

Prospecting in-situ resources for future crewed missions to Mars

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ABSTRACT

The installation of planetary and lunar human outposts might be an important step for future solar system exploration by both public space agencies and private companies. Humans living and working in these artificially created habitats will possibly depend, among other life support approaches, on bio-regenerative life support systems to produce and recycle oxygen and water, and to produce food. A variety of natural resources suitable life support can be readily found on Mars, and to a lesser extent on the Moon. Instead of launching all resources (e.g., water, propellant, food and other materials) from Earth, it could potentially be much more cost effective to send automated machinery to harvest resources from the Martian surface and atmosphere in preparation for the arrival of humans. The exploration of these natural resource deposits, the concentration of the raw materials contained in them, and the feasibility of mining and refinement are open questions that require further consideration. Here we address the concept of harvesting resources in situ by reviewing the potential of several large deposits of hydrated minerals found on the surface of Mars thanks to previous orbital detections. We also present estimates of water volumes potentially retrievable from specific deposits and describe additional uses of the hydrated minerals for example as fertilizer for food production.

1. Introduction

Establishing human outposts on the Moon or Mars is seen as an important step in future solar system exploration by many members of the community. In recent years, private companies have joined national and international space agencies in this quest and have made decisive contributions. By 2025, the European Space Agency (ESA) is preparing a mission to demonstrate that water or oxygen production is possible on the lunar surface. In this effort, oxygen is likely to be the first resource produced locally to support crewed missions, contributing to the propellant supply or the life support systems. The National Aeronautics and Space Administration (NASA) has also taken a first step toward exploring the use of local resources with the Mars Oxygen In-Situ Resource Utilization Experiment (MOXIE) on the Mars 2020 "Perseverance" rover, producing oxygen from Martian atmospheric carbon dioxide [1]. All of these efforts fall under the umbrella term In Situ Resource Utilization (ISRU). Expanding options for ISRU on planetary bodies might significantly reduce the total overall mass that needs

to be sent to the Moon or Mars. Sacksteder and Sanders aptly described ISRU as: "the collection, processing, storing and use of materials encountered in the course of human or robotic space exploration that replace materials that would otherwise be brought from Earth" [2]. Many ISRU technologies are currently under development; for example, the reduction of metal oxides such as ilmenite (FeTiO_3) for H_2O production (ilmenite/glass reduction with H_2), the chemical conversion of regolith to oxygen via carbon-thermal reduction with CH_4 pyrolysis vapor phase reduction, the production of oxygen from (lunar) regolith via vacuum pyrolysis, the production of water from carbon dioxide and hydrogen with carbon monoxide as a side product using the reverse water gas shift with H_2 , or the solid oxide electrolysis convert CO_2 into O_2 as demonstrated with the MOXIE experiment at Jezero crater on Mars [3]. Implementing these ISRU systems might ultimately foster sustainable maintenance and expansion of a human outpost. When considering the prospect of sustaining life in the vast expanse of an alien planet, a Bio-regenerative Life-Support System (BLSS) promises an advantage in terms of mass efficiency compared to non-bio-regenerative, i.e., chemical or physical life support systems, especially for protracted mission

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Abbreviations

BLSS	Bio-regenerative Life-Support System
CRISM	Compact Reconnaissance Imaging Spectrometer for Mars
CTX	Context Camera
DTM	Digital terrain model
FREND	Fine-Resolution Epithermal Neutron Detector
HRSC	High Resolution Stereo Camera
ILD	Interior Layered Deposit
ISRU	In Situ Resource Utilization
MHS	Monohydrated sulfate
MOLA	Mars Orbiter Laser Altimeter
MOXIE	Mars Oxygen In-Situ Resource Utilization Experiment
OMEGA	Observatoire pour la Minéralogie, l'Eau, les Glaces et l'Activité
PHS	Polyhydrated sulfate

durations [4]. BLSS have the benefit of managing biological waste through biological processes exclusively. In addition, if higher plants are cultivated, they offer psychological comforts and nutritional benefits derived from the presence of plant life and as fresh food [5]. Thus, BLSS systems realized in the form of one or multiple greenhouses, are a promising component for sustaining a human presence on lunar or Martian terrain [6,7]. In order to develop complete self-sufficiency in a more distant future as described by Cannon and Britt [8], diverse resources will be needed in large quantities. In this context, the current work aims to describe specific locations and their prospective resource types, including ice or hydrated minerals, that could provide a maximum of feedstock for BLSS systems and would therefore represent optimal candidate landing sites as future exploration targets.

2. Rationale: reducing logistics from Earth to Mars

Reducing logistics from Earth for crewed missions to Mars is a critical challenge that needs to be addressed for sustainable and successful human missions. It is important to note that entirely eliminating logistics from Earth is a long-term goal and would not be achievable in the initial phases of crewed missions. By continuously improving technologies and adopting sustainable practices, Martian self-sufficiency can be gradually increased and reliance on Earth minimized. Modularity and redundancy are important factors regarding the design of a Martian base. If a critical system fails, backup modules can ensure continued operation until repairs are possible. 3D printers can for example use locally available materials to manufacture tools, such as surgical instruments [9], spare parts, and even habitats [10]. The use of advanced robots and autonomous systems can assist with tasks including mining, construction, and maintenance. This reduces the need for human intervention and re-supply of equipment.

Of special interest are closed-loop life support systems, which promise to be efficient life support systems that recycle and purify air, water, and waste, minimizing the need for constant resupply from Earth. Sustainable agricultural methods including hydroponics or aeroponics allow growth of large quantities of food in a small space [11]. On a 3-year mission for example, each astronaut would require a minimum of 3600 kg of normally hydrated food, or at least 840 kg of 90 % dehydrated food respectively, plus packaging weight, [12]. NASA's Life Support Baseline Values and Assumptions Document (BVAD) lists a daily total water usage value per crewmember of 10.17 kg for an early habitat infrastructure. A permanent habitat however, would require 28.08 kg per crewmember per day [13]. Based on the latter value, ~10 tons of potable water per crewmember per year would be required. This amount of potable water needs to be transported from Earth or produced via an

open loop system using ISRU techniques. A permanent outpost with six crewmembers would require a water recycling system as an integral component of the general Life Support System (LSS) recycling facility that produces ~60 tons of water per year. The mass of such an LSS system would likely consist of several tons, excluding spares and consumables. These water recycling values represent only rough estimates, since they contain several individual studies and higher values can be expected.

Resupply of food and water is complex and costly, especially for mission scenarios with delivery destinations as far away as Mars. Considering these factors, food production using horticultural methods is a potentially important option to reduce transport from Earth. Here, a controlled environment is essential, to avoid possible contamination (e.g. by perchlorates, dust hazard etc.) and to guarantee a reliable harvest. Over the last 40 years, several studies have shown that crops including wheat, soybean, potatoes, rice and vegetables can be efficiently grown on hydroponic or soilless media (e.g. Refs. [14,15]). In fact, crop cultivation in controlled environments can even meet or surpass record yields [16]. From 2018 to 2022, the EDEN ISS project from the German Aerospace Center operated a space-analog test facility greenhouse near the Neumayer III station in Antarctica, potentially resulting in the closest Mars analog we can find on Earth. In the first year of operation, 268 kg of edible biomass was produced on the 12.5 m² cultivation area of the greenhouse [17] with soilless media. Based on current research, providing 100 % of the required food for a crewmember should be accomplishable with a cultivation area of 40 m²–65 m² [18–20]. Besides the nutritional and psychological benefits of growing plants for food production, additional advantages include removing CO₂ from the atmosphere, keeping water in a recycling loop, and producing oxygen. These findings emphasize the potential of BLSS and can provide estimates of the potential contribution to logistics and required transport of materials for long duration crewed missions.

3. Exploitable resources

Water will be the most important resource needed by humans when they are sent to the Moon or Mars. Not only will it serve as a consumable for future astronauts and for plant cultivation, but also for the production of propellant and oxygen, and for construction use. Water could even serve as radiation shielding if procurable in sufficient amounts. A NASA ISRU study [21] found promising potential for production of substantial quantities of water on Mars using systems that could be aligned with the human mission's architectural design in at least four prospective types of surface materials: Mid-latitude ice, hydrated sulfates, phyllosilicate deposits, and the ubiquitous regolith. In the conclusions of that study [21], the highest potential resources are (buried) ice and hydrated minerals. Also, a technological review on the development of ISRU systems in general confirms this finding [22]. Observational evidence of large H₂O reservoirs in near surface in the equatorial regions of Mars were described by Mitrofanov et al. [23], based on neutron screening with the FREND instrument onboard the ExoMars Trace Gas Orbiter. However, these detections could be associated with either water ice in the form of permafrost, or with large quantities of hydrated minerals. In the following sections we describe these water reservoirs on Mars in more detail and also describe potential additional uses of the specific raw materials and feedstock in BLSS.

3.1. Ice

The water concentration in the Martian atmosphere is very low (<0.03 %) and has a very high spatial, diurnal and seasonal variability [24], making extraction of water difficult. At the surface of Mars, water is only permanently stable at the poles. Massive amounts of water are present in the polar ice caps, especially the northern polar ice cap. However, these regions are not readily accessible and crewed missions would need to overcome substantial difficulties and hardships in such inhospitable,

forbidding regions as the ice caps. At lower latitudes, water is only stable in the subsurface. Recent impact craters have revealed water ice deposits, estimated at 90 % by volume within a meter below the surface at latitudes as low as 39°N [25,26]. Gamma ray and neutron spectroscopy maps suggest widespread water ice presence in the mid to high latitudes within 1 m of the surface [27]. In addition, an abundance of periglacial features such as lineated valley fill and concentric crater fill [28] can be found at the surface, hinting at the presence of ice deposits. Also, radar sounding revealed subsurface interfaces believed to represent the bottom of massive buried ice sheets in different parts of the northern lowlands [29,30]. Particularly at lower latitudes, the structure of the upper tens of meters of the Martian soil remains largely unknown as does the extent of vertical and lateral inconsistencies. These factors produced challenges for the HP3 mole instrument on the InSight's mission, resulting in a depth of only 40 cm when digging through of the regolith [31].

3.2. Hydrated minerals

In contrast to subterranean ice, hydrated minerals offer a promising and reliable potential for water extraction directly at the surface of Mars and at lower latitudes. A large diversity of hydrated minerals such as phyllosilicates, hydrated silica, zeolites, and sulfates have been detected from orbit on the surface using visible near infrared (VIS-NIR) reflectance spectroscopy [32–34]. The presence of these minerals suggests a broad history of water-rock interaction and alteration in different environments and at different episodes during the evolution of Mars. Bibring et al. [35] proposed a classification scheme divided into “phyllosian”, “theikian” and “siderikan” eras, episodes in which respectively mostly phyllosilicates, sulfates, and iron oxides were formed. This trend represents a transition in climate from warm and wet to more acidic, cold, and hyper arid, as we observe Mars today. Therefore, these specific mineral categories and the raw materials sought can be found in clearly delimited areas, which is a tremendous advantage for ISRU ventures. Fig. 1 illustrates the diversity and abundance of hydrous minerals on Mars as described by Ref. [36]. Minerals were sorted into classes based on their VNIR spectral features, each class corresponding to a group of minerals with similar spectral features. The number of detections for each mineral class is indicated as order of magnitude as it strongly depends on the size of the spots that are considered. However, surface morphology and dust coverage also influence whether these minerals can be detected from orbit. It was quickly recognized that Fe/Mg phyllosilicates are by far the most common exposure of all hydrous detections [33,37], followed by Al-rich clay minerals and the opal class. The vast majority of phyllosilicate outcrops on Mars is found in the Noachian-aged southern highlands, whereas sulfate deposits are mostly

detected in Hesperian-aged terrains [38]. Clay mineral deposits have been detected from orbit, partly covering very large areas [38–41]. At the surface, the hydrated silicates contain on average ~5 wt% of water and in some localized areas up to 20 wt%, depending on the type of clay species present [42].

In contrast to the widespread phyllosilicate-bearing areas, particularly across the Mawrth Vallis region, hydrated sulfates appear more localized at the surface. In the Mawrth Vallis region these hydrated sulfate deposits can be 1 km or more thick, while the phyllosilicate deposits are typically tens of meters to 300 m thick. A variety of large-scale, water-bearing sulfate deposits have been discovered in various regions of Mars (e.g. Ref. [35]). Among them, magnesium- and potassium sulfates including kieserite ($\text{MgSO}_4 \cdot \text{H}_2\text{O}$), epsomite ($\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$) and K-jarosite $\text{KFe}_3(\text{SO}_4)_2(\text{OH})_6$. By far the largest hydrated sulfate deposits are found in Meridiani Planum [33]. Here, the sulfate-rich region extends over an area greater than 100,000 km^2 . The regional stratigraphy within the so-called etched terrains and hematite plains of Meridiani Planum consists of a sulfate-rich lower unit of kieserite and polyhydrated sulfates (PHS), an intermediate clay-bearing unit composed of Fe and Al-rich smectites, and an overburden of PHS and jarosite, gypsum and hematite [43]. In 2004, the NASA Mars Exploration Rover “Opportunity” landed in the western hematite plains of Meridiani Planum and confirmed many of the observations made from orbit.

4. Case study of regions of interest - great mineral diversity versus large deposits

We describe in this section as a case study two prominent regions on Mars, the first exhibiting a high diversity of hydrated minerals, the latter featuring large, relatively uniform deposits. We discuss the corresponding advantages and disadvantages of these example regions.

4.1. Great mineral diversity at Mawrth Vallis

Mawrth Vallis is an ancient flood channel (Figs. 2 and 3), located at 23°N and 342°E and discharging into the Chryse Planitia plains. Here, the OMEGA (Observatoire pour la Minéralogie, l'Eau, les Glaces et l'Activité) [44] and CRISM (Compact Reconnaissance Imaging Spectrometer for Mars) [45] instruments have identified a great diversity of altered minerals in association with light-toned exposures of Noachian bedrock (Fig. 3).

The plateau around the channel displays a thick >200 m stratigraphic section of light-toned layered deposits that have near-infrared (NIR) spectral characteristics consistent with a variety of clay minerals [46]. These clay-rich layers extend over much of Arabia Terra, more than 1000 km in the southern direction, and represent a stratigraphic sequence [47]. The sequence is divided into multiple units that exhibit spectral evidence for Fe/Mg-smectites, Al-smectites, ferrous phases, amorphous silica, kaolinite, ferrous mica, and sulfate minerals indicating a rich geological history that may have included multiple aqueous environments [39]. In addition to the expansive clay-bearing unit, several mineralized light-toned fractures and veins indicate additional episodes of interaction between the rocks and fluids, after the formation of the main part of the clay unit. The diversity, amount, and proximity of resources at Mawrth Vallis is unmatched on Mars, making this region one of the most valuable sites for exploration-related resources on Mars [48,49]. The smectite clays and hydrated silica offer a substantial resource for water extraction as well as Fe, Al and Si as raw material for processing or manufacturing. In addition, two large impact craters with diameters surpassing 100 km can be found in the region. McLaughlin impact crater and Oyama crater (Fig. 3). Craters of this size impacting during deposition of the clay-bearing sequence could have also created hydrothermal environments that lead to formation of important ore deposits [50].

4.2. Large deposits in Juventae Chasma

Juventae Chasma represents another interesting exploration target. It

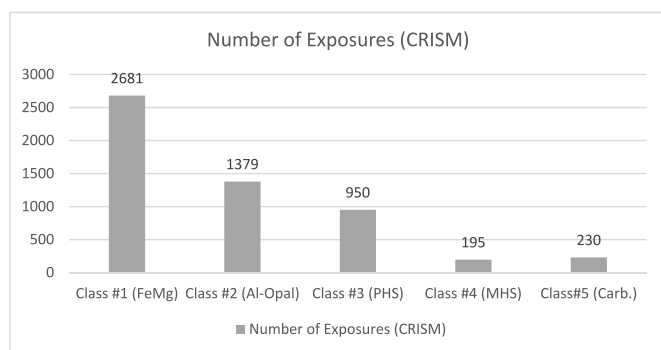


Fig. 1. Diversity of hydrated minerals on Mars, compiled after [35]. The detections are sorted into five spectral classes encompassing the entire diversity found by the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) pinpoint detections. Class #1: Fe/Mg phyllosilicate clay (smectite, vermiculite and chlorite group), class #2: Hydrous aluminosilicates (Al-smectite, kaolins, hydrated silica), class #3: Poly/Semi-hydrated sulfate (PHS), H_2O or OH bearing, class # 4: Monohydrated sulfate (MHS), class #5: Carbonates.

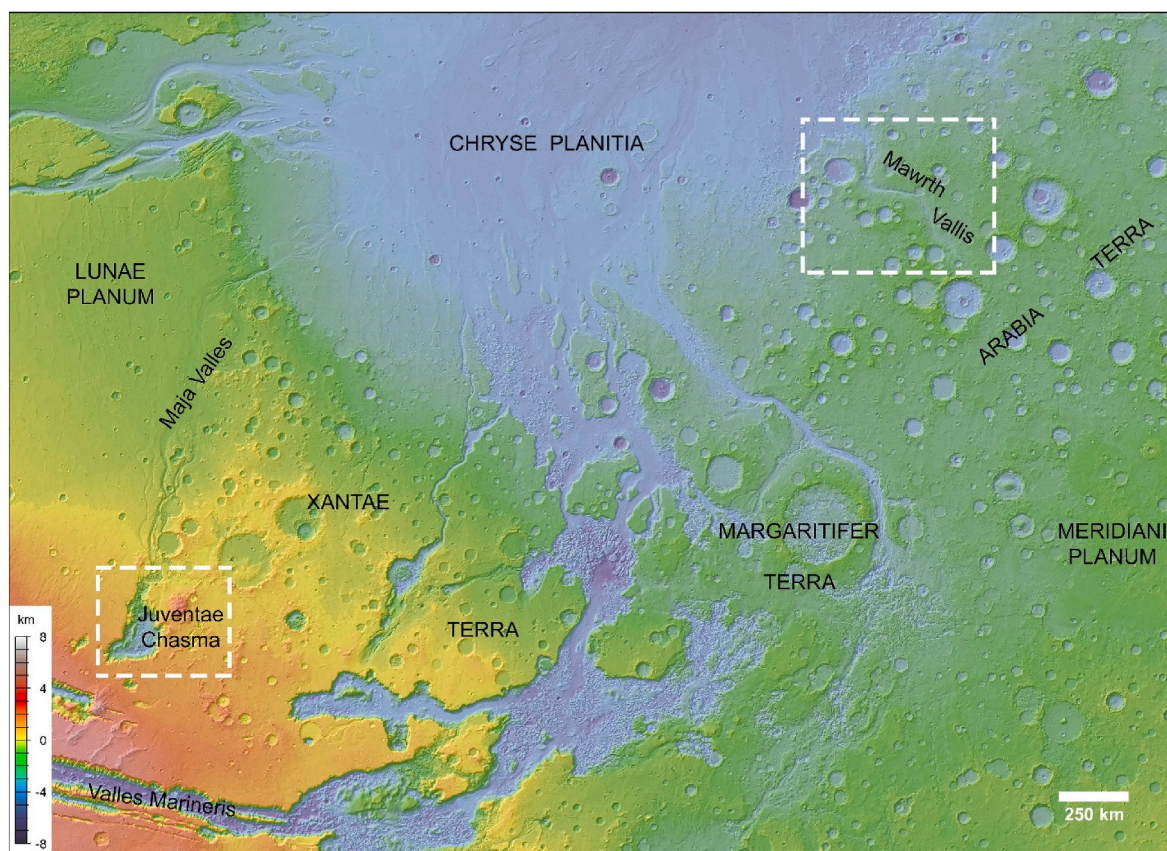


Fig. 2. Color-coded Mars Orbiter Laser Altimeter (MOLA) map showing the example regions of our case study in dashed white box. Note that large mounds can be spotted in Juventae Chasma at this scale. North is up. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

is a >5 km deep basin located north of Valles Marineris at 4°S and 298°E, extending ~190 km in east-west and ~270 km in north-south direction. To the north, the chasma is connected to the Maja Valles outflow channel. Juventae Chasma contains four light-toned layered mounds, or Interior Layered Deposits (ILDs), informally named A to D [51,52] from south to north (Fig. 4). An early study using images collected from the OMEGA spectrometer on board Mars Express first discovered that the ILDs are composed of monohydrated (MHS) sulfates with one water molecule and PHS, which have multiple water molecules built in their structure [53]. The ILDs have high albedos and are much lighter in tone than the surroundings. They show thermal inertia values between 350 and $850 \text{ J m}^{-2} \text{ s}^{-1/2} \text{ K}^{-1}$ [52], that the ILDs consist of dust covered sedimentary rock. The deposits are very large, ranging from the smallest mound A 25.15 km^3 to the largest mound C with 1028.23 km^3 [54]. The majority of the MHS exhibits a kieserite signature. The PHS show different Mg and Fe-PHS phases such as for example starkeyite ($\text{MgSO}_4 \cdot 4\text{H}_2\text{O}$) [55]. The high H_2O content makes these deposits especially interesting for water extraction [56]. In addition, the hydrated sulfate materials could be used for nutrient solutions in hydroponic systems.

As mentioned before, Juventae Chasma is not the only hydrated sulfate-bearing deposit of this kind. Similar deposits can be found in many chasmata throughout Valles Marineris such as Candor, Eos, Ganges, Hebes, Melas, Ophir, and Tithonium, Chasmata [32,53,57–59]. In comparison to many other ILDs, especially the massive stratigraphy found in Meridiani Planum, the deposits in Juventae Chasma show a relatively uniform mineralogy and are found standing quite freely, not capped by an overburden so that unhindered access to the resources appears possible.

4.3. Advantages and disadvantages of the regions of interest

Due to their respective unique geology and mineralogy, Mawrth Vallis

and Juventae Chasma have both been proposed multiple times as potential landing sites for robotic Mars missions (e.g. Refs. [60–62]. Horgan et al. [49] investigated the Mawrth Vallis region as a potential goal for human missions to the surface of Mars due to its great mineralogic diversity and resource potential. However, we differentiate here between short-term exploration missions and outposts for extended or even permanent stays. Short missions may require fewer and more specific raw materials than extended stays and logically have less time for accumulation and production of the specific resource. Energy consumption for water extraction is much higher for phyllosilicates than for polyhydrated sulfates [21]. Mawrth Vallis offers an easily accessible site with a high diversity of minerals in a reasonably small space. This means that travel distances from the deposit to the processing site could be minimized. From a scientific point of view, Mawrth Vallis is an exceptionally interesting place for geology and astrobiology and is located directly at the dichotomy boundary, facilitating potential scientific excursions in all cardinal directions. However, the region is mostly composed of phyllosilicate deposits and only a few localized hydrated sulfate deposits were detected from orbit. While polyhydrated sulfates can already start to dehydrate at room temperature (see section 5.), smectites typically only start dehydrating at $35 \text{ }^\circ\text{C}$ [63,64]. In addition to this, the physical properties of clays (plasticity, swelling properties) might also represent a challenge for automated excavation and dehydration, for example in an Auger dryer. This could mean that higher energy consumption would be required for water extraction at this region.

Juventae Chasma stands out for its extraordinarily large and relatively uniform hydrated sulfate deposits. Like many other sulfate deposits on Mars, Juventae Chasma is located in a deep canyon, which could make exploitation difficult. If we assume, however, automated machinery excavating and processing raw materials in preparation for a human arrival on Mars, remote “production sites” are quite conceivable. Also, natural sulfate deposits tend to be relatively soft and friable and

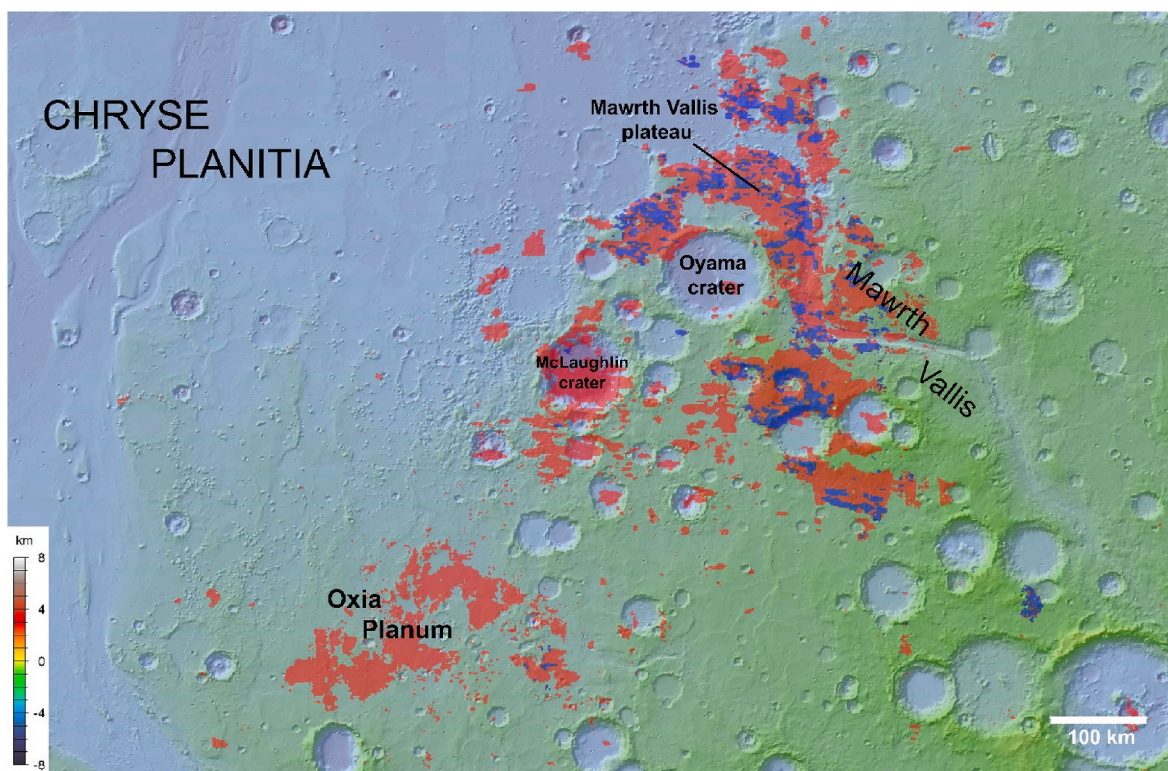


Fig. 3. MOLA map of Mars showing CRISM and OMEGA detections of the clay-rich outcrops in the Cryse Planitia region. Fe/Mg phyllosilicates (nontronite, saponite, chlorite and serpentine) mapped in red. Al/Si-rich clays (kaolins, smectites, opal and allophane) shown in dark blue. Note the important deposits in the Mawrth Vallis plateau. Data derived from ExoMars landing site study [48]. North is up. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

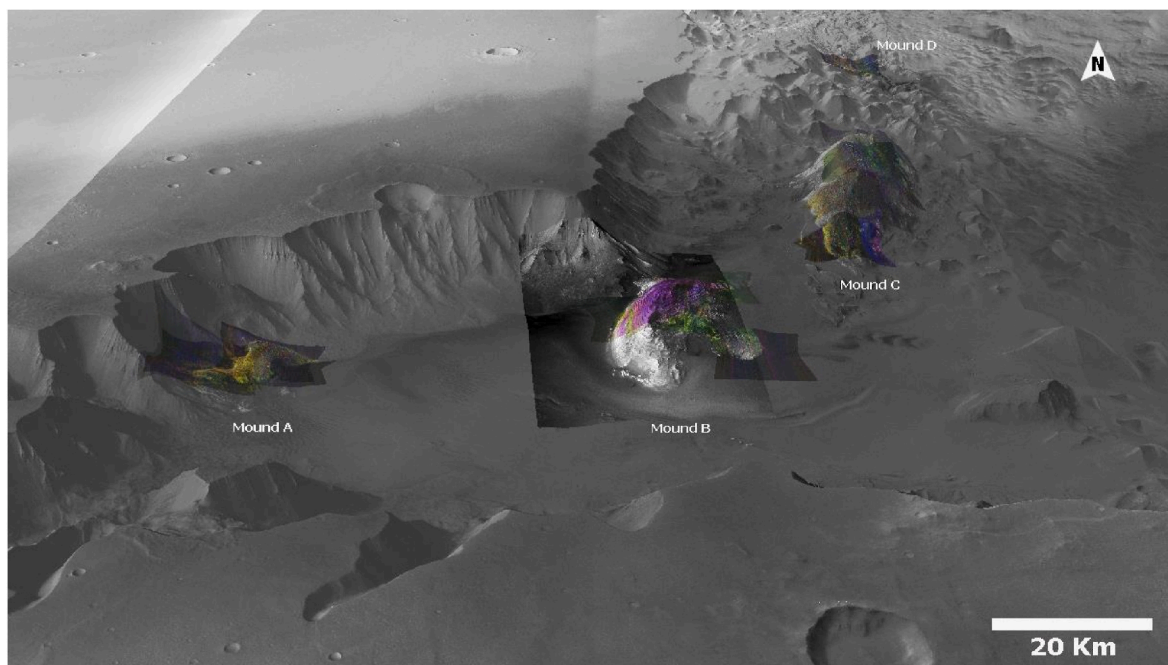


Fig. 4. Oblique view of the sulfate-bearing mounds in Juventae Chasma. HRSC image mosaic and digital elevation model. CTX image (mound B) and CRISM overlay showing polyhydrated sulfate in purple and monohydrated sulfate in yellow. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

might therefore be better suited for automatic mining activity. The continual advancement in drone technology and the very successful technology demonstration of the Ingenuity helicopter of the Mars 2020

mission [65], for example could play a role in this respect. Furthermore, it is possible to quantify the resources if we consider the deposits are relatively homogenous and to measure potential reserves.

5. Extraction and quantification water resources from hydrated sulfates

A sufficient amount of water is an essential requirement for an extended stay on Mars. As already indicated above, it is quite conceivable to harness the water contained in hydrated sulfates, for this purpose. Among all the aforementioned water reservoirs, water extracted from sulfates appears to be, according to the current state of science, the most plausible Earth-independent water resource on Mars. However, the presence of impurities in natural mineral outcrops should also be considered, especially when explored by means of remote sensing as in the cases described here. If we assume a deposit composed of 80 % of the hydrated mineral phase of interest and 20 % detritus, the water content is then reduced by 20 %.

The dehydration of mono- and polyhydrated sulfates is theoretically relatively straightforward, fast, and energy-efficient to conduct. In early experiments, Ide [66] investigated the hydration and dehydration of MgSO_4 hydrates. He describes that the dehydration of PHS such as epsomite $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$ begins spontaneously in a dry atmosphere at 20 °C. According to Ref. [66], in a high-vacuum pump using the desiccant P_2O_5 , it is possible to establish a water concentration gradient that leads to significantly faster dehydration to anhydrite (e.g. MgSO_4). On the other hand, the removal of water from kieserite, resulting in the formation of anhydrite MgSO_4 , is only achievable through heating to a dehydration temperature exceeding 360 °C (see also [67]).

Heide [68] investigated the ‘Influence of Mechanical Stress on Salt Hydrates’ and observed significant changes during sample preparation, especially when crushing the sample. He describes that the magnesium sulfate mirabilite $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$ is unstable at temperatures above 32 °C and normal humidity (~30–50 %). He notes that due to mechanical stress, the mineral’s spectral signature was no longer measurable. According to Heide [68], epsomite $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$ reacts like mirabilite under mechanical stress. In 1966, Heide demonstrated thermogravimetrically in a ‘Brief Original Communication’ that epsomite ($\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$) releases 1 mol of H_2O , similar to bound water, to form hexahydrate ($\text{MgSO}_4 \cdot 6\text{H}_2\text{O}$) at temperatures above 52 °C. Gently crushing the sample at 52 °C would already be sufficient to initiate the dehydration process. At 103 °C, the loss of precisely 1 mol of H_2O is measurable [69]. The reverse process of rehydration leads to anhydrous magnesium sulfate being hydrated to hexahydrate, and kieserite is directly hydrated to heptahydrate. This process of dehydration and rehydration could serve another vital function, in addition to in-situ water extraction. Posern [70] and Okhrimenko et al. [71] describe a ‘thermochemical heat storage’ system that can be adapted for Mars. The dehydration-hydration-rehydration reactions of magnesium sulfates are always endothermic-exothermic reactions.

Ide [66], Braitsch [72], Okhrimenko [71], and others focused on the transitions of Mg and Fe sulfates in detail. In practical applications for water extraction, it would be sufficient to set the specific temperatures from 170 °C to 360 °C to effectively remove the required water from the respective sulfate. The expected amount of water can be calculated both stoichiometrically in moles and, based on the respective percentage, of water in the sulfate. Kieserite consists of 87 % MgSO_4 and 13 % H_2O . Hexahydrate already has a water content of 47 %, while epsomite has 51 % H_2O . This means that 1 m^3 of kieserite contains 130 L of water, whereas for hexahydrate and epsomite, it is 470 L and 510 L of water, respectively. For the sulfate mounds described at Juventae Chasma, the volumes of the hydrated sulfate deposits were mapped in an ArcGIS environment using a bundle block adjusted HRSC DTM with 50 m resolution per pixel and an HRSC image with 12.5 m resolution overlain. The average maximum deviation in the datasets is described to be less than 1.5 % [73]. Thus, the Juventae Chasma deposits alone could provide sufficient water for generations (see Table 1).

5.1. Valuable additional products from hydrated minerals

In addition to a water resource, phyllosilicate minerals offer a variety of other valuable uses for human outposts. Phyllosilicates could, for example, be used to produce ceramics [75]. The large specific surface area of the phyllosilicate particles and the ability of smectite clays to exchange cations also allow for the usage of these clays as ion exchangers for example as a filter for water treatment or for decontamination purposes. The clay mineral chlorite can for example be used as filler in plastic materials or in joints and gaskets. Foamed clay, a very porous, burned clay product can be used as building insulating material and for hydroponics. The utilization of Martian clays as construction material has also been studied [76].

A BLSS system can provide access to fresh vegetables and fruits during long-duration missions. Particularly beneficial are for example plants with high water content that are prone to quality degradation if stored for extended periods of time. In particular, crops such as tomatoes, peppers, cucumbers, various types of lettuce, radishes, spinach, various herbs (basil, chives, parsley, mint, coriander) and strawberries. The EDEN ISS project had a mobile test facility undergoing trials in Antarctica from 2018 to 2022, aiming to enable the production of essential resources like food, oxygen, and water [17]. To cover the nutritional needs of different plants in a hydroponic system, the Hoagland solution has been the proven method used for decades [77]. The Hoagland solution provides all essential elements for plant nutrition and, at different dilutions and with some modifications, is appropriate for supporting growth for a wide variety of plants [78] and was used for the EDEN ISS mission. The used amounts of fertilizer salts used are described in Table 2.

Evaluating the fertilizer compounds listed in Table 2, it becomes clear that important fractions of species could be provided directly on Mars. Minerals mined from hydrated sulfate deposits could be used in pure form, without refinement as a component of the nutrient solutions in hydroponic systems for food production in BLSS systems. The nitrogen and phosphorus compounds are readily available in stored astronaut urine, in parts showing better growth results than conventional fertilizers [80]. This leaves magnesium sulfate as the last high-consumption compound, to a certain extent a waste product from water extraction. Other (lower-consumption) elements for a nutrient solution like for example boron [81] or copper [82] and zinc [83] have also been detected on Mars by landed instruments. If all of these fertilizer compounds could be found or produced on Mars, the supply from Earth for fertilizer per crewmember could be reduced by roughly 94 kg per year if we assume a median cultivation space of 50 m^2 per crewmember [18–20]. However, even 282 kg of fertilizer per crewmember for a 3-year mission are an important logistical aspect, also compared to the 3600 kg of normally hydrated food or the 840 kg of 90 % dehydrated food required [11] as described in section 2.

6. Conclusions

Mars offers abundant raw materials that are of potential value for future human endeavors. Numerous vital elements can be found directly at the surface. The natural geological variations in ore deposits can

Table 1

Calculated water content in liters (L) for specific hydrated and polyhydrated sulfate minerals. The volumes of the selected mounds in Juventae Chasma derive from HRSC measurements as described in [54,74]

Mound	Volume [km ³]	Water content in Kieserite $\text{MgSO}_4 \cdot \text{H}_2\text{O}$ [L · 10 ¹²]	Water content in Hexahydrate $\text{MgSO}_4 \cdot 6\text{H}_2\text{O}$ [L · 10 ¹²]	Water content in Epsomite $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$ [L · 10 ¹²]
A	25.15	3.27	11.82	12.83
B	213.28	27.73	100.24	108.77
C	1028.23	133.67	483.27	524.40
D	104.01	13.52	48.88	53.04
Total	1370.67	178.19	644.21	699.04

Table 2

Nutrient demand of various plants during the EDEN-ISS 2018 experiment phase (9 months). In total, 268 kg of fresh, edible biomass was produced on 12.5 m². Adapted from Ref. [79].

Nutrient	Nutrient Requirements for Leafy Crops [g]	Nutrient Requirements for fruity crop [g]	Total nutrient consumption [g]
Calcium nitrate [Ca(NO ₃) ₂ ·4H ₂ O]	2548.00	4417.50	6965.50
Ammonium nitrate [NH ₄ NO ₃]	272.72	579.20	851.92
Iron chelate DTPA (11.4 %) [C ₁₄ H ₁₉ FeN ₃ NaO ₁₀]	52.08	80.96	133.04
Calcium chloride [CaCl ₂]	105.00	184.00	289.00
Potassium nitrate [KNO ₃]	2374.40	3192.60	5567.00
Magnesium sulfate [MgSO ₄]	364.00	870.40	1234.40
Magnesium nitrate [Mg(NO ₃) ₂ ·7H ₂ O]	193.20	0.00	193.20
Potassium sulfate [K ₂ SO ₄]	0.00	572.80	572.80
Monopotassium phosphate [KH ₂ PO ₄]	722.40	1164.80	1887.20
Manganese sulfate [MnSO ₄ ·H ₂ O]	0.896	11.136	12.032
Zinc sulfate [ZnSO ₄ ·7H ₂ O]	1.960	7.584	9.544
Borax [Na ₂ B ₄ O ₇ ·10H ₂ O]	7.582	13.184	20.766
Copper sulfate [CuSO ₄ ·5H ₂ O]	0.473	1.312	1.785
Sodium-molybdate [Na ₂ MoO ₄ ·2H ₂ O]	0.274	0.800	1.074

significantly impact viability of exploration sites and of the engineering architecture. The mining site must not necessarily be located close to the crewed habitat if robotic mining is possible and transportation feasible. Therefore, comprehension of these features is crucial for selecting and optimizing a particular technical design. This underlines the need for accurate resource exploration missions. Refinement and restructuring must be investigated to provide reliable fabrication systems since ISRU indeed is able to drastically cut down logistical dependence from Earth.

We have demonstrated that the exploration of hydrated sulfate deposits bears a number of key advantages. The most important resource is water. By mining (poly) hydrated sulfate minerals for water extraction, valuable by-products can be won. Dehydration-hydration-rehydration of Mg-sulfates are exothermic/endergonic reactions that could be used as a heat source (e.g. day/night cycles).

We investigated two case studies of potential landing sites, Juventae Chasma and Mawrth Vallis. Juventae Chasma offers abundant water resources in extraordinarily large and relatively uniform hydrated and polyhydrated sulfate deposits, not mantled or capped by overburden. The Mawrth Vallis example offers a wide variety of hydrated minerals across a broad region that is readily accessible. This region clearly demonstrates the need for more landed prospector missions to such targets in order to precisely map and examine specific deposits for potential ISRU use. This also applies to the Meridiani Planum region where, despite a landed rover mission many open questions remain. Immense water masses are stored in the Meridiani rocks, maybe representing the largest accessible water deposit on the planet known to date.

Thus, gathering this crucial information should be the near-term main goal of future exploration expeditions. The knowledge of the surface and subsurface, as well as precise dimensions of potential resource regions are required in order to establish “reserves” for a future presence of human settlements on Mars.

CRediT authorship contribution statement

Christoph Gross: Writing – review & editing, Writing – original draft, Supervision, Resources, Investigation, Conceptualization. **Muna Al-Samir:** Writing – original draft, Validation, Formal analysis, Data curation. **Janice L. Bishop:** Writing – review & editing, Validation, Investigation, Formal analysis. **François Poulet:** Writing – review & editing, Validation, Investigation. **Frank Postberg:** Writing – review & editing, Formal analysis. **Daniel Schubert:** Writing – review & editing, Validation, Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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