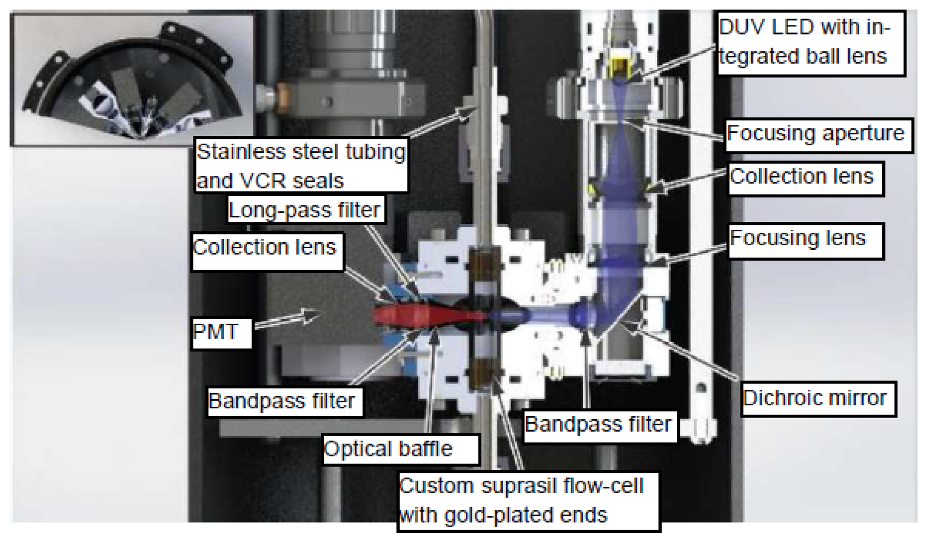


Fig 9h. Drill-embedded UV fluorometer to characterize biogenicity of glacial slurry, including sensitivity to biological cell structures.

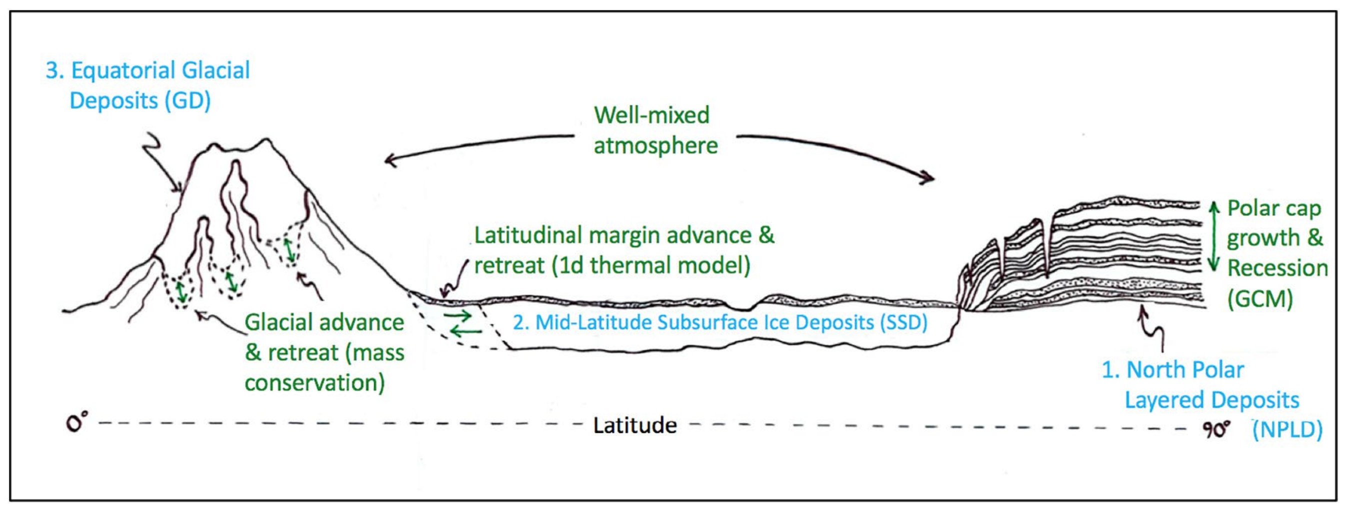


Figure 8. H_2O exchange reservoirs in the martian critical zone during celestial mechanics of the last few Ma. The layering in mid-latitudinal ice sheets, as targeted by GANGOTRI, would archive isotopic signatures of H_2O exchange with high-altitudes (e.g., Olympus Mons) and the polar zones. Current model for NPLD can be refined and cross-calibrated with celestial mechanics models by sampling the mid-latitudinal glacial strata. [Vos et al., 2019]

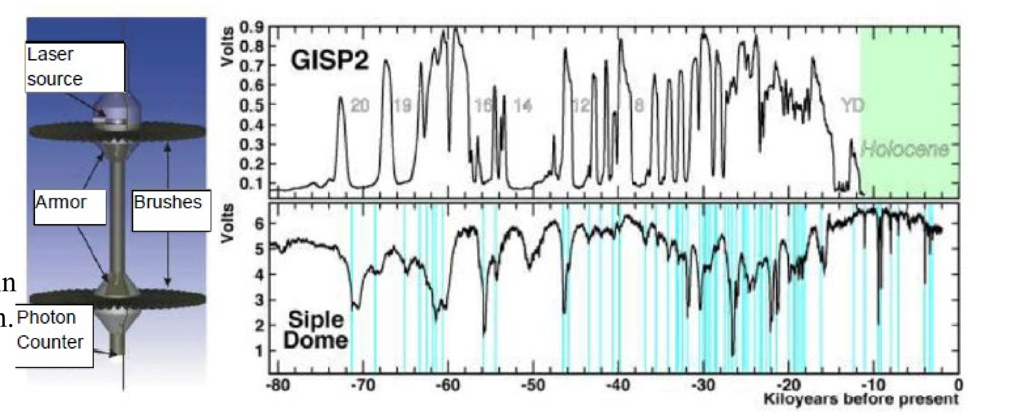


Fig 9i. Drill-embedded dust logger for insight into climatic cyclicity and episodic deposition from silicate sediment in the glacial column. Example spectra from Antarctic sites. [Bramall et al., 2005, 2007]

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