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Executive Summary / Abstract:

Planetary geologic and geomorphic mapping for targeting resource mapping, such as volatiles and mineral resources are introduced. Main applications and drivers for resources on planetary bodies, mainly the Moon and Mars, are listed. The type of resources and their geologic context and related processes are introduced. Methods, techniques and datasets used in the search for resources are introduced and briefly described. Exemplary mapping and scientific efforts are listed. Future applications of earth-based mineral resource prospection and mapping will be needed, provided suitable datasets are available.

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- **List of acronyms and abbreviations**

Table 1: Acronyms and abbreviations

Acronym	Description
API	Application Programming Interface
CaSSIS	Colour and Stereo Surface Imaging System
CRISM	Compact Reconnaissance Imaging Spectrometer for Mars
CUGB	China University of Geosciences Beijing
ESA	European Space Agency
FAIR	Findable, Accessible, Interoperable, Reproducible
FREND	Fine Resolution Epithermal Neutron Detector
GUI	Graphical User Interface
HiRISE	High-Resolution Imaging Science Experiment
ISRU	In situ resource utilisation
JRA	Joint Research Activity
KREEP	Potassium, Rare Earth Elements and Phosphorus
LIPs	Large igneous provinces

LMO	Lunar Magma Ocean
NA	Networking Activity
NS	Neutron Spectrometer
MARSIS	Mars Advanced Radar for Subsurface and Ionosphere Sounding
MEX	Mars Express Spacecraft
MOST	Ministry Of Science and Technology
MRO	Mars Reconnaissance Orbiter
MSR	Mars Sample Returns
NASA	National Aeronautics and Space Administration
OMEGA	Observatoire pour la Minéralogie, l'Eau, les Glaces et l'Activité
PDS	Planetary Data System
PSA	Planetary Science Archive
RDM	Research Data Management
SHARAD	Shallow Radar
TGO	Trace Gas Orbiter

USGS	United States Geological Survey
UVVIS	Ultraviolet visible camera
VA	Virtual Access

Introduction

A variety of natural resources can be found at the surface of Inner Solar System terrestrial planetary bodies. While their exploitation for Earth applications does not seem economically viable (at least in the near future), long-term human missions to the Moon or Mars might benefit and take advantage of locally available resources. For example, as payload capacity is limited in space travel, the locally available water, building material or even locally produced fuel could allow more ambitious and longer-term missions.

This document intends to provide references and introductory materials regarding natural resources that can be found on the planetary bodies that will be targeted for future human exploration, that is Mars and the Moon. After a non-exhaustive overview of resource types and reservoirs, as well as the associated geological processes, exploration methods and implementation of geological mapping are discussed below.

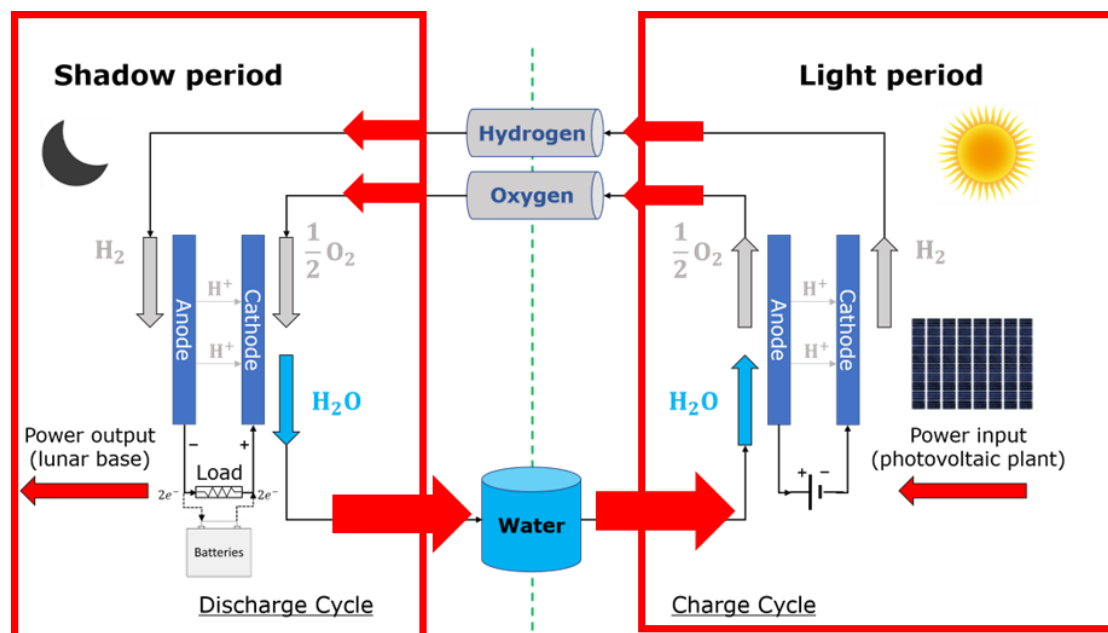


Figure 1: Workflow proposal on In-Situ energy and fuel production from H₂O. Credit: ESA-PANGAEA.

1. Resource applications

1. 1.1. In-situ propellant production

During the Apollo program, a fully-fuelled Saturn V rocket had a mass of more than 2800 tons whereas its dry mass was more than 10 times less, highlighting the staggering proportion of propellant mass with respect to the launcher's total mass. The ascent stage of the Apollo Lunar Module had a dry-mass equivalent of 44% of the total mass. The amount of propellant required for lift-off represents a constraint to the mass of the payload that every mission is able to put in space, limiting propeller availability for the return to Earth. If alternative sources of fuel could be used (i.e., exploiting materials available on the Moon's surface), the prices and efficiencies of the missions may improve greatly. While taking off the surface of the Moon is a technical challenge (even with its low gravity and lack of atmospheric drag), it is relatively easier than leaving Mars' surface. Consequently, no mission has ever attempted to take off from the surface of Mars to reach Mars' orbit. Through several missions in the coming years, the NASA-ESA joint Mars Sample Return (MSR) campaign intends to return back to Earth the first samples from the surface of Mars, (Meyer et al., 2022). Therefore, it is clear that in-situ propellant production is one of the keys to allow long-term return missions to the Moon, and Mars.

On the Moon, proposals have been made to produce fuel and oxidizer by extracting H_2 and O_2 from potential water ice reservoirs in shadowed craters, regolith or hydrated minerals (**Figure 1**) (Anand et al., 2012). On Mars, atmospheric CO_2 combined with H_2O found in water ice reservoirs could be used to produce CH_4 and O_2 through the Sabatier reaction (Starr and Muscatello, 2020).

1.2. Building material for habitats and resources for survivability

Another solution to reduce the payload at launch and allow long-term missions would be the construction of a habitat for future astronauts employing locally available materials. On the Moon, several proposals were made to use widely available lunar regolith to produce concrete which could be used to build shelter for astronauts (Cesaretti et al., 2014, Davis et al., 2017). With such material, the thick-walled and sustainable habitat would protect them from extreme temperatures, radiations or micro-meteorite impacts. The production of such material may require water; however, some studies proposed some synthesis solutions that would not require any (e.g. Wang et al., 2017).

Although metallic and non-metallic mineral resources are more complex to use, they could become valuable assets for industrial purposes in later stages of exploration. For example, it is probable that lunar or Martian habitats will rely on solar cells to obtain energy, hence the use of locally gathered silicon and other metals would facilitate the production and maintenance of these systems and the associated electrical infrastructure (Abbud-Madrid, 2017). Metals are also valuable in several other technological applications, and as they can be by-products of first-need processes, such as the extraction of oxygen by metalysis (Lomax et al., 2020), their eventual exploitation would facilitate a sustained presence of humans in space.

Extracted oxygen and water from mineral water-ice resources could be used for survivability as well and would reduce the need of a full-recycling process as it exists onboard the International Space Station. This would add redundancy to survivability, increasing the astronauts' safety, and reduce regular supply needs in material related to it.

2. Resource type, reservoirs and geological processes

2.1. Water and other volatiles

Since the beginning of lunar exploration, due to extreme temperatures during the diurnal phase and the lack of atmosphere, the surface of the Moon was thought to be completely deprived of volatiles. However, recent observations have revealed that water is present today at the surface of the Moon in the form of ice (Feldman et al., 1998), hydroxyl (OH) in mineral phases and absorbed within regolith grains (Clark, 2009; Pieters et al. 2009), within volcanic glasses (Saal et al. 2009).

Similarly to the Earth, primitive water could have been delivered to the Moon during late accretion through comets and chondritic asteroids (Svetsov and Shuvalov, 2015). Among the various mineral phases found in lunar samples collected during the Apollo program, only apatite has been found to contain a measurable amount of hydroxyl, with a concentration up to ~15000 ppm and ~3400 ppm in lunar mare and highland samples, respectively (Barnes et al., 2013, 2014).

It was suggested that permanently shadowed craters could exist on the polar regions of the Moon where the sublimation rate of any water ice there would be low enough for it to be preserved over several billions of years (Watson et al., 1961, Siegler et al., 2015).

On Mars, water ice is extensively present at the poles (e.g., Titus et al., 2003; Vos et al., 2022), but groundwater ice appears to be also spatially widespread at mid to high latitude, including at shallow (i.e., relatively accessible) depths (e.g., Harish et al., 2020). Hydrated minerals are instead frequent all over the Martian surface (Carter et al., 2013, 2022; Riu et al., 2022).

2.2 Mineral resources

The search for volatiles in planetary settings has been a strong research topic in recent years; this is logical as fuel supply and life support systems are the primary challenges as space exploration is entering a new era of hopefully extended presence of humanity on extra-terrestrial bodies. Although the importance of volatile exploration is indisputable, there is no harm in looking ahead to the mineral resources that would eventually support industrial processes and habitability on the Moon and Mars.

Mineral resources can be roughly divided into metallic and non-metallic for description purposes. The first ones are related to typical industrially used metals such as Fe, Al, Ti, Mg, Cr and the platinum group elements (PGE - Pt, Ir, Os, Ru, Rh, Pd) (Crawford, 2015); and the non-metallic are other useful light elements such as Si, O, P, S and N mainly. All the prior elements are somewhat available on the Moon and Mars, so it is worth understanding the geological processes that can lead to their concentration.

2.2.1 Primary differentiation

The geological configuration of the Moon and the resources associated with it are greatly defined by its early formation stages and the modification processes that followed. The most widely accepted theory about the formation of the Moon is the giant impact, where a Mars-sized object impacted the Earth (Hartmann and Davis, 1975). Two significant consequences of this process are the near absence of volatiles in the lunar mantle and crust (Geiss and Rossi, 2013), and the subsequent formation of the Lunar Magma Ocean (LMO). This enabled a strong differentiation between an olivine-pyroxene-rich mantle, a middle layer enriched with incompatible elements called KREEP, and a plagioclase-rich crust (Hubbard et al., 1971). From

this initial state, the geologic evolution of the Moon can be divided into four big stages, which define the current lunar terrains.

First, the crystallization of the LMO occurred around 4.4 Ga (Nemchin et al., 2009), giving place to the lunar highlands, mainly composed of ferroan-anorthosite (FAN), due to the strong differentiation suffered by these rocks, they are usually enriched in Al and Ca, which is reflected in their derived soils, which may be recoverable. The second stage corresponds to the emplacement of intrusive rocks in the lunar crust, and although they can hardly have reached the surface due to their high density, secondary processes such as massive impacts could have excavated them. The lunar intrusive rocks vary in composition, but the samples returned by the Apollo missions showed interesting concentrations of Cr in chromite and Cr-spinel, Fe-Ni-metal, and phosphates enriched in REE such as apatite and RE-merrillite (Shearer et al., 2015). In the third stage, between 4.1 and 3.0 Ga (Hartmann and Davis, 1975), the lunar maria formed by the impact of large asteroids, as large volumes of basaltic lavas filled the basins created after the collisions. Lunar maria are probably the most desired locations for mineral retrieving, as they are typically enriched in Mg, Fe, O, Si, and Ti (Anand et al., 2012, Rasera et al., 2020). Finally, the late stage consists in the later modification of the prior rocks by space weathering and tectonics, which will be addressed afterwards.

The KREEP rocks deserve a special mention, as they are a primary target due to the amount of rare elements present in them (Figure 2). Their name comes from their enrichment in K, REE, and P. They are mainly accumulated in the Imbrium and Procellarum basins, but lower accumulations are also present in other ancient locations such as the Apollo basin. These rocks are thought to have formed between the crust and the mantle, as an accumulation of incompatible elements, although it is not clear how they reached the surface, they may have been incorporated in the upwelling basalts that filled the basins (Warren and Wasson, 1979) or exposed and ejected by the Imbrium basin impact at its margins and surroundings (Hiesinger and Head, 2006)

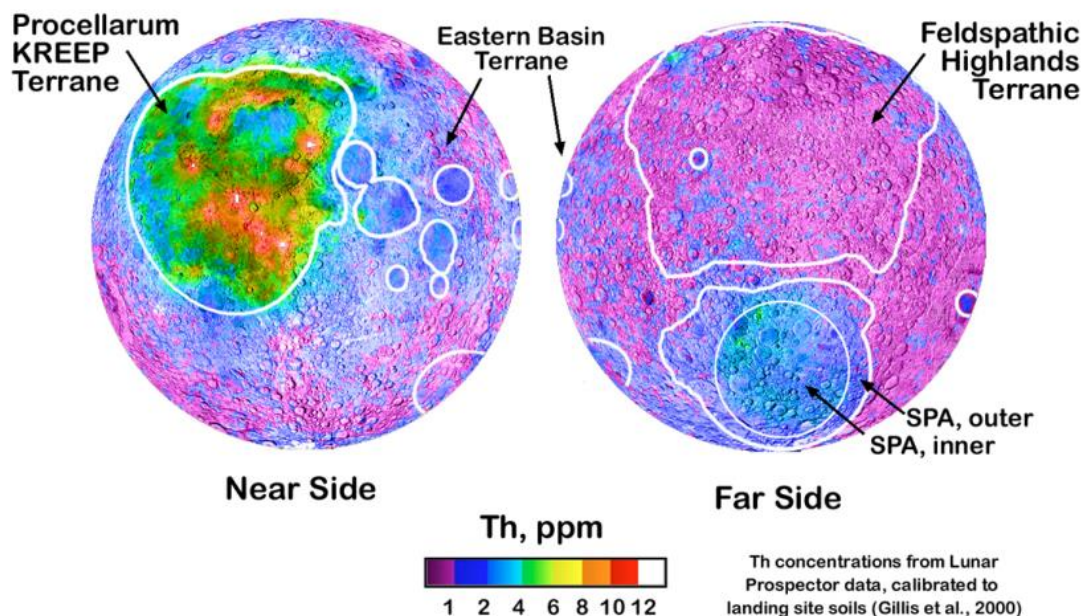


Figure 2: Distribution of KREEP rocks on the surface of the Moon, which is related to the amount of Th (Jolliff et al, 2021).

The case of Mars is more complicated, as the red planet has overcome several episodes of resurfacing and its early geological configuration is not totally clear. If Mars had a global magma ocean in its first millions of years of existence, it is believed that it quickly differentiated into crust, mantle, and core (Kruijer et al., 2017). The Martian crust is considerably less differentiated than that of the Earth, so it had a bulk mafic composition, with occasional anorthositic terrains in the older terrains. Following the initial differentiation, the Martian surface was the subject of massive volcanic extrusions, fed by mantle plumes that lasted several millions of years. These activities created large igneous provinces (LIPs), especially around the Tharsis region, where multiple shield volcanoes and pateras dominate the landscape. On the Earth these geological settings tend to be enriched in siderophile elements such as Ni, Cu, Ti, PGE, Fe; so similar deposits could be expected on Mars, especially around Vallis Marineris and the walls of big impact craters, where older sequences may be exposed (West and Clark, 2010).

Other less understood and potentially interesting systems are dyke swarms, emplaced during late-stage magmatism in structurally weak regions. They can vary in scale, from generating large grabens around the Tharsis region to covering the floor of the Chasmata that lies parallel to Vallis Marineris (Mège and Gurgurewicz, 2016). Basaltic dykes on Earth are associated to important ores of PGE, Au, Pt and Cu, so they could be an interesting target on Mars, especially the ones that show relationships with water-rich systems, for example in the floor of Ophir Chasma or the Syrtis Major region (Bramble et al., 2017).

2.2.2 Hydrothermal and other secondary processes

The accumulation of ore minerals can also be the result of secondary processes, and in some cases, it might be even greater than in primary sources. The most sought of these environments are the ones related to hydrothermal alteration of pre-existing rocks, as they have been a major source of valuable minerals on Earth. Other examples of secondary systems are evaporitic deposits, mineral-enriched sediments, and crater impact systems.

Hydrothermal activity on the Moon should be most probably discarded due to the lack of water in its interior (Geiss and Rossi, 2013). Nevertheless, other volatiles may have played a role in the formation of apatite veins and the few pyroclastic deposits that have been detected on the Moon's surface (Jolliff et al, 2021). These volatiles, probably rich in S, and CO₂, might have mobilised important recoverable quantities of Fe, Ni and Co (Shearer et al., 2015). On the other hand, hydrothermal activity is probably a game-changer in terms of Martian resources availability. It is already well known that in the Noachian and Hesperian period of Mars, water was present both on the surface and in subsurface systems, which in combination with the extended volcanic activity in the Tharsis region, created an optimal environment for hydrothermal alteration to occur (West and Clark, 2010). The advantage of hydrothermal alteration is the constant mobilisation of metals by fluids enriched in Cl, S, P, or CO, which could give place to the accumulation of several valuable metals (Zn, Pb, As, Ag and Au). A special type of hydrothermal activity is the one induced by meteoritic impacts, which are common on Mars. In this scenario, the circulation of heated fluids and cooling melts mobilise metals from the crustal rocks and the meteorite itself (West and Clark, 2010). These scenarios are particularly attractive, as the extreme stress during the impacts would have formed severely fractured regions where the fluids could mobilise and deposit their load (**Figure 3**).

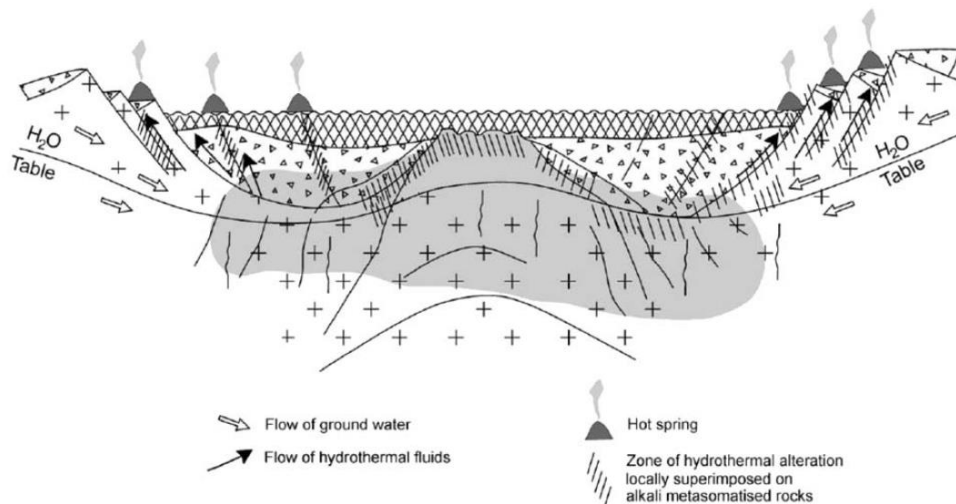


Figure 3: Structure of and hydrothermal system induced by a meteoritic impact (from West and Clark, 2010).

The wet past of Mars is not only important for its role in the hydrothermal activity, but other processes also involving water diversify on resource opportunities on Mars compared to the Moon. The ancient water reservoirs on Mars are usually covered by large sequences of phyllosilicates, hydrous sulphates, oxides, and evaporitic deposits. All the prior groups of minerals contain valuable industrial materials such as gypsum, kieserite, jarosite, hematite, montmorillonite, and others (Wang et al., 2006). Two remarkable examples of these processes are the “blueberries”, hematite spherulites found by the Opportunity rover, and the large deposits of phyllosilicates and sulphates across the floor of Vallis Marineris.

Finally, the action of the wind is strong on Mars and might play an important role in sorting and concentrating minerals. As mentioned before, the Martian crust has a general basaltic composition, so minerals like chromite and ilmenite should be eventually sorted and concentrated in black eolic sands and dunes (West and Clark, 2010).

2.3.3 Regolith

The regolith is an important component of planetary surfaces, especially on the Moon, where extended endogenic processes stopped billions of years ago. The regolith is the cumulus of unconsolidated debris produced during meteoritic impacts, it covers basically all of the lunar surface and it might even have several tens of metres of thickness. The regolith is mainly composed of lithics, agglutinates, glass, and some mineral crystals (McKay and Ming, 1990). Due to its extended presence and its mineral variability, the regolith can be the first resource to be exploited in human exploration. Apart from hosting potential fuel propellants and water, it can be a source of oxygen and iron, thermo-chemical reduction and metalysis processes have been proposed to this end (Rasera et al., 2020). Other potential uses of regolith is as construction material for lunar basecamps, its capability to shield cosmic radiation is promising and some ideas of creating “lunarcrete” from regolith have been brought before (Osio-Norgaard and Ferraro, 2016, Meurisse et al., 2020).

Martian regolith would represent a similar type of resource to the one on the Moon. Furthermore, due to its wider mineralogical diversity, it might even be suitable for agricultural purposes, as it contains the main elements needed for the proper development of plants, although their high salinity might be a concern (Fackrell et al., 2021).

3. Detection and reservoir size estimation

3.1. Earth analogues/terrestrial methods

The detection of mineral resources in planetary settings is not an easy task, as usually the only way to obtain information about these rocks is through remote sensing. The estimation of the size and quality of the reservoirs is even more difficult, because of the lack of physical samples to do geochemical analysis, hence there is no reliable way to measure the actual concentrations, distribution or mineral assemblages of the reservoirs. For this reason, the comparison with proven reservoirs on Earth is useful. If a deposit on our planet has the same bulk composition and geologic history as the ones on the Moon and Mars, it is possible that similar element concentrations can occur. Although in no way can this approach confirm the existence of a deposit, it at least allows us to discriminate the valuable mineral that could possibly be encountered in those bodies.

In both Mars and the Moon, the basaltic compositions of their crust constraints significantly the comparisons with Earth, and the difference between the two would be the almost complete lack of volatiles in the Moon. Probably the most relatable analogues are those that originated within basaltic districts; a good example is the Stillwater Mafic Complex in the United States, a Precambrian mafic and ultramafic intrusion that has been mined for more than 100 years to obtain Cr, Cu, PGE, Fe and coal (Page, 1997). As mentioned in the prior section, mafic intrusions were common during the evolution of the Moon and Mars, so similar deposits might be possible. Another good example is the Great Dyke of Zimbabwe, a massive intrusive structure that is the second largest deposit of PGE on Earth (Naldrett and Wilson, 1990). Another possible scenario, derived from the large intrusions, is the contact metamorphism of hosting rocks and the mobilisation of elements, although harder to spot due to its small-scale action, some Apollo samples were classified as hornfels (Pernet-Fisher and Joy, 2021), allowing the possibility of deposits associated with contact metamorphism.

With regards to possible hydrothermal alteration systems on Mars, there are several examples on Earth that could very well represent what can be found there. The hydrothermal alteration of the Northwestern Norrbotten ore Province in Sweden occurs mainly over basaltic sequences and is enriched with iron oxides, Au and Cu (Andersson et al., 2020). Special scenarios are the hydrothermal systems related to meteoritic impacts, even as these events are less likely to happen on the Earth than on Mars, they are usually important locations for mineral exploration. The Sudbury basin is one of the biggest Ni and PGE reservoirs on Earth, and other craters have been also mined or potentially contain diverse deposits (James et al., 2022).

Another two examples are the “blueberries” (Chan et al., 2004), which have been also found on Earth, as the hematite marbles in India (Ray et al., 2021); and the basaltic dunes formed around volcanoes in Iceland and other volcanic islands (Edgett & Lancaster, 1993).

3.2 Spectroscopy

The most powerful tool available for the compositional analysis of planetary surfaces is spectroscopy, a technique that usually takes advantage of the particular reflectance of each mineral across the light spectrum (Zambon et al., 2020). Instruments can be multispectral or hyperspectral, the first ones cover only a few wavelengths (usually 8 or 9) and the second have a wide spectral coverage and a smaller sampling interval (around 50 to 80 channels). The

sampling interval is known as spectral resolution, which in combination with the spatial resolution (pixel size) defines the capabilities of the spectrometer.

Both types of spectrometers have been used in the exploration of the Moon and Mars, either in global or local analysis. Multispectral sensors allow the creation of band composites, a technique that highlights the relationships between wavelengths and hence, between their mineralogical properties. The Ultraviolet visible camera (UVVIS) on board the Clementine mission was a multispectral sensor that scanned the whole surface of the Moon, one of the most interesting products of this mission is the global UVVIS colour ratio, a band composite that is sensitive to the presence of titanium and iron in the surface (**Figure 4**)(Lucey et al., 2000). Another example of a global mosaic is the thorium global map, that was constructed with the Gamma-ray data of the lunar Prospector, and is used to find regions enriched in KREEP (Hagerty et al., 2006).

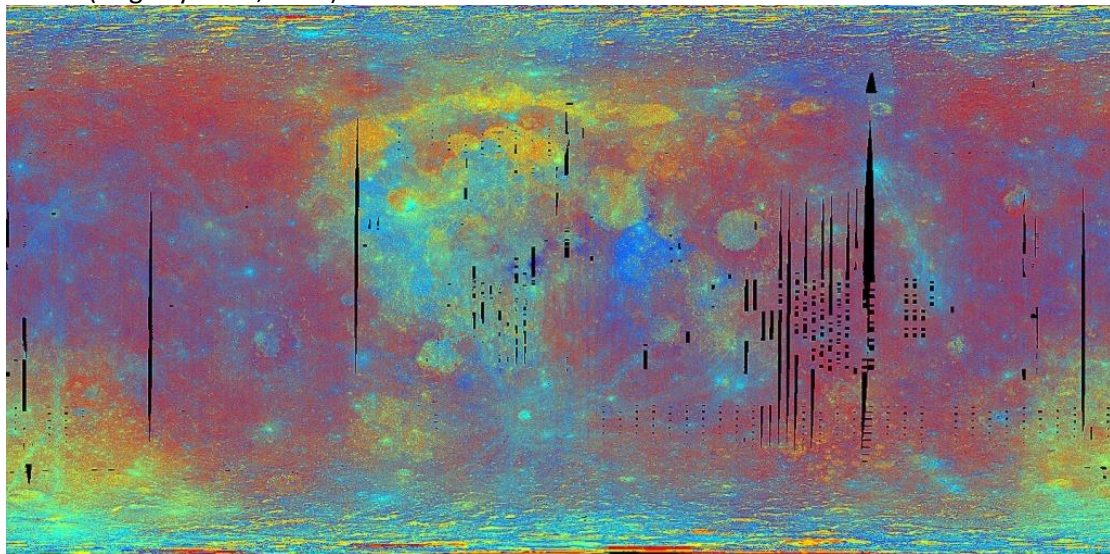


Figure 4: Global UVVIS colour ratio of Clementine. The red channel represents areas that are low in titanium, or high in glass content, the green channel is sensitive to the amount of iron on the surface, and the blue channel reflects the surfaces with high titanium (USGS, 2015).

Although multispectral data can be useful to spot the main differences between terrains, hyperspectral data is necessary to identify specific mineral species. M3 is a hyperspectral sensor onboard Chandrayaan-1; it has a good spectral resolution, but its spatial resolution does not completely allow local analysis. Nevertheless, explorations at local and regional scales are possible and had shown important results. Klima et al. (2011) identified locations with low Ca-pyroxene, which in turn points to locations where ancient plutonic bodies (and their mineralizations) might be outcropping at the surface. Other important spectral indexes that can be applied to M3 data were compiled by Zambon et al. (2020), and even if they don't allow the recognition of specific mineral species, they are powerful tools to characterise the geological setting that could host mineralizations.

The spectral information of Mars is considerably better, as the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) on board MRO (Murchie et al., 2007), or OMEGA (Bibring, et al., 2004) on board MEX have substantial spectral and spatial resolutions (around 19 metres/pixel). The higher spatial definition allows detailed explorations of the Martian surface, especially when coupled with High-Resolution Imaging Science Experiment (HiRISE) data and CaSSIS on board TGO. CRISM has allowed the recognition of the mineral species referred to in the previous section, as the quality of the data allows a direct correlation with laboratory-obtained spectra (**Figure 5**). Good examples of the use of CRISM to recognise minerals are the study of Syrtis Major by Bramble et al. (2017), the characterization of

hydrothermal alteration in Nili Fossae by Brown et al. (2010), and the recognition of iron oxides and phyllosilicates in the flows of Ophir Chasma, by Wendt et al. (2011).

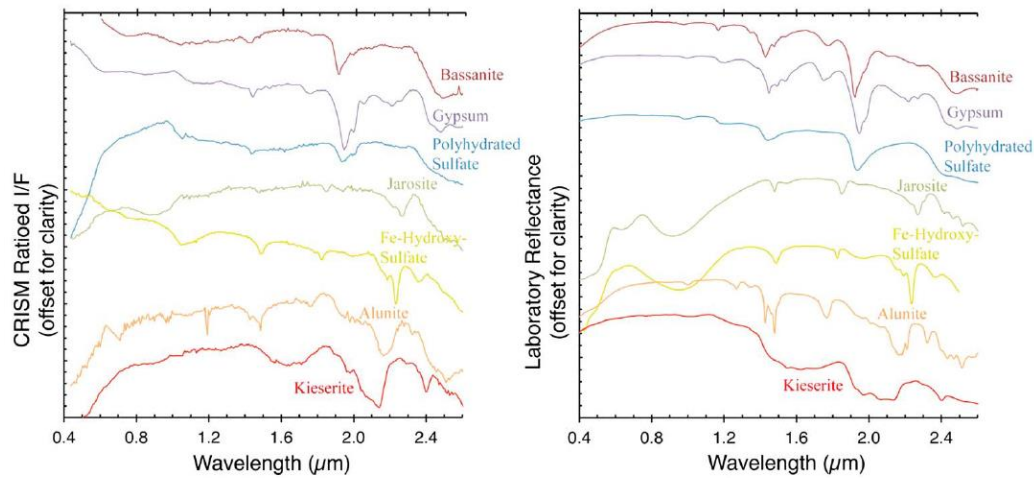


Figure 5: Some mineral spectral signatures recovered from CRISM and their laboratory counterparts. The quality of the CRISM spectra allows safe recognition of minerals, some of them potential ore minerals.

3.3. Detection of ground ice on Mars

Various methods of remote sensing can be used to assess the presence of water near the surface, either by direct detection or by the use of a proxy. On Earth, freeze-thaw cycles of ground ice in periglacial regions can create a range of geomorphological landforms such as patterned ground (Oehler and Allen, 2011), pingos (Grosse and Jones, 2011; Page and Murray, 2006) or solifluction lobes (Johnson et al 2012). Similar features are well visible in high-resolution remote sensing imagery and have been used to infer the presence or the past-presence of ground ice (e.g. Mellon et al., 1997, Mangold et al., 2004).

Similarly to mineral deposits, spectroscopy can be used to detect water ice absorptions but instruments such as OMEGA and CRISM can study only what is right at the surface. In that case, ground ice has to be exposed by new impacts (**Figure 6**) (Byrne et al., 2009) or on scarps (Vijayan et al., 2020).

Ground-penetrating radars, such as the SHARAD instrument onboard Mars Reconnaissance Orbiter (Seu et al., 2004) or MARSIS onboard Mars Express (Jordan et al., 2009) have been used to extensively study the subsurface of the polar ice caps on Mars, which are mainly composed of water and CO₂ ices, layered with dust. Such instruments can probe the subsurface at variable depths (up to 500 m and 5 km, at a vertical resolution of 10-20 m and 50 m for SHARAD and MARSIS respectively - Fois et al., 2007) and might be suited to identify ice patches at shallow depths or liquid water presence Stuurman et al. 2016, Morgan et al., 2021).

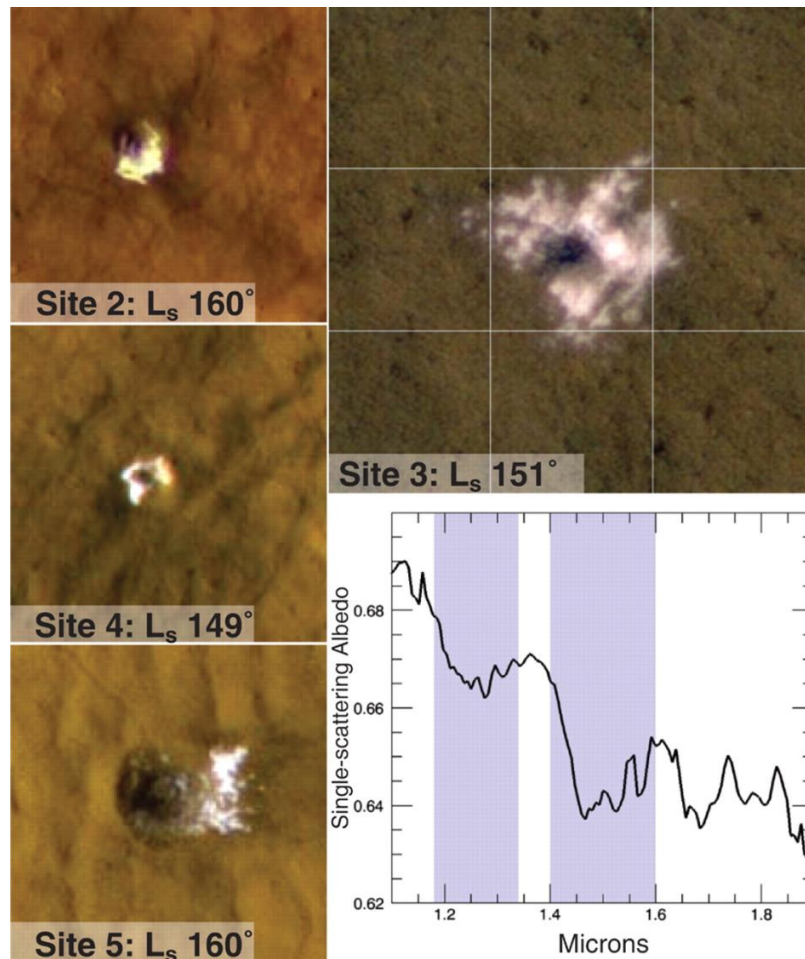


Figure 6: New impact craters visible on HiRISE images exposing ice with a CRISM spectrum showing water-ice absorptions. Impact craters are found among polygonal terrain formed by freeze-thaw cycles. From Byrne et al. (2009).

In addition, neutron spectrometers such as the Fine Resolution Epithermal Neutron Detector (FREND - Mitrofanov et al., 2018) or Neutron Spectrometer (NS - Boyton et al., 2003) can be used to estimate the H-abundance not only directly at the surface but up to 1-2 meter below. Compared to surface imagers, these can provide a good estimate of the water-ice content located under the surface. However, one should be careful as a high H-abundance does not necessary implies a high-water ice content since hydrated minerals have a similar signature on neutron spectrometers. Compared to surface hyperspectral imaging systems, neutron spectrometers also have a much lower resolution (10s of meters vs 10s-100 km), therefore they can only be used at a larger scale.

3.4. Structural patterns/geophysics

Spectroscopy is clearly the most powerful tool to identify mineral deposits, but sometimes the data does not have the required spectral/spatial resolution, or the nature of the studied terrain makes their interpretation difficult. In those cases, other generalist techniques help to define the value of a location.

Back on Earth, structural geology plays a key role in defining the viability of mineral deposits, faults systems are usually the main location where mineralizing fluids flow and accumulate their load, they can also allow igneous bodies to reach the surface. Given this importance, it is worth analysing the surface and subsurface geological discontinuities and structural

patterns in search for potential deposits. This kind of studies are not uncommon on Earth: Kelka et al. (2022) used both optical imagery and geophysical data to locate high-porosity areas in the Gawler Craton in Australia, where densely fractured areas corresponded well with already existing mines. As for planetary surfaces, Cañón-Tapia & Jacobo-Bojorquez (2022) defined the sub-volcanic structure beneath Marius Hills in the Moon by analysing the distribution of volcanic vents. Both Mars and the Moon have good-resolution optical data, and gravimetry and magnetometric data, so the application of these techniques may enhance the estimation of potential reservoirs. Low-altitude, high-resolution data are missing, though, and scales comparable to those approached on Earth through airborne sensors are not achievable at this point. Future lander or rover-based survey platforms might offer a suitable approach locally.

4. Geological mapping and modelling of resources

The geological mapping of resources is basically the construction of thematic maps of minerals, mineral assemblages, volatiles concentration or any other resource of interest. Given that versatility, the implementation of resource-focused mapping can be based largely on the very same cartographic techniques and standards (see Naß, et al. 2020), as well as 2D (see Pondrelli et al., 2021) and 3D (see Penasa, et al. 2022) geological mapping approaches.

Global hydrated mineral mapping on Mars has been recently achieved using OMEGA (Riu et al. 2022) and even CRISM data (Clark et al. 2022), whereas a good example of a detailed mineral mapping in a potential human landing sites can be found in Pajola et al. (2022), where the authors studied a water-rich zone and the associated hydrated minerals. Hagerty et al. (2006) refined the abundance of Th on the surface of the Moon. Wiseman et al. (2008) identified hematite deposits in the Miyamoto crater on Mars.

Although the procedures to identify water and other volatiles are different, the mappings techniques and products are similar. Morgan et al. (2021) identified water ice in the northern latitudes of Mars. Whereas Li & Miliken (2017) did the same for the Moon.

With the current datasets available for planetary exploration it is difficult to create 3D models of subsurface deposits. Nevertheless, similar approaches on Earth exemplify the potential products that would eventually be generated on the Moon and Mars with the right equipment. Detailed geological models can be replicated with geophysical and mineralogical information obtained with drill holes (Le Vaillant et al., 2017).

5. Outlook and perspective

- Planetary resource mapping is not yet well-established. This is due in part to the necessity of specialised data to properly define the reservoirs, but also because until recently the ISRU (in situ resource utilisation) has been considered something ahead of the state of space exploration. Both of these points will substantially change in the near future.
- The present deliverable and guide serve as a starting point for the construction of thematic maps of resources, and points to useful examples of previous works in the area.
- More prototypes and implementations of resource-based geologic/geomorphic maps are required, even if the current data available is not ideal for this purpose; the mapping community should be prepared to develop detailed resources map once proper data is available.

Note: a live version of this document will be available on the GMAP wiki at:

<https://wiki.europlanet-gmap.eu/bin/view/Main/Documentation/Resource%20mapping/>

A useful collection of references related to Lunar landing site studies is maintained by the Lunar and Planetary Institute¹.

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¹ https://www.lpi.usra.edu/lunar/site_studies/

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