

Characterization of geological settings related to intrusive magmatism on the Moon and Mars

by

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*Y el muchacho vio en las pantallas y el papel
todos esos planetas, galaxias y estrellas; y su aún
joven mente no entendía como todo eso podía
estar ahí afuera. Se le presentó un universo infinito,
lleno de misterios, preguntas y belleza. La
curiosidad, aquel noble impulso primigenio, se
adueñó de su mente, y desde entonces se propuso
entenderlo todo, en la medida de lo posible. Y eso
le tomó toda su vida.*

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Abstract

In this research, I explored the geology of igneous intrusive domes in the Moon and Mars. These structures, and the geological processes associated with them, have not been widely investigated outside Earth, mainly due to the difficulty in locating them. Intrusive domes are worth studying since they can reveal information about the properties of the crust and the rise of magma through it; also, they could host mineral resources interesting for space exploration. I decided to do a detailed analysis of two systems: the Valentine Domes on the Moon, and the Utopia Planitia Dome field on Mars, focusing on their properties at the surface. I followed a cartographic approach in this research, using geostratigraphic units to characterize the locations and define their geological evolution. This methodology requires the combined analysis of geomorphologic, stratigraphic, and compositional properties, compiled in comprehensive maps and block diagrams of the areas. In both locations, the individual domes were small compared with the total area modified by the igneous systems, so I investigated each location at two scales: a regional one to check the geological properties of the hosting units and their stratigraphical relationships, and a detailed one, where I focused on the properties of the domes and how they were emplaced. I used medium and high-resolution datasets, especially panchromatic images, digital elevation models, and hyperspectral cubes; these products were corrected and processed, to be later analyzed in geographic information systems. While analyzing the Valentine Domes, I noticed the lack of an open-source tool to work with the spectral data of the Moon, I decided to recreate the workflows developed by previous authors in the programming language Python and make it available for the scientific community. This led to the creation of the ***MoonIndex*** library, a tool to process spectral cubes and generate spectral indexes for the Moon. With the aid of ***MoonIndex***, I performed the geological analysis of the Valentine Domes, a system of two laccoliths near the western rim of the Serenitatis Basin. The first result was the discovery of a new dome, which was detected by using the aspect parameter (direction of the slope). I also found that several smaller structures such as rilles, dykes, and secondary domes are associated with the main domes. These newly defined structures showed that the intrusive system is bigger than previously known and that it was active for almost 1 Gyr. The dome field in Utopia Planitia is different from the lunar location, hundreds of domes were emplaced in a large area, near the northern Martian dichotomy. The study of the domes showed they originated from an intrusive-to-extrusive system, since their shapes range from cryptodomes to volcanic domes. Two distinct groups of domes were identified, which represent different stages of igneous activity. Some domes were able to reach the surface creating extrusive structures, while the majority were emplaced near the surface, a small number of the last remained trapped underground as cryptodomes, but eventually, most of them were uncovered, forming the wide variety of domes we observe today. The lunar and Martian domes show some similarities, they are likely basaltic, have a small incidence in the surface morphology, and their parental magmas took advantage of structural features to reach the surface. However, the genesis of the system is different. The Valentine

Domes formed under a polygenetic style, where several magmatic events occurred in the same spot, originating in a magma chamber below the system. On the other hand, the dome field in Utopia Planitia originated in a monogenetic system, where only a single event occurred in each spot, from magma coming from deep sources. This research will open the door to discovering new intrusive systems and to better understand the ones already known, these structures might be relevant in the future of space exploration, so studying them is valuable for the time to come.

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Abbreviations

NASA: National Aeronautics and Space Administration.
CNSA: Chinese National Space Administration.
ESA: European Space Agency.
PSR: Permanently shadowed regions.
KREEP: Rocks enriched in potassium (K), rare-earth elements (REE), phosphorus (P).
LMO: Lunar magma ocean.
FAN: Ferroan-anorthosite.
DEM: Digital elevation model.
LRO: Lunar reconnaissance orbiter.
WAC: Wide angle camera.
ASP: Ames stereo pipeline.
LOLA: Lunar Orbiter Laser Altimeter.
LALT: Laser Altimeter.
UV-VIS: Ultraviolet/Visible Camera.
NAC: Narrow Angle Camera.
M3: Moon Mineralogy Mapper.
MRO: Mars reconnaissance orbiter.
THEMIS: Thermal Emission Imaging System.
HiRISE: High Resolution Imaging Science Experiment.
CTX: Context Camera.
CRISM: Compact Reconnaissance Imaging Spectrometer for Mars.
SPA: South pole Aitken basin.
ROI: Region of interest.
INAF: Istituto Nazionale di Astrofisica.

Chapter 1: Introduction

1.1. Problem definition

The efforts to explore the Solar System either with robotics instruments or by sending humans to planetary surfaces are ramping up. This is evidenced in the ongoing missions of different space agencies, such as the Artemis program of the National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA) (NASA, 2020), the Chang'e Project of the Chinese National Space Administration (CNSA) (Lin et al., 2018), and several space programs of other countries. The Moon and Mars are the main targets for this new push, given their closeness to Earth and the knowledge we have accumulated of them during the last decades. However, several obstacles need to be addressed to fulfil the end goals of these programs, for example, some of them involve the creation of base camps on the Moon and Mars, which require a solid knowledge of the terrain, the selection of potential landing sites, extensive logistics, and plenty of resources. Because of that, understanding the geology and the processes occurring in these planetary surfaces is of primary importance, as well as the identification of potential resource deposits that could sustain its future exploration (Lewis et al., 1993).

The major geological provinces and structures on the Moon and Mars have already been widely studied, even global geological maps exist for both planetary bodies (Fortezzo et al., 2020, Tanaka et al., 2014). However, in the context of human and robotic exploration, medium and small-scale features gain a bigger relevance, and naturally, many of them are not well understood and have not been mapped yet. These kinds of geological settings are worth studying, especially the ones that have been overlooked before. This would allow an adequate selection of landing sites and possible settlements locations, since it is important to consider their geologic and environmental conditions, as well as the availability of potential resources.

One of the less studied phenomena in the Lunar and Martian surfaces is the formation of intrusive igneous domes. These structures are produced by the cooling of magma underground, and their eventual transition to the surface (Philpotts and Ague, 2022). Even if these structures are common on Earth, only a handful of examples have been located and studied on other planets (e.g. Wöhler and Lena 2009, Farrand et al., 2021). This is the result of how difficult it is to locate them using remote sensing data, and their resemblance to other non-igneous structures. Nevertheless, several domes are probably scattered around planetary surfaces waiting to be discovered, so it is important to understand their formation, the geological processes acting over them, and their association with other features like dykes, rilles, pits, and volcanic vents, all of them appealing for space exploration (e.g. Braden and Robinson, 2012).

Also, intrusive domes can host important minerals for future exploration. Major efforts have been made to identify primary resources available on the surface of the Moon and Mars (e.g., Haskin et al., 1997; Anand et al., 2012; Abbud-Madrid, 2017). Important sources have been identified thanks to these surveys, such as the potential of Lunar regolith and the Permanently shadowed regions (PSRs) to host water ice, metals, and several useful volatiles (Haskin et al., 1997; Volger et al., 2020). Other examples are the High-Ti zones and the rocks enriched in K, rare-earth elements, and P (KREEP), found in the Lunar Maria (McLeod and Krekeler, 2017). Although the prior cases are encouraging, the study of other geological settings like intrusive domes widens the possibilities for exploration. These features and other igneous structures derived from them have been extensively studied and used on Earth. Intrusive bodies can be valuable reservoirs by themselves, such as the Stillwater Mafic Complex in the United States (Page, 1997). Furthermore, secondary processes can produce important reservoirs of minerals, like contact metamorphism aureoles, such in the Duluth Complex in Minnesota (Fuller, 1980) or the emplacement of dyke-swarms, as in Zimbabwe (Naldrett and Wilson, 1990). All the previous scenarios have in common that they are related to mafic intrusions in igneous complexes. Similar scenarios are expected in the Moon and Mars due to the compositions of their rocks and the presence of extended volcanic episodes, so it is worth looking for the signals of these processes.

For the previous reasons, in this thesis I studied and mapped two locations with intrusive domes that have not been explored in detail before: The Valentines domes on the Moon (30.69 N, 10.20 E), and the dome field in Utopia Planitia on Mars (centered 41°N, and 77°E).

1.2. Objectives

The general objective of this research was to characterize and understand how, why, and when these intrusive domes were produced on the Moon and Mars. These planetary bodies were selected for this research due to the availability of high-resolution data, the likelihood of encountering this kind of geological setting, and their importance in space exploration. To achieve that goal, we mainly followed a cartographic approach, by creating geostratigraphic maps of both locations, which are products that combine geomorphological, spectral, tectonic, and temporal information (e.g. Yingst et al., 2023, Massironi et al., 2021).

Incremental steps were necessary to produce these maps and fulfill the main objective. The first one was the preparation and processing of remote sensing datasets. This required applying complex workflows for each type of data. For most of the datasets I followed workflows using open-source techniques, but there was none available for the hyperspectral data of the Moon. To overcome this issue, I developed a Python tool to extract meaningful information from these type of datasets. Once the high-level products were ready for interpretation, a second step was to define and implement a mapping methodology suitable for the study areas.

Finally, once the maps and interpretations of both locations were done, I compared the properties of the intrusive domes in the Moon and Mars and discussed their potential as locations for future exploration.

With this research, I expect to extend the scientific knowledge about the formation and evolution of intrusive igneous domes, as well as opening the door for more detailed studies about their compositions during future missions, which could help address their potential as possible resource sources and find ways to take advantage of them in the upcoming plans for planetary exploration. As tangible results, I generated an open-source python tool for the scientific community, geostratigraphic maps of both locations, and an assessment of the physical and chemical properties of these intrusive features.

1.3. State of the art

1.3.1. Geological mapping

Geology has been a key tool to construct knowledge about the terrain, especially in unvisited locations like other planets. This was understood early in the exploration of the Solar System, the focus of the Apollo missions was to recover rock samples from the Moon, which greatly enhanced our understanding of the Earth-Moon system formation, as well as the nature of planetary dynamics (e.g. Taylor, 1975). The process of studying a location starts with the collection of information, and usually ends with the thematic cartography of the selected place. Retrieving data from locations outside Earth is challenging, since apart from specific cases like the Apollo missions or the Martian rovers (Sun et al., 2023), most of the information we receive comes from remote sensing instruments orbiting other planets. This scenario requires scientists to get the most out of the existing datasets, so new and more refined approaches for old and deprecated missions are valuable (e.g. Goossens et al., 2021). The collected information can be used in several ways, but maps will always be key products. A map is a symbolized image of reality and is intended to represent the variability of elements in the terrain and their temporal and spatial relationships (Kainz, 2020). Since the terrain can be interpreted in several ways, the elements on a map depend on the methodology used to create it and the use it will have. Traditionally, maps of planetary surfaces record either geomorphological, geological, or compositional information, but recent methodologies aim to comprise these topics in a single entity: geostratigraphic maps (e.g. Luna et al., 2024, Wright et al., 2024).

The process of creating geostratigraphic maps can be seen in **Figure 1.1a**. The usual approach consists of generating two distinct sets of units that would later be combined in a single set of geostratigraphic units. The initial sets of units depend on the available data, but ideally, they would be morphostratigraphic and spectral units (Wright et al., 2024). The first ones are the product of the geomorphological analysis of a surface accompanied by considerations about the stratigraphy of these units (Massironi et al., 2021); this methodology is common between

planetary scientists, since it allows the most reliable description of a location when there is no direct lithological information. On the other hand, spectral units are obtained by interpreting the composition of a surface using spectral signatures and indexes (Zambon et al., 2022). The combination of the prior information to define geostratigraphic units can be done in different ways, either by generating decision-making trees that evaluates the clearness of both types of units in a single location, and selecting the better one (Yingst et al., 2023); or by superposing the contacts of both units and analyzing their relationships (Wright et al., 2024). In this research I followed a modified approach due to the relatively small size of the intrusive domes. The lunar and Martian domes do not exceed 50 km in diameter, and secondary structures associated with them can be as small as 100 meters wide. The available optical and terrain datasets allowed a detailed analysis of even the smaller features, but the resolution of the spectral information was at least one order of magnitude lower than the optical one. Due to this limitation, the definition of spectral units for the whole study areas would have been ineffective. Instead, high resolution morphostratigraphic units were first defined, and later modified according to spectral information when necessary (**Figure 1.1b**). This way I ensured that the units were defined using the data with the best resolution, but still discriminated according to their compositions.

The size of the intrusive domes not only affects the methodology to define units, but also the mapping scale. The individual domes are usually small and isolated, but the total area affected by the igneous system is larger. This makes it difficult to detail the individual characteristics of the domes and to analyze their regional interaction using a single mapping scale, so I decided to map the studied zones using two, a regional and a detailed scale. The regional mapping covers the total study area, focusing on the terrains where the domes were emplaced and their relationship with the surroundings. This scale was also useful to define large structural patterns, and to detect subtle large-scale features related to the intruding systems. The detailed mapping was intended to describe the limits, small-scale structures, and composition of the domes. At this scale it was possible to discriminate between the types of domes by describing their geomorphological and compositional particularities. The Valentine domes on the moon were close enough to be covered by a single detailed map, but the ones in Utopia Planitia were too scattered, so a representative map was done.

1.3.2. The Moon

The current lunar geologic configuration is greatly defined by its formation and the processes that followed. The most widely accepted theory about the formation of the Moon is the giant impact (Hartmann and Davis, 1975), where a Mars-sized body crashed with Earth, giving place to a debris ring that eventually accreted to form the Moon. Two of the big consequences of this formation process are the apparent depletion of volatiles in the lunar mantle and crust, due to the extreme conditions during the event (Geiss and Rossi, 2013); and the subsequent formation of the Lunar magma ocean (LMO), which enabled a strong differentiation between

an olivine-pyroxene-rich mantle, a middle layer enriched with incompatible elements called KREEP, and a plagioclase-rich crust (Wood et al., 1970; Hubbard et al., 1970). The geological evolution of this initial state can be divided into three big stages. First, the crystallization of the LMO occurred around 4.4 Ga (Nemchim et al., 2009), giving place to the lunar highlands, mainly composed of ferroan-anorthosite (FAN). Second, the formation of the lunar maria by the impact of large asteroids that formed wide basins and their subsequent infill with lava, between 4.1 and 3.0 Ga (Geiss and Rossi, 2013, and ref. therein). And finally, later modification by space weathering, and tectonic and thermal deformation.

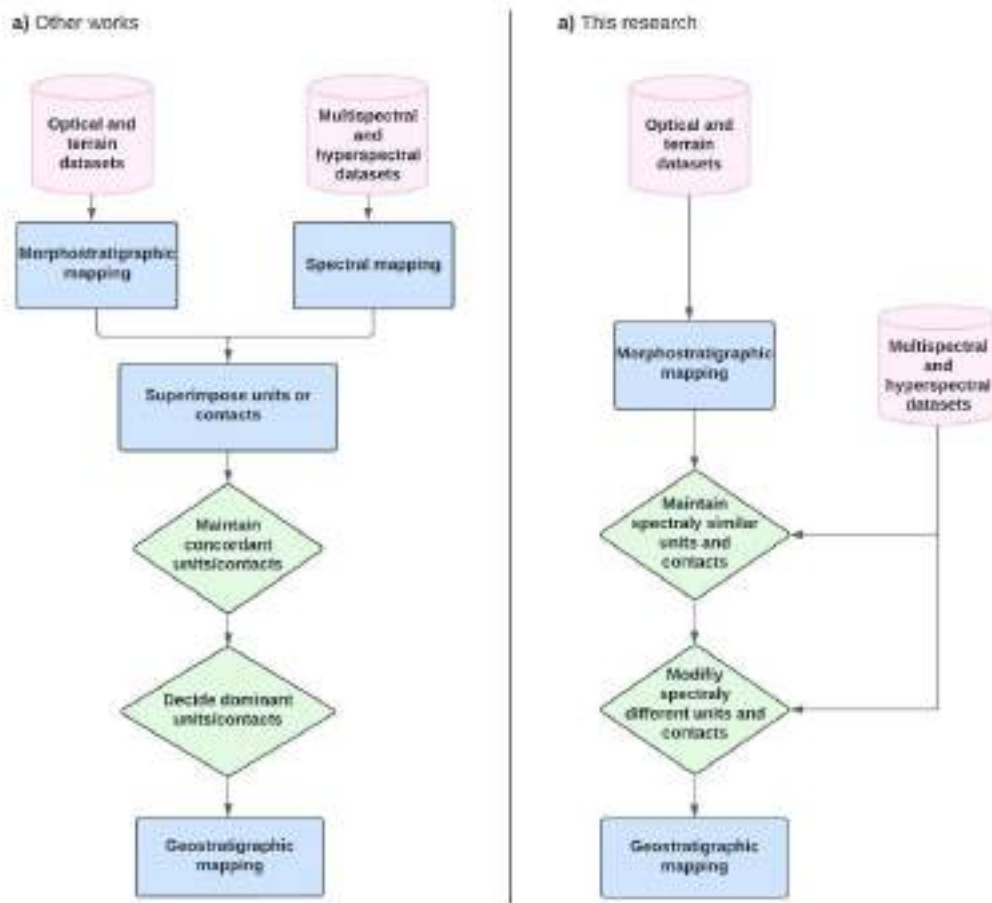


Figure 1.1: Flow-chart showing the methodologies to generate geostatigraphic maps. a) Creating two different sets of units to later combine them (based on Wright et al., 2024; Yingst et al., 2023). b) Modifying morphostratigraphic units with spectral information, used in this research.

From the prior definitions, the geology of the Moon can be roughly framed into the highlands-maria dichotomy, or genetically speaking, LMO products-extrusive volcanism products (e.g. Taylor, 1975). The importance of extrusive igneous processes goes beyond the formation of the maria, other expressions of this activity can be found around the Moon. There are big-scale volcanic complexes like Mons Rümker (e.g. Zhao et al., 2017) or the Marius Hills (e.g. Heather et al.,

2003); as well as several small-scale landforms, which dominate the diversity of lunar volcanism. Lunar rilles carved by lava flows are commonly found in the maria (Garfinkle 2020), in some cases associated with pits of high scientific interest (e.g. Wanet and Robinson 2022). Less common are pyroclastic deposits, which can be associated with cinder cones or fractures in the surface (e.g. Gustafson et al., 2012). Although the influence of extrusive igneous activity on the lunar surface is substantial as seen in the previous examples, that is not the case for intrusive igneous processes.

1.3.2.1. Intrusive activity on the Moon

At first glance, the Moon may look like a place where intrusive bodies should be common, but the physical properties of the lunar interior limit their proliferation. The ascension of magmatic bodies from the mantle is controlled by the density of both the intrusion and the host rock, and the distribution of stress in the crust (Hutton, 1988). In the lunar case, the density difference is big, being the one of the anorthositic crust 2.5 g/cm^3 and the one of the mafic mantle 3.3 g/cm^3 . This generates a neutrally buoyant zone in the interface of both layers, so the potential intrusive bodies stagnate in the lower crust, and thus it is not possible for them to reach the surface (Head and Wilson, 1992; Wieczorek et al., 2013). In other locations like Earth, secondary factors like the presence of volatiles, plate tectonics, and the crusts thicknesses can allow denser magmas to become buoyantly positive; however, the Moon does not count with these tools, especially in the thicker and lighter highlands (Head and Wilson, 2017). The prior situation leaves only two opportunities for the intrusive bodies to reach the surface, either by the excavation of stalled bodies during big impact events, or by the intrusion of dykes and laccoliths in the maria, where the crust is considerably thinner (**Figure 1.2**) (Wieczorek et al., 2013; Chenet et al., 2006).

Even with those difficulties, the existence of intrusive rocks on the Moon was verified in samples from the Apollo missions, some fragments were grouped in a set of genetically related rocks: the Mg-suite (Shearer et al, 2015). This group is thought to be the result of an intrusive episode between 4.5 and 4.1 Ga, in between the crystallization of the LMO and the formation of the large impact basins (Wieczorek et al., 2006). These ancient bodies would be initially trapped at depths around 10-30 km under the young and thick crust, but portions of them would have come to the surface by one of the methods defined before, the excavation of depth materials due to massive impact events, such as the ones that formed the Imbrium, Apollo, and Serenitatis basins (e.g. Isaacson and Pieters, 2009).

A secondary effect of large impacts was the thinning of the excavated crust. This allowed the emplacement of intrusive rocks by the other mentioned method: the intrusion of small bodies in a weak and fractured portion of the lunar crust. Since the lunar maria are the larger and most distinguishable terrains formed by this process, these intrusive bodies are mainly found on them. The secondary magmatism triggered by the large impacts produced both effusive lavas and small

intrusions like dykes and domes (Head and Wilson, 2017). Dykes can be commonly found in maria, either outcropping on the surface as linear or sinuous ridges, or emplaced underground, and generating grabens and aligned cinder cones in the surface (Head and Wilson, 2017).

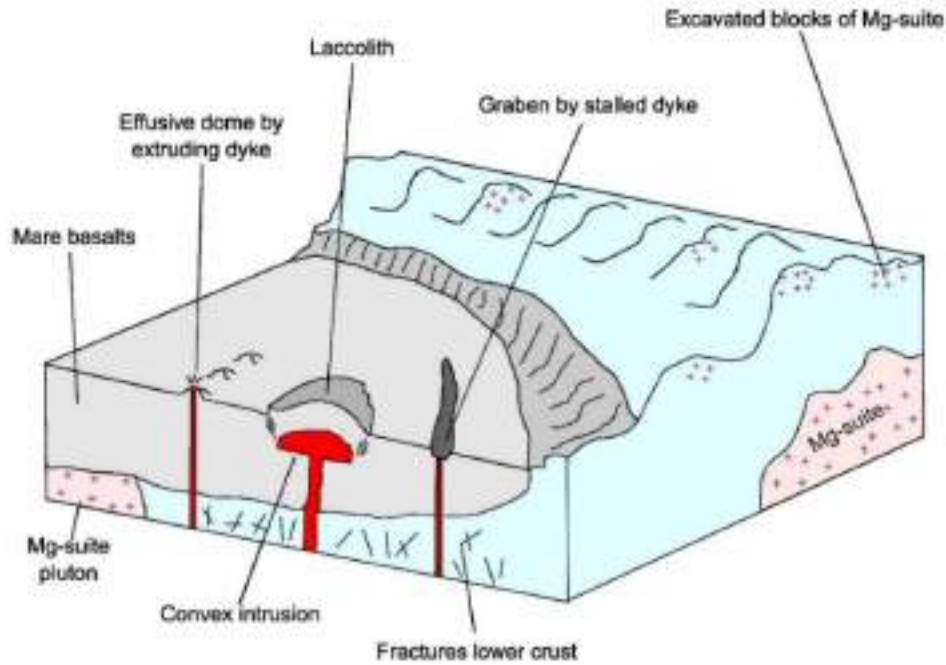


Figure 1.2: Depiction of the two possible processes that can bring intrusive igneous rock to the surface. The first option is driven by large impacts that excavate intrusive rocks emplaced in the lower crust, and deposit them as ejecta in the rim of the larger lunar basins. In the second case, secondary magmatism is generated in large basins due to the thinning of the crust, the surface expression of these intrusions are laccoliths/intrusive domes (figure not to scale). Taken from Suárez-Valencia and Rossi (2024).

Intrusive domes are less common than dykes. Only a handful of them have been previously identified by Lena et al. (2013), a list of them can be seen in **Table 1.1**. This lack of identified intrusions is partially explained by the difficulty in locating them. They are characterized by their small slope, large diameter, low circularities and subtle effect on the topping units. In none of the cases the main intrusive body reached the surface (Wöhler and Lena, 2009). Lena et al. (2013) mainly used telescopic images with large incidence angles to define their shapes and morphometric parameters, but recent high-resolution datasets justify revisiting these locations. Of the domes in **Table 1.1**, the Valentine Domes (V1 and V2) (30.69° N, 10.20° E) were likely the most representative intrusive structures, due to their size, shape, fracturing, and to the existence of several secondary domes and dykes on top of them. For this reason, they were selected as the lunar study zone for this doctoral research.

Name	Area (Km ²)	Center (x) and (y)	Major axis (Km)	Minor axis (Km)	Circularity	Altitude (m)	Slope (°)	Volume (Km ³)	Depth (Km)
K2	4571.12	-24, -28.01	71.48	69.34	0.97	196	2.83	46.89	11.40
Ga1	1469.92	-15.05, -1.04	50.43	34.42	0.68	62.5	4.23	45.91	2.20
V1	1136.37	10.06, 30.82	33.94	29.43	0.87	160.5	4.40	63.48	2.50
V2	124.38	10.12, 32.01	13.52	9.84	0.73	62.5	3.70	4.95	0.38
M13	1546.66	-31.67, 11.76	62.43	26.05	0.42	243.5	5.13	174.79	2.90
Ar1	1722.48	0.71, 55.76	38.68	31.31	0.81	158.5	3.10	52.32	3.50
Gr1	677.67	-68.57, -4.4	35.67	16.43	0.46	79	4.22	28.70	2.40
Ari1	6441.33	6.03, 32.88	116.89	77.54	0.66	222.5	3.51	1109.77	7.90
Ha2	543.84	-48.11, -10.66	23.97	21.91	0.91	51	2.46	9.91	1.10
C11	92.03	36.71, 11.07	10.33	9.66	0.94	30.5	2.75	1.34	0.50
C16	234.87	32.37, 11.94	17.69	15.00	0.85	147	3.60	5.87	0.63
Pa1	568.10	-47.88, -26.52	34.55	19.34	0.56	152.5	2.85	8.68	0.91
L6	380.80	-28.66, 47.04	21.29	19.90	0.94	160.5	3.12	34.24	0.83
Du3	147.04	71.38, 5.59	14.23	9.91	0.70	103	2.35	7.05	0.53
C9	35.14	34.6, 7.06	6.68	5.83	0.87	1	2.13	0.02	2.50
C10	43.15	35.21, 9.98	7.55	6.80	0.90	16.5	2.74	0.29	1.90

Table 1.1: List of lunar intrusive domes with their main morphometric parameters (Modified from Lena et al., 2009).

1.3.2.1. The Valentine Domes

The Valentine Domes are located at the west margin of the Serenitatis Basin (**Figure 1.3**). When Lena et al. (2013) first described the zone, they found two different edifices, a big asymmetrical dome 35 km in diameter (V1), and a small one to the north with 11 Km in diameter (V2). During my analysis of the zone I found another dome southeast of the other edifices, having this one 43 Km in diameter (V3). The three structures have the typical low altitude and small slope of lunar intrusive domes, especially V3. The topping units of the domes do not have evident differences with the surrounding lavas of the mare, implying that the intrusive rocks have not reached the surface extensively. Wöhler et al. (2009) identified a large fault at the east side of the dome V1, while to the west the dome dips gently and disappear beneath the mare. In a general way, the three structures can be considered as laccoliths (Schmiedel et al., 2017).

Perhaps the most interesting feature of the Valentines Domes is the presence of secondary structures on top of them, especially of V1. They are small, round, and bright hills that appear embedded in the top layer of the dome. They have been classified as Kipukas by previous authors, old fragments of ejecta, surrounded by the flood basalts that filled the basin (Wöhler et al., 2009; Hackman and Carr, 1996), but the analysis made here suggest another origin. These structures, as well as the structural patterns dissecting these domes, indicate that the intrusive system was extended and vigorous, and that intrusive rocks could have eventually reached the surface.

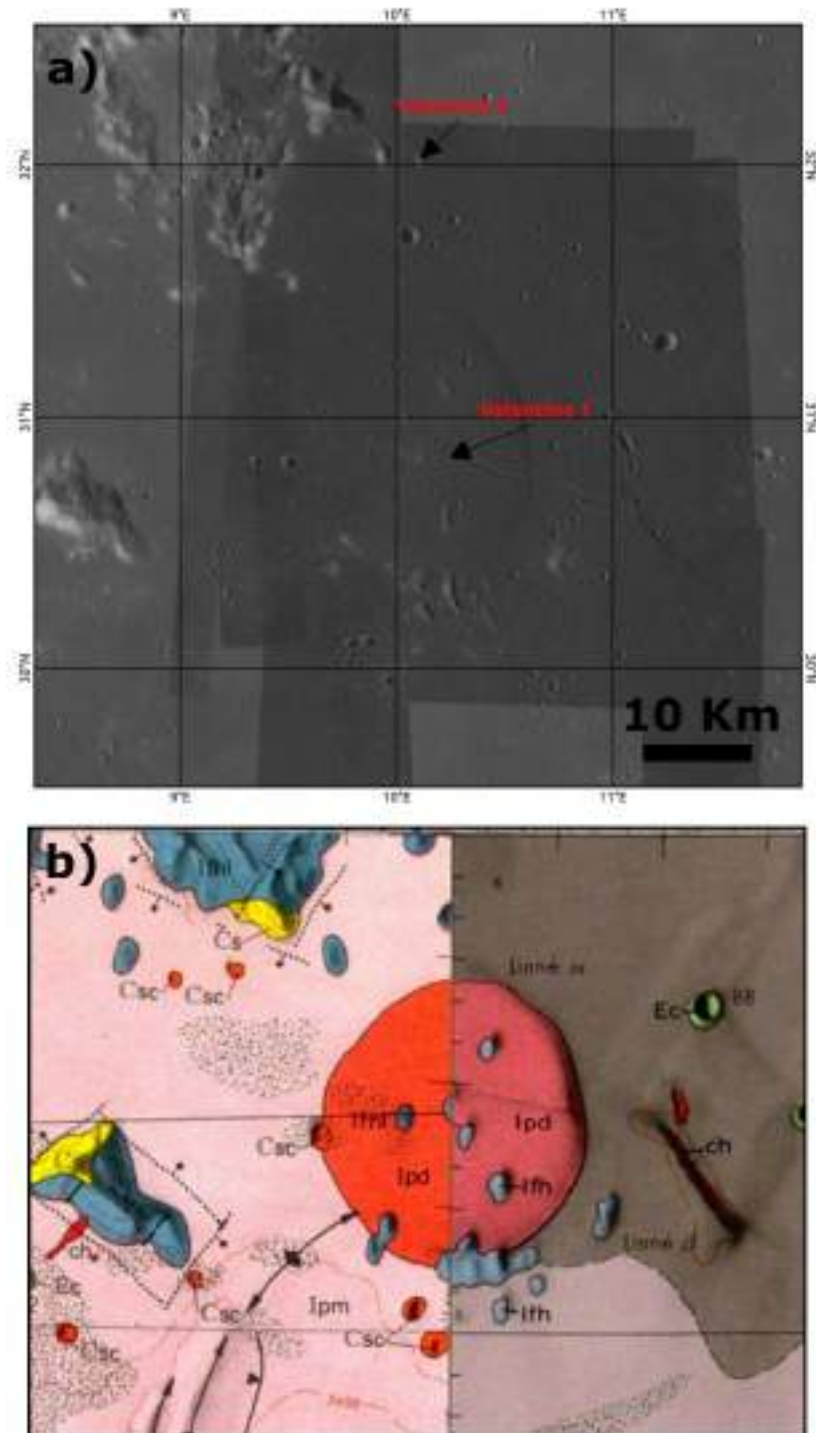


Figure 1.3: a) View of the two domes in the Valentine region, the basemap is a combination of WAC and NAC images. b) Geologic map: *lpd*: Dome material, *lfh/lfhl*: Hummocky ejecta material, *Csc*: Secondary craters, *Ch*: Chain craters, *lpm*: Imbrium mare material (Modified from Hackman and Carr, 1966).

1.3.3. Mars

Although it is not 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). Little remains from this early stage or pre-Noachian period, as the reworking of the surface was strong in the next millions of years. The Noachian period started around 4.1 Gyr ago, which is characterized by intense volcanic production accompanied by surficial water activity and high erosion rates (Carr and Head, 2010). Most of the Noachian terrains were reworked by valley networks or outflow channels, but some hints of plutonic rocks are still present. The more complex geological activity on Mars in comparison to the Moon makes it more likely to host igneous intrusive activity. Carter and Poulet (2013) detected several outcrops of anorthosite around crater rims and the slopes of Noachian aged massifs, suggesting these spots can be the result of localized, less-mafic plutons, or mixed debris of the hypothetical ancient global magma ocean. Another concentration of plagioclase-rich igneous rocks of this age was detected northeast of Noachis Terra by Wray et al. (2013), where several outcrops of white and fractured rocks are spread inside crater floors and intercrater plains.

In the Hesperian period, ranging from approximately 3.6 to 3.0 Gyr, erosion and the activity of surficial water decreased abruptly (Howari et al., 2021). The limit between the Noachian and Hesperian periods was characterized by extended volcanic episodes, as well as the formation of outflow channels (Carr and Head, 2010). It was in this time that important volcanic provinces consolidated, like the shield volcanoes in the Tharsis Region (Williams et al., 2008); and also when others started forming, like the Syrtis Major (Bramble et al., 2017).

1.3.3.1. Intrusive activity on Mars

The intensive volcanism of the early Hesperian was accompanied by the emplacement of intrusive features, especially dyke swarms and domes. Most of the dyke swarms on Mars are closely related to the areas surrounding the Tharsis region (Mege and Gurgurewicz, 2016), especially around Vallis Marineris. This can be explained by the extended flexural deformation that this massive volcanic region created in the surrounding crust, giving space for secondary intrusions (Ernst et al., 2001). However, intrusive domes have not been reported near the Tharsis.

Although more domes may exist on Mars compared to the Moon, recognizing them as intrusive in origin is more difficult. While on the Moon only igneous activity can create dome-like structures, on Mars there are other processes that give place to similar landforms. Periglacial landforms are common at medium and high latitudes on Mars, structures like pingos (Soare et al., 2013), mud-volcanoes (Ivanov et al., 2014), and polygonal mesas (Zhang et al., 2024), can resemble the typical structure of a small igneous dome. Fortunately, those structures have been previously studied in detail, and their origin can be discriminated by analyzing the

local geology. A dome field of igneous origin in Arcadia Planitia was described by Rampey et al. (2007) and Farrand et al. (2021). The field is composed of hundreds of small and round-shaped domes that are scattered in a vast area. The morphology of the edifices varies drastically, there are domes with and without a vent on top, some of them have associated lava flows, others only show aprons in their flanks, and there are even some “cryptodomes”, which are shallow protuberances that look like buried intrusions. To explain these differences, Farrand et al. (2011) proposed a formation model (**Figure 1.4**) for the domes, in which either the intrusions reached the surface and erupted; or were emplaced near the surface, interacted with the permafrost, and eventually were exhumated. These structures are interesting and worth comparing to the work done in the Valentine Domes, so I choose to study a similar location in Utopia Planitia, also mentioned by Farrand et al. (2021).

1.3.3.2. Western Utopia Planitia

Utopia Planitia is a large flat region in the northern hemisphere of Mars, it is thought to have been formed by a large asteroid impact (Thomson and Head, 2001). Most of the zone was affected by an extensive resurfacing event during the early Hesperian; however, it is not clear if this event was volcanic or sedimentary (Head et al., 2002; Tanaka et al., 2003). After this major change, smaller volcanic and glacial events have taken place in Utopia Planitia. Lanz et al. (2014) described a group of cinder cones and fractures that showcase fissure magmatism; and De Toffoli et al. (2019) located what appear to be dyke swarms associated to domes. Pingos, mud volcanoes, and debris aprons are all common in Utopia Planitia, and they play a major role in the current morphology of the zone (Lefort et al., 2009). Finally, Utopia Planitia has been a key location for robotic exploration, initially by the Viking 1 (Mutch et al., 1976), and more recently by the Zhurong rover (Wu et al., 2022).

The dome field analyzed in this research is located in the western margin of Utopia Planitia (centered at 41°N, 77°E) (**Figure 1.5**). The domes lie in a gently dipping zone between the Nylosyrtis Mensae and the center of the basin. Hundreds of individual domes are scattered across the zone, they have an average diameter of 3 Km, and their average altitude is 80 m. Similar to the domes in Arcadia Planitia described by Farrand et al. (2021), there is a great variety of morphologies associated to the edifices, as well as clear interaction between them and periglacial units.

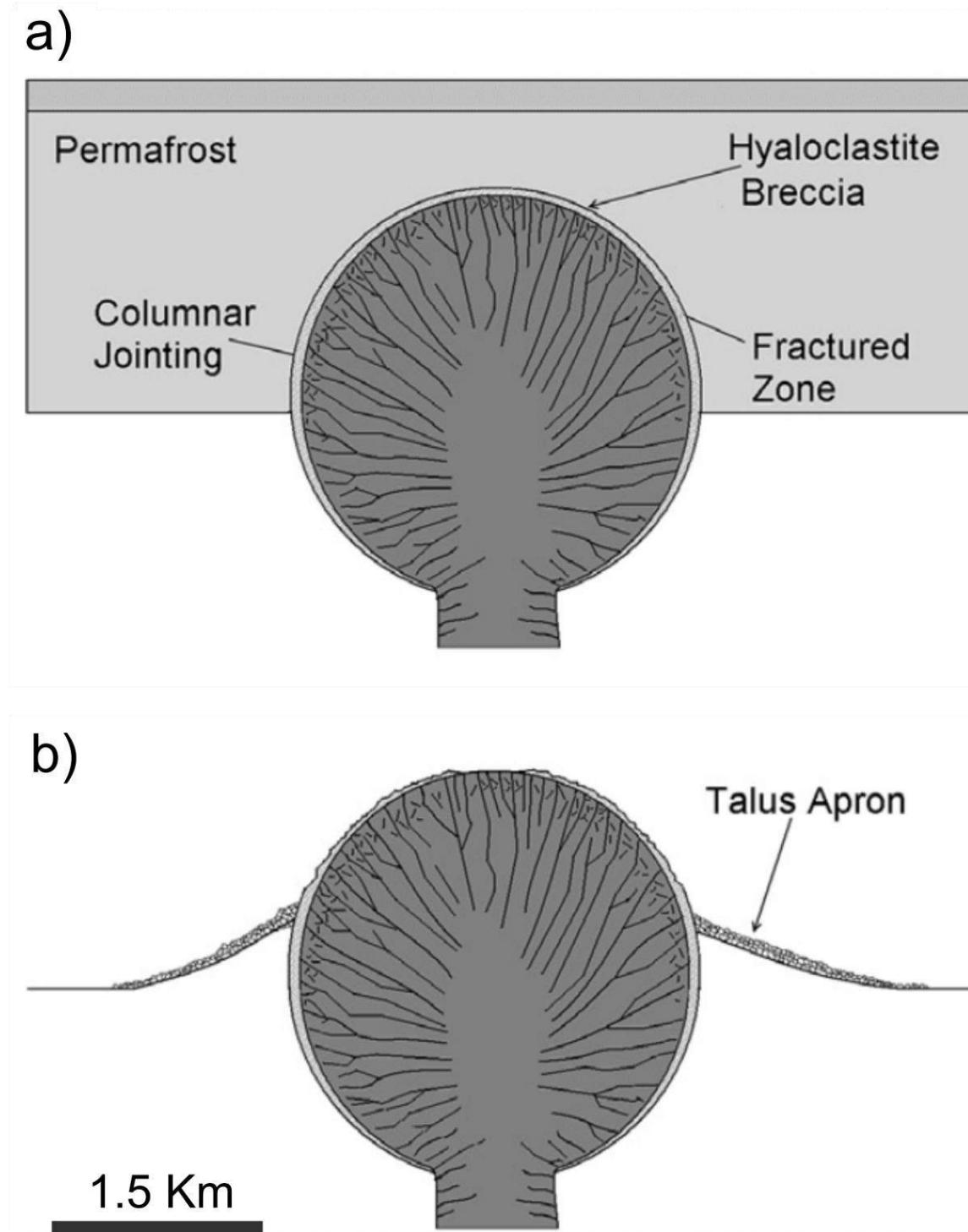


Figure 1.4: Model of formation for the domes in Arcadia Planitia. a) The dome is emplaced close to the surface and interacts with the permafrost, forming a crust of hyaloclastite. b) The dome is exhumated and debris aprons are formed (Modified from: Farrand et al., 2011).

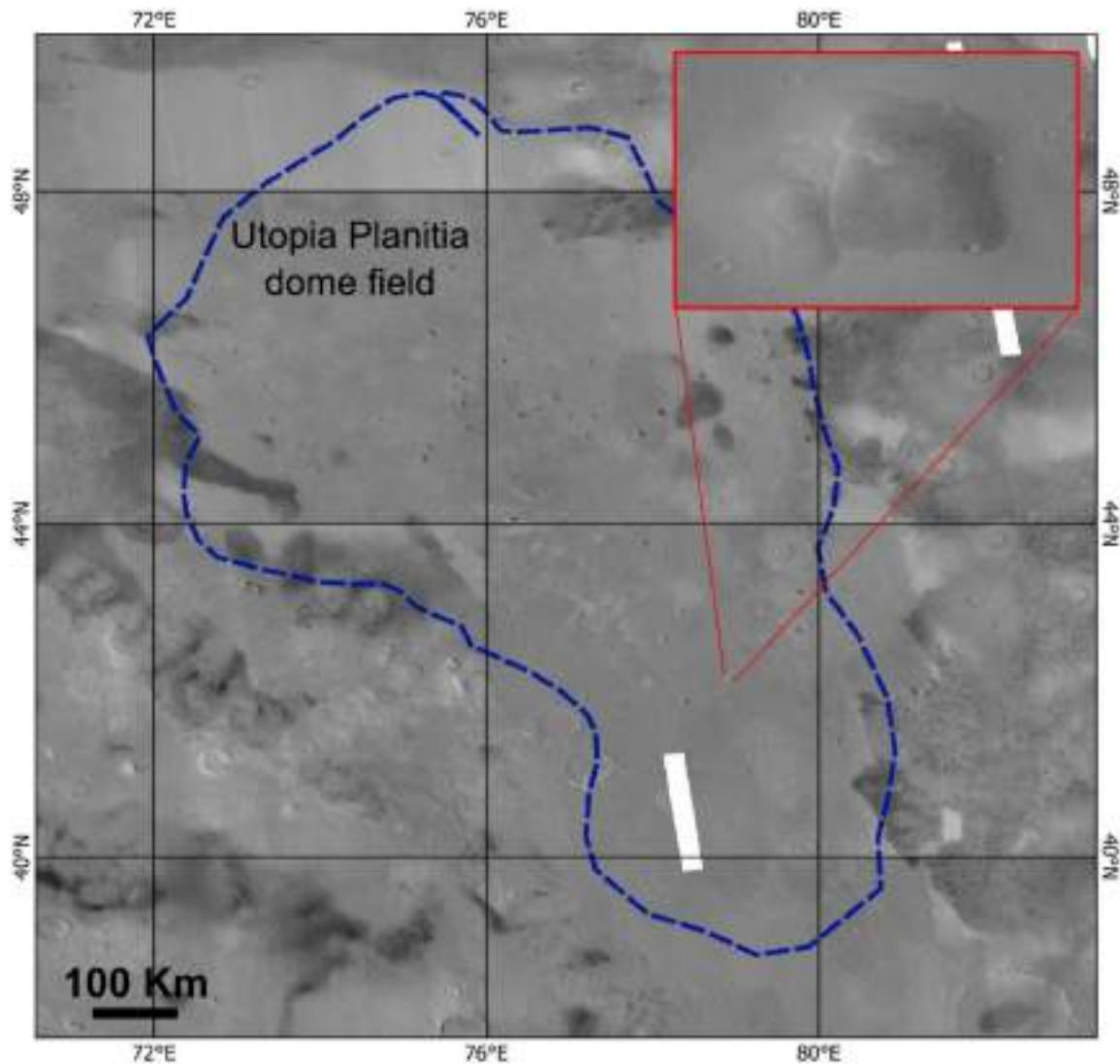


Figure 1.5: Location of the Utopia Planitia dome field. Hundreds of domes are scattered in a large area.

1.4. Overview of the datasets and software

1.4.1. Data

Given that this research is focused on two locations on Mars and the Moon that have not been directly visited by rovers or humans, I used remote sensing datasets as my source of information. Although the datasets for the Moon and Mars differ on the resolution and their acquisition technique, they can be grouped into three classes: optical imagery, digital elevation models (DEMs), and spectral imagery. The Moon and Mars have been monitored extensively, so there was plenty of high-

quality data available to conduct this research. To fulfill the two-scales mapping approach, we selected medium-resolution datasets to make the regional analysis, and high-resolution datasets to analyze in detail the morphological and mineralogical characteristics of the zones.

1.4.1.1. The Moon

The medium-resolution data for the Moon was retrieved from the “Astropedia” web repository of the United States Geological Survey (USGS). It consists of global mosaics taken by different spacecrafts in the last decades.

- Wide Angle Camera (WAC) (Speyerer et al., 2011): The WAC instrument is on board the Lunar Reconnaissance Orbiter (LRO). The global mosaic of WAC selected for this study was constructed from several tiles, it has a spatial resolution of 100 m/pixel and is centered at 643 nm, optimal for geomorphological analysis.
- Laser Altimeter (LALT) (Barker et al., 2016): Altimeter, this time on board the Kaguya spacecraft. A global DTM with a spatial resolution of 51 m/pixel was derived from this instrument. Both DTMs will be used to analyze the morphometric properties of the zones.
- Ultraviolet/Visible Camera (UV-VIS) and Near-infrared CCD Camera (NIR) (Lucey et al., 2000): These instruments were onboard the Clementine spacecraft. A global compositional map was derived from them using a band composite of three channels: 50/415nm in red, 415/750 nm in blue, and 750/1000 nm in green. It will be used to analyze the regional composition of the zones. It has a spatial resolution of 100 km/pixel.
- Diviner Lunar Radiometer Experiment (DIVINER) (Lucey et al., 2021): On board LRO, designed to measure the temperature of the lunar surface. A key product is the Christiansen feature, a portion of the spectrum sensible to plagioclase. It has a spatial resolution of 3.5 km/pixel.
- Gravity Recovery and Interior Laboratory (GRAIL) (Goossens et al., 2021): Was a missions dedicated to collect gravitational data around the Moon. The bouguer anomaly is a key product to interpret the density of the subsurface materials. It has a spatial resolution of 7 km/pixel.

The high-resolution datasets were searched using the “Lunar Orbital Data Explorer” web searcher and retrieved from the Planetary Data System (PDS) Geosciences Node.

- Narrow Angle Camera (NAC) (Robinson, 2009): The NAC instrument is on board the Lunar Reconnaissance Orbiter (LRO). We selected images with incidence angles between 60-80° and others below 30°, to obtain morphologic and compositional information respectively. The images were processed to have a spatial resolution of 2 m/pixel. A DTM with a spatial resolution of 3 m/pixel was derived from this data using the Ames Stereo Pipeline (ASP).

- Moon Mineralogy Mapper (M³) (Malaret, 2011): This spectrometer is on board the Chandrayaan-1 spacecraft. It has a spatial resolution of 110 m/pixel and a spectral resolution of 50 nm ranging between 540 and 2970 nm.

1.4.1.2. Mars

Medium-resolution dataset for Mars were retrieved from the “Astropedia” web repository of the United States Geological Survey (USGS). It consists of global mosaics taken by different spacecrafts in the last decades.

- Thermal Emission Imaging System (THEMIS) (Chrisentensen et al., 2013): This camera is on board the Mars Odyssey spacecraft. Two infrared global mosaics were made with this data (day and night), they have a spatial resolution of 100 m/pixel and can be used to determine the rocks' thermal properties.
- High Resolution Stereo Camera (HRSC) (Fergason et al., 2018): This camera is on board the Mars Express spacecraft. HRSC is a multispectral camera with a spatial resolution of 12.5 m/pixel, DTMs can also be derived from these images. It will be used to make the regional analysis of the zone.
- High Resolution Imaging Science Experiment (HiRISE) (McEwen, 2007): This high-resolution camera is on board the Mars Reconnaissance Orbiter (MRO) and is the most detailed data of the Martian surface. For this study, we will use images with a spatial resolution of 25 cm/pixel to make the geostratigraphic analysis.
- Context Camera (CTX) (Malin, 2007): Also, on board MRO. This camera functions as a regional approximation for the analysis made with HiRISE. The images have a spatial resolution of 6 m/pixel.
- Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) (Murchie, 2006): Also, on board MRO. This spectrometer has a spatial resolution of 18 m/pixel and a spectral resolution of 6.55 nm ranging between 362 and 3920 nm.

1.4.2. Processing

1.4.2.1. ISIS

All the high-resolution images were radiometrically and geometrically corrected using the Integrated Software for Imagers and Spectrometers (ISIS) (Laura et al., 2023), developed by the USGS. We followed the procedure suggested by Öhman (2016), the processes vary slightly between the products, but the overall workflow is as follows:

- Format conversion: To process the data in ISIS, it must be transformed from the .IMG format to the .CUB format. This is done with the commands *Ironac2isis/chan1m32isis/mroctx2isis*.

- Camera update: The command *spiceinit* was run in all the cubes, which makes a camera update for each of them and prepares the SPICE kernels for the next steps.
- Radiometric correction: The command *lrowaccal/ctxcal* conducts the dark, flat-field, radiometric, and temperature corrections to the data.
- For HiRISE data, there is a script called *hiedr2mosaic.py* which performs the prior steps when run with a set of images.
- Map projection: In this step, the data was projected using a .map file with the information about the coordinate system, and the *cam2map* command. Every zone of interest has its own coordinates of origin centered in it, to avoid deformation.
- Mosaicking: Where necessary, the *noseam* command was used to mosaic together the different WAC or HiRISE images.
- Format conversion: Finally, the data was converted to a .TIF format to be ingested in QGIS. This was done using the *gdal_translate* command.

1.4.2.2. DEMs creation

Some specific locations of the study zones were covered by more than one high-resolution image, this creates a region where two images overlap, which in turn allows the application of stereogrammetry to create high-resolution topographic data. I used the Ames Stereo Pipeline (ASP) software to carry on this process (Beyer et al., 2018), following the workflow suggested by Beyer et al. (2022):

- Bundle adjustment: The function *bundle_adjust* generates a self-consistent view of the terrain by correcting simultaneously the properties of all the cameras involved in the process.
- Stereogrammetry: In this step the software will create a cloud point with the altitude information derived from the stereopair. This is done with the *stereo* command.
- Alignment: With the command *pc-align* it is possible to link the point cloud with a ground truth or with a controlled DTM. For the Moon we used the DTM from Kaguya, and for Mars the DTM from HRSC.
- DTM construction: The final step is the interpolation of the aligned point cloud to create the DTM, this is done with the *point2dem* function.

1.4.2.3. Hyperspectral cubes processing

The processing of hyperspectral images was the most challenging part of the data preparation stage. Since every hyperspectral cube is composed of multiple images, the final product is complex and not easily manageable. On the same line, the workflows to prepare and analyze the data are not as well defined as for optical imagery. For the case of Mars, we used the Map-Projected Targeted Reduced Data Record (MTRDR) CRISM cubes, which are ready for a spectral analysis. The latter was done on the proprietary software ENVI and using the CRISM analysis toolkit (CAT) module (Morgan et al., 2017). The case of the Moon was more

complex, the hyperspectral cubes from M³ are only available in its non-corrected version; and although the data can be projected using ISIS, there are no commands to apply radiometric corrections to the data. Furthermore, there are no workflows or toolkits to further analyze the data or to create derived products. Since these datasets were fundamental to analyze the Valentine domes on the Moon, the first major milestone of this research was to create an open-source tool to generate spectral indexes from this data, which I later used to generate the geostratigraphic maps. The resulting library was called ***MoonIndex*** (Suárez-Valencia, 2024).

1.4.2.4. QGIS

All the geospatial analysis and the creation of the maps were done in QGIS. I also used the Mappy plugin to facilitate the cartographic process, as well as other extensions focused on the structural analysis (Penasa et al., 2020). The maps were later exported and edited using Inkscape.

1.5. Research approach

This document is structured according to the article-based thesis modality. The following three chapters correspond to papers published or ready to be submitted to peer-reviewed journals, they are followed by a chapter describing additional activities done in my doctorate; and finally, a general discussion and conclusions chapter is presented to wrap up the topic. The three papers presented next are incremental steps to fulfil the main objective of the research, that is to understand the formation processes and geological setting of intrusive domes in the Moon and Mars. Next, I summarize the articles and their role in reaching that goal.

Paper 1 - MoonIndex, an Open-Source Tool to Generate Spectral Indexes for the Moon from M3 Data: The first document was focused on the technical aspects of the creation of ***MoonIndex***, the open-source tool to generate spectral indexes from M³ data. This was the first part of the research as it was necessary to obtain the datasets used for the next part of the research.

Paper 2 - Geostratigraphic mapping of the intrusive Valentine Domes on the Moon: This paper was focused on the analysis of the Valentine Domes on The Moon. In here I detailed how the intrusive system formed and the particularities of this lunar system.

Paper 3 - Origin of the dome field in western Utopia Planitia, on Mars: The final paper consisted of the analysis of the dome field in Mars. By detailing the formation of this system I got a point of comparison between this system and the lunar one, allowing me to discuss their differences and similarities.

Chapter 2: MoonIndex, an Open-Source Tool to Generate Spectral Indexes for the Moon from M3 Data

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2.1. Paper significance on the thesis

Geomorphological and spectral analysis were needed to conduct a geostratigraphic mapping of the Valentine Domes. The first one mainly required the use of high-resolution optical images, which are easily obtainable and have well documented processing workflows. However, this is not the case for spectral analysis, since the workflow for processing M³ cubes and the way to exploit them is not so straightforward.

Since I needed to use this data anyway, I saw this as an opportunity to contribute to the lunar scientific community, so I decided to create a tool to simplify the work with M³ cubes. That is how the idea of creating **MoonIndex** arose, it is a python library that removes the spectral continuum and creates spectral indexes from M³ cubes, which are products ready for geological interpretation. The spectral information used to interpret and map the Valentine Domes were prepared in this tool.

2.2. Abstract

Spectral indexes are tools widely used to analyze the composition of planetary surfaces. Many indexes have been formulated over the years to map the lunar surface, but there is no unified database for them. In this work we describe an Open-Source Python package called MoonIndex, that recreates thirty-eight indexes compiled from the literature, using data from the Moon Mineralogy Mapper (M3). The processing started with the filtering of the data cubes to reduce the noise, the continuum of the spectrum was then removed using a convex hull or a second-and-first-order fit method. Later, the indexes were calculated, following as possible the original formulations. The results on spectral indexes calculated before the continuum removal were similar to those of the original formulations. Conversely, the results obtained for spectral indexes calculated after the continual removal were not always coherent. Some indexes, like the band depth, are especially sensitive to the removal method, as well as the derived band areas and asymmetries. We also recreated RGB composite maps, our results highlight the

compositional patterns in a similar way as the ones in the literature, even if the color ramps can differ. The products of ***MoonIndex*** are open, ready for interpretation, versatile, consistent, and cross-comparable.

2.3. Introduction

The surface of the Moon has a limited mineralogical diversity, it has been broadly divided into two types of terrains, the “highlands” which are anorthosite-rich and relatively light-toned, and “maria”, dark-toned plains of effusive lavas enriched in mafic and opaque minerals (Taylor, 1976, Hiesinger and Head, 2006). In the highlands, the dominant minerals are calcium plagioclases (Taylor, 1972, Warren and Korotev, 2022), while in the maria mafic compositions become important showing higher abundances of clinopyroxene (CPX), orthopyroxene (OPX), and olivine (Agrell et al., 1970, Albee, 2003). The clear definition of the lunar mineralogy has been driven by the samples returned by space missions (Prissel and Prissel, 2021), but due to their limited coverage of the lunar surface, the use of remote sensing techniques is still the only way to assess the mineralogy of the Moon at a global level. In this respect, the formulation and use of spectral indexes is a straightforward way to approach and visualize the mineralogical diversity of the Moon. In this study we present and describe MoonIndex, an open-source Python library that generates spectral indexes derived from the data of the Moon Mineralogy Mapper (M³).

After the end of the Apollo missions, the exploration of the Moon shifted towards the use of remote sensing spacecraft around the Moon. These orbiters allowed global and long-lasting surveys of the surface, including the study of mineralogical and elemental variations across lunar terrains. The first spacecraft with this purpose was Clementine. It was launched in 1994 and it was equipped with the Ultraviolet/Visible (UV/Vis) and the Near-Infrared CCD (NIR) cameras (Nozete, 1995), which combined 11 filters between 300 nm and 2700 nm. This spectral range was selected to obtain information suitable for the recognition of the dominant minerals on the surface of the Moon (**Figure 2.1**). Clementine was followed by the Lunar Prospector, launched in 1998, it allowed the derivation of potassium, thorium, and iron maps of the surface from its gamma-ray spectrometer (Lawrence et al., 1998). The Selenological and Engineering Explorer (SELENE/Kaguya) was launched in 2007 (Sasaki et al. 2003), it carried the first hyperspectral sensor orbiting the Moon, its Spectral Profiler consisted of 296 bands between 522 nm and 2600 nm. Shortly after, in 2008, the Chandrayaan-I spacecraft was launched, and its payload included hyperspectral sensor called the Moon Mineralogy Mapper (M³) (Pieters et al., 2009, Green et al., 2011). M³ acquired data in the spectral range between 430 nm and 3000 nm, similarly to Kaguya/Spectral Profiler, but with a higher spatial resolution. It operated in two spectral sampling modes: the “Target Mode”, characterized by a spectral sampling of 10 nm, with a total of 256 channels; and the “Global Mode”, reaching a spectral sampling of 20 nm in the shorter wavelengths and 40 nm in longer ones, adding up to 85 channels (Green et al., 2011). In both cases the spatial resolution is

around 110 meters/pixel for the products of the first orbital period, and around 240 meters/pixel for the products of a second one. The spectral cubes usually cover long swaths of the lunar surface. Due to the limited amount of the targeted mode products and the almost total coverage of the global mode ones, we decided to optimize the workflow for the latter.

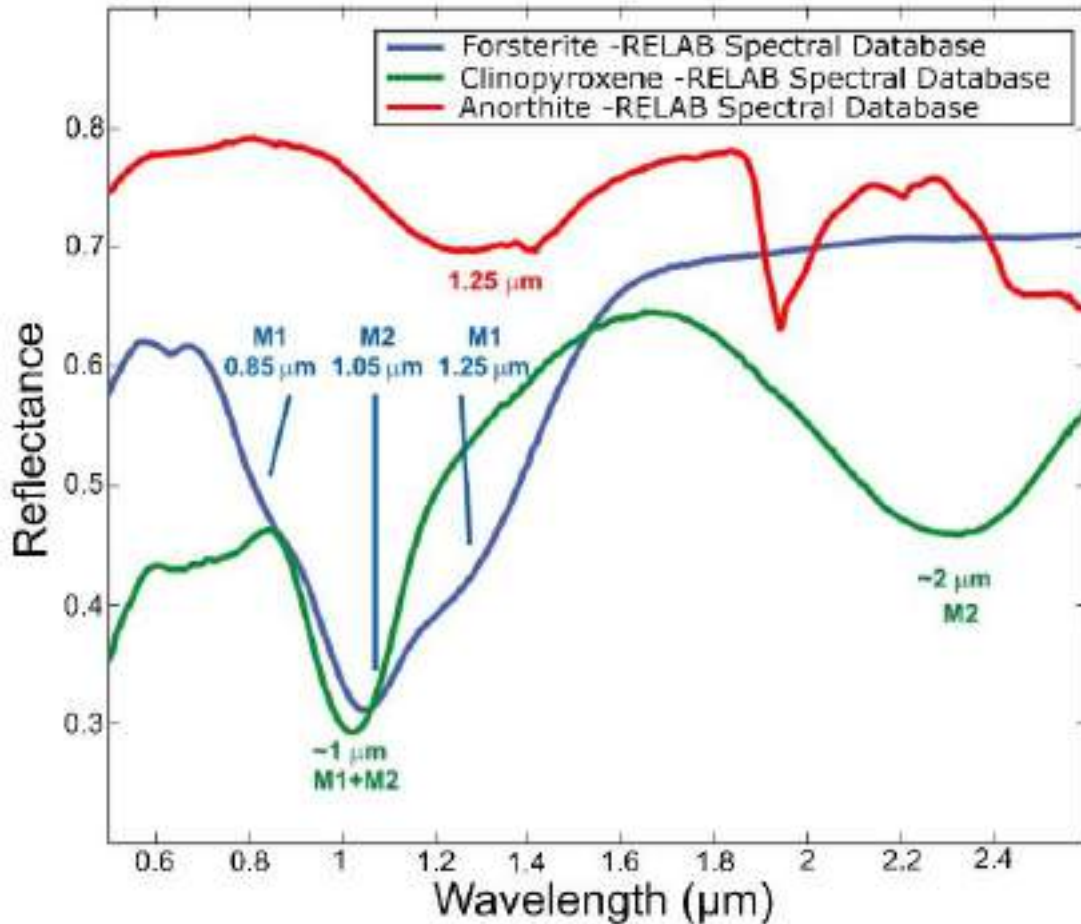


Figure 2.1: Spectral signatures of the main mineral species on the lunar surface. The three absorption features of olivine are shown in blue (M1, M2, M3). The two absorptions of pyroxene are shown in green (M1, M2). The high reflectance spectrum of plagioclase is shown in red, showing the occasional absorption feature at 1.3 μm. Modified from Arnold et al. (2016).

2.3.1. Lunar mineralogical diversity

M³ acquired data in the spectral interval between 0.45 μm and 3 μm, corresponding to the range where the major mafic minerals and water ice exhibit clear absorption features. **Figure 2.1** shows an example of some minerals with scientific interest on the Moon (pyroxene, plagioclase, and olivine) showing specific spectral signatures in the visible-near infrared range (Arnold et al., 2016). Olivine presents three absorption features ranging between 0.85 μm and 1.3 μm, this is attributable to the presence of Fe²⁺ within the M1 and M2 octahedra sites

(e.g. Burns 1993), creating a wide absorption feature around 1.1 μm . Nevertheless, changes in the composition of the olivine can slightly shift the position of the band center of the absorption, with a shift towards longer wavelengths with increasing fayalite, i.e. Fe^{2+} (e.g. Burns, 1993; Sunshine and Pieters, 1998). Grain size also has a role in the position of the band center, as smaller particles will shift their location to shorter wavelengths (e.g. King and Ridley, 1987). Pyroxene exhibits two strong absorptions centered at 1 μm and 2 μm , respectively. These absorptions are mainly the result of crystal field transitions of Fe^{2+} cations in the M1 and M2 octahedral sites, however, the presence of different abundances of Ca^{2+} (and related Mg^{2+}) also influence the absorption bands of pyroxenes (Burns, 1993; Klima et al. 2011). In fact, pyroxene with a larger amount of Fe^{2+} and Ca^{2+} show band center positions shifted towards longer wavelengths (Klima et al., 2007, 2011) as well as extreme composition shows wider 1.0 μm and weak or absent 2.0 μm band. Different from the other major minerals, plagioclase has a higher reflectance and is almost featureless in the near infrared (NIR), even if small amount of Fe^{2+} produce an absorption band around 1.3 μm , which is not easily recognizable in the data of M3 (e.g. Ohtake et al., 2009, Cheek et al., 2013, Serventi, 2013). To properly analyze the plagioclase composition, one should rely on thermal infrared (TIR) data, such as that obtained by the Diviner instrument onboard the Lunar Reconnaissance Orbiter (LRO) (Lucey et al., 2021). An additional shallow absorption band centered around 3 μm , which is associated to hydrated minerals, has been identified by M3 data (Pieters et al., 2009). As well as an absorption feature between 1.5 μm and 3 μm , related to the presence of spinels (Pieters et al., 2014, Moriarty et al., 2023). In general, a spectrum that shows an absorption feature at 2 μm indicates the presence of pyroxene, one with a stronger signal at 1 μm implies the presence of olivine, and a spectrum with shallow absorption in both regions represents an absence of the mafic minerals, and thus the abundance of plagioclase.

Since the lunar surface is a mixture of minerals, the actual spectrum is more complex than the ones obtained from single species (**Figure 2.2a**). Other factors also add a layer of complexity. Instrumental errors need to be considered, as well as the overall signature of the regolith (Green et al., 2011). But the bigger factor is that the lunar spectra show an overall positive and steep slope (**Figure 2.2a**), this effect is known as spectral reddening and is the result of space weathering. This alteration is produced by the combined action of solar wind, cosmic radiation, and micrometeoroid bombardment. This produces nanophase iron particles, responsible for the increased spectral slope, a reduction of the reflectance, and the weakening of some absorption bands (Hapke, 2001; Xu et al., 2023). Spectral reddening hinders the absorption band analysis; therefore, it is necessary to remove the spectral slope. A typical way to remove the spectral slope effects is to apply a continuum removal (**Figure 2.2b**).

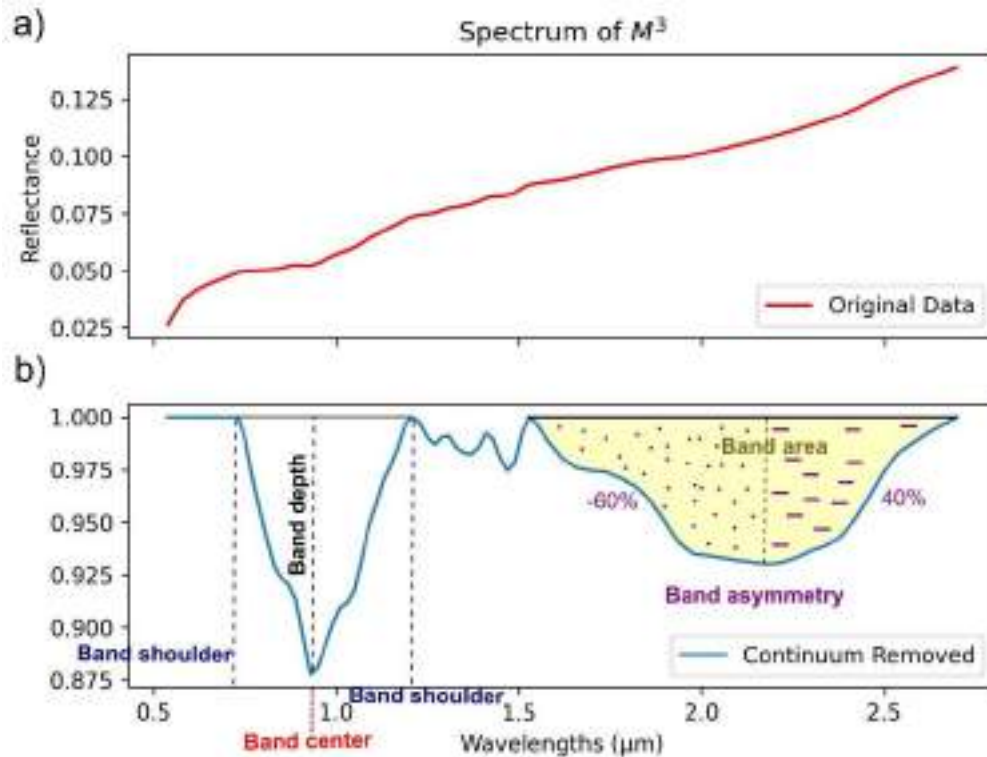


Figure 2.2: a) Example of a reflectance spectrum extracted from M3 data before continuum removal, showing the steep slope of the continuum. b) Same spectrum after the continuum removal. The main spectral parameters are indicated in the plot. The band center is the wavelength at the minimum point of the absorption, the band depth is the value at the minimum, the band shoulders limit the absorption, the band area is the total coverage of the absorption, and the asymmetry measures the distribution of the area at each side of the minimum as a percentage.

2.3.2. Techniques to exploit spectral data

Several approaches can be used to analyze spectral data acquired by remote sensing instruments. A common method is the use of spectral indexes, those are specific combinations of bands, or band operations, that highlights a specific portion of the spectrum and thus a mineralogical composition (e.g. Montero et al., 2023). The definition of the indexes is supported by an analysis of the shape of the identified absorption bands (through the band centers, band depths, bands shoulders, band areas, spectral slopes, etc) (**Figure 2.2b**); or by operating over specific spectral bands, like calculating spectral ratios. In some cases indexes are presented as RGB composites, false-colored images that are created by combining three indexes in the red, green, and blue channels. This allows an easier visualization of the results by comparing several indexes at the same time and supporting the interpretation (Liu and Mason, 2009).

Other techniques can also be applied to spectral datasets. The Modified Gaussian Model (MGM) (Sunshine et al., 1990; Clenet, 2009) allows the retrieval of mineralogical information from a representative spectrum. Furthermore, spectral

unmixing models (e.g. Adams et al., 1993; Farrand et al., 2006; Horgan et al., 2022), and radiative transfer models (Corley et al., 2018), focus on the reconstruction of synthetic spectra using the Hapke reflectance model (Hapke, 1993), which computes the expected reflectance of minerals from their chemical and crystallographic properties. Although the spectral indexes technique does not easily allow an absolute measurement of mineral abundances in complex spectra, it is still the most flexible, as many types of indexes can be created. This allows a targeted survey of desired minerals and an easy analysis of their spatial relationships with other ones, including minor species like spinel. For the previous reasons, we focused our work on the compilation of spectral indexes present in the literature for the Moon and within the spectral range of M³, to later recreate them on the Open-Source programming language Python.

2.3.3. Spectral indexes from the literature provided by MoonIndex

The spectral parameters are intrinsic to the mineral species, which means spectra are comparable regardless of the planetary body. Many parameters were defined in the laboratory (e.g. Adams and Filice, 1967; Adams, 1974; Karr, 1975), and were later applied to the Moon. A detailed list of all the spectral indexes considered in this work is shown in **Table 2.1**. Spectral indexes depend on the characteristics of the spectra considered, for this reason, literature provides a large and evolving number of parameters. Therefore, no unified database of spectral indexes for the Moon is present. Nevertheless, some works went a long way listing important indexes. Zambon et al. (2020) describes eleven indexes suitable for being derived from the data of M3. These indexes focus on the band centers and band depths around 1 μm and 2 μm , which help on the identification of mafic minerals; the spectral slope, which is a way to measure the maturity of the surface; a Clementine-like color composite map (Red: 750 nm/540 nm, Green: 750 nm/1000 nm, Blue: 540 nm/750 nm), suitable to identify regions enriched in mafic minerals (with different enrichment on iron or titanium), plagioclase and glass-bearing materials (Lucey et al., 2000).

The rest of the collected indexes were thought of for specific cases. Wu et al. (2012) updated the FeO and TiO parameters formulated by Lucey et al. (2000). Horgan et al. (2014) used the band area and asymmetry to highlight different mineral and glass compositions. Corley et al. (2018) defined a simple band ratio to highlight the presence of olivine, and Bretzfelder et al. (2020) made an RGB composite based on the integrated band depth (IBD) around 1 μm and 2 μm , and the band depth at 1.9 μm to create a contrast between olivine and the two types of pyroxenes. Besse et al. (2011) also used the integrated band depth (IBD) to differentiate between pulses of lava floods. Finally, Pieters et al. (2014) and Moriarty et al. (2023) used band ratios of non-continuum removed spectra designed to detect spinel and anorthosite. Finally, we adapted three other indexes for this work, the band area and asymmetry at 2 μm , and a chromite parameter following the formulation of Moriarty et al. (2023).

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Parameter Name	Abrev. Name	Formulation	Interpretation	Source
Reflectance at 540 nm	R540	R_{540}	High values (Higher than 0.03) → bright fresh material, plagioclase. Low values (Lower than 0.03) → dark terrain, pyroxene, and other mafic minerals.	Adams and McCord (1971)
Band center at 1 μm	BCI	$BCI = \min \sim \left(\frac{R_{1000nm}}{R_c 1000nm} \right)$ $R_c = \text{Removed continuum spectrum}$	Compositional variations of the principal mineralogical phases (pyroxenes, olivines, and plagioclases). Low-Ca pyroxenes have values lower than 0.99, high-Ca pyroxenes have values higher than 0.99.	Adams (1974)
Band center at 2 μm	BCII	$BCII = \min \sim \left(\frac{R_{2000nm}}{R_c 2000nm} \right)$	If the band center is shifted to lower wavelengths, it may show abundance of low-Ca pyroxene. Low-Ca pyroxenes have values lower than 2.15, high-Ca pyroxenes have values higher than 2.15.	Adams (1974)
Band depth at 1 μm	BDI	$BDI = 1 - \frac{R_{1000nm}}{R_c 1000nm}$	Abundance of the principal mineralogical phases and their grain sizes, also abundance of opaque phases. Values depend on the minerals involved and their proportions.	Adams (1974)
Band depth at 2 μm	BDII	$BDII = 1 - \frac{R_{2000nm}}{R_c 2000nm}$	Abundance of the principal mineralogical phases and their grain sizes, also abundance of opaque phases. Values depend on the minerals involved and their proportions.	Adams (1974)

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Spectral slope at 1 μm	SS	$Sl = \frac{R(\text{Max shoulder } BCI) - R540nm}{(\text{Wave}(\text{Max shoulder } BCI) - 540nm) * R540nm}$	Low values $\rightarrow$ fresh terrains, dark terrain. High values $\rightarrow$ older terrains, space weathering.	Hazen et al. (1978)
Clementine-like red channel	Clem RED	$ClemRED = \frac{R750nm}{R540nm}$	High values imply low titanium regions, or high glass contents.	Lucey et al. (2000)
Clementine-like green channel	Clem GREEN	$ClemGREEN = \frac{R750nm}{R1000nm}$	High values show enrichment of iron in the surface, and mafic minerals.	Lucey et al. (2000)
Clementine-like blue channel	Clem BLUE	$ClemBLUE = \frac{R540nm}{R750nm}$	Higher values imply high titanium content and bright slopes.	Lucey et al. (2000)
Band depth at 1.9 μm	BD1900	$BD1900 = 1 - \frac{R1900nm}{R_c1900nm}$	Highlights differences in mafic compositions when combined with IBDI and IBDII.	Bretzfelder et al. (2020)
Integrated band depth at 1 μm	IBDI	$IBDI = \sum_{n=0}^{26} 1 - \frac{R(789nm + 20n)}{R_c(789nm + 20n)}$	It shows high values when olivine and pyroxene are present. Values depend on the minerals involved and their proportions.	Bretzfelder et al. (2020)
Integrated band depth at 2 μm	IBDII	$IBDII = \sum_{n=0}^{21} 1 - \frac{R(1658nm + 40n)}{R_c(1658nm + 40n)}$	It shows high values when pyroxene is present. Values depend on the minerals involved and their proportions.	Bretzfelder et al. (2020)
Band area at 1 μm	BAI	$BAI = \sum_{n=0}^{La} \left(1 - \frac{R(ICnm + 20n)}{R_c(ICnm + 20n)} \right) * SR$ <i>IC = Channel where the absorption begins</i> <i>SR = Spectral resolution</i> <i>La = Amount of channels covered</i>	Useful to differentiate between mineral species. Bigger areas imply the presence of more mafic minerals. When plotted against the band center gives information about the mixture of mafic minerals.	Cloutis et al. (1986), Zhang et al. (2016)

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Band area at 2 μm	BAII	$BAII = \sum_{n=0}^{La} \left(1 - \frac{R(ICnm + 40n)}{R_c(ICnm + 40n)} \right) * SR$	Useful to differentiate between mineral species. Bigger areas imply the presence of more mafic minerals. When plotted against the band center gives information about the mixture of mafic minerals.	This paper, Zhang et al. (2016)
Band asymmetry at 1 μm	ASYI	$ASYI = \frac{BAIR - BAIL}{BAIR + BAIL} * 100$ <i>BAIR = Right side of the band area</i> <i>BAIL = Left side of the band area</i>	Useful to identify glass-bearing mixtures with high asymmetries. Asymmetries higher than 15 points to the presence of glass. When plotted against the band center gives information about the mixture of mafic minerals.	Cloutis et al. (1986)
Band asymmetry at 2 μm	ASYII	$ASYII = \frac{BAIIR - BAIIL}{BAIIR + BAIIL} * 100$	Useful to identify glass-bearing mixtures with high asymmetries. When plotted against the band center gives information about the mixture of mafic minerals.	This paper
Olivine parameter	OI	$OI = \left(\frac{R1699}{0.1 * R1050 + 0.1 * R1210 + 0.4 * R1329 + 0.4 + r1469} \right) - 1$	A higher value implies a major abundance of olivine. This index is only indicative, to properly quantify the amounts of olivine, the use of a radiative transfer model is suggested.	Corley et al. (2018)
Spinel ratio	Sp1	$Sp1 = \frac{R1450nm}{R1750nm}$	A higher value implies a major abundance of spinel. This index is only indicative, it is not intended to be a quantitative tool.	Pieters et al. (2014)
Spinel ratio	Sp2	$Sp2 = \frac{\left(\frac{R1250nm - R750nm}{500} \right) * 1350 + R1250nm}{R2600nm}$	A higher value implies a major abundance of spinel. This index is only indicative, it is not intended to be a quantitative tool.	Moriarty III et al. (2022)

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Pyroxene ratio	Px	$Px = \frac{R700nm + R1200nm}{R950nm}$	A higher value implies a major abundance of pyroxene. This index is only indicative, it is not intended to be a quantitative tool.	Pieters et al. (2014)
Pure anorthosite ratio	An	$Px = \frac{R1000nm + R1500nm}{R1250nm}$	A higher value implies a major abundance of anorthosite. This index is only indicative, is it not intended to be a quantitative tool.	Pieters et al. (2014)
Band depth at 950 nm	BD950	$BD950 = 1 - \frac{R950nm}{R_c950nm}$	While combined with other indexes to create the RGB6 composite is useful to study lunar maria. A higher value implies the presence of mafic minerals.	Besse et al. (2011)
Band depth at 1.05 μm	BD1050	$BD1050 = 1 - \frac{R950nm}{R_c950nm}$	While combined with other indexes to create the RGB6 composite is useful to study lunar maria. A higher value implies the presence of mafic minerals.	Besse et al. (2011)
Band depth at 1.25 μm	BD1250	$BD1250 = 1 - \frac{R1250nm}{R_c1250nm}$	While combined with other indexes to create the RGB6 composite is useful to study lunar maria. A higher value implies the presence of mafic minerals.	Besse et al. (2011)
Reflectance at 1.58 μm	R1580	$R1580nm$	While combined with other indexes to create the RGB7 composite is useful to study lunar maria.	Besse et al. (2011)
Iron oxide parameter	Fe	$Fe = -\arctan\left(\frac{\left(\frac{R918nm}{R757nm}\right) - 1.19}{R757nm - 0.06}\right)$	Higher values imply the presence of iron. The percentage of FeO in weight can be derived from the parameter: $wt\%FeO = 8.878 * Fe^{1.8732}$	Wu et al. (2012)
Titanium parameter	Ti	$Ti = \arctan\left(\frac{\left(\frac{R561nm}{R757nm}\right) - 0.71}{R757nm - 0.07}\right)$ $wt\%FeO = 2.6275 * Ti^{4.2964}$	Higher values imply the presence of titanium. The percentage of FeO in weight can be derived from the parameter:	Wu et al. (2012)

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Chromite parameter	Cr	$Cr = \frac{\left(\frac{R1350 - R750}{600}\right) * 1500 + R1350}{R2750}$	Higher values imply the presence of chromite. This index is only indicative, it is not intended to be a quantitative tool.	This paper
RGB composite	Abrev. Name	Formulation	Interpretation	Source
RGB Clementine-like color composite	Clem	R: ClemRED, G: ClemGREEN, B: ClemBLUE.	Red channel → low titanium regions, or high in glass content (see the highlands, pyroclastic deposits). Green channel → amount of iron in the surface, mafic minerals. Blue channel → high titanium. Lunar surface maturity.	Lucey et al. (2000)
Color composite 1	RGB 1	R: SS, G: BDI, B: BDII.	When red dominates, space weathering is major, blue/green zones correspond to less mature terrains.	Zambon et al. (2020)
Color composite 2	RGB 2	R: SS, G: R540, B: BCII.	Blue areas are characterized by high iron/titanium, red zones are a lack of that.	Zambon et al. (2020)
Color composite 3	RGB 3	R: SS, G: R540, B: BDI.	This RGB combination gives information on terrain maturity and reflectance.	Zambon et al. (2020)
Color composite 4	RGB4	R: BCI, G: BCII, B: BAI.	Pyroxene rich material is seen in blue/yellow/green, glass and olivine in pink/yellow, plagioclase in red.	Horgan et al. (2014)
Color composite 5	RGB5	R: ASYI, G: BCII, B: BAI.	Pink and yellow show glass-bearing mixtures, blue a mixture of pyroxenes.	Horgan et al. (2014)
Color composite 6	RGB6	R: BD950, G: BD1050, B: BD1250.	Blue could imply the presence of olivine, red/purple the presence of Mg-	Besse et al. (2011)

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			pyroxene, yellow the presence of Ca-pyroxene.	
Color composite 7	RGB7	R: IBDI, G:IBDII, B: R1580.	Red is olivine rich, highlands rich in plagioclase appear blue, low-Ca pyroxene appear in green and yellow.	Besse et al. (2011)
Color composite 8	RGB 8	R: BD1900, G: IBDII, B:IBDI.	Dark blue corresponds to olivine signatures, cyan to clinopyroxene.	Bretzfelder et al. (2020)
Color composite of spinel	Spanpx	R :Px, G: Sp2, B: An.	Pyroxene in red, presence of spinel in green, and anorthosite in blue and yellow.	Moriarty III et al. (2022)

Table 2.1: List of spectral indexes collected in the literature. A total of 28 single-band parameters and 10 RGB composites were implemented.

2.4. Data

As our goal was to generate a set of consistent spectral indexes, we opted for optimizing the tool for the global mode captures of M³, in this way we always worked with the same spectral sampling and similar spatial resolutions. We selected the data from the Planetary Data System (PDS) (Malaret et al., 2011), using the PDS Geosciences Node Lunar Orbital Data Explorer (LODE) search tool.

2.4.1. Data formats

M³ data is available as cubes with an IMG file extension, each cube is a three-dimensional array of data, which stores spatial information in a two-dimensional plane, and spectral information in the third dimension. Other additional files contain ephemerides, geometries, calibration data, and metadata. To map-project the data it is necessary to download the geometric data of the radiance image and the derived reflectance cube, the latter being the one used for the retrieval of the spectral parameters. The reflectance cubes available in the PDS have 83 bands, missing the first two bands, corresponding to 0.46 μm and 0.5 μm . The reflectance data in the PDS is already calibrated for thermal and photometrical anomalies (Clark et al., 2011; Lundeen et al., 2011). Other authors have noted problems with this correction, especially after the 2 μm range, where the thermal emission of the lunar surface should be considered (Bandfield et al., 2018; Li and Milliken, 2017). In this work we use the reflectance cubes of the PDS, but further processed products can also be ingested to **MoonIndex**. The spatial resolution of the global mode data used in this paper is around 110 meters/pixel, while the spectral sampling is variable, being 0.02 μm between 0.5 μm to 1.5 μm , and 0.04 μm between 1.5 μm and 3 μm . Global mode cubes cover a substantial portion of the lunar surface, so one or two cubes are usually enough to study medium-sized landforms. On the global mode, the data is captured at full resolution, and is afterwards downsized to reduce it to the desired resolution. M³ captured data intermittently across two orbital periods, usually with high solar zenith angles (Green et al. 2011), as a result, there are not many locations covered by more than one or two cubes taken at different times.

M³ data is affected by some artifacts, making it difficult to develop general procedures to remove or improve these issues (Green et al., 2011). In particular, all M³ files display vertical stripes due to thermal issues with the instrument. The stripes are present in all wavelengths, but their intensity varies from cube to cube. We also detected an anomalous increase in reflectance from right to left in some cubes. This effect is particularly strong at longer wavelengths, affecting the band depth, area, and asymmetry (Green et al., 2011). The photometric correction of the cubes is not reliable for incidence angles higher than 70 degrees, which especially affect steep slopes on craters. Finally, there are some cubes taken in the same area that are not correctly projected with respect to each other, this may be a problem with the SPICE information of the data (Acton et al., 2016). Although

the mentioned artifacts reduce the quality of the information, almost every cube still has plenty of data that can be analyzed.

2.4.2. Case study regions

All the indexes collected and formulated in this work are applicable to any location on the lunar surface. Here, as a study case, we compare our results with those of three other authors that also focused on spectral indexes (**Figure 2.3**).

2.4.2.1. Apollo Basin

The Apollo basin (36.1°S 151.8°W) was the target of Zambon et al. (2020). It is a large multiring impact basin within the northern part of the South Pole Aitken basin (SPA) (Moriarty and Pieters, 2018). It has an estimated age of 3.98 Ga (Ivanov et al., 2018) and was later filled by basaltic flood lavas. The Apollo basin has a big geomorphological and compositional diversity (Ivanov et al., 2018, Potter et al., 2018), most of the zone is dominated by highlands terrains, but a large basaltic flood is emplaced at the center of the basin. This diversity makes it a good target to test the variability of the spectral parameters. Zambon et al. (2020) used the band center, depth, and spectral slope to study the mineralogical composition of the region. We will compare our results for these same parameters. We used the reflectance cube M3G20090813T213525.

2.4.2.2. Vallis Alpes

Vallis Alpes (49°N, 3°E.) was studied by Bretzfelder et al. (2020). The Vallis Alpes and Montes Alpes are landforms located in the northern rim of the Imbrium basin, they are northeast trending structures, including a central linear rille and parallel mountain ranges at both sides of it. The mountains are probably ejecta blocks of the Imbrium impact, which according to Klima et al. (2011) are enriched in low-Ca pyroxene. Bretzfelder et al. (2020) identified olivine outcrops in the surface using the integrated band depths and the band depth at 1.9 μm , suggesting the presence of plutonic rocks excavated from the lower crust (Shearer et al. 2015). We recreated these parameters to identify the presence of olivine in the region. The reflectance image used for this target is M3G20090608T125102.

2.4.2.3. Aristarchus crater

The Aristarchus Crater (23.4°N, 47.2°W) was analyzed by Horgan et al. (2014). It is a well-preserved Copernican complex crater, it shows high albedo and sharp morphologies, which correspond to impact products (Mustard et al., 2011). The structure of its ejecta is clearly visible, including several types of impact melt, basement rocks and structural patterns. Horgan et al. (2014) used the band centers, areas and asymmetries to study and classify the ejecta and glass bearing lithologies around the crater. The reflectance M3 cube used for this target is M3G20090209T054031.

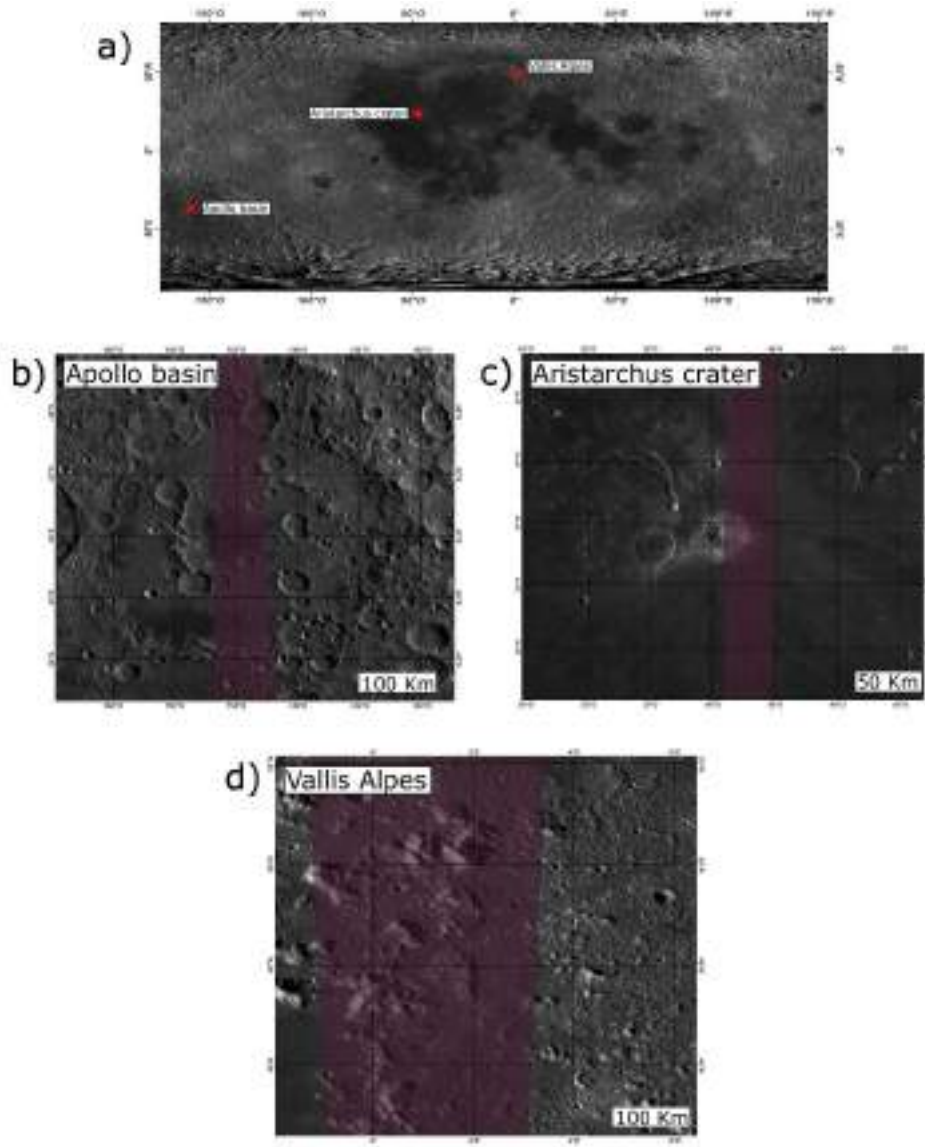


Figure 2.3: a) Regions selected to test the MoonIndex tool. b) Apollo Basin, a large impact structure in the South Polar Aitken basin (SPA), target of Zambon et al. (2020). c) Aristarchus crater, a Copernican impact structure enriched in glasses, target of Horgan et al. (2014). d) Vallis Alpes, a linear rille in the rim of the Imbrium basin, target of Bretzfelder et al. (2020).

2.5. Methods

The use of other software is necessary before and after the application of *MoonIndex*. An important step to properly use remote sensing images is the spatial projection of the data, which locates the images on the surface of a planet. For planetary bodies, this process is challenging and has been optimized before in software like the Integrated Software for Imagers and Spectrometers (ISIS)

(Laura et al., 2023). For this reason, we did not recreate this step within the Python workflow. Then, **MoonIndex** can be applied to map-projected M³ reflectance cubes. As for the indexes derived from our tool, we strongly recommend their use with geospatial software such as QGIS or ArcGIS, which are well-optimized for high level remote sensing data interpretation. The whole workflow applied is summarized in **Figure 2.4**.

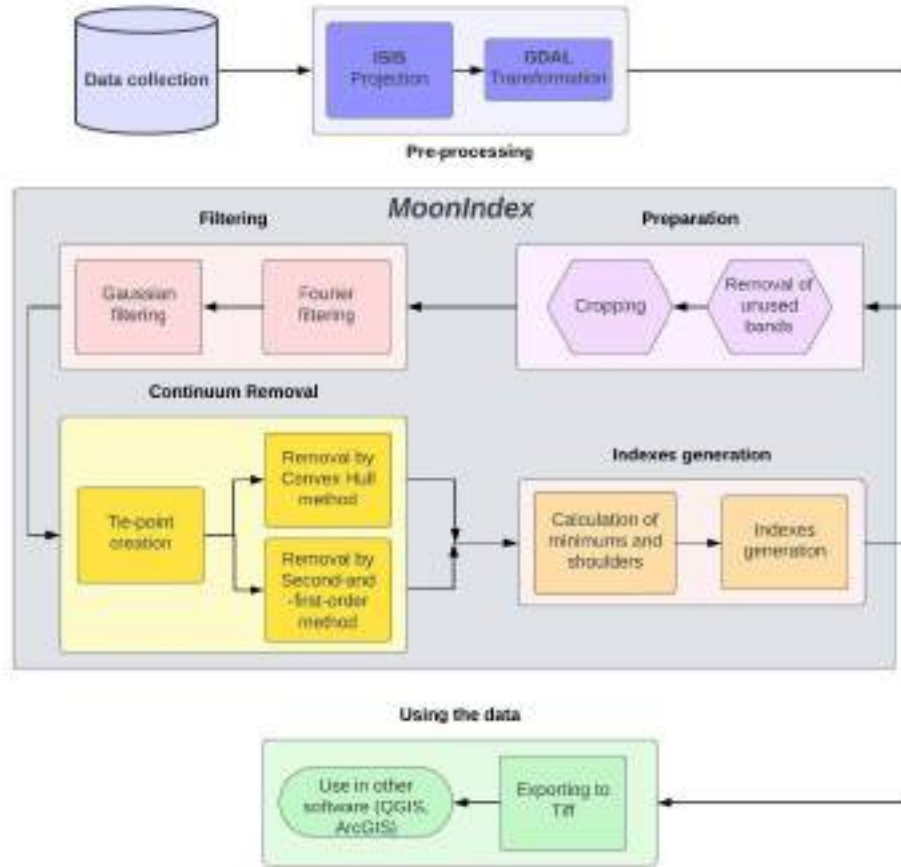


Figure 2.4: Flow-chart of the full procedure to create spectral indexes using MoonIndex.

2.5.1. Preprocessing

To process M³ cubes through *MoonIndex*, the user first needs to map-project them and change their format to Tiff/Geotiff using ISIS and the Geospatial Data Abstraction Library (GDAL) (Rouault et al., 2023). The first step is the ingestion of the data to ISIS, the importing command of ISIS only accepts the radiance product of M³, so we performed a change in the associated LBL file of the radiance cube to use the reflectance data (e.g., Figuera et al., 2018). The modification consists in changing the name of the radiance cube by the one of the reflectance cube in the “^RDN_IMAGE” parameter under the “/* Description of Radiance-corrected image file */” section of the LBL file. This tricks ISIS to accept the reflectance cube,

and to continue the pre-processing. As the data of M³ usually covers a substantial portion of the Moon, sometimes it is necessary to reduce the extent of the cube, this is usually necessary when the data comprise the poles. The polar region covered by the cube can be cropped to a smaller size in ISIS. Then, we geographically projected the cube to a pre-defined coordinate system. After the projection, the format of the data was changed from CUB to TIF using GDAL. At this point, the data is ready to be ingested on the tool. The commands used in this step can be found in **Section 2.11.2**.

2.5.2. Data processing using *MoonIndex*

The *MoonIndex* tool is designed to automatically work, after an initial configuration of the input and output paths. The indexes are calculated from a set of Python functions developed in this work, which are optimized for the technical characteristics of M³. The workflow can be divided into three main stages (**Figure 2.4**): filtering, continuum removal (when needed), and indexes generation. We used Python libraries that are produced/written to work with spatial imagery data, like *xarray* (Hoyer and Joseph, 2017), *openCV* (Bradsky, 2000), and *rasterio* (Gillies and others, 2013). And we also used common operational libraries like *numpy* (Harris et al., 2020), and plotting ones like *matplotlib* (Hunter, 2007). A detailed description of the libraries is found in Section **2.11.3**.

2.5.2.1. Cube adjustments

Some minor corrections are needed before working with the data. The first two bands of the reflectance cube do not contain spectral information, so they are removed, this means that the initial band of the data is 0.54 μm . The pixels with no-data values are reassigned to zero, to avoid problems in the processing. Due to the M³ observation strategy, a large part of the cubes is acquired from north to south pole, increasing the file dimension and making the data processing difficult (Green et al., 2011). For this reason, a specific tool to resize the data is fundamental for easier data processing. In this regard, we develop a function dedicated to crop the data using the coordinates of the desired regions (**Figure 2.5**). Nevertheless, the user can still opt to process the full cube by simply not using this function.

2.5.2.2. Filtering

The striping of the cubes can disrupt the data, both the spectral profiles and the images for each wavelength have a periodic noise that makes interpretation more difficult (**Figure 2.6a**). Since no instrumental calibration is provided by the team of M³, we opted for filtering the data. Some of the recreated spectral indexes require operations over specific bands, so we did not apply processes that reduce the dimensions of the data, like the Minimum Noise Fraction (MNF) method used in M³ cubes by Kodikara et al. (2015). Instead, we followed a simple two-step smoothing method proposed by Shkuratov et al. (2019) for M³ cubes, which

consists of a Gaussian convolution followed by a Fourier filtering. After several attempts we obtained better results inverting the order of the filters, as less striping is visible after generating the indexes.

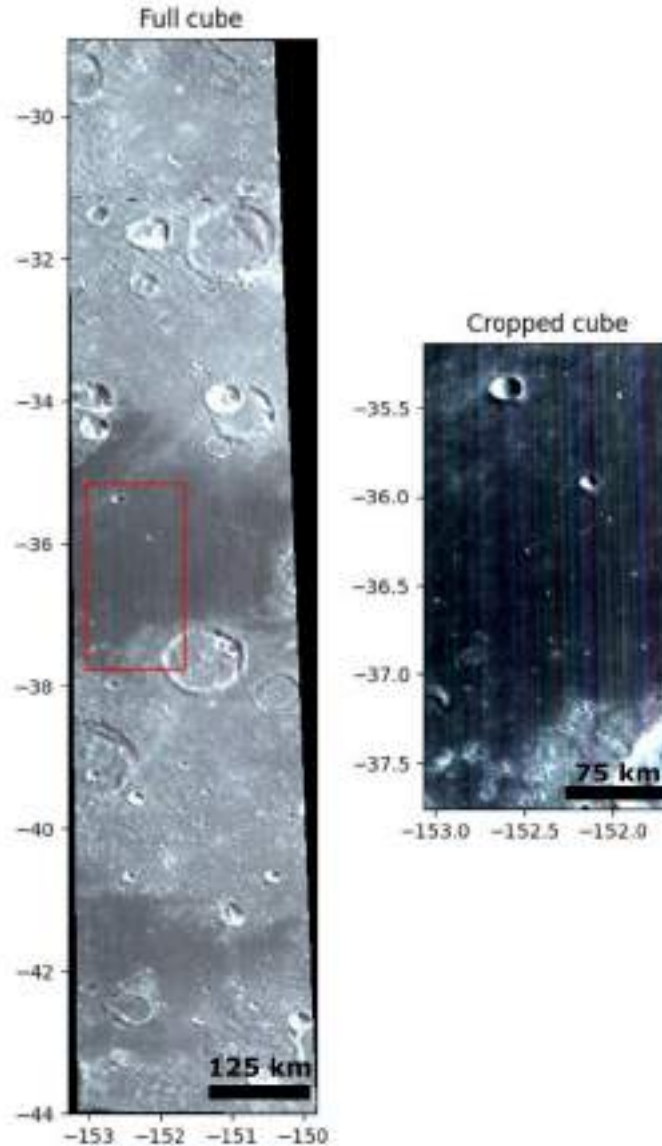


Figure 2.5: Cropping function of the tool. M3 cubes are generally large, so the use of subsections when possible is recommended.

The Fourier filtering was computed individually for each band of the cube. The process starts by applying a 2D Fourier transform, the resulting image is in the Fourier or frequency domain, which shows the distribution of frequencies contained in the original spatial domain (Broughton & Bryan, 2018). In the Fourier domain, it is possible to identify some frequencies responsible for the vertical striping of the data, which horizontally cross the Fourier image at its center (**Figure 2.6b**). Once the position of the stripes was identified, we applied a mask to the data, multiplying by zero the regions dominated by their frequencies (**Figure 2.6c**). The size of the mask corresponds to 60% of the width of the image, and 2% of its

altitude; these measurements were established manually as it removes the major number of stripes without damaging the frequencies of the actual data, usually accumulated at the center of the Fourier image. The user has the possibility to change the size of the filter. Lastly, an inverse Fourier transform is applied to the masked images, recovering the filtered cube in the spatial domain. After the Fourier filtering, a simple 1D Gaussian filter is applied to the data, this time over the spectral dimension. This process smooths the spectral signatures of each pixel, allowing the identification of the main mineral absorption bands (**Figure 2.7a**). The filter is only applied between $0.54\ \mu\text{m}$ and $2.85\ \mu\text{m}$, to avoid an undesired trend caused by the instrumental errors at longer wavelengths. As most of the minerals on the Moon have absorption bands in shorter wavelengths, we decided not to include those unfiltered last four bands. Finally, we examined that the filters do not affect the actual data. We generated ratioed images between the filtered and unfiltered cubes, and then checked that variations of over 2% were not achieved outside the location of the vertical stripes (**Figure 2.7b**).

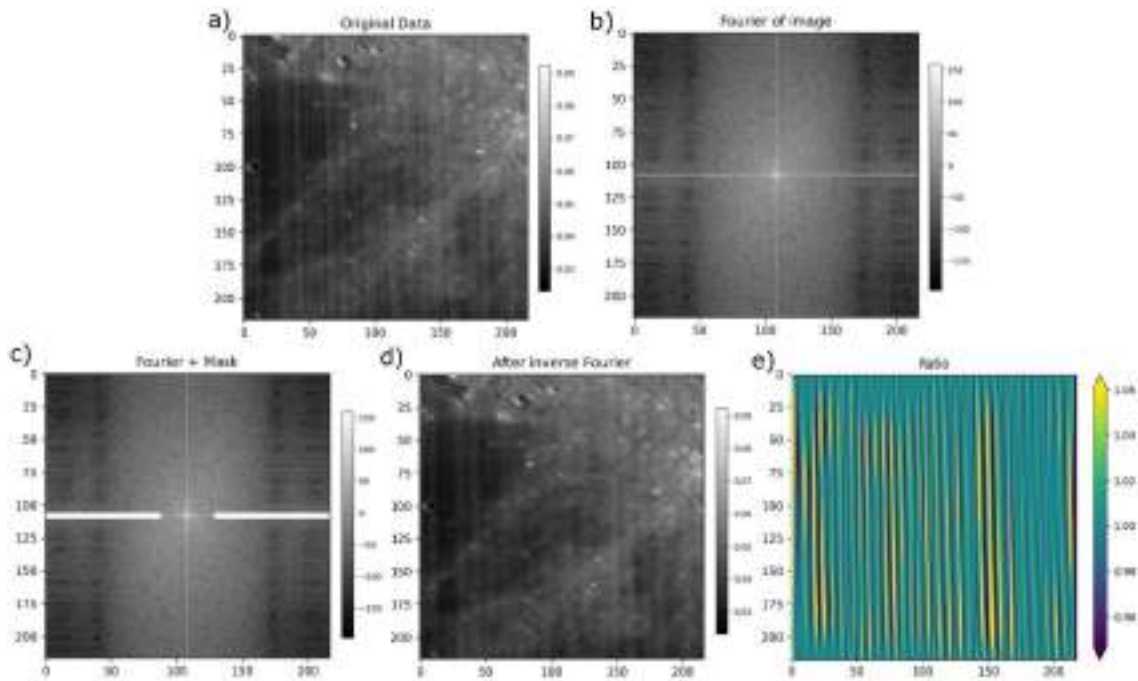


Figure 2.6: Fourier filtering of the Apollo Basin cube, the gray scale ramp represents reflectance. a) Original data with the typical vertical striping of M³. b) Fourier image of the data, the strong horizontal line contains the frequencies of the vertical stripes. c) Filter applied to the data, the pixels inside the rectangles are multiplied by zero. d) Image after the filtering, showing a reduction in the number of vertical stripes. e) Ratio between the original image and the one after the Fourier filtering.

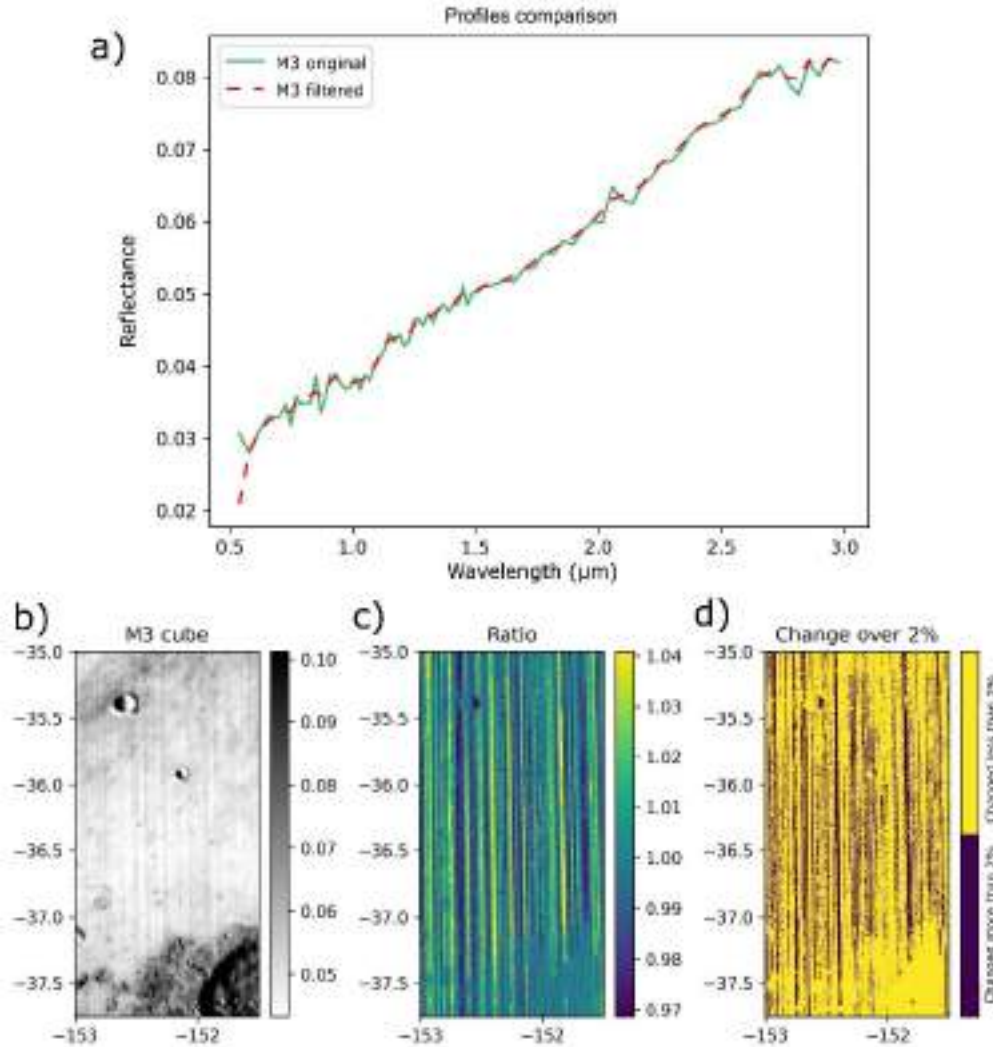


Figure 2.7: a) Comparison of the spectral profiles before and after the Gaussian filter, the orange line is smoother and allows a better interpretation of the absorption bands. b) Images of the original cube, c) the ratio between the last and the Gaussian-filtered cube, d) and the location with changes over 2% on reflectance (black pixels). These images show the surface data is not affected by the filtering process.

2.5.2.3. Continuum removal

Some indexes require a continuum removal of the spectrum to be performed. The continuum of a spectrum is considered the background absorption signal, which results from the interaction of several properties of the analyzed surface (e.g., Clark and Rush, 1984; Zhang et al., 2016). The continuum on the spectral signatures of M³ is a positive slope that overlaps the relatively weak absorption of the minerals, it results from the combined signals of the lunar regolith and the products of space weathering. In the lunar case, a major contribution to the continuum is due to space weathering effects, which in turn can be used to measure the maturity of the surface (Lucey et al., 2000). Even when the continuum plays a major role in M³cubes, its removal uncovers the spectral properties of the

minerals on the surface and allows the analysis of parameters related to absorption bands (**Figure 2.8**).

Several approaches have been used to remove the continuum of lunar spectra, we decided to implement two of these methods in **MoonIndex**. Since this process consists of removing the overall trend of the data, the most common approach in literature involves calculating the continuum as a linear or polynomial fit between the first and last value of the spectrum, and then using it to divide the original data (e.g., McCord et al., 1972; Clark and Roush, 1984). Similarly to Zambon et al. (2020, and references therein), we applied a second-and-first-order fit method to remove the continuum of M³ data. By considering the spectral properties of the minerals on the lunar surface, the removing function was calculated independently for each absorption band. Around the 1 μm band, a second order fit was used, and for the one around the 2 μm , a linear fit function was applied. We named this approach as the “second-and-first-order fit method” in our tool (**Figure 2.8b**). Nevertheless, the polynomial order of this method can be modified for both absorption bands. The other approach implemented is the convex hull method (Graham, 1972), in this case, the continuum is calculated as the enveloping function of the spectral data, consisting of lines interpolated over every consecutive point of the spectrum. This method has the advantage of being completely independent of arbitrary limits for the absorption bands and that it highlights the shape of every absorption feature. We implemented this approach as the “convex hull method” in our tool (**Figure 2.8a**). Although the code is flexible by allowing the use of both continuum-removal methods, we recommend the convex-hull one, since its automatic detection of the band shoulders would work better in locations where the mineralogy differs from the typical plagioclase-pyroxene-olivine dominance (as the position of the band shoulders in the second-and-first-order fit method are fixed to the usual ranges of these minerals).

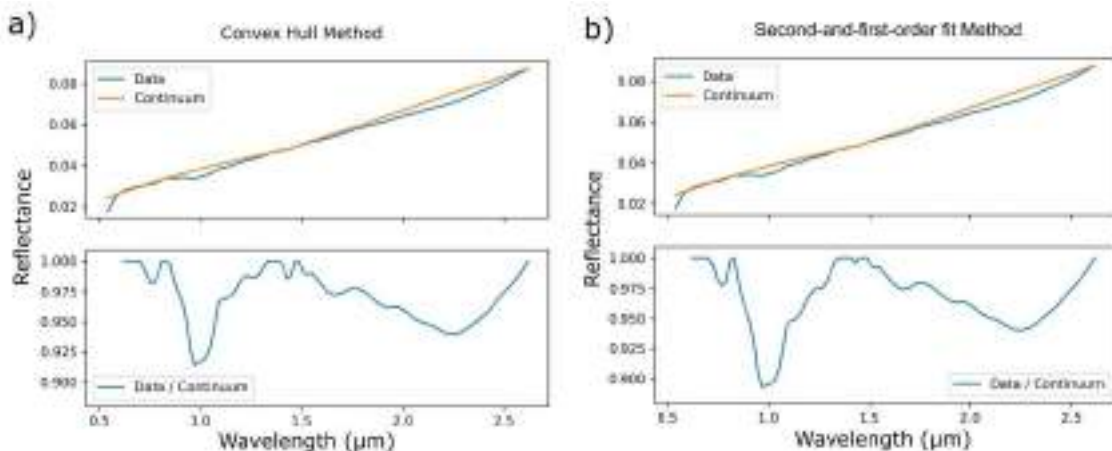


Figure 2.8: Continuum removal methods applied by MoonIndex. a) Convex-hull method, it used an envelope around the vertex of the spectrum. b) Second-and-first-order fit method, it used a second order polynomial around the 1 μm absorption band, and a linear fit around the 2 μm absorption band.

An additional challenge was encountered when the spectra had a rapidly increasing slope, this creates an effect where the local maximums are masked, especially near the right shoulder of the 1 μm absorption band (also the left shoulder of the 2 μm absorption band). This resulted in an incorrect calculation of the convex hull and the second-and-first-order fit methods, since the algorithm was not able to find the local maximum. To bypass this problem, we created a tie-point between 1 and 2 μm , which is set to a higher value than the surrounding data, ensuring that the continuum removal process will count it as a maximum. This artificial point marks the closure of the absorption band at 1 μm and the beginning of the one at 2 μm , only when the spectral signature is too featureless to be detected. The position of the tie-point was defined as the most prominent peak of the difference between the original spectrum and its continuum, calculated with a linear fit between 1.02 μm and 2.09 μm . We selected this range since the absorption band at 1 μm usually closes inside it.

2.5.2.4. Key parameters extraction

Once the continuum has been removed, the data is ready for the retrieval of spectral indexes. Two parameters were calculated first, the position of the minimum reflectance and the position of their two surrounding shoulders, for both the 1 μm and 2 μm bands. These parameters are key to calculate other indexes since they define the limits of the two main regions of mineralogical interest. The minimum is also used to derive the band depth, while the shoulders are necessary to calculate the band areas, which in turn allows the definition of the band asymmetries. The position of the minimum reflectance (or maximum absorption) is simply defined as the wavelength where the spectrum has its lower value, this is calculated independently for the 1 μm and the 2 μm band, being the tie-point the limit for both. The positions of the shoulders were defined as the first local maximums to the left and right of the band minimum. Since this operation is done after the removal of the continuum, the shoulders have values equal to one (**Figure 2.2**). Also, the data after 2.65 μm was cut from all the spectra, so this value is set as the right shoulder of the 2 μm band for every pixel.

Once the continuum removal was performed, we made a second-order polynomial fit around the minimums and maximums to further reduce the noise of the resulting indexes, this is done within a window from two wavelengths lower up to two wavelengths higher.

We established detection limits for the key parameters using thresholds for the band depths since it would not be accurate to analyze the absorption band if it is too shallow. Below the thresholds, the band center, depth, area, asymmetry, and derived parameters are not calculated. The definition of the limit was done using the cube for the Apollo Basin, since it contains several types of terrains, and thus is representative of the overall lunar mineralogy. The lowest meaningful detection would be around 0.005 since the level of the noise is typically lower than this value (**Figure 2.S2**). However, a higher threshold was established using the distribution

of the band depths at 1 and 2 μm , we choose a limit at 1.5 standard deviations to the left, that is 0.026 for the 1 μm absorption, and 0.017 for the 2 μm absorption. By doing a manual check of spectra with band depths below these values, we found that the absorption features are usually anomalous, and should not be computed (**Figure 2.S3**). A total of 0.15% pixels were filtered for 1 μm , and 0.35% at 2 μm for the Apollo basin cube. By setting these limits it is possible that some true detections would be lost, especially for cubes with wider distributions or less mineralogical variation; nevertheless, most anomalous detections might be avoided, and the number of pixels removed below these limits is not substantial.

2.5.2.5 Indexes generation

A total of 28 indexes were reconstructed in this work. In **Table 2.1** we report the calculation of the parameters, their significance, and exemplary RGB composites that use them. We created Python functions that generate a raster for every index listed in **Table 2.1**.

Among the parameters, the ones done before the removal of the continuum consists of simple operations between bands. Those can be quickly calculated in Python after ingesting and filtering the data. As an example, the pyroxene ratio formulated by Pieters et al. (2014) was calculated as:

$$Px = \frac{R700 \text{ nm} + R1200 \text{ nm}}{R950 \text{ nm}} \quad (1)$$

Where, for example, R700 is the reflectance at 700 nm. A list with all the formulations can be found in **Table 2.1**. For the parameters done after the continuum removal, the calculation involves operations between the continuum and the spectrum. The band center and the band depth are defined as (Adams 1974):

$$BCI = \left(\frac{RB \text{ nm}}{RB_c \text{ nm}} \right) \quad (2)$$

$$BD = 1 - \frac{RB \text{ nm}}{RB_c \text{ nm}} \quad (3)$$

Where RB is the reflectance of the spectrum, and RB_c the value of the continuum. The band area was calculated for the two main absorption bands at 1 μm and 2 μm with (Cloutis, 1986):

$$BA = \sum \left(1 - \frac{RB \text{ nm}}{RB_c \text{ nm}} \right) * SR \quad (4)$$

Where SR is the spectral sampling of the cube, and the summation is limited by the positions of the shoulders of the absorption bands. Finally, the asymmetry is calculated as the difference in the area between the right and left half of the absorption band (**Figure 2.2**). Given as a positive percentage when the asymmetry

is higher to the right, and negative when it is higher to the left. A more complex index is the integrated band depth (IBD) (Bretzfelder et al., 2020), that is the sum of the band depths at each point along the full extension of an absorption band. It was calculated as:

$$IBD = \sum 1 - \frac{R(B\ nm + SR)}{RB_c(B\ nm + SR)} \quad (5)$$

A few indexes were adapted in this work from previous authors. Horgan et al. (2014) avoided using the band area and asymmetry at 2 μm since the absorption features of pyroxenes at longer wavelengths is not fully captured by the range of M^3 . Nevertheless, we believe calculating them is still useful, so we use the same method as their counterparts at 1 μm , closing the spectrum at 2.5 μm to avoid hydroxyl absorptions at 2.8 μm and the instrumental errors of the last channels. At last, we generated a chromite parameter. Since the reflectance spectrum of chromite is like the one of spinel, but with absorptions bands located at slightly longer wavelengths (Cloutis et al., 2004), we followed the approach of Moriarty et al. (2023) for spinel. The parameter is a ratio between an extrapolated value at 1.5 μm , using the slope between 0.75 μm and 1.3 μm , and the reflectance value at 2.7 μm . Like on the spinel parameter, this should highlight regions where the 2 μm absorption is higher than usual. It is important to consider that the spectrum of both minerals is similar, so a unique parameter that differentiates between them is difficult to achieve.

2.5.2.6. RGB composites delivered

The parameters can be combined between each other in RGB composites to highlight mineral associations or variations in the composition of the surface. **Table 2.1** shows examples of RGB composites used by previous authors, for the sake of clarity we arbitrary named the composites with consecutive numbers. Among them are the Clementine-like composite of Lucey et al. (2000), three composites suitable for the exploration of mafic minerals and evaluate surface maturity by Zambon et al. (2020) (RGB1, RGB2, and RGB3), two composites focused on crater ejecta by Horgan et al. (2014) (RGB4 and RGB5), two composites to detect mafic minerals by Besse et al. (2011) (RGB6 and RGB7), the olivine detection composite of Bretzfelder et al. (2020) (RGB8), and the spinel composite of Moriarty et al. (2022). Furthermore, other combinations of parameters can be done to highlight different compositions or mineral associations. For this reason, we created a python function that combines all the indexes in a single tiff file, this allows the user to reproduce each one of the listed RGB composites and more in a geoprocessing software like QGIS.

2.5.3. Deployment

MoonIndex is deployed as a python package with an MIT license. It is reachable from the web repositories PyPI and GitHub. Some exemplifying products will be

showcased in the Space Browser of the EXPLORE platform (Nodjoumi et al., 2022). The source code of the tool is fully available at GitHub (Suarez-Valencia, 2023), so the user has the option to modify it to its needs.

2.6. Results

In this section we will showcase our results obtained with the convex hull continuum-removal method for a selected set of indexes, that we will later compare with the results of previous authors. Nevertheless, the results for all the calculated indexes are reported in the supplementary materials (**Figure 2.S4**). The analysis of the images and the subsequent interpretation of the mineralogy are particular to the selected study zones, so the user must consider the regional properties of their targets when using the products of *MoonIndex*.

2.6.1. Filtering

Our first goal was to reduce the noise of the data using a Fourier and a Gaussian filter without losing much scientific information of the general shape of the spectrum and the absorption bands. In **Figure 2.7c**, the ratio between the original image and the filtered one shows that the residual information is concordant with the stripes on the non-filtered cube (**Figure 2.7b**), furthermore, the crater in the bottom-left has little residuals, since the striping was not as strong in this location. Another test was to identify the pixels that overcame a change of over 2% during the filtering (**Figure 2.7d**), which are shown in black. These pixels are consistent with the original striping, which means that the surface information that was visible before the filtering (yellow) was not affected by the process.

2.6.2. Band center and depth

The bands centers and depths calculated by *MoonIndex* for the Apollo basin are shown in **Figure 2.9a, b, c, and d**. The band center defines the position of the absorption features to study, which in the case of pyroxenes and olivines is related to their composition (Burns, 1993; Klima et al. 2011). The band depth in turn reflects the amount of that mineral, since a stronger signal indicates a higher abundance within a mixture (Clouts et al., 1986). On the band center at 1 μm there is a clear difference between the areas corresponding to highlands and maria (**Figure 2.9a**). The first ones have centering values around 0.93 μm , indicating at least a lack of pyroxenes; while in the mare, the band is centered at longer wavelengths, around 1.04 μm , resulting from the presence of pyroxene on the basaltic lavas (Klima et al., 2011). Furthermore, the variations inside the maria hints to a compositional variation of pyroxenes, since OPX tends to have lower center values than CPX. The band depth at 1 μm also allows the identification of mafic minerals (**Figure 2.9c**), if the levels of space weathering is equivalent, greater band depths indicates a major abundance of them. The band depth at the center of the basin shows values around 0.13, while in the surrounding highlands it is only around 0.05. The position of the band center at 2 μm inside the maria

varies between 2.05 and 2.2 μm , further pointing to some variations in the composition of pyroxenes. Finally, the band depth at 2 μm shows strong absorption in the maria of around 0.08, further pointing to the presence of pyroxene (**Figure 2.9c, d**). Olivine does not show features in the 2 μm spectral range, so a comparison between both band depths can help identify its presence (see Index RGB 8) (Isaacson et al., 2011).

Some instrumental and acquisition artifacts are also seen. The band depth at 2 μm is especially sensitive to the already mentioned thermal instrumental error that causes a decrease of the values from right to left of the M³ cubes at longer wavelengths (Green et al., 2011), resulting in the maria regions to the left of the image showing a similar depth as the highlands. Steep regions with high incidence angles show anomalous values on all the indexes, therefore information in those zones is not reliable.

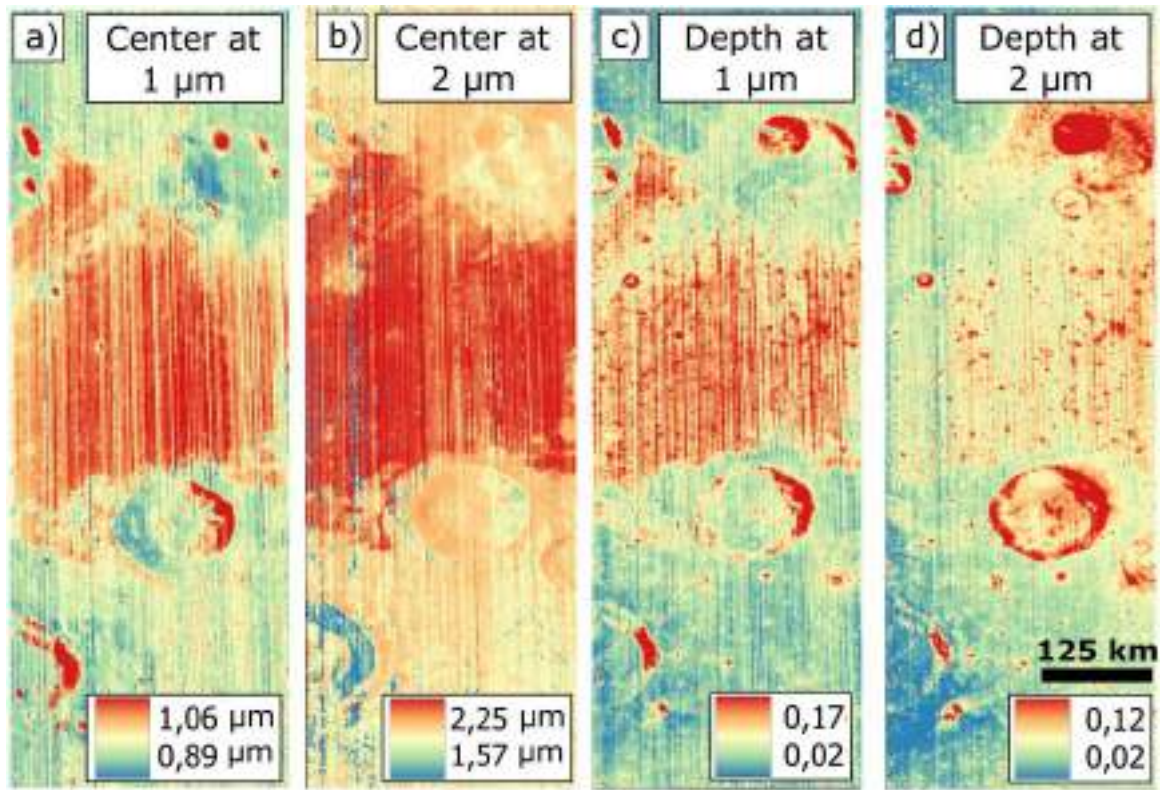


Figure 2.9: Initial parameters calculated by *MoonIndex* for the Apollo basin. a) Band center at 1 μm , lower values (blue) correspond to highlands materials, while higher values (red) are due to the presence of mafic minerals in the mare. b) Band depth at 2 μm , also allows differentiation between highlands and mare. c y d) Band center and depth for 2 μm , they serve a similar purpose as their 1 μm counterparts.

2.6.3. Band area and asymmetry

To showcase the band area and asymmetry obtained by **MoonIndex**, we use the cubes over the Aristarchus crater, which has a well-preserved ejecta blanket around and a variety of glass-bearing materials (Mustard et al., 2011). The band area corresponds to the region inside the continuum and the absorption band (**Figure 2.2**). The band area is useful to identify ejecta (Horgan et al., 2014), as well as mineralogical differences, since OPX-rich ejecta has a higher band area value than CPX-rich ones (Cloutis et al., 1990). The band asymmetry quantifies the shape of the absorption band by comparing the area to the left and right of the position of the band center, negative values imply a bigger area left of the center, and positive values the opposite. The band asymmetry is useful to identify glass and olivine-bearing ejecta, as well as plagioclase. Since mixtures of pyroxene with those materials result in higher asymmetries than only pyroxene (Horgan et al., 2014). For the band area at 1 μm in the Aristarchus crater, the ejecta is clearly recognizable as a zone with low values scattered around the crater (**Figure 2.10a**). In the band asymmetry at 1 μm , the only contrasting feature is the negative values of the northern ejecta (**Figure 2.10b**), which previous authors have identified as a mixture of OPX and anorthosite (Chevrel et al., 2009). In the band area at 2 μm , the pattern of the ejecta is not so clear compared to its 1 μm counterpart, the lower values in the southern half of the ejecta indicate a lower amount of pyroxene on it (**Figure 2.10c**). As for the band asymmetry at 2 μm (**Figure 2.10d**), we found that the landforms are clearer than in its 1 μm equivalent. Still, higher values are encountered in the ejecta south of the crater in both asymmetries, pointing to the presence of glass-bearing lithologies (Horgan et al., 2014).

Negative values dominate the 2 μm asymmetry, meaning that the absorption band is broader left of the 2 μm center. This effect is introduced by closing the absorption band at 2.5 μm , which cuts parts of the band at longer wavelengths and ends up affecting the area and shape of the band, and thus also the asymmetry.

2.6.4. RGB composites

The Clementine-like color composite (Red: 750 nm/540 nm, Green: 750 nm/1000 nm, Blue: 540 nm/750 nm) produced by **MoonIndex** for the Vallis Alpes region is showcased in **Figures 2.11**. This composition, originally formulated by Lucey et al. (2000), displays highlands material in red, due to glass agglutinates, and maria in yellow-green due to the combination of mafic minerals signals. Our result is concordant with this distribution, since the yellow location to the south of the image corresponds to the Imbrium mare, and the red zone that covers the majority of the image is the rim of the Imbrium basin, a highlands-like terrain. A smaller linear-shaped concentration of mafic minerals is also identifiable to the north, which is related to the basaltic flood inside the Vallis Alpes.

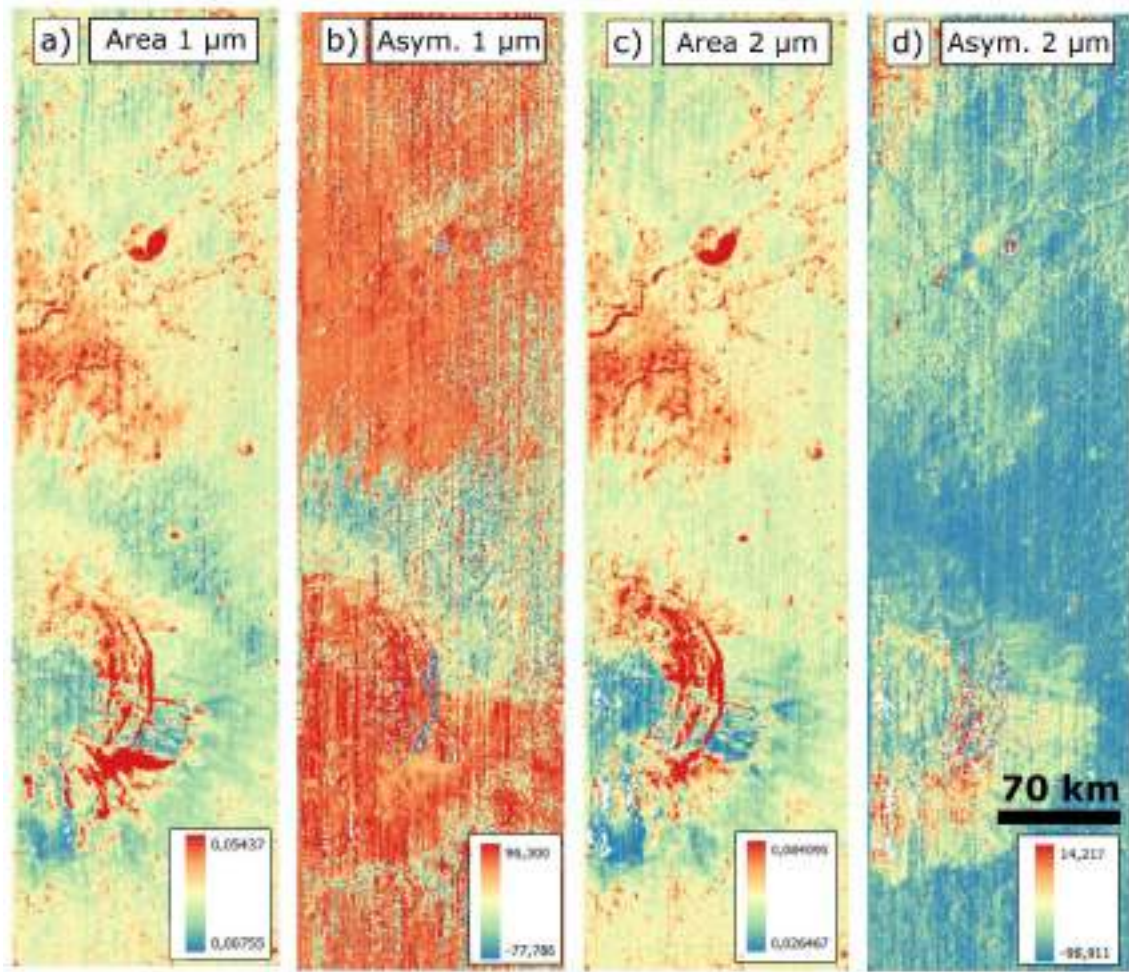


Figure 2.10: Band areas and asymmetries calculated by MoonIndex for the Aristarchus crater. a) Band area at 1 μm , the ejecta of the crater is clearly visible, the higher values, in red, indicate enrichment in OPX. b) Band asymmetry at 1 μm , higher values indicate the existence of glass-bearing ejecta. c) Band area at 2 μm , the low values at the southern part of the ejecta indicate low abundance of pyroxene. d) Band asymmetry at 2 μm , higher values also point to glass-bearing ejecta, but the widespread lower values are due to the band being cut off at 2.5 μm .

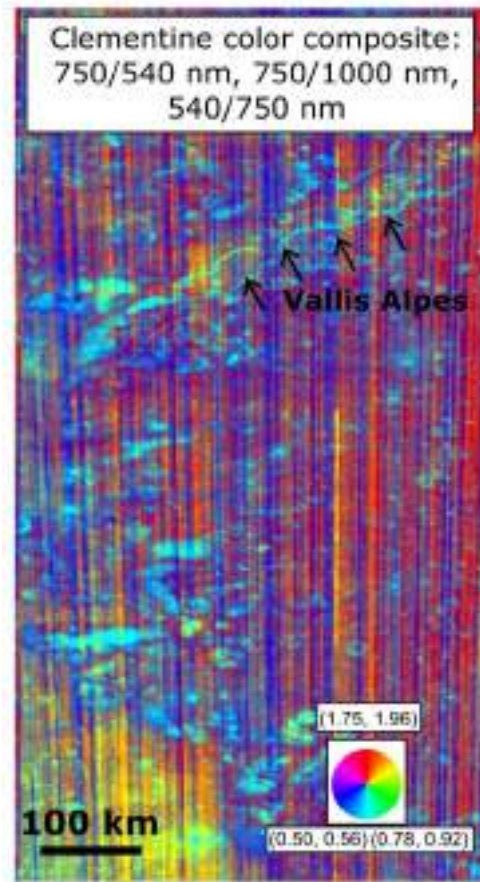


Figure 2.11: Clementine-like color composite created with MoonIndex. The red channel is 750 nm/540 nm, the green channel is 750 nm/1000 nm, and the blue channel is 540 nm/750 nm. The highlands appear in red due to the concentration of glassy agglutinates, and the maria and basaltic floods appear in yellow-green due to the combination of mafic minerals. Vallis Alpes shows a signal pointing to mafic minerals.

2.7. Discussion

2.7.1. Filtering

To evaluate the effect of the filters, we compared our results with the ones of Zambon et al. (2020) on the Apollo basin. **Figure 2.12** shows the position of the band centers at 1 μm . A reduction in the number of vertical stripes is achieved with the combined filtering applied by MoonIndex (**Figure 2.12a**), this is more noticeable in the highlands around the Apollo basin, where the information of the surface is not so distorted by vertical lines with anomalous values, as is the case for the band center of Zambon et al. (2020) (**Figure 2.12b**). Furthermore, the spectral patterns of the surface are maintained after the filtering, the higher values at the center of the basin and their progressive reduction to its edges is equally recorded in both images, meaning that details were not lost. This is also true for small surface features, like the several craters in the southern highlands (black

circles in **Figure 2.12**), which can be recognized in both versions of the index by their centering at longer wavelengths compared to their surroundings. There are other filtering methods for hyperspectral data apart from the one used in this work, different approaches include the transformation of the data using Principal Component Analysis (PCA) combined with pixel local grounding (PLG) (Zhang et al. 2010), or some variation of the MNF method mentioned earlier (Luo et al., 2016). Further work is needed to test and implement these options in **MoonIndex**, which is facilitated and encouraged by the Open-Source nature of the tool. Another further implementation to enhance the visualization of the resulting indexes would be to remove pixels with high incidence angles, which would require the extraction of this metadata from the OBS.IMG file downloaded from the PDS and its integration to the code of **MoonIndex**.

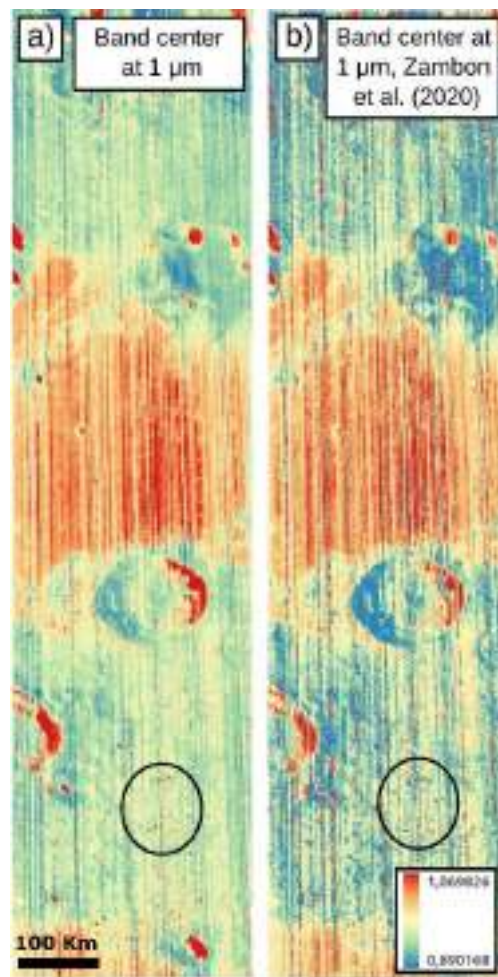


Figure 2.12: Band centers at 1 μm for the Apollo basin. a) Band center calculated in this work, after the Fourier and Gaussian filtering, the number of vertical stripes is less than in a non-filtered cube, especially on the highlands. b) Band center calculated by Zamboni et al. (2020). The black circles contain small craters, the signal of these geological features is maintained after the filtering, as well as the major spectral features.

2.7.2. Parameters

The resemblance of our parameters with the ones in the literature varies. For the indexes that are formulated before the continuum removal, such as the Clementine-like index, the results are consistent with the original data, with changes only in the spatial resolution and the noise patterns, both particular to each instrument. Nevertheless, for the indexes obtained after the continuum removal, we identified variations with respect to the original formulations, which are related to the methodologies used by every author. In **Figure 2.13** we compare our results for the band center and depth at 1 μm with the ones of Zambon et al. (2020). **Figure 2.13a** shows the ratio between the band centers, the major differences can be seen in red vertical lines and in the rims of big craters. The first ones are related to the removal of vertical stripes during the filtering, and the second ones to high incidence angles at the slopes of the craters. This indicates that there are no major variations in the surface data, except at particular locations inside big craters. The distribution of both histograms (this work in blue, Zambon et al. (2020) in red), also reflects a similar trend in both indexes (**Figure 2.13c**), most of the pixels in both cases are centered between 0.9 and 1.1 μm . Still, the band centers of Zambon et al. (2020) have a slight shift to shorter wavelengths, especially in high-slope crater rims (**Figure 2.12b**). Major differences can be seen in the ratio of the band depth at 1 μm . The red areas are widespread, and although most of them are due to the de-stripping of our data, changes are considerable in locations with clear signals of the surface (**Figure 2.13b**). This is more noticeable in the histograms of the band depths (**Figure 2.13d**), where the values of Zambon et al. (2020) accumulate more at higher values. As the band area and asymmetry are both derived and linked to the band depth, our results also diverge in a similar way from the ones of other authors. This major discrepancy in the band depth compared to the band center is the result of using different continuum-removal methods, as we will discuss later.

2.7.3. Color composite maps

The comparison of our RGB color composite maps with the ones in the literature presents certain difficulties. The source material from previous authors is not always available, therefore we cannot properly configure parameters like the band stretch or rendering method. Nevertheless, even when the specific colors and tonalities of the indexes may vary between works, the patterns of the geological features on the image and their differences should remain identifiable. This should allow for robust enough cartographic use of derived data.

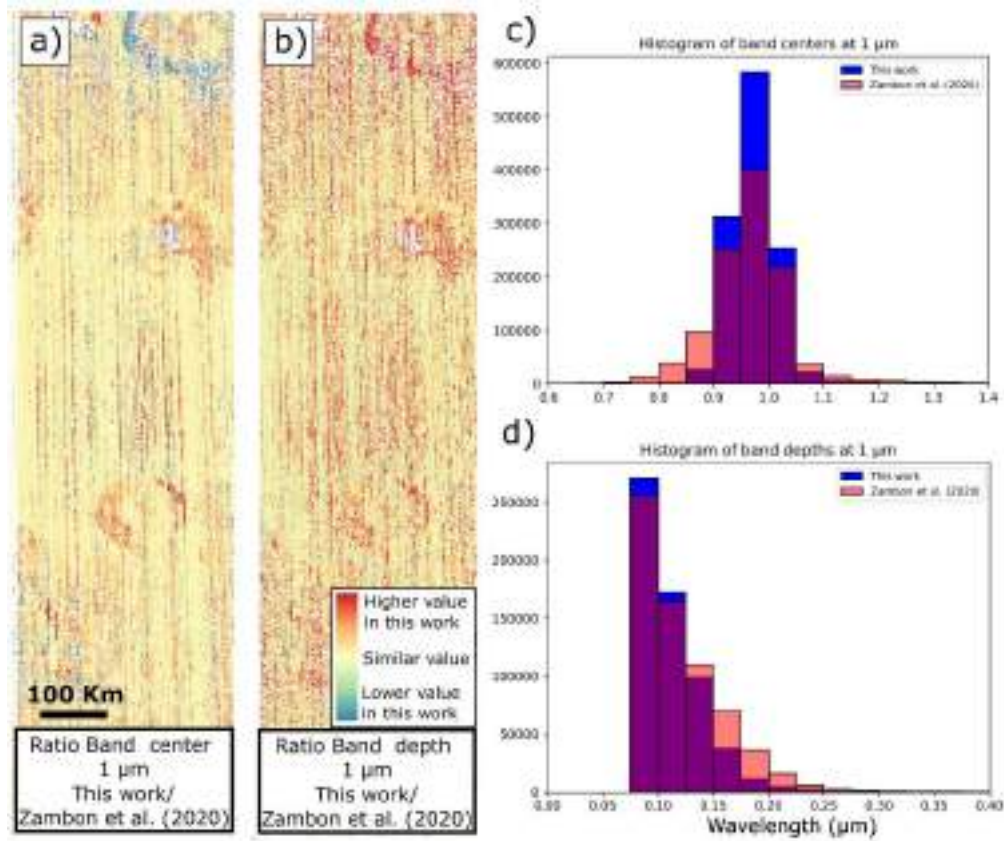


Figure 2.13: Comparison of our results and the ones of Zambon et al. (2020), for the band center and depth at 1 μm in the Apollo Basin. a) Ratio of the band centers, the major differences correspond to removed noise or crater rims, b) Ratio of the band depths, more discrepancies can be seen apart of the stripes and crater rims, c) Histogram of values for the band centers, trends are similar, with a small shift to smaller wavelengths in Zambon et al. (2020), d) Histogram of values for the band depths, a bigger shift is seen in this case, as the results of Zambon et al. (2020) accumulates at higher values. The difference in the counts in the histogram is due to a major amount of no data pixels in the results of Zambon et al. (2020).

The RGB 4 index (Red: Band center at 1 μm , Green: Band center at 2 μm , Blue: Band area at 1 μm) recreated in this work is close to the original one produced by Horgan et al. (2014) (**Figure 2.14a and 2.14b**) for the Aristarchus crater. The main colors are maintained, and the geological features are easily recognizable. This index is particularly useful to differentiate between pyroxenes, OPX is seen in blue, CPX in yellow, and a mix between them is green. Ejecta glass is also visible in magenta and orange. Although both indexes are generally compatible, there are some differences in the distribution. In our results the blue areas are smaller, indicating a lesser amount of OPX in the ejecta blanket. The black regions on the original index are pink in our work, which correspond to shadows or melt with no major signal around the 1 μm band. On the other hand, the differences are bigger for the RGB 5 (Red: Band asymmetry at 1 μm , Green: Band center at 1 μm , blue: Band center at 2 μm), also originally formulated by Horgan et al. (2014) (**Figure**

2.14c, d). This index is intended to highlight glass-bearing lithologies due to their high asymmetries, which will appear in pink and yellow. Both indexes are consistent north of the Aristarchus crater; the large pink area north of the crater is followed by the yellow-dominated locations. To the south, the results of Horgan et al. (2014) show lesser amounts of glass, while ours have a pink area that fits well with the ejecta blanket of the crater. The index that differs the most with the one of Horgan et al. (2014) is the band asymmetry at 1 μm , this is probably related to the continuum-removal method used by the prior authors, which applied a second order polynomial fit to the data.

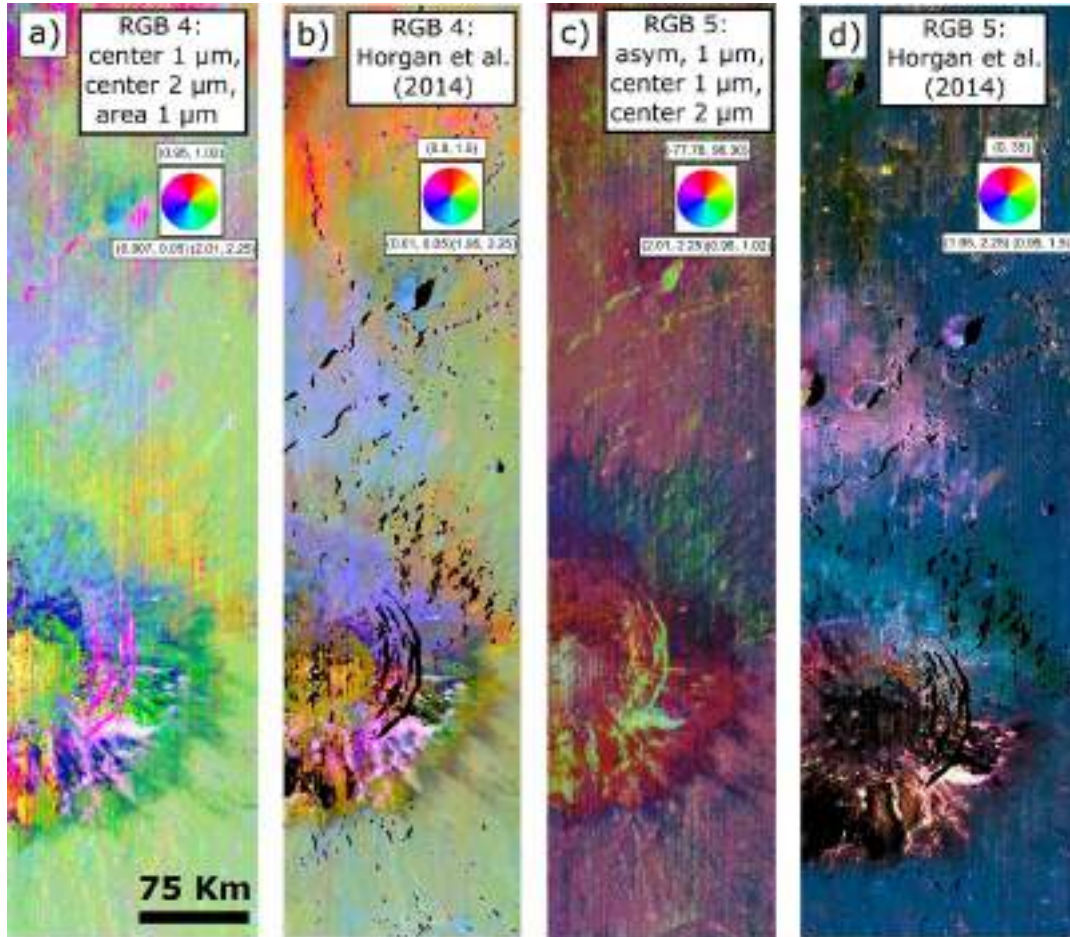


Figure 2.14: Comparison between our results and the ones of Horgan et al. (2014) for the Aristarchus crater. a) RGB 4 recreated in this work, the red channel is the band center at 1 μm , green is the band center 2 μm , and blue is the band area at 1 μm . b) original RGB 4 by Horgan et al. (2014), both color ramps are consistent, and the ejecta blanket and its compositional variation are seen in both cases, blue implies OPX, yellow CPX and green a mix of both. c) RGB 5 recreated in this work, the red channels are the band asymmetry at 1 μm , green is the band center at 1 μm , and blue is the band center at 2 μm ; overlaid by the band area at 1 μm in grayscale. d) original formulation of the RGB 5 by Horgan et al. (2014), the color ramp is less consistent, especially at the ejecta south of the crater, nevertheless the distribution of glass-bearing rocks (yellow and pink) is consistent north of the crater. The stretch values of Horgan et al. (2014) are unknown.

Another index worth comparing is RGB 8 (Red: Band depth at 1.9 μm , Green: IBD at 2 μm , Blue: IBD at 1 μm), originally formulated by Bretzfelder et al. (2020) for the Vallis Alpes region. On the original index, yellow corresponds to OPX, cyan to CPX, and most important, dark blue shows olivine-bearing massifs. Our results show a different color ramp (**Figure 2.15**). This occurs because we used a modified method to calculate the band depth at 1.9 μm ; instead of creating a specific continuum for the band, we measure the depth directly on the convex-hull removed spectra. But even if the calculation and the resulting color ramp are different, the same geological patterns are still identifiable in both composites. In our results, CPX is still yellow, OPX is light-toned blue, and olivine-bearing rocks appear in dark purple. An example of the last is the isolated mountain next to the southern edge of Vallis Alpes, which shows a strong olivine signal in both indexes (**Figure 2.15**). Since this index was thought specifically to identify olivine, our result is still relevant and applicable for that purpose.

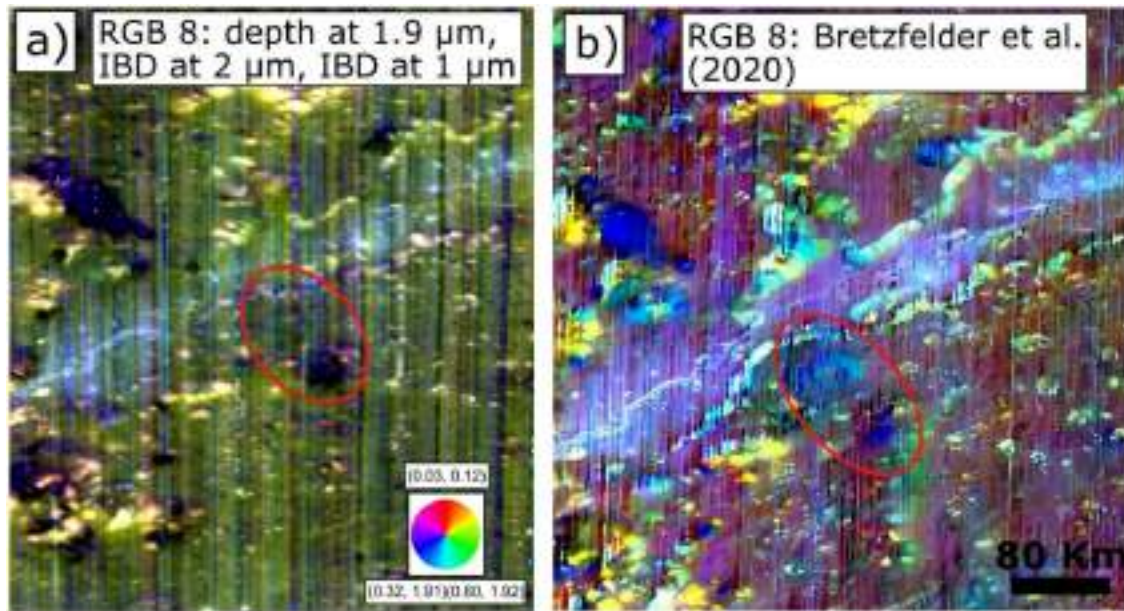


Figure 2.15: Comparison between our results and the ones of Bretzfelder et al. (2020) for the Vallis Alpes. a) RGB 8 recreated in this work, red is the band depth at 1.9 μm , green is IBD at 2 μm , and blue is IBD at 1 μm . b) original formulation of the RGB 8 by Bretzfelder et al. (2020). Stretch values are unknown. The ramp color is different in both cases, due to a change in the calculation of the band depth at 1.9 μm . Nevertheless, the pattern of geological features is maintained, for example the dark blue spots on the original index correspond to olivine (red circle), and in our recreation those same areas appear purple.

2.7.4 Effect of the continuum-removal technique

The differences between our results and the ones of the previous authors are produced by several factors. The method used to remove the continuum is the

main variable affecting the indexes. Since most of the previous authors used a combination of linear fits and second-order fits within defined intervals (Horgan et al., 2014, Zambon et al., 2020), a comparison between the results of our convex hull and second-and-first-order fit methods is helpful to explain the changes.

The general shape of the resulting continuum-removed spectrum is similar in both methods (**Figure 2.16a**), and all the parameters of the absorption bands are well represented and easily measurable. The position of the band center is not greatly affected by the removal method; the average difference between both procedures is 5 nm at the 1 μm absorption band, and 25 nm at the 2 μm band, which is in both cases smaller than the spectral sampling of M³ for those regions. On the other hand, the band depth is especially sensitive to the selected method, which can be appreciated by subtracting the images (**Figure 2.16b**). At 1 μm the band depth varies considerably, higher values are obtained with the second-and-first-order fit method in the highlands (**Figure 2.16a**), while in the mare the result is the opposite (**Figure 2.16c**). This inconsistency is the result of the way in which both methods define the continuum line. The second-and-first-order fit interpolates a second order polynomial function between two arbitrarily defined shoulders, while the convex hull draws a straight line connecting the local maximums it automatically computes (**Figure 2.8**). Hence, when the absorption band is weak, like on the highlands, the concave shape of the second-and-first-order fit method creates a slightly higher distance to the spectrum, resulting in bigger band depth values (**Figure 2.16d**). As for the maria regions, it looks like the convex hull method is identifying the right shoulder at longer wavelengths, which produces a deeper band depth. The band depth at 2 μm is less affected by the method, the variation is lower than in the 1 μm band, and most of the values are inside one standard deviation (**Figure 2.16e**). The second-and-first-order fit method uses a straight line for the 2 μm absorption band, thus the result is closer to the also linear interpolation done by the convex hull. Subsequent indexes like the band area and asymmetry are also affected in similar ways, especially at the 1 μm absorption bands, as larger band depths will result in larger band areas.

Several other factors are surely responsible for changes on the resulting indexes, but the lack of source materials for some of the indexes makes them difficult to evaluate. During the preprocessing of the data many factors could change, if the authors applied custom filtering or workflows before calculating the indexes, that would affect the end-result. Another difficulty is added to the RGB composites, even if the formulations are similar, we cannot be sure of the color stretch or the display settings of the original indexes. Small changes in the intervals of the values displayed by each channel can greatly modify the color ramp of a composite. In any case, the geological and spectral features on our composites are consistent with the original ones regardless of their tonality, so the products of **MoonIndex** appear to be reliable for geological analysis.

The reconstruction of spectral indexes from such varied sources makes it difficult to accomplish a high fidelity in all of them. This is especially true when some of

those indexes were formulated several years ago, with different missions, methodologies, and technologies. Nevertheless, our methodologies and results are consistent with each other, so the analyses derived from them are complementary and comparable. Given this context, consistency between the data is important when applied to the geological analysis of a region on the Moon, so we recommend the users of **MoonIndex** to use only one of the continuum removal methods for each project they might work on.

2.8. Conclusions

Spectral indexes are an easy and versatile way to approach the compositional analysis of the Moon. **Table 2.1** highlights proven indexes found in the literature, but other operations or RGB composites can be made with the products of **MoonIndex** to explore different mineralogical properties. During our recreation of the spectral indexes in python we added certain improvements to the data of M³. The Gaussian and Fourier filtering proved useful to reduce the vertical striping typical of M³ cubes, allowing the retrieval of clearer spectra, especially from cubes that otherwise would be almost useless for geological interpretation.

The implementation of the convex hull method to remove the continuum has certain advantages over the second-and-first-order fit method. As it creates an envelope over the local maximums, the shape of the absorption bands present on the spectrum should be identified correctly. Furthermore, the convex hull works automatically over the data, removing the necessity of establishing arbitrary limits for the interpolations. We recommend the use of the convex hull method over the second-and-first-order fit method, still both methods are implemented in **MoonIndex**.

The fidelity of the reconstructed indexes varies for several reasons. The most important one is related to the use of the convex hull method to remove the continuum, opposite to the polynomial fits applied by previous authors. But other factors unreported in the literature likely affected the results, such as the preprocessing routines, filtering methods, or the visualization parameters of the composites. Nevertheless, despite some changes in tonalities and values, the reproduced indexes have a similar scientific meaning in all cases and highlight the same compositional properties as the original formulations. The indexes produced by **MoonIndex** are consistent with each other, but the methodologies and algorithms described in this work should be considered when comparing them with indexes from other works.

Finally, **MoonIndex** was created to give a better accessibility to this kind of product to the scientific community. The package is Open-Source and freely available, so the users can modify it for their own purposes. The necessity to preprocess the data in other not-so-intuitive software like ISIS and GDAL may make the task difficult, but other tools like the EXPLORE platform or the GMAP Jupyter Hub (Nodjoumi et al., 2022), could contribute to ease the process. It is worth mentioning that the commercial software ENVI is typically used instead of

ISIS for georeferencing and calibrating M³ data, and although we advocate for freely accessible software, the products derived from ENVI could be processed by **MoonIndex** without problems after being ingested to Python.

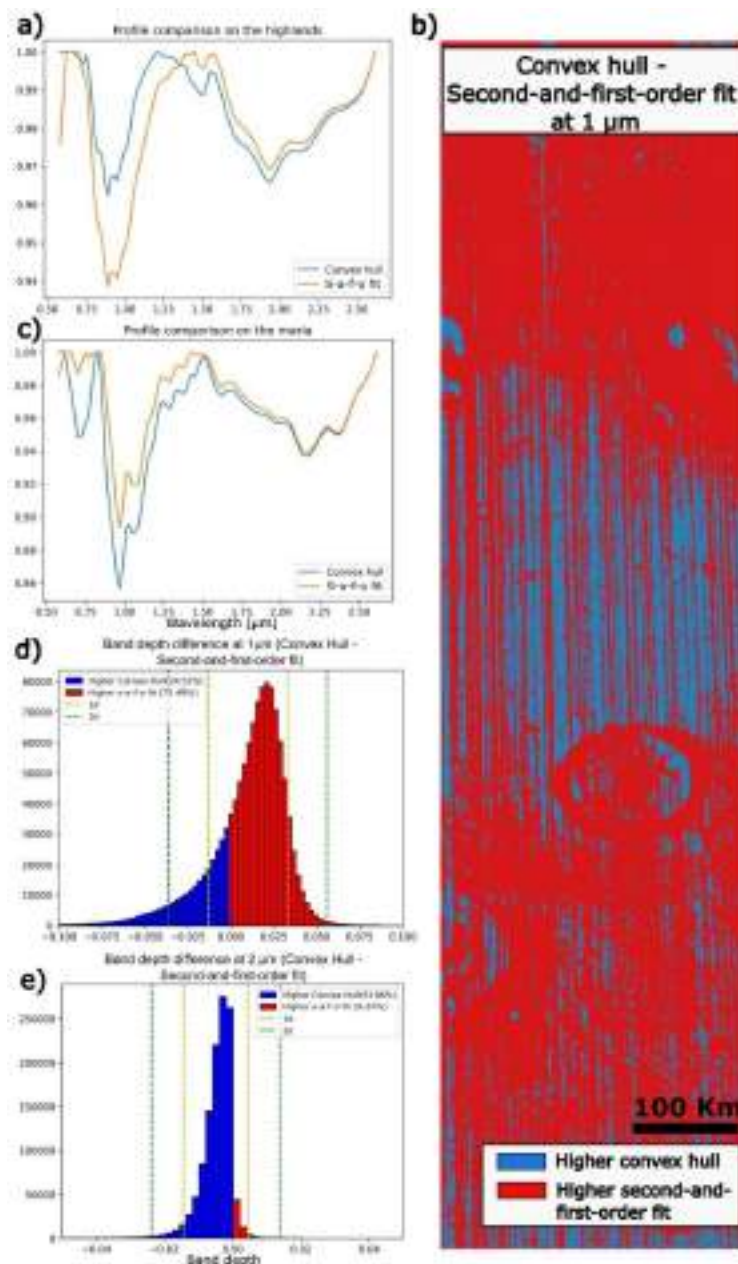


Figure 2.16: Comparison between the band depth results of the convex hull and the second-and-first-order fit methods for the Apollo basin. a) Spectral profiles of the same pixel on the highlands using the two methods, the band depth is greater with the second-and-first-order fit method. b) Image showing the difference between the results of the methods, in red regions where the second-and-first-order fit returned higher values, in blue the opposite. c) Spectral profiles on the mare, this time the convex hull has a higher band depth. d) Histogram of the values at 1 μm , the values are scattered more than two standard deviations. e) Histogram of the values at 2 μm , the difference between both methods is close to zero, and the values are not so scattered.

2.9. Acknowledgments

This research was done on the framework of the EXPLORE project, that has received funding from the European Union's 2020 research and innovation program under grant agreement No 101004214. Additionally, we had support from the GMAP project, part of the Europlanet 2024 RI has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 871149.

2.10. Open Research

MoonIndex is available for Python 3.10 and higher in the PyPI repository. The tool is released under the GNU general public license. The source code, exemplary Jupyter notebooks, definition of functions, and workflows can be accessed via GitHub and Zenodo (Suarez-Valencia, 2024). The raw datasets used in this work can be accessed through the PDS, and versions ready to use on **MoonIndex** are reachable at: Suarez-Valencia et al. (2024).

2.11. Supporting information

2.11.1. Introduction to supporting information

In this supplementary material we detail the preparation of the data before being ingested to **MoonIndex**, and the libraries used in python to generate the spectral indexes. Since the code to process the data in ISIS is not included on **MoonIndex**, we will show the workflow we followed to map-project the images. Furthermore, we showcase 24 indexes resulting from our workflow, we show only the images obtained by the convex hull continuum-removal method, since it was the one used in the main text. For an explanation about the meaning of the indexes, refer to **Table 2.1** in the main text. The map-projected M³ data cubes and the resulting indexes for the Apollo basin, Vallis Alpes, and Aristarchus crater can be found in this Zenodo repository: <https://zenodo.org/records/10014564>.

2.11.2. Pre-processing of cubes

The preprocessing of the data in ISIS consists on the map-projection of the cubes to a predefined coordinate system. ISIS does not recognize the higher-processed reflectance cube as an input, so the radiance cubes and associated files also need to be used. Before the projection could be done, we changed the name of the radiance cube by the one of the reflectance cube in the LBL file, this is done in the “^RDN_IMAGE” parameter under the “/* Spectral calibration parameters and radiometric gain factor data */” section of the file (**Figure 2.S1**).

Chapter 2: MoonIndex, an Open-Source Tool to Generate Spectral Indexes for the Moon from M3 Data

```

55
56 /* Spectral calibration parameters and radiometric gain factor data */
57
58 CH1:SPECTRAL_CALIBRATION_FILE_NAME = "M3G20001211_RDN_SPC.TAB"
59 CH1:RAD_GAIN_FACTOR_FILE_NAME     = "M3G20001211_RDN_GAIN.TAB"
60 CH1:GLOBAL_BANDPASS_FILE_NAME     = "M3G20001211_RDN_BPF.IMG"
61
62 /* Description of Radiance-corrected image file */
63
64 OBJECT = RDN_FILE
65 *RDN_IMAGE = "M3G20001204T192552_V03_RDN.IMG"
66 RECORD_TYPE = FIXED_LENGTH
67 RECORD_BYTES = 103360
68 FILE_RECORDS = 18593
69
70 OBJECT = RDN_IMAGE
71 LINES = 18593
72 LINE_SAMPLES = 304
73 SAMPLE_TYPE = PC_REAL
74 SAMPLE_BITS = 32
75 UNIT = "W/(m^2 um sr)"
76 BANDS = 85
77 BAND_STORAGE_TYPE = LINE_INTERLEAVED
78 LINE_DISPLAY_DIRECTION = DOWN
79 SAMPLE_DISPLAY_DIRECTION = RIGHT
80 END_OBJECT = RDN_IMAGE
81
82 END_OBJECT = RDN_FILE
83

```

Replace by the name of the reflectance cube

Figure 2.S1: Replacement of names on the radiance LBL file.

Once the replacement has been done, the full processing on ISIS and GDAL can be done with the following bash commands:

Listing all files to do the batch processing

```
ls *V03_L1B.LBL | sed s/_L1B.LBL// > Imputs.lis
```

Transformation from IMG to cubes

```
chan1m32isis from=\$1_L1B.LBL loc=\$1_LOC.IMG obs=\$1_OBS.IMG
to=\$1.cub -batchlist=Imputs.lis
```

Actualization of cubes kernels

```
spiceinit from=\$1.cub -batchlist=Imputs.lis
```

Making a new list

```
ls *V03.cub | sed s/.cub// > Imputs2.lis
```

Map projection, a map template need to be previously created

```
cam2map from=\$1.cub map=M3.map to=\$1_lv2.cub PIXRES=map -
batchlist=Imputs2.lis
```

Stretch

```
stretch from=\$1_lv2.cub to=\$1_lv2_nonull.cub NULL=65535 -  
batchlist=Imputs2.lis
```

Listing all files

```
ls *.cub | sed s/.cub// > Imputs.lis
```

Translate

```
for f in *_nonull.cub; do  
gdal_translate -a_nodata 65535 "$f" "${f%.*}.tif"  
done
```

Once these commands have been run, the cubes will be projected and in .TIF format, and ready to ingest on **MoonIndex**.

2.11.3. Libraries used

We used several python libraries during our workflow. Here we will discuss the application of all of them, and the full code can be access via the GitHub repository (<https://github.com/Javierunal16/MoonIndex>).

Preparation: During the preparation we used *rioxarray* to open the data cubes, and *numpy* to open the text file with the wavelengths for each M³ channel. Then, *matplotlib.patches* is required to clip the cube to the desired extent, and *matplotlib.pyplot* to graph the data. In the RGB composites we used *sklearn.preprocessing* to normalize the values before plotting.

Filtering: To filter the cube we rely on libraries designed for image processing. First, *cv2* and *numpy* were needed to apply the Fourier filtration. And later, *numpy*, *specutils* and *astropy* were used to apply the 1D Gaussian filter.

Continuum removal: We tried several option to apply the convex hull to the spectra, but we ended up using *numpy* and *scipy.signal* to find the midpoint and to calculate the convex hull. As for the second-and-first-order fit method, only *numpy* was needed.

Indexes generation: The creation of indexes is straightforward after the continuum removal, most of them require band operations that can be covered by *numpy*.

Deployment: The code was compiled using *wheel* and uploaded to PyPI with *twine*.

2.11.4. Figure of noise distribution

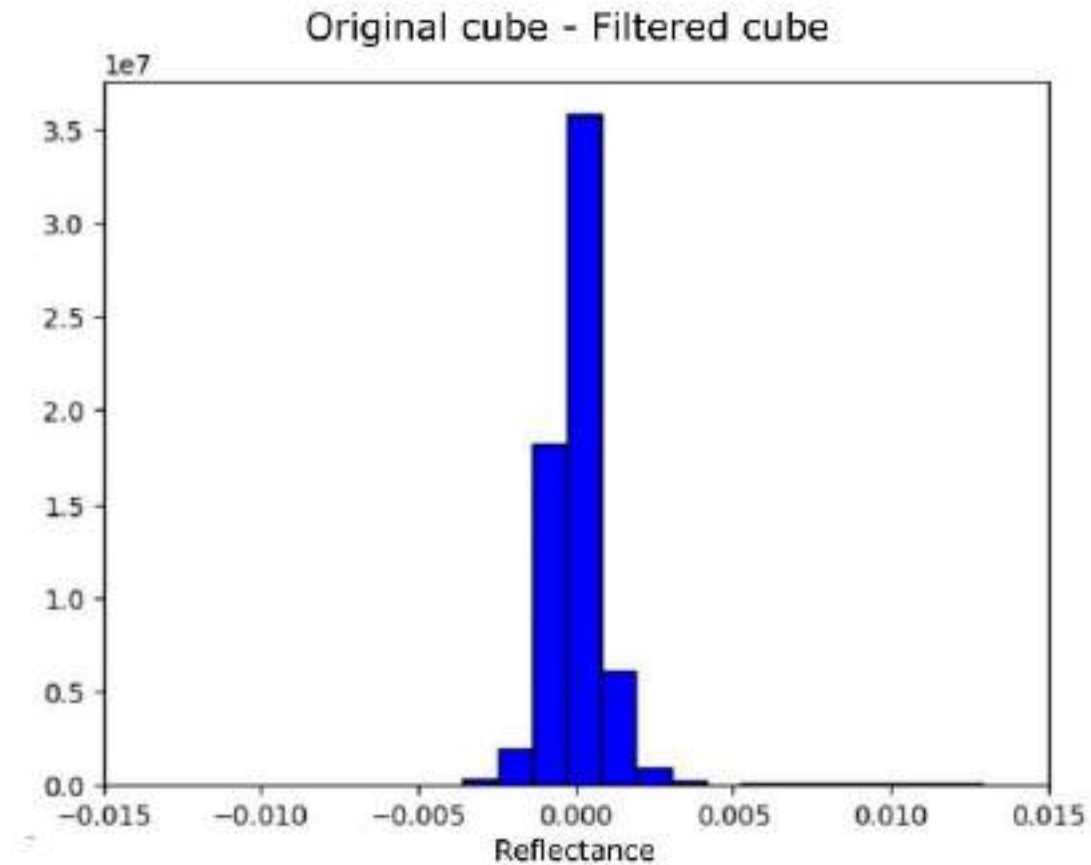


Figure 2.S2: Distribution of the noise values for the Apollo basin cube for all the wavelengths. The values were obtained by subtracting the filtered cube to the unfiltered one. Most of the noise values are lower than 0.005 (which is well below the usual values of the band depth), so the detection limit of the band depth must be greater than this value.

2.11.5. Figure about the threshold for the band depth

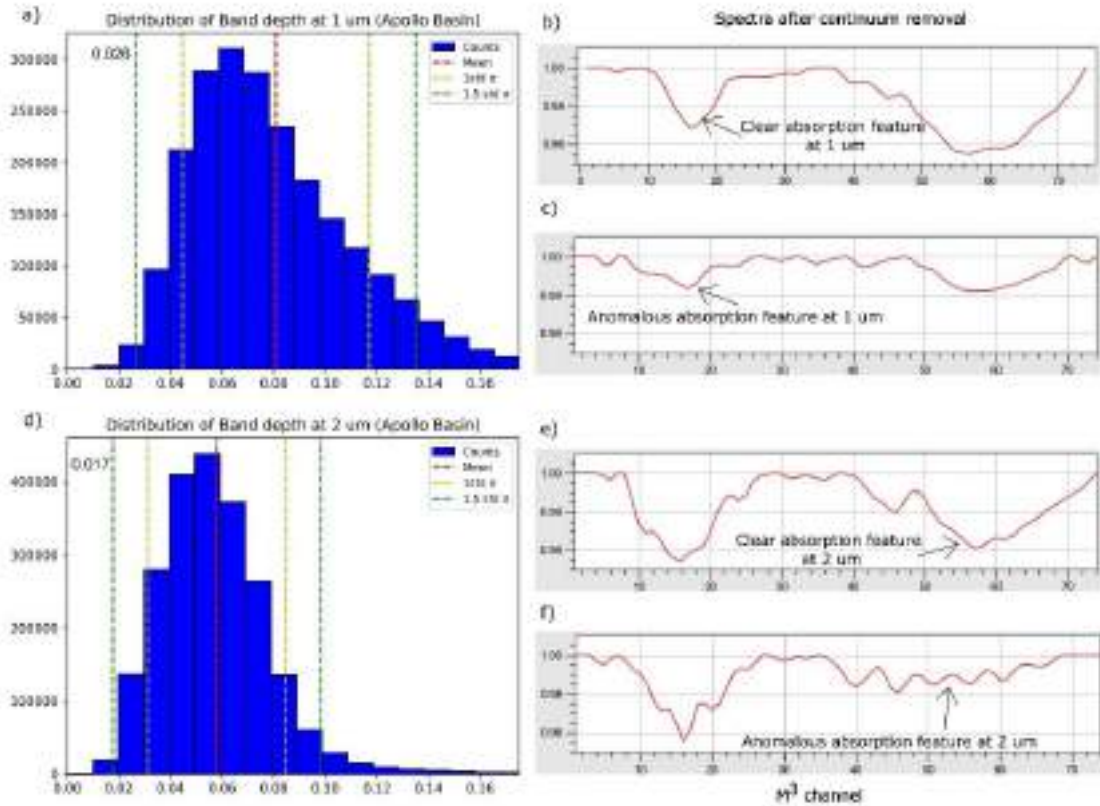
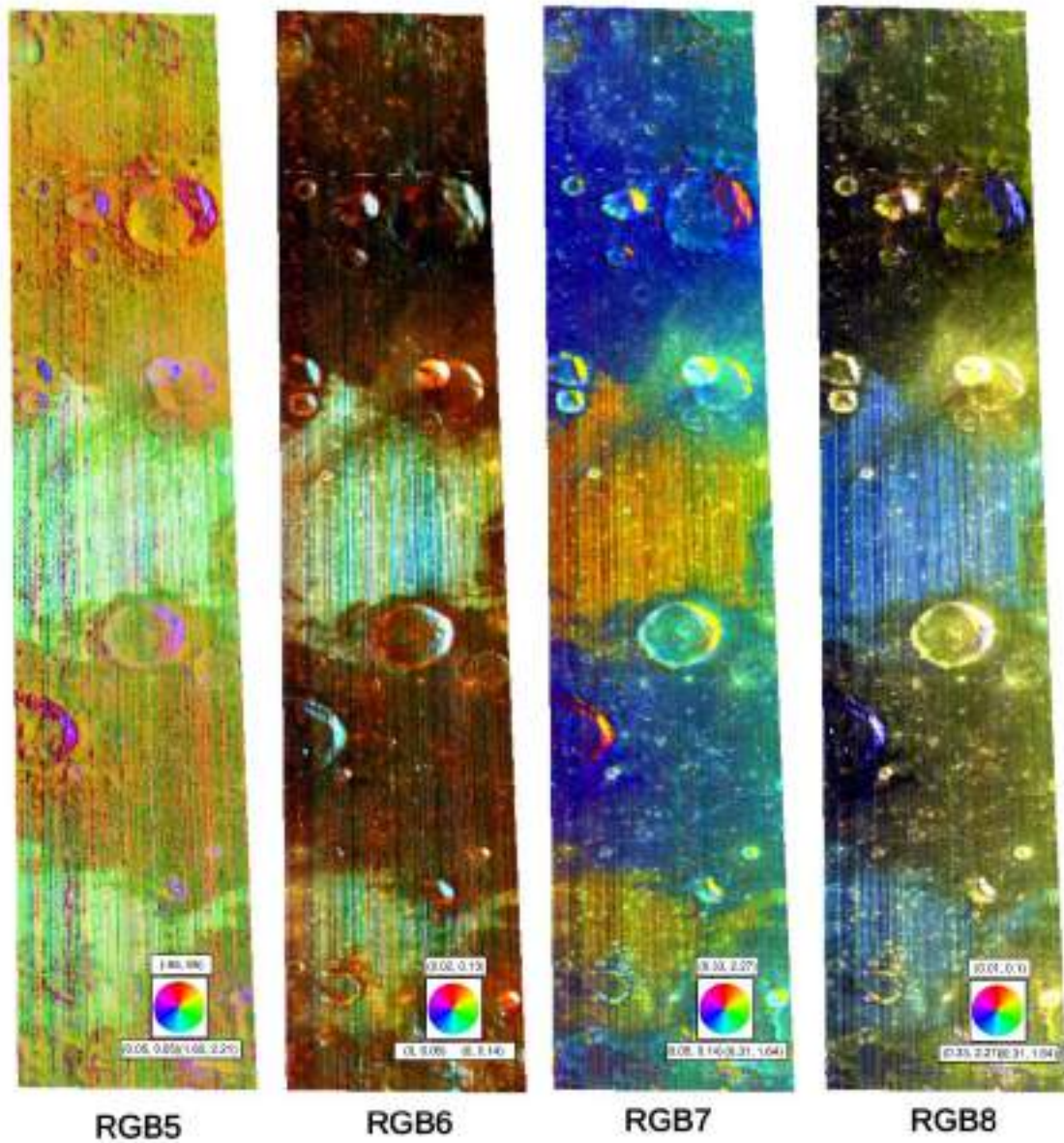
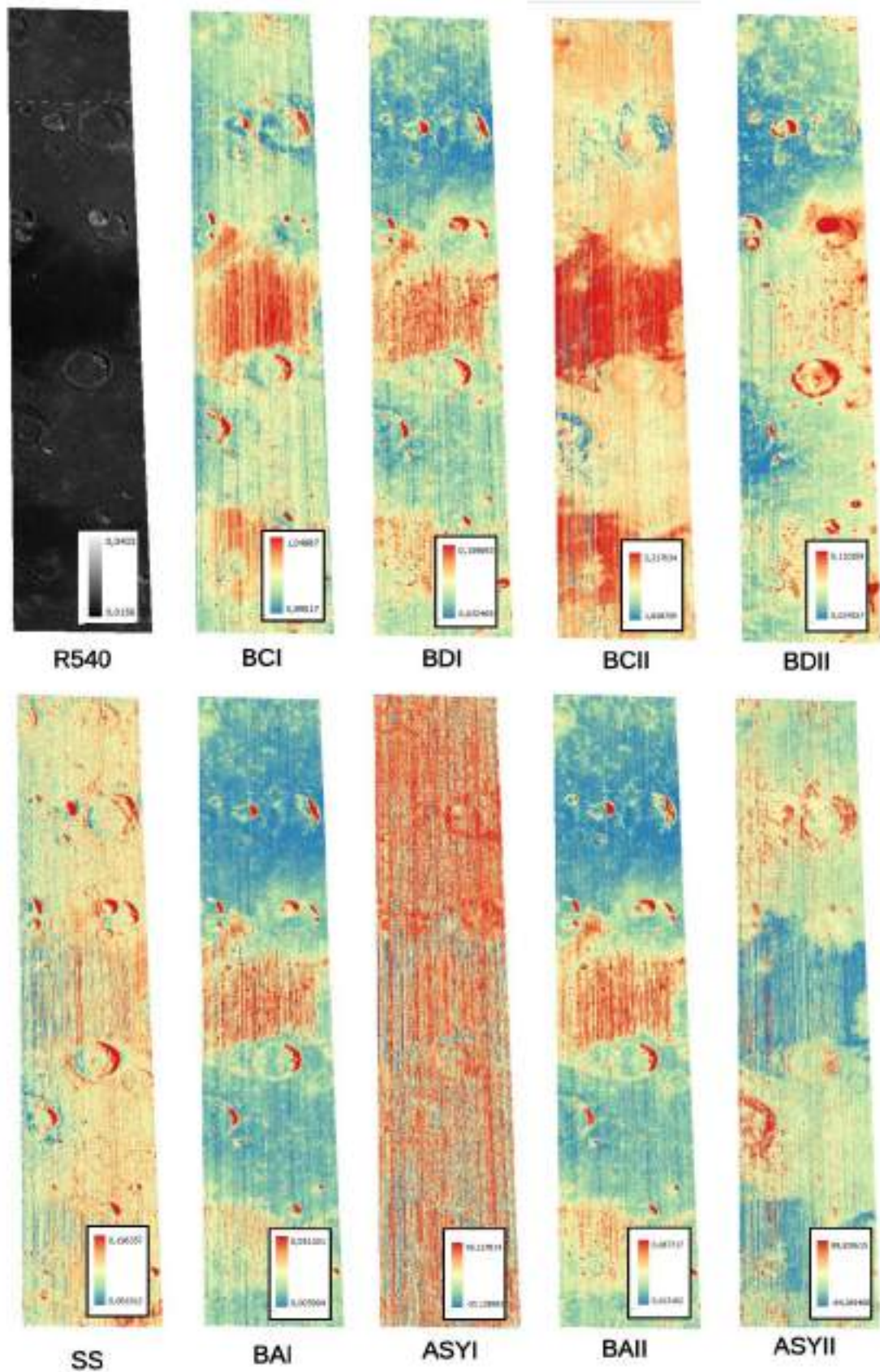


Figure 2.S3: The Apollo basin covers highlands and mare terrains, representing the major mineralogical variations on the Moon, for this reason this cube was selected to define a detection limit for the calculation of the band depths. a) Distribution of the band depth at 1 μm , after 1.5 standard deviations to the left (0.026), 0.16% of the pixels are filtered. b) Sample spectrum over the 0.025 limit, the absorption band at 1 μm is well defined. c) Sample spectrum below the 0.026 limit, the absorption band is anomalous. b) Same for the band depth at 2 μm , in this case below 0.017, 0.35% of the pixels are filtered. e) Sample spectrum over the 0.017 limit, the absorption is well defined, f) Sample example below the 0.017 limit, the absorption is anomalous.

2.11.6. All the indexes for the Apollo Basin



Chapter 2: MoonIndex, an Open-Source Tool to Generate Spectral Indexes for the Moon from M3 Data



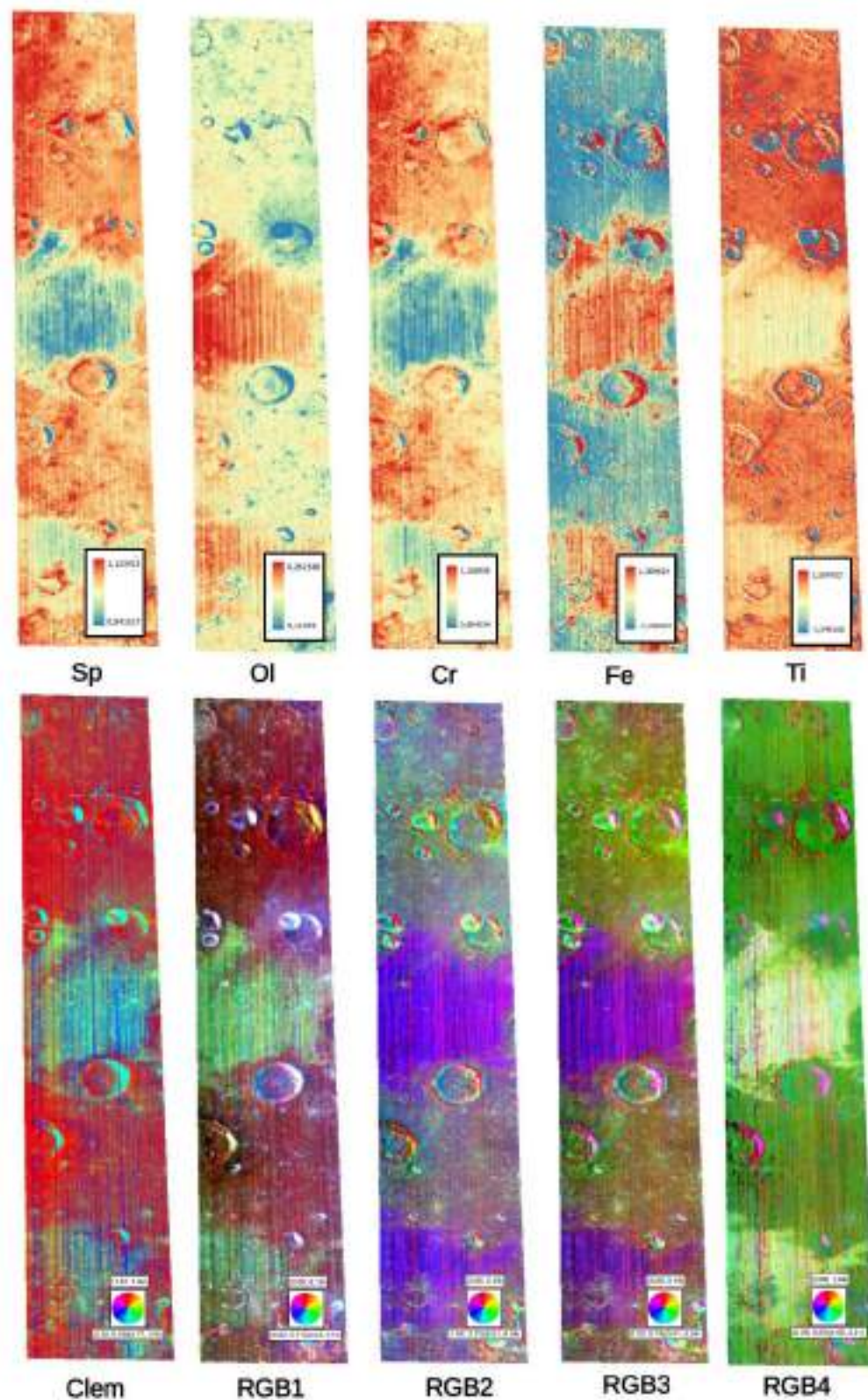


Figure 2.S4: Spectral indexes derived from *MoonIndex* in the Apollo basin, using the convex-hull method.

Chapter 3: Geostratigraphic mapping of the intrusive Valentine Domes on the Moon

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3.1. Paper significance on the thesis

This portion of the research was focused on the geological interpretation and mapping of the Valentine Domes system, I used the products generated by **MoonIndex** as well as other high-resolution datasets, validating the utility of spectral indexes for lunar geological mapping. The Valentine Domes are a well-developed system of laccoliths, which makes it a suitable candidate to study these phenomena in the lunar context.

From this I was able to characterize how these intrusive domes formed and evolved under lunar conditions, which was useful to later compare it with the Martian domes and their particularities. Finally, this work can be a workflow to identify and study lunar intrusive domes, which could lead to a better survey of similar structures.

3.2. Abstract

Lunar intrusive domes have not been widely studied in the past due to their rare occurrence on the lunar surface, and the difficulty in locating them in satellite images. Most of the known structures were discovered using images with low illumination angles, including data from the Lunar Orbiter, telescopic images, and photos taken during the Apollo Missions. These intrusive domes are characterized by an oval shape and small slopes. We analyzed one of these systems, the Valentine domes, located near the rim of the west Serenitatis Basin with modern techniques and datasets from the Lunar Reconnaissance Orbiter (LRO) and Chandrayaan-1 missions. We created a geostratigraphic map of the area, combining geomorphological and spectral classifications. The aspect map (direction of the slope) proved to be the most suitable product to locate and delimit these structures; using it, we identified a new dome southeast of the principal body, suggesting that the intrusive system is larger than previously thought. It was found that the three domes can be classified as laccoliths; and that several secondary structures such as rilles, dykes, and secondary domes represent different stages of intrusive activity in the area. Based on crater counting analysis, we determined

that the intrusive activity began after 2.98 ± 0.15 Ga and lasted at least until 1.88 ± 0.5 Ga ago.

3.3. Introduction

Lunar geological activity has been largely dominated by igneous and impact-related processes (e.g., Shearer et al., 2023). Large impacts were responsible for the formation of the observed major basins, as well as the generation of large amounts of ejecta and their subsequent accumulation in the surrounding areas (e.g., Geiss and Rossi, 2013; Liu et al., 2021). Extrusive igneous processes have also played a major role in the present geology of the Moon, creating the vast fields of basaltic materials called maria (e.g., Taylor, 2007). Other expressions of extrusive activity include large volcanic complexes, such as Mons Rümker (e.g., Scott and Eggleton, 1973; Zhao et al., 2017) or Marius Hills (e.g., McCauley 1967; Huang et al., 2011), but several small-scale landforms dominate the diversity of lunar volcanism. Lunar rilles carved by lava flows are commonly found in the maria (Garfinkle 2020), and in some cases, they are associated with pits of high scientific interest (Wanet and Robinson 2014). Less common are pyroclastic deposits, which can be related to cinder cones or fractures in the surface (Gustafson et al., 2012). Extrusive magmatism even plays a role in small-scale features, like the rim-moat structures common in the lunar maria, which were probably formed in the last stages of maria formation (Zhang et al., 2017). Although the extent of extrusive igneous activity on the lunar surface is substantial as seen in the previous examples, the effect of intrusive igneous processes are less known.

3.3.1. Intrusive rocks on the Moon

The absence of widespread intrusive bodies on the lunar surface is related to the mechanisms of intrusive activity itself. The ascent of magmatic bodies that cooled under the surface is controlled by the buoyancy of both the intrusion and the host rock, and the distribution of stress in the crust (Wilson and Head, 2017). In contrast to Earth, on the Moon there is no widespread mechanism such as crustal contamination that allows the composition of mantle magmas to evolve and overcome their density difference with the lighter upper crust (e.g., Shearer et al., 2006, Wieczorek et al., 2006). This impedes the rise of the magma, consequently, the intrusive bodies tend to lose heat and stall within the lower crust (e.g., McCallum and Schwartz, 2001). Nevertheless, some rock fragments among the samples returned during the Apollo, Luna, and Chang'e-5 missions have been interpreted as intrusive in origin (e.g., Papike et al., 1998, Zhang et al., 2021; Laul and Schmitt, 1973). Two distinct groups of rocks were identified, the Mg-suite, characterized by the presence of silicates with high contents of magnesium (Shearer et al., 2015); and the Al-suite, enriched in alkaline elements and with significant concentrations of rare earth elements (Snyder et al., 1995). The named

samples were found both as complete fragments or as small aggregates in lunar breccias, and an estimated crystallization depth of 40-50 km was constrained for the Mg-Suite (Shearer et al., 2015).

There are only two routes through which these fragments (or any other intrusive body) may have reached the lunar surface. Either by the mechanical exhumation of intrusive bodies from the lower crust or by their intrusion into regions where the crust was thin. Both instances could have resulted from large impacts on the lunar surface (**Figure 3.1**). Numerical simulations suggest that the largest impacts on the Moon could have excavated materials as deep as the mantle (e.g., Miljković et al., 2015). Through this process, rocks of the Mg-suite and Al-suite would have been scattered on the surface as ejecta or enclosed in the structurally uplifted central peaks of complex craters (Klima et al., 2011, Bretzfelder et al., 2020). Another outcome of large impacts was the thinning and fracturing of the crust, which could create conduits where magma from the mantle ascends, erupts, and infills the craters (Hartmann and Wood, 1971). This induced magmatism would also produce small and relatively shallow intrusions such as dykes and laccoliths (Head and Wilson, 2017). Due to this formation process, these intrusions have been found mostly within maria. Dykes and related geological features can also be commonly found in maria, either directly on the surface as linear or sinuous ridges, or generating other structures when stalled near it, such as linear grabens or aligned cinder cones (Head and Wilson, 2017).

Intrusive domes are less common since only a handful have been identified, mainly by Whöler et al. (2009) and Lena et al. (2013). Individual domes have not been studied in detail before this work, mainly due to their subtle effect on the surface and the difficulty in locating them. These structures are interesting due to their morphology and the geologic processes associated with their emplacement on the lunar surface. New data have been obtained since the work done by Lena et al. (2013), allowing a high-resolution analysis of these structures, which is important for improving our understanding of their formation. In this work, we carried out a geostratigraphic analysis of the Valentine Domes region (30.69° N, 10.20° E), which allowed us to interpret their origin and infer the properties of lunar intrusive domes in a broader context. We chose to study the Valentine Domes due to their complex manifestation at the surface. The system is composed of three oval structures with gentle slopes, one of them has a thrust fault at one side, which is typical for laccoliths. Furthermore, there are several small-scale mounds and fractures near or inside the domes, which are possibly caused by intrusions associated with the magmatic systems. These last features are not present in other candidates located by Lena et al. (2013), which makes the Valentine Domes stand out. These features suggest that the intrusive system had further effects on the surface beyond the formation of the laccolith, which does not seem to be the case for other lunar intrusive domes.

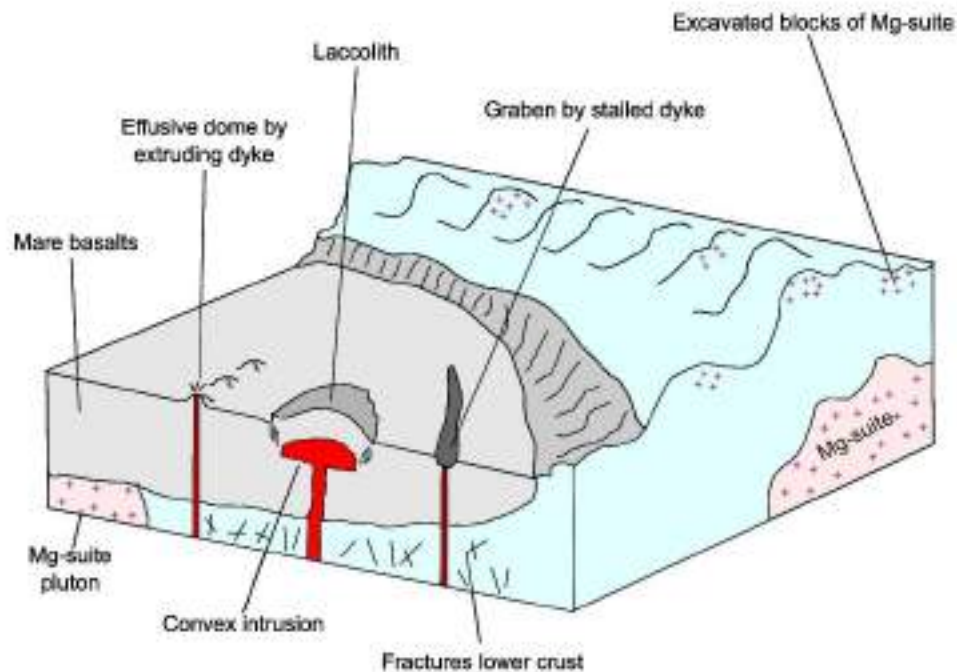


Figure 3.1: Conceptual diagram representation of the two possible processes that can result in the emplacement of intrusive igneous rocks on the surface: first, by large impacts that can exhume intrusive rocks from the lower crust and deposit them as ejecta on the rim of lunar impact basin; or second, as induced magmatism generated in large basins due to the thinning of the crust, expressed on the surface as laccoliths/intrusive domes (figure not to scale).

3.3.2. Intrusive domes on the Moon

Lena et al. (2013) defined 16 candidate intrusive domes using telescopic pictures and images from the Wide Angle Camera (WAC) onboard the Lunar Reconnaissance Orbiter (LRO) (Robinson et al., 2010). These structures can be differentiated from effusive domes because they do not have summit or lateral vents, nor lava flows associated with them. Additionally, they are typically wider, shorter, and more oval-shaped than other types of domes, ranging from 20 to 120 km in diameter, and between 30 to 240 m high (Lena et al., 2012). These properties make them difficult to locate in optical or spectral images since they do not create an abrupt change in the topography or the composition of the surface. This is especially true for images in the visible range of the maria, where the opaque tones of the basaltic lavas can obscure shallow and wide structures like intrusive domes. These domes typically behave as laccoliths, which are convex-shaped uplifts made of pre-existing basaltic lavas, deformed by intruding plutons that stalled near the surface (Schofield et al., 2021). Lena et al. (2013) used the method of Kerr and Pollard (1998) to calculate the depth of the intrusions, obtaining values between 0.5 and 1 km. All the candidate intrusive domes occur on maria or transitional areas, and none are found in the highlands. This suggests that they are not

fragments of the basement trapped in the mare, but rather structures formed from intruding magma (Lena et al., 2013).

3.3.3. Valentine Domes

The Valentine Domes are located in the northwestern region of Mare Serenitatis (30.69 N, 10.20 E), near the rim of the basin (**Figure 3.2**). The system was originally mapped as volcanic in origin by Hackman (1996). However, it was later described as a possible intrusive system by Whöler and Lena (2009), consisting of a main dome with a diameter of 30 km (V1), and a second dome to the north, with a diameter of 11 km (V2). Both were classified as laccoliths. These authors also derived a Digital Elevation Model (DEM) from telescopic images, from which they measured a maximum altitude of 130 m for V1 and 80 m for V2. Lena et al. (2013) highlighted two linear structures on V1, a fault that uplifts the east margin of the dome, and a rille that cuts the structure with an NW-SE trend. According to the global geological map of Fortezzo et al. (2020), both domes are located within Eratosthenian lavas, younger than the Imbrian lavas that dominate the center of the Serenitatis Basin.

3.4. Data

Prior studies mainly used telescopic data and images from the Apollo missions since they could feature low illumination angles, thus generating large shadows and contrasts that allowed them to more confidently define the shape of the domes. Newer and more diverse datasets have become available since then, which we employed to analyze the domes at a high spatial resolution. We utilized two types of panchromatic images, both obtained by the LRO spacecraft. The first dataset was the global WAC mosaic produced by Speyerer et al. (2011), with a spatial resolution of 100 m/px, and the second dataset were images from the Narrow Angle Camera (NAC). We obtained 23 images from the Planetary Data System (PDS) (Robinson, 2009), and then created a high-resolution mosaic of the area with a horizontal spatial resolution of 3 m/px. We also used two DEMs with different resolutions, the global LRO (LOLA)-Kaguya (LALT) mosaic produced by Barker et al. (2016), with a resolution of 59 m/px; and a DEM derived from NAC stereo pairs, with a spatial resolution of 3 m/px. To interpret the composition of the surface we generated spectral indexes derived from hyperspectral data obtained by the Moon Mineralogy Mapper (M^3) onboard Chandrayaan-1 (Green et al., 2011). The data cube had a spatial resolution of 110 m/px and contained 85 channels covering the 430 nm-3000 nm spectral range. The cube was downloaded from the PDS (Malaret, 2011). Since plagioclase is not easily recognized from M^3 data, we also used the global Christiansen Feature map from Lucey et al. (2021), derived from the Diviner Lunar Radiometer Experiment onboard LRO. The Christiansen feature is a position of minimum reflectance and maximum emission of certain silicates in the thermal infrared range, which is particularly useful for identifying plagioclase since its absorption features do not overlap with those of pyroxene and olivine, as

it occurs in the near-infrared range. Finally, we analyzed the Bouguer gravitational anomalies derived from GRAIL, using the basemaps developed by Goossens et al. (2021). A list of all the products used in this work can be found in **Table 3.S1**.

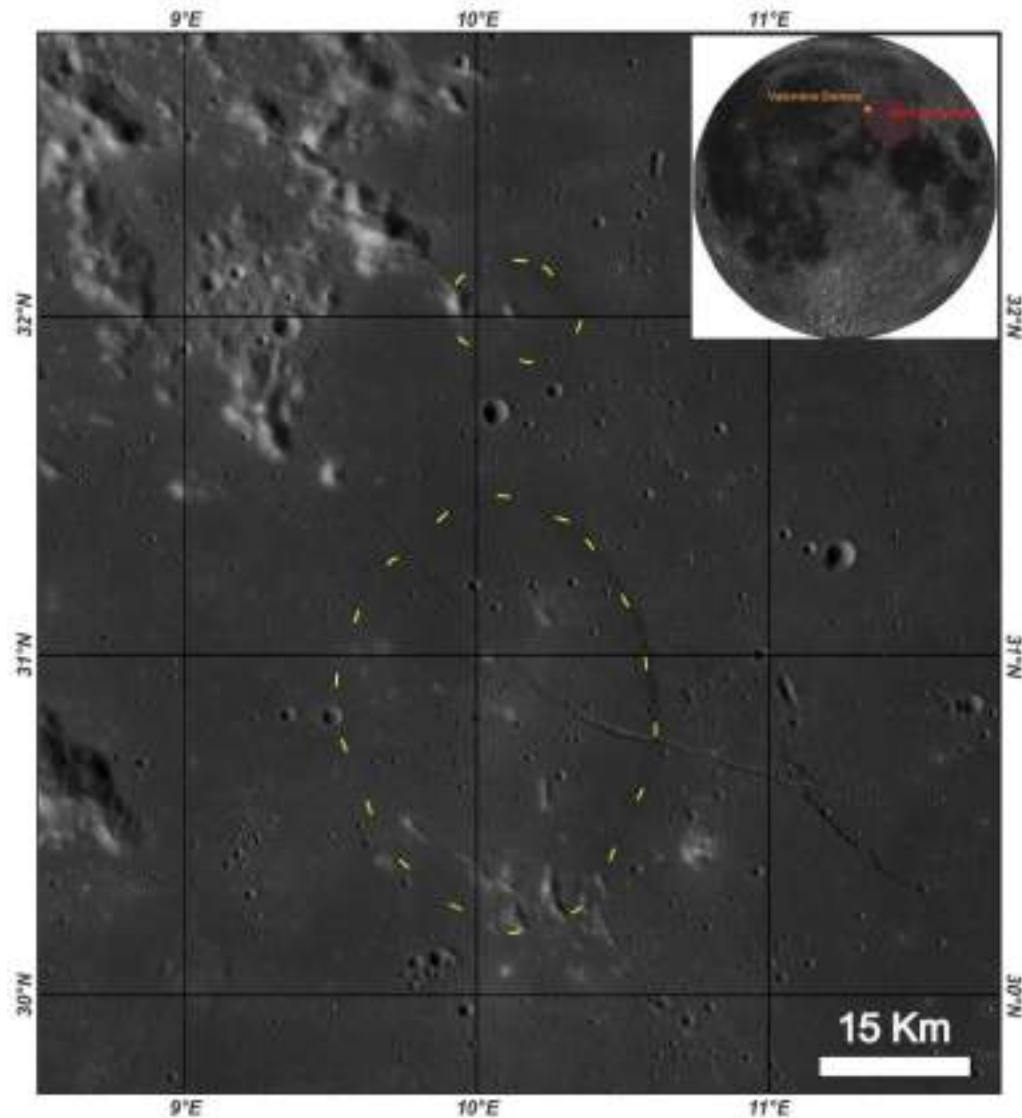


Figure 3.2: Location of the Valentine domes near the rim of the Mare Serenitatis (30.69° N, 10.20° E). The image is centered in the main dome (V1), which is an oval-shaped structure 30 km in diameter. To the north lies the smaller secondary dome V2, 11 km in diameter.

3.5. Methods

3.5.1. Data correction and projection

Data derived from other authors were ready to analyze, but the NAC images and the M³ cube needed further processing. Both products were converted to map-projected images using the Integrated Software for Imagers and Spectrometers

(ISIS) (Laura et al., 2023) and the Geospatial Data Abstraction Library (GDAL) (Rouault et al., 2023). The processing of NAC images included importing to ISIS, a radiometric correction, a noise correction, the map projection, and finally, the generation of a TIF file usable in geospatial software. The processing of M³ cubes was more convoluted, the importing command of ISIS only accepts the radiance product of M³, so we modified the associated LBL file of the radiance cube to use the reflectance data (Figuera et al., 2018). Following these steps, the map projection and format transformation were completed successfully. A detailed description of the scripts used in this process can be found in **Section 3.11.4**.

3.5.2. Derived products

We found that a better understanding of the shape of the domes could be achieved by studying the DEMs and derivative products. The spatial resolution of the LRO-Kaguya DEM is not high enough to define small structures, so we created a stereo DEM using the Ames Stereo Pipeline (ASP) (Beyer et al., 2018). We used five overlapping NAC images to generate a DEM that covered the entire area. We created three more terrain products derived from both DEMs using the geospatial software QGIS: a hillshade, a slope map, and an aspect map (**Figure 3.3**), they were made with the homonymous tools of QGIS. These products greatly enhanced the morphology of the domes and the landforms on top of them, but the aspect map was especially useful in delimiting the boundaries of the domes. This is because the aspect parameter features the azimuth direction of the slope, regardless of its magnitude, so the limits of the domes are visible even when the slope is low (Florinsky, 2012).

We also derived 28 spectral indexes from the M³ cube to complement the classification of geological units (**Table 3.S2**). This process was carried out using the Python library **MoonIndex** (Suárez-Valencia et al., 2024), which takes the map-projected cube as input and performs the filtering, the removal of the continuum, and then generates a set of spectral indexes aimed at characterizing mineralogy. These spectral indexes are focused on highlighting the properties of the absorption bands around 1 μm and 2 μm , since they record the interaction between the mafic minerals common on the lunar surface: olivine, clinopyroxene and orthopyroxene. Other indexes use mathematical operations on certain bands to showcase the presence of other minerals or compounds, like spinel, iron oxide, or anorthosite. (Suarez-Valencia et al., 2024). We also used spectral signatures after the continuum removal to discuss specific differences between certain structures. In this work we used the convex hull continuum-removal method (Graham, 1972).

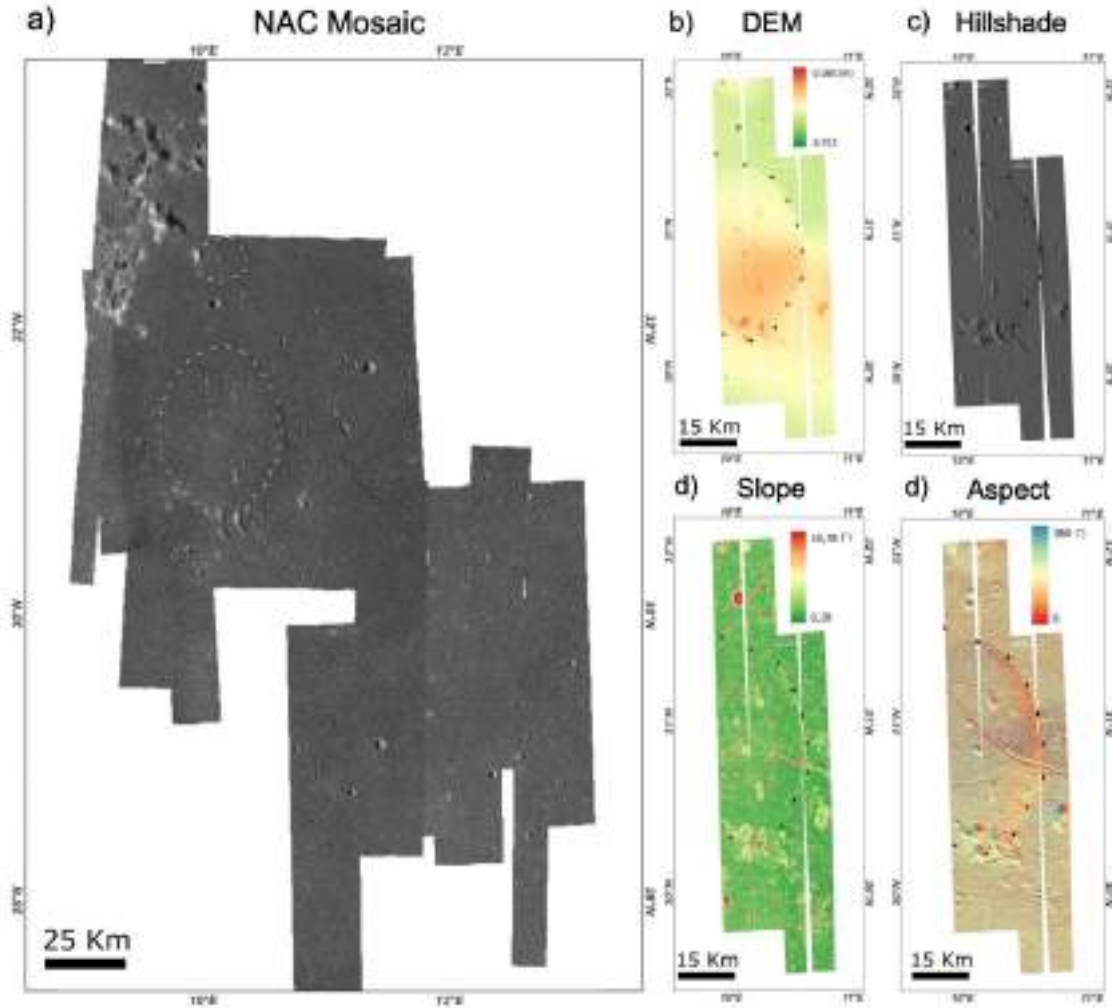


Figure 3.3: Detailed datasets used to create the geomorphological map. a) Mosaic of NAC images of the area, b) DEM of the area derived from NAC stereo pairs images, c) Hillshade derived from the DEM, d) Slope derived from the DEM, e) Aspect derived from the DEM, the dome is especially clear in this product.

3.5.3. Mapping techniques

To characterize the Valentine domes in detail, we decided to map them at two scales. On a regional level, we focused on establishing relationships between the major domes and rilles and how they fit in with the geological configuration of the Serenitatis basin rim. At the detailed scale, we mapped just the domes and their surroundings, since several secondary and small landforms lie within them, and are key to understanding the evolution of the intrusive system. We used a hybrid approach to define the units on the map (e.g., Canale et al., 2023; Yingst et al., 2023; Massironi et al., 2021). In this method, the final map is a combination of previous geomorphological and spectral maps, defined by a categorized tree of decisions (Yingst et al., 2023). Instead of combining two maps, we decided to

define geomorphological units first, which were later refined or modified according to the spectral information (Fassett and Head, 2008; Wright et al., 2024; Tognon et al., 2024). We followed this approach since in our case the resolution of the panchromatic data is more than ten times higher than the spectral information; also, it would be impractical to create a single spectral map or several maps for each one of the 28 indexes. Finally, we also added relative ages to the units. For the smallest units this was done by analyzing cross-cutting relationships, and for the larger ones the age was defined using the crater size-frequency counting technique (Neukum et al., 2001), and with the updated chronology model of Yue et al. (2022). We also performed a buffer crater-counting analysis to study the relationship between the larger rilles and the domes (Kneissl et al., 2014). The analysis and mapping of the data were carried out in the geoprocessing software QGIS with the aid of the Mappy plug-in (Penasa, et al., 2023), the crater counting was performed with the CraterTools extension of ArcGIS (Kneissl et al., 2011), and the age determination in the Python version of the software CraterStats (Michael, 2021).

3.6. Results

We first present the regional mapping, which allowed us to identify large-scale trends of the underlying magmatic bodies and other surficial structures not identified by previous authors. We then move to the detailed mapping of the domes, which records the specific properties of the laccoliths and defines the stratigraphic relationships between the different intrusive pulses of the system. The complete maps at both scales can be seen in **Figures 3.S4 and 3.S5**.

3.6.1. Regional setting

The greatest morphological contrast in the area occurs between the rim and the mare of the Serenitatis basin. The rim has high albedo, scarped topography, and a dominant abundance of plagioclase, according to the map of Lucey et al. (2021) (**Figure 3.S1**). In contrast, the mare is dark toned, has a smooth texture, and does not show a detectable signal of plagioclase; this is the result of a major abundance of mafic minerals, which can mask the signal of plagioclase even if it is present (Arnold et al., 2016). However, the small-scale mounds inside V1 do have a higher signal of plagioclase, probably due to a smaller amount of mafic minerals. We also checked the Bouguer gravitational anomaly using the map of Goossens et al. (2021), and although we found a strong positive anomaly beneath the mare, there is a ring-like structure with a lower anomaly near the intrusive domes (**Figure 3.S2**). The GRAIL spatial resolution does not allow a detailed analysis of this feature, but its origin might be related to a buried impact crater.

3.6.1.1. New dome

As mentioned in the previous section, locating the intrusive domes is not a straightforward process. Using the aspect map derived from the Kaguya DEM we

were able to recognize a new dome (V3) (**Figure 3.4, Figure 3.5**). It has a diameter of 43 by 33 km, making it the biggest dome of the Valentine system (**Figure 3.4 a, b**). V3 is oval-shaped and asymmetric, its eastern flank is more pronounced than the western one, but it does not have a steep scarp like V1. The emplacement of this dome had little effect on the surface, as the only noticeable feature in the mare is a narrow linear rille that crosses the dome in an NW-SE direction (**Figure 3.4**). V3 has a gentle slope of 0.43° , compared to the 4.3° of V1, which might be the reason why it was not identified by Lena et al. (2013).

Another interesting feature lies between V1 and V3, the last segment of the long linear rille that dissects V1 since it is slightly uplifted in comparison to the rest of the rille. In the aspect map, a linear bump crosses the rille with an NE-SW trend, like the main wrinkle ridges in the area (**Figure 3.4a**). Nevertheless, the feature does not resemble a wrinkle ridge, since it is wider and their edges are not sinuous. We interpret this structure as an incipient uplift generated by another intrusive body. Its shape is irregular, and its borders are diffuse, so we classified it as an incipient dome (**Figure 3.5**). After locating these new structures, we evaluated their relationships with the developed domes V1 and V2. Using the Kaguya DEM and the aspect map, we observed a slight bump in the mare that encloses V1, V3, and the incipient dome (**Figure 3.4 a, c**). The affected area of the mare spans more than 2700 Km².

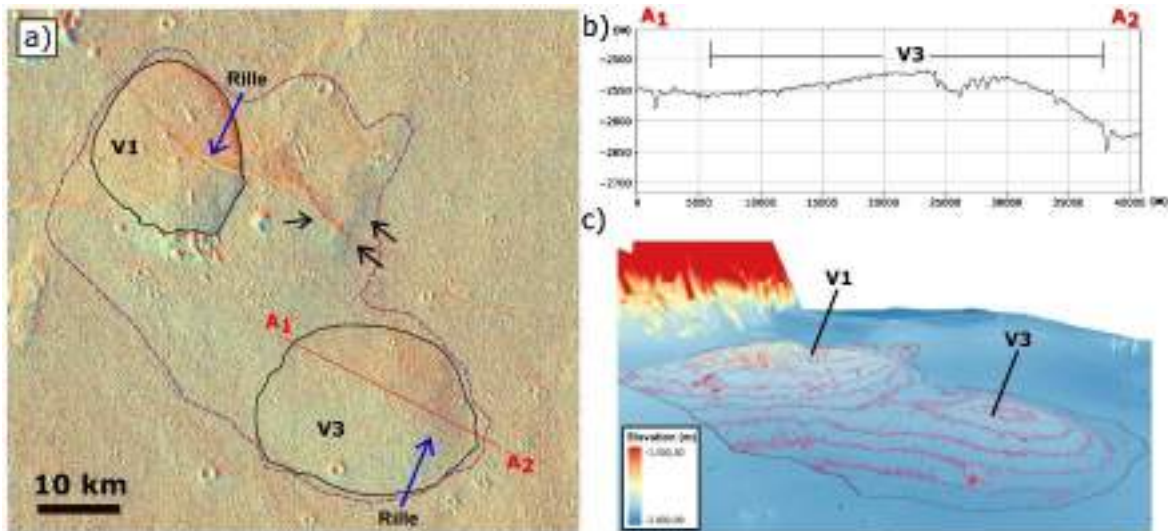


Figure 3.4: Total area affected by the Valentine intrusive system. a) Location of the newly discovered V3, the largest dome of the three. It has a limited effect on the overall surface topography. The black arrows point to the incipient dome, and the blue arrows to the rilles cutting the domes. b) Profile of V3, the dome is asymmetric, having a steeper slope to the east. c) 3D view of the area, showing the upwelled mare around the two larger domes.

3.6.1.2. Regional geostratigraphic mapping

The regional geostratigraphic map can be seen in **Figure 3.5** (1:100,000 scale). Because of its location at the rim of the Serenitatis basin, the area is largely dominated by highlands and mare units. The igneous units related to the intrusive system are concentrated towards the middle of the area and will be analyzed further in the detailed mapping section.

3.6.1.2.1. Highlands/rim units

The highlands units make up the rim of the basin, which are characterized by an elevated topography, bright color in optical data, a strong signal of plagioclase in the Christiansen feature (**Figure 3.S1**), and the relative absence of mafic minerals in the spectral indexes derived from M^3 (**Figure 3.6a**). The most extended unit is represented by Hilly materials (*lhim*), characterized by an abrupt topography and blocky appearance. The main mineral signature is anorthosite, but some escarps suggest the presence of olivine in the olivine-detecting index (**Figure 3.6b**). This unit probably originated as part of the impact ejecta linked to the formation of the basin. The other unit in this group is Hummocky material (*lhum*), which is differentiated from *lhim* only by its lower topography and a more hummocky texture. According to the global map of Fortezzo et al. (2019), both units are Imbrian in age, although they may be older.

An additional highlands unit is represented by Kipuka (*lk*), which refers to blocks of highlands material that were embedded by mare units, like islands, so their optical and compositional properties are the same as other highlands units. Whöler and Lena (2009) classified all the structures inside and around V1 as kipukas, but in this work, we separate them between kipukas and secondary intrusive domes.

3.6.1.2.2. Mare units

The mare units in the area represent three different phases of lava flooding, which together are the most extensive units in the study area. Although the intrusive domes were mapped as distinct units for clarity, it is important to mention that the intrusive rocks most likely did not reach the surface, so the mare units represent the actual composition of the domes at the surface.

Apart from some slight color changes, the three units are all dark-toned, flat, and have a smooth texture. Nevertheless, the phases show variations in composition and age, which were the criteria used to differentiate them. The younger unit is Mare material 1 (*Em1*), which is located on the western edge of the basin. It has an estimated age of 2.9 Ga according to Fortezzo et al. (2019) and Hiesinger et al. (2011), but we obtained instead an Absolute Model Age (AMA) of 2.59 ± 0.3 Ga, using the crater-counting method. Compositionally, it is dominated by a strong signal of mafic minerals (**Figure 3.6c**). The V2 dome is intruding below this unit, as well as the western part of V1. The unit Mare material 2 (*lm2*) differs from the other two due to a relatively higher concentration of spinel (**Figure 3.6c**). An AMA

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of 3.32 ± 0.1 Ga was estimated for this unit (**Figure 3.12**). This unit extends over most of the area on top of V1. Finally, the older flood basalt in the region is represented by Mare material 3 (**Im3**), this unit covers the northeast part of the area and it is spectrally similar to **Em1**. We calculated an Absolute Model Age (AMA) of 3.66 ± 0.01 Ga for this unit (**Figure 3.12**), and it mantles the entire area of V3.

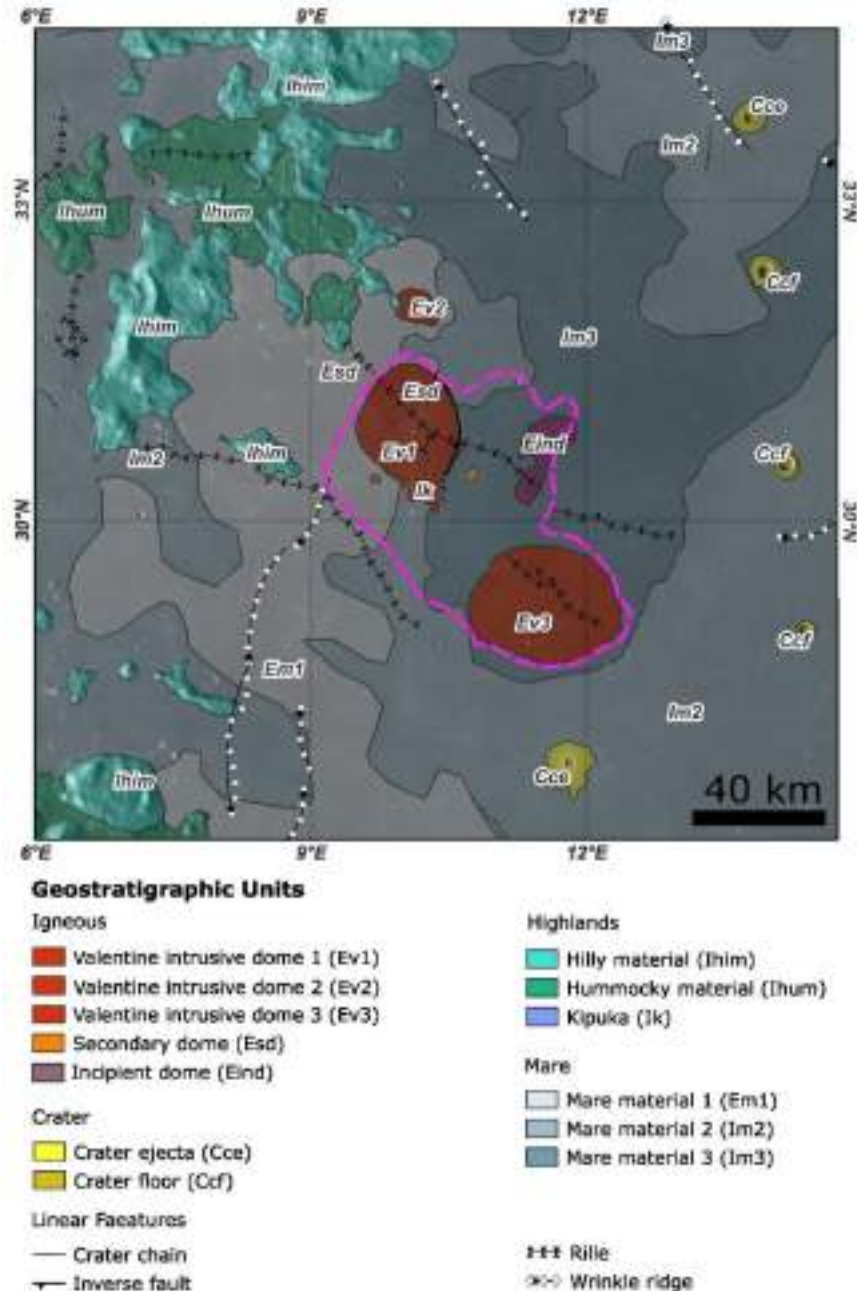


Figure 5: Regional geostratigraphic map of the region. The total area affected by the main uplift from the intrusive dome is outlined in pink. The basemap is a global WAC mosaic (Speyerer et al., 2011).

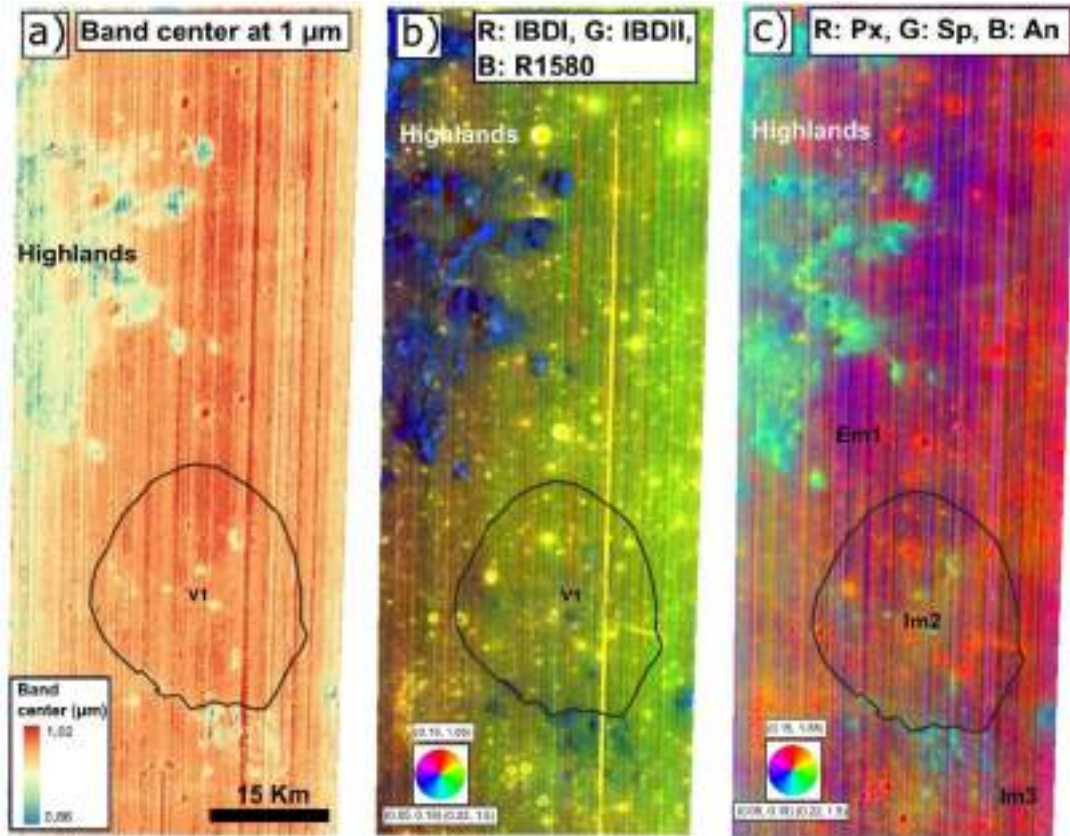


Figure 3.6: Spectral indexes used in this work. a) Band center at 1 μm , longer wavelengths suggest the presence of pyroxene and olivine. b) RGB composite highlights the presence of anorthosite in blue, pyroxene in green, and olivine in red. c) RGB composite that highlights pyroxene in red, spinel in green-yellow, and anorthosite in light blue.

3.6.1.2.3. Craters units

All impact structures in the investigated location are either single simple craters or are arranged in crater chains (**Figure 3.5**). Single craters were mapped as two units: the crater floor (Copernican and Eratosthenian, **Ccf**, **Ecf**) unit, and the crater ejecta (**Ece**, **Ece**) unit, when the latter was present. Crater chains were mapped as linear features on the regional scale due to resolution constraints, but as a crater chain (**Ecc**) unit in the detailed map. The relative age of the craters can be estimated by the apparent degradation of their rims and ejecta (Agarwal et al., 2019), therefore we classified the ones with clear and bright ejecta, and with a sharp rim, as recent, that is Copernican in age; and the ones without ejecta or/and with eroded rims as at least Eratosthenian in age, although they might also be Imbrian.

3.6.2. Detailed analysis

We analyzed high-resolution NAC images centered on the intrusive domes area, and we produced a detailed geostratigraphic map with a scale of 1:25,000 (**Figure**

3.7). At this scale, structures related to deformation are also more prominent, which led to a new classification of several volcano-tectonic units. Highlands, mare, and crater units are also represented in the area, so their definition is the same as in the regional mapping.

3.6.2.1. Volcano-tectonic units

We consider volcano-tectonic units to be those structures that were formed by deformation and fractures triggered by any kind of igneous activity (Azzaro et al., 2012). All the units are located inside the mare, so their composition is the same as the overlying lava flows. The most common volcano-tectonic units are wrinkle ridges (**lwr**), which appear as elongated sinuous ridges inside the mare. Their origin has been attributed to the cooling of lava and the subsequent thermal contraction phase (Watters, 1988), which produced small ridges surrounded by thrust faults. Another common structure in the mare are grabens, linear depressions on the surface that can be formed by either stalled dykes or by extensional stress (Head and Wilson, 2017). Those created by the latter process were mapped as structural graben (**lsg**) units. Last, a pair of structural hills (**lsh**) were found close to the end of the rille that crosses V1, and next to an incipient dome (**Eind**) unit (**Figure 3.8a**). These hills are polygonal mesas that are surrounded by steep scarps. Their origin is probably related to the deformation produced by an underlying intrusion, consistent with their closeness to the incipient dome.

3.6.2.2. Igneous units

The igneous units in the area originated from both intrusive and extrusive activity. Among the extrusive ones, we found a few volcanic vents (**Evv**). These are irregular and oval structures, with gently elevated boundaries encircling an inner depression (**Figure 3.8b**). They are not spectrally distinct from the mare, and we found no anomalies in either the band area or band asymmetry at the 1 μ m band, which is found in glass-bearing compositions (**Figure 3.9 a, b**) (Horgan et al., 2014). This lack of contrast with the surrounding mare means that there are no recent pyroclastic deposits around the vents, indicating that they probably have not been active in recent geological times. Other extrusive features are dykes (**Ed**), which are vertical intrusions that reached the surface close to V1 and V2, creating linear ridges that cut across different mare units. Their spectral signature differs from those of the mare units, as the absorption features of the mafic minerals appear weaker, probably due to a lower concentration of these minerals or some variations in the maturity of these materials (**Figure 3.9c, d**). This type of spectral signature is common to other secondary structures found near the main domes. Dykes also influence the formation of rilles (**Er**), which represent grabens created by the extensional stress generated by a dyke that stalled near the surface (e.g. Head and Wilson, 2017). The larger rille in the area spans more than 50 km and runs from the rim of the basin to the Eind unit, crossing V1 and other secondary structures (**Figure 3.8c**). We also found a shorter rille (30 km) atop V3. The walls of the rilles have a similar spectrum to the mare, but the absorption of mafic

minerals is considerably stronger (**Figure 3.9e, f**). This is the result of fresher materials and minerals being exposed by the rille.

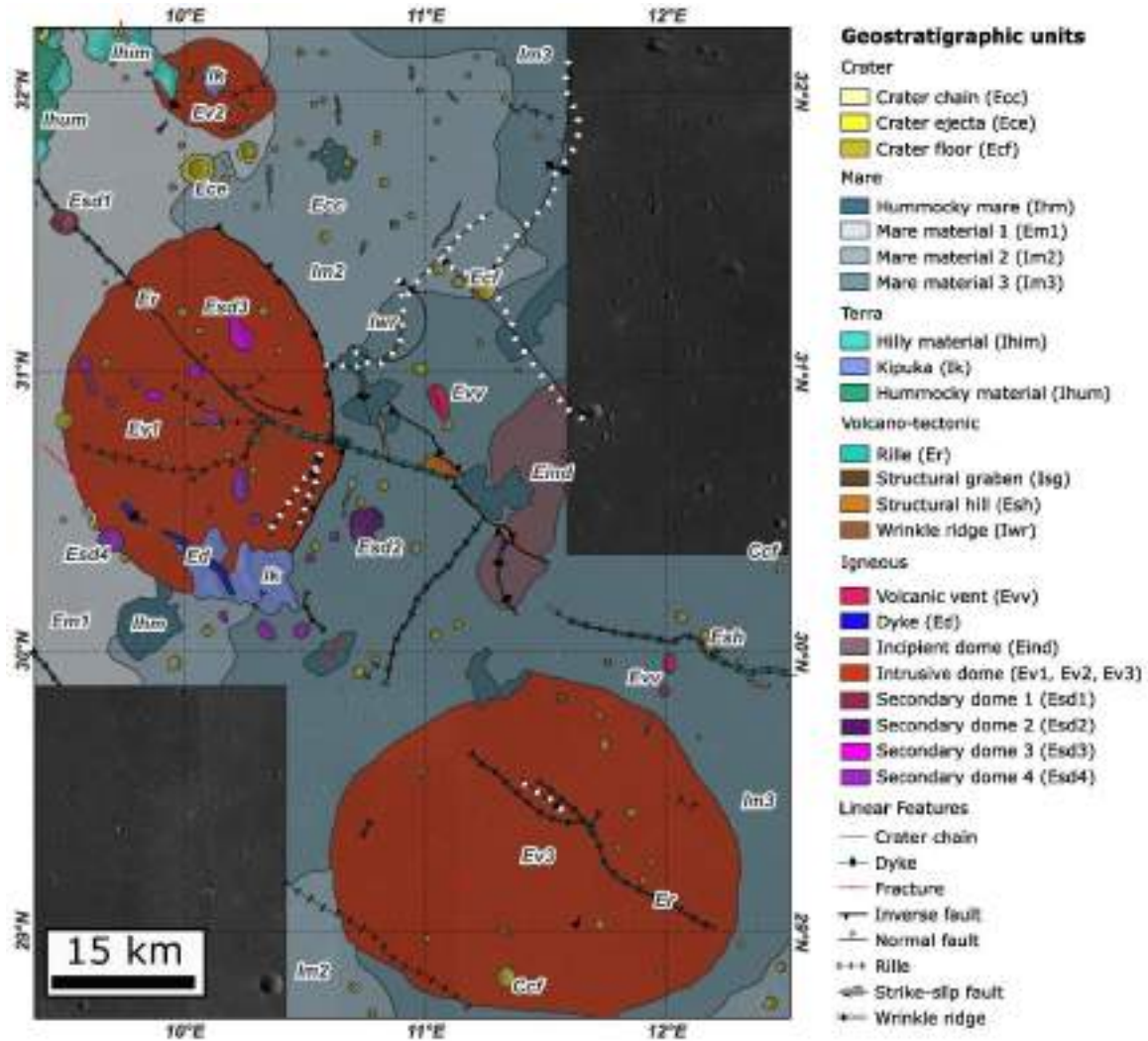


Figure 3.7: Detailed geostatigraphic map of the area. The boundaries of the mapped area correspond to the geographical extent of the relevant NAC images.

Of the three main domes (**Ev2, Ev2, Ev3**), V1 and V2 contain several smaller structures on top of them. These structures were originally classified as kipukas by Whöler et al. (2009), but we found some that do not fit the description. A couple of actual kipukas (**Ik**) were located at the southern limit of V1 and in the middle of V2 (**Figure 3.10a**); they are characterized by an irregular shape and by having a spectral signature similar to the units in the highlands. The other structures were classified as secondary intrusive domes (**Esd1, Esd2, Esd3, Esd4**): they are round-shaped, aligned to each other, lie near the main rille, and none of them show a volcanic crater on the summit (**Figure 3.10b, c, d, e**). They are all located inside or near V1, and none around the other domes. The spectral signature of the exposed materials is similar to the highlands, but they show a higher band depth

and a centering at longer wavelengths around the 1 μm band. Both parameters imply a higher abundance of mafic minerals compared to the rim units *lh*_{um} and *lh*_{im} (e.g. Adams, 1974; Klima et al., 2011).

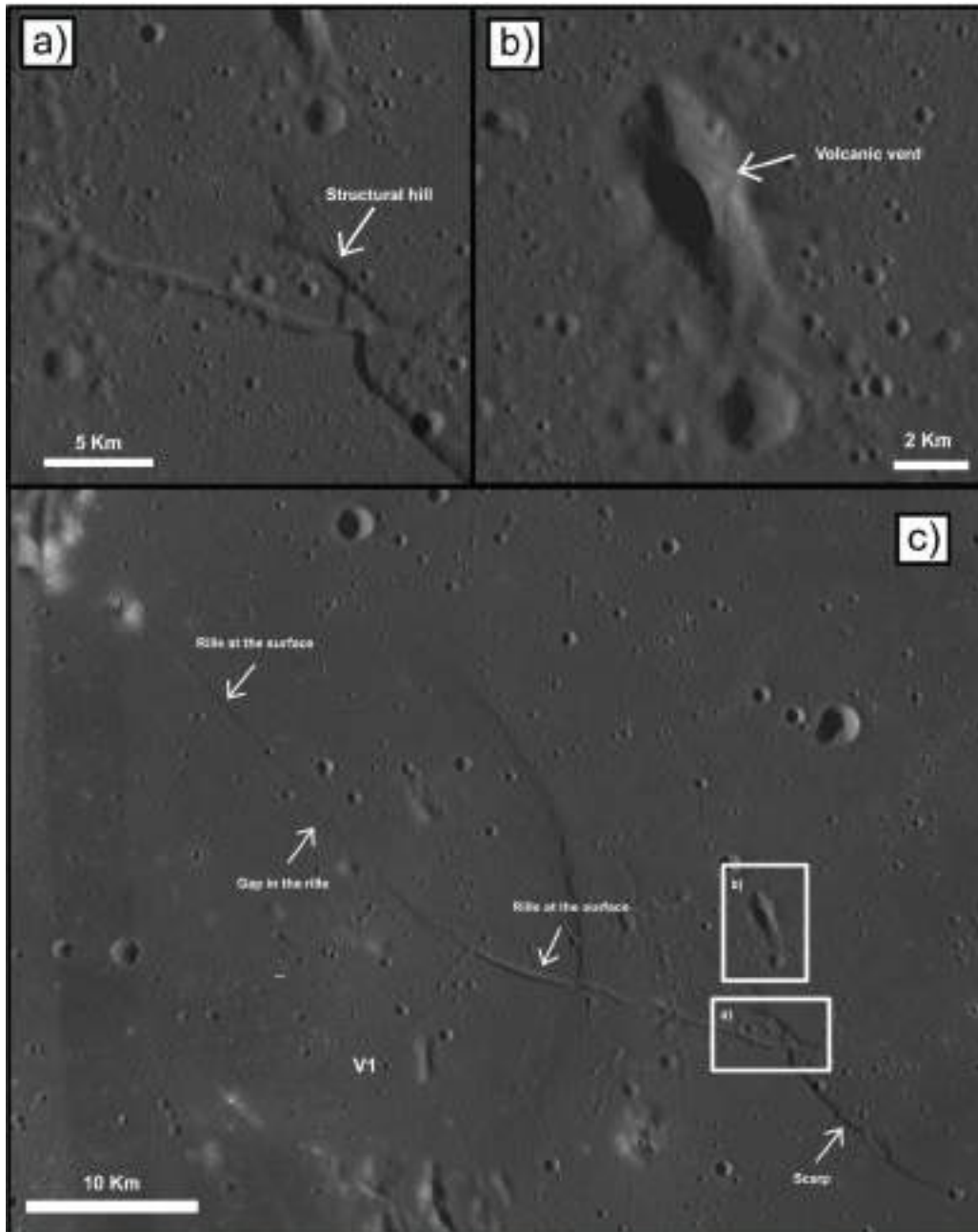


Figure 3.8: a) Structural hill, a polygonal structure at the end of the main rille. b) Possibly a volcanic vent, characterized by its elongated shape and the absence of a defined rim. c) The largest rille in the area. It begins at the northwest corner of V1, disappears at its center, and reappears to the southeast. Once the rille ends, a scarp continues to the southeast for another 8 km.

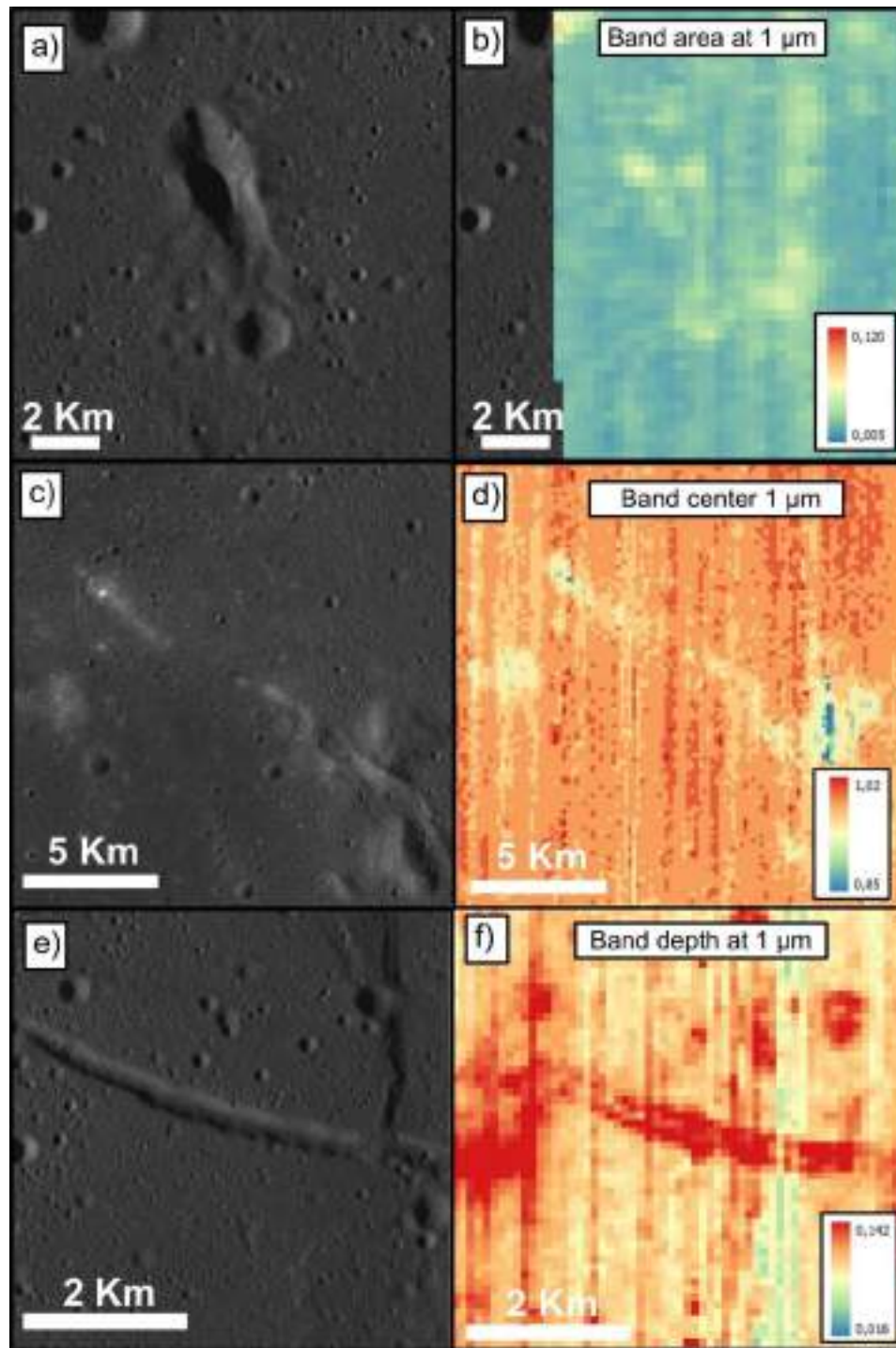


Figure 3.9: a, b) The volcanic vent does not spectrally differ from the surrounding mare in the band area at 1 μm , which implies that the vent has not erupted in recent times. c, d) The band center at 1 μm of the dyke is lower, which implies there is a smaller abundance of mafic minerals or a difference in soil maturity. e, f) The walls of the main rille have a strong absorption in the band dept at 1 μm , which implies that the rocks are fresher.

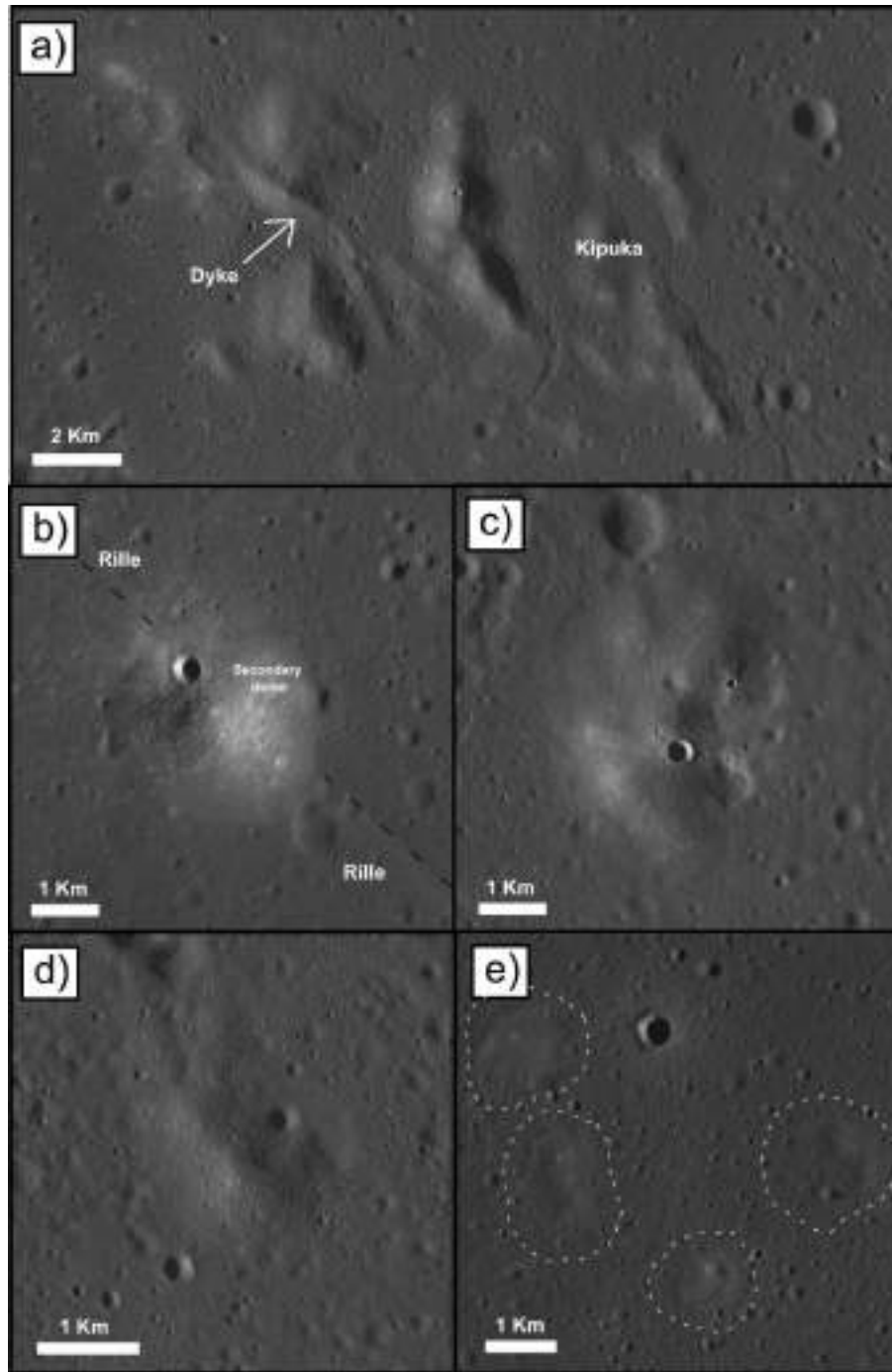


Figure 3.10: Type of secondary structures inside V1. a) Kipukas, remnants of ancient ejecta embedded in the mare, and a dyke that intruded the west part of the group. b) Secondary dome *Esd1*, a round and bright structure superimposed to the main rille crossing V1, implying a younger age. c) Secondary dome *Esd2*, irregularly shaped, it is the biggest of these structures. d) One dome of the *Esd3* units, smaller than the previous ones, with a similar tonality to the surrounding mare. e) A group of four domes of the *Esd4* unit, they are small hills nearly indistinguishable from their surroundings.

3.6.3. Structural considerations

The rilles, wrinkle ridges, and grabens that were too small to be represented as units were mapped as linear features (**Figure 3.7**). Regardless of the size, local wrinkles ridges have a preferential NE-SW trend, which is aligned with the regional pattern of bigger structures. The area around V1 is heavily fractured due to a network of rilles and faults that developed on top of it. Two compressional structures were found. The first one is a major thrust fault that limits the eastern flank of V1, creating a scarp that reaches 60 m in height. The most significant uplift occurs toward the middle of the dome, where it is cut by the main rille; while to the north and south, the scarp gradually fades, becoming almost indistinguishable from the mare. The scarp is also displaced horizontally when it meets the main rille, which is caused by a strike-slip fault that developed at this location (**Figure 3.11**). The second important thrust fault was found to the east of V1, following the end of the main rille, linked to a 15 km long scarp and the structural hills of the unit *Esh*.

Grabens and rilles are the result of extensional stress, and they dominate the area following two main directional trends. The main rille cuts the dome in an NW-SE direction, similar to the trend of other smaller fractures. The middle section of the main rille is not completely developed (thin section of the rille on top of V1 in **Figure 3.7**), instead an incipient and long normal fault connects the more developed portions of the rille to the north and south. Another major deformation occurs in an almost perpendicular direction, where two minor rilles run from the southern half of V2 to intercept the main rille, following an NE-SW trend.

3.6.4. Crater size-frequency distribution

It was difficult to establish the relative age of the domes since the material covering the intrusions corresponds to the flood basalts that fill the basin, making a standard crater counting technique not viable since it would only retrieve the age of the latest lava flow event. Nevertheless, an alternative method known as buffer crater counting can be applied to linear features (Tanaka 1982, Fassett and Head, 2008), and the rilles cutting V1 and V2 are long enough to conduct this analysis. The method consists of counting the craters that intersect the linear feature in question; given that this produces too few data points, we also counted the craters whose ejecta also overlap the linear features. The total area of the intersecting craters was buffered around the linear feature, and the age was computed using the software CraterStats (Michael 2021; Kneissl et al. 2015). We also applied the usual crater counting technique to the flood lavas on top of both domes. The mapped areas and the resulting ages can be seen in **Figure 3.12**.

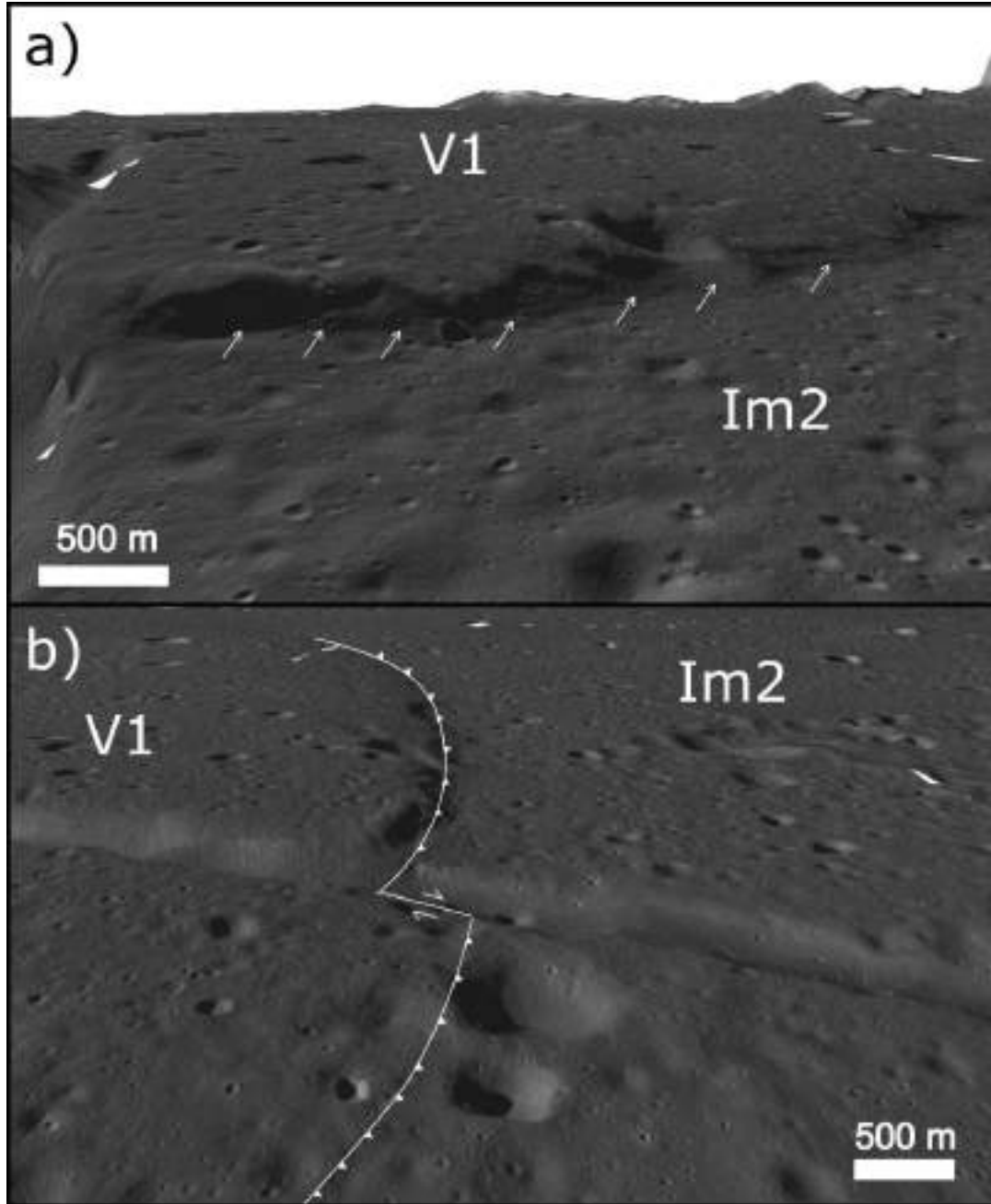


Figure 3.11: Structural features of V1. a) The east flank of V1 is a scarp up to 60 m high, this section is uplifted by a thrust fault. b) When the mentioned scarp crosses the main linear rille, the feature is translated by a dextral strike-slip fault. South of the rille the scarp is still visible, but it is smaller.

We estimated ages of 2.59 ± 0.3 Ga and 3.32 ± 0.1 Ga for the units **Em1** and **Im2**, respectively (both mantling V1) (**Figure 3.12b, c**), while for the unit **Im3** (mantling V3), we calculated an age of 3.66 ± 0.01 Ga (**Figure 3.12d**). These estimations disagree with those of Hiesinger et al. (2011), probably due to the far smaller area comprised in our analysis. Still, the stratigraphic relationships

between the units remain the same, the materials on top of V3 (*Im3*) are older than those over V1 (*Im1* and *Im2*). Although these ages do not correspond to the intrusion of the domes, they put an upper limit on their formation. The lower limit is given by the ages of the buffered crater counting, which gives 1.88 ± 0.5 Ga and 2.06 ± 0.4 Ga for the two parts of the main rille cutting V1, and 1.81 ± 0.3 Ga for the small rille on V3.

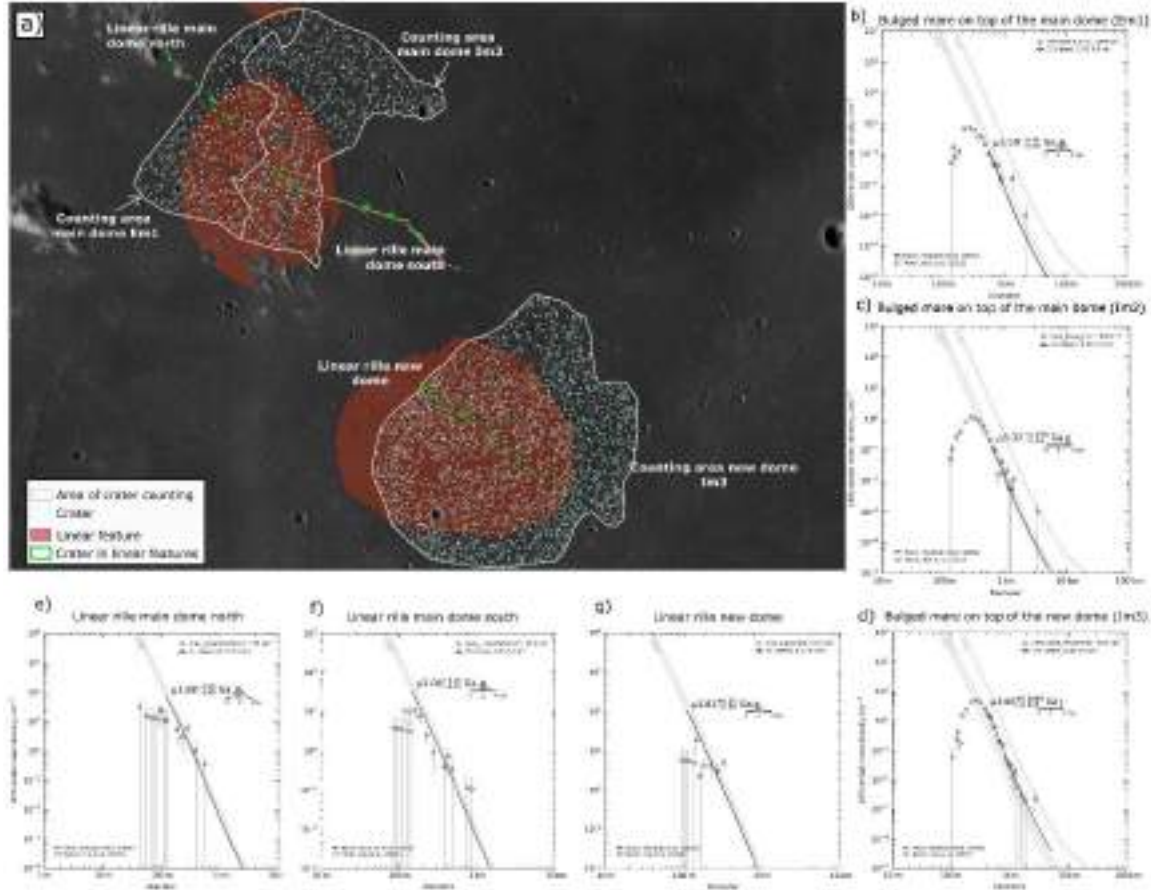


Figure 3.12: Crater counting analysis. a) The two areas where the standard crater counting was carried out are shown in white and the craters counted inside in light blue; the linear features analyzed are pink, and the craters that cut them are green. b) and c) the ages of the mare on top of V1 and V2. d), e), f) the age of the linear features using the buffered crater counting method.

3.7. Discussion

3.7.1. Kipukas vs Secondary Domes

The origin of the secondary structures on top and around V1 has major implications for the geological history of the area. If they were kipukas, as suggested by Whöler et al. (2009), then the igneous rocks of the intrusive system never reached the surface, contrary to the scenario of them being secondary domes. The criteria to differentiate them were both geomorphological and spectral.

The shape of the structures can be classified as irregular or oval-shaped. The irregular ones have a sharp contact with the mare units, and internally they consist of scattered hills. Their texture resembles the rim units, and if they originated as ejecta, it would be consistent with their lack of orientation (**Figure 3.10a**). The oval-shaped structures are round and dome-like, have diffused contacts with the mare units, and have an average height of 100 m, which is lower than the irregular-shaped structures (~250 m) (**Figure 3.10b, c, d, e**). Some are aligned along two preferential directions, while the non-aligned ones lie on top or near the main rille. These properties, and their clustering near V1, suggest that the oval-shaped structures originated from an igneous process. The lack of pyroclasts and craters on their summits indicates they are not cinder cones, as would be the case for structures in other lunar locations (Henderson et al., 2023).

A spectral analysis was useful to further discriminate between these structures (**Figure 3.13**). We produced an RGB composite where the red channel represents the spectral slope at 1 μm , the green channel the band center at 1 μm , and the blue channel the band depth at 2 μm (**Figure 3.13a**). This representation highlights the differences between the types of secondary structures, as both the kipukas (*Ik*) and the rim units (*lhim*) are represented by the same orange color, while the secondary intrusive domes are seen in various tonalities of pink. Furthermore, color differences are noticeable between the secondary domes. A dome directly associated with the linear rille appears in bright pink (**Esd1**), the larger dome in the area has a red-yellow tone (**Esd2**), a set of domes aligned with a NE-SW trend are pale pink (**Esd3**), and the final group is aligned in an NW-SE trend and has a pink-yellow color (**Esd4**).

We also compared the spectral signatures of every type of secondary structure, as well as the background mare (*Im2*). The spectra were analyzed after removing the continuum from the signal (**Figure 3.13b**). The weaker absorptions are found in the *Ik* and *lhim* units, indicating a lower abundance of mafic minerals, and further suggesting the same genesis for both units. The unit *Im2* shows strong absorptions at 1 μm and 2 μm , typical of pyroxene-rich basalts. All the spectra of the domes lie between those two types of signatures, suggesting intermediate abundances of mafic minerals. Also, the band center of the signatures from domes is located at shorter wavelengths than those of the *Im2* unit, which suggests a higher concentration of Mg-rich pyroxenes (Klima et al., 2011). The units **Esd1** and **Esd2**, especially the latter, have intermediate absorption at 1 μm and a strong absorption at 2 μm , this anomaly is probably related to the presence of spinel, which has a strong absorption around 2 μm , enhancing the typical absorption of pyroxenes (Moriarty et al., 2023). The units **Esd3** and **Esd4** have a lower reflectance than the other domes near the visible range and at 1.5 μm , suggesting they have a higher maturity than the other domes, and thus may be older (Lucey et al., 2000).

To confirm that our proposed secondary domes are different from the kipukas and the rim units, we conducted a clustering analysis. Since these structures are small at the spatial resolution of M^3 , only a few pixels can be sampled for each

unit. Therefore, we opted for a direct comparison between the distribution of the band centers of the units, to check if they followed any distinct pattern. We plotted the band center at 1 μm versus the band center at 2 μm for the areas highlighted in **Figure 3.13a**, each plot contains the scatter of the rim unit *lhim* versus one of the secondary structures (**Figure 3.13c, d, e**). Since the band center is strongly related to composition (e.g. Adams, 1974), we would expect a strong clustering of the points if the composition of both units were similar. **Figure 3.13c** plots the distribution of the units *lhim* and *Esd3*, although some pixels of both units overlap (black), the majority of the points of *lhim* are clustered at shorter band centers (green), and the ones of *Esd3* are concentrated at longer band centers (blue). This indicates that this set of secondary domes is spectrally different from the rim material, further pointing to a difference in their origin. A similar result was found for *lhim* and *Esd4* (**Figure 3.13d**). On the other hand, the same exercise for the *lk* and *lhim* units returned a different result (**Figure 3.13e**), in this case, the points for both units are scattered with no clear clusters, so the units cannot be spectrally differentiated. From this analysis, we concluded that the *lk* unit is indeed compositionally closer to the rim units, and probably genetically unrelated to other secondary structures.

3.7.2. Geologic evolution

The reconstruction of events in the region relied on both the estimation of the formation ages and the stratigraphic relationships between units (**Figure 3.14**). Given the relatively small geographical scale of some units, such as the secondary domes, the crater-counting approach does not fit the task. Furthermore, some of the domes are concentrated in small areas, so it was not possible to establish clear stratigraphic relationships. In those cases, their formation times were constrained by contextual geological information, as well as the local geological setting.

The first recognizable event was the formation of the Serenitatis Basin. Previous authors tried to associate ages obtained from the radiometric dating of lunar samples to the formation of the basin: Černok et al. (2021) proposed an age of 4.2 Ga, while Spudis et al. (2011) gave a lower limit at 3.8 Ga. Its formation is attributed to the impact of a large asteroid, which created the impact basin, and excavated the ejecta that made up the rim units *lhim* and *lhum*, as well as the kipukas (*lk*) protruding from the mare infill. Another consequence of the impact was the thinning and fracturing of the crust, this weakening subsequently allowed the emplacement of extended flood basalts derived from mantle materials (e.g. Van Dorn, 1969, Geiss and Rossi, 2013). In our study area, this is represented by three flows: first *lm3*, which was emplaced around 3.66 ± 0.01 Ga, then *lm2*, emplaced around 3.32 ± 0.1 Ga, and finally *Em1*, which was dated at 2.59 ± 0.3 Ga. The formation of wrinkle ridges (*lwr*) and structural grabens (*lsg*) is related to the thermal evolution of the flood basalts (Watters, 1988), which started as soon as the first lava flow began to cool down and continued until the last pulse reached thermal stability. The pair of volcanic vents found in the region (*Evv*) could have formed as early as the emplacement of the first lava pulse, but they might also be related to the later emplacement of the intrusive domes. The latter scenario seems less likely

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since the vents do not share spectral or structural properties with the intrusive system.

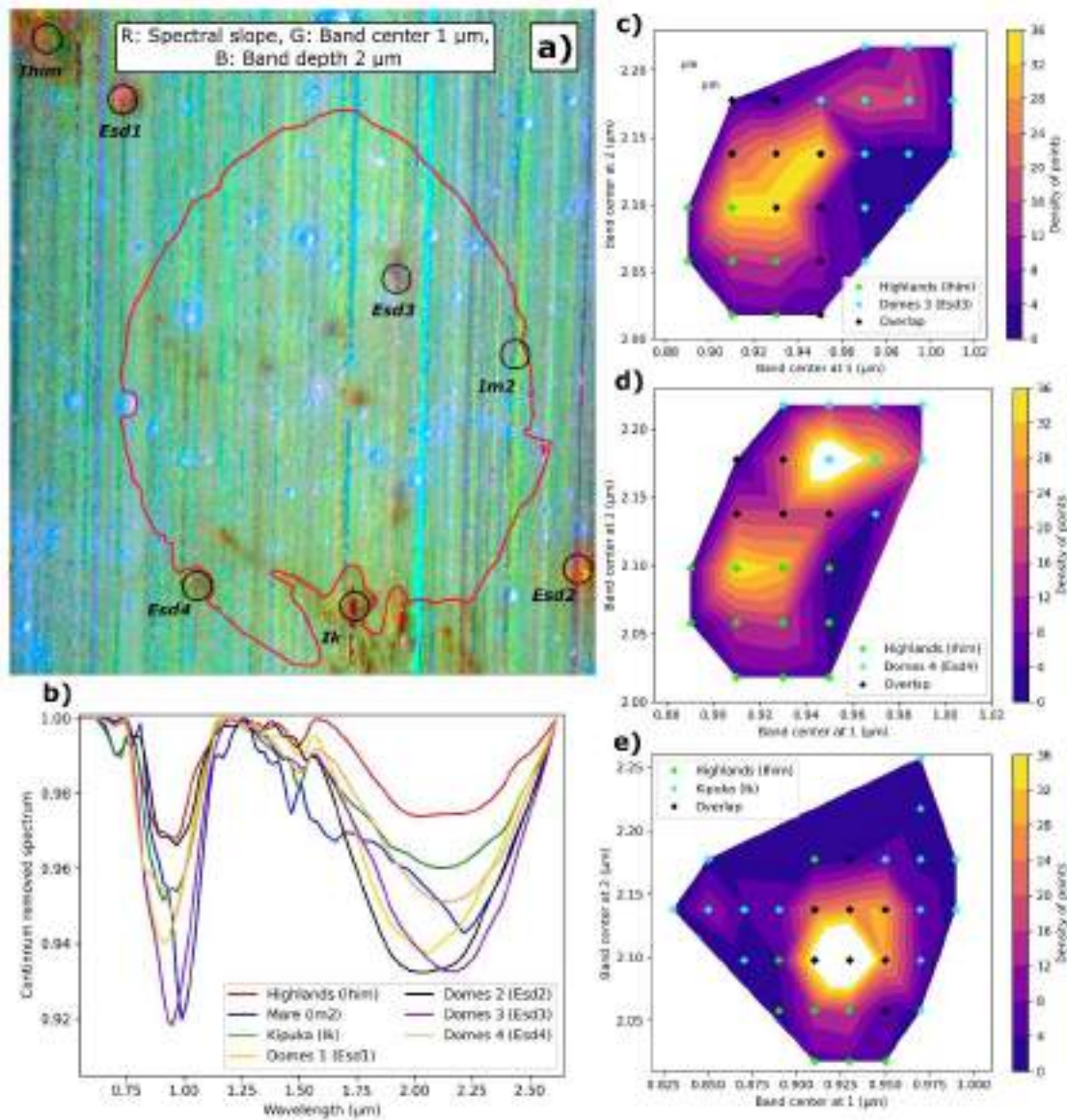


Figure 3.13: a) RGB composite showing spectral differences between the groups of domes (*Esd1*, *Esd2*, *Esd3*, *Esd4*), kipukas (*Ik*), rim unit (*Ihim*), and mare (*Im2*). b) Plot of the spectra of the different units after the continuum removal, the areas sampled are highlighted by black circles in Figure 13a. The weaker absorptions are found in the *Ihim* and *Ik* units, while the strongest are in the *Esd2*, *Esd3* and *Im2* units. c) Plot of the band center at 1 μm vs the band center at 2 μm for the pixels inside the black circles in Figure 13a, the contours in the background account for the density of pixels plotted. The plot of the band centers for the *Ihim* and *Esd2* units shows two clear clusters (cyan and green dots), even if there is some overlap between units (black dots). d) The plot of the *Ihim* and *Esd4* units shows a similar result. e) In the case of the *Ihim* and *Ik*, there are no clear clusters of points, so they are not mineralogically distinguishable.

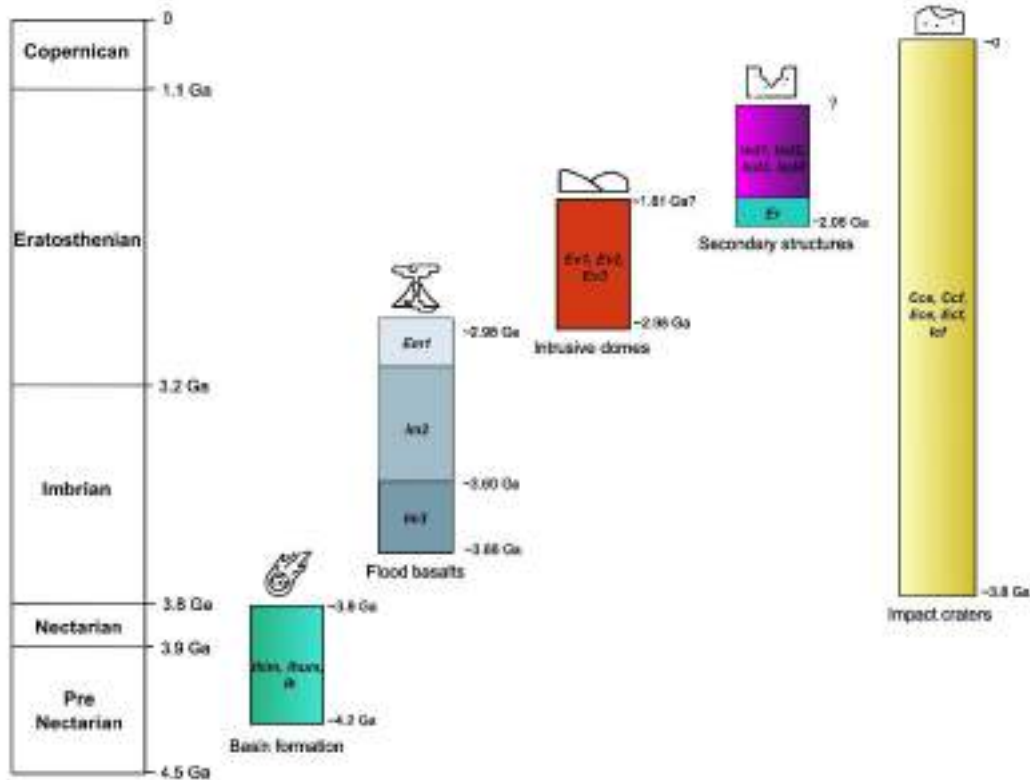


Figure 3.14: Geological evolution of the area. The Serenitatis basin and its rim were formed by a meteorite impact, this created the rim units and kipukas, and triggered the emplacement of flood lavas. The main domes intruded after the last flood event and the formation of the main rilles, which was followed by the formation of dykes, secondary domes and smaller rilles. Finally, asteroid impacts have occurred throughout time.

The emplacement of the large domes **Ev1**, **Ev2**, and **Ev3** is related to the intrusion of a large igneous complex below the area. The location of the intrusive system near the rim of the basin suggests that the upwelling magma was transported along the large annular faults typically formed at the edges of the lunar impact basins (Collins et al., 2022). The area enclosing the three domes is also slightly elevated compared to their surroundings, this uplift cross flood basalts of different ages, thus, it likely originated from the underlying intrusive system. The domes have an asymmetric shape, low topography, and sometimes faulted scarps, which are typical properties of laccoliths (Schofield et al., 2021). However, these structures prove difficult to date since a crater-counting approach only produces an AMA of the covering flood lavas. We propose that they formed after all the lava events occurred (after 2.98 Ga), since the three mare units are uplifted by at least one dome. We also know that they predate, or at least formed synchronously with the large rilles (**Er**) on top of V1 and V2. These linear features are the result of intruding dykes stalled near the surface, which were also fed by the larger intrusive body. The rilles are dated between 1.81 ± 0.3 and 2.06 ± 0.4 Ga, which would also be the lower limit to the formation of the laccoliths. At least V1 continued raising

after this time, since the main rille is slightly uplifted where it crosses the thrust fault limiting V1 to the east. The secondary domes **Esd1**, **Esd2**, **Esd3**, and **Esd4** are small intrusions likely related to intruding dykes. Even if only **Esd1** were superimposed to the main rille, the alignment of the other sets of domes points to a similar origin. This means that these later domes formed after 1.88 ± 0.5 Ga. We know that the four groups are mineralogically different, meaning that they formed from different sources of magma and probably at different times. Nevertheless, we could not establish stratigraphic relationships between them to further discriminate their formation sequence. Our mapping suggests that **Esd1** and **Esd2** are younger, due to their sharp borders and higher reflectance in the visible range.

3.7.3. Potential reservoirs

On Earth, intrusive bodies represent important reservoirs of mineral resources. Some minerals are hosted in the intrusive body itself, such as the Platinum Groups Elements (PGE), an example is the Stillwater complex in the United States (Page, 1977; Lightfoot and Evans-Lamswood, 2014). Other resources are generated by the interaction of the intrusion with external factors, such as the formation of skarns in the Yeshan deposit in China, due to contact metamorphism between the intrusion and the host rock (Zhao et al., 2022). There is a potential for the Valentine domes and other secondary domes to host minerals of interest for the upcoming lunar exploration. However, there are some differences between the intrusions on the Earth and those on the Moon. The lunar crust and mantle are at least moderately depleted of water (Hauri et al., 2015), this greatly inhibits the mobilization of minerals hosted in the intrusion to the areas with contact metamorphism and beyond, which is the main mechanism of mineral concentration in these systems. This makes it less likely that skarn-like or hydrothermal-related deposits could have developed on the Moon. Another important difference is that the dominant composition of the lunar rocks is basaltic, as in the case of the Valentine domes, consequently, deposits related to felsic intrusions would not be common, apart from some specific cases like the Gruithuisen domes (e.g. Braden and Robinson, 2011). Given this context, mineralizations in lunar intrusions, if present, would be more like those where the ore minerals are hosted inside the intruding mafic rocks themselves, like the Stillwater complex or the great Zimbabwe dyke (Wilson, 1996). Commonly, valuable materials accumulate in those settings, especially iron, PGE, and chromites. The main dome of the Valentine system has an interesting feature in the thrust fault that defines its eastern flank, intrusive rocks may be outcropping along the hanging block of the thrust, facilitating access to the intruding rocks. Furthermore, the fault itself and the network of fractures associated with it can act as weak areas where minerals can be hosted. Finally, although the data of M³ is good enough to analyze the general mineralogy of a region, datasets with higher resolution would be necessary to

address the real potential of ore minerals in these systems, as well as the recovery of physical samples that could be analyzed in the laboratory.

3.8. Conclusions

Intrusive domes are probably one of the least studied landforms on the Moon. This is because intrusive processes are hard to observe due to their subtle effects on the surface. We found that given their low topography, large extent, and small slope, the aspect map is a key product to help identify them. This product clearly shows the direction of the slope, indifferently of its magnitude, thus accentuating the physical boundaries of the domes. We are confident that there is still a considerable number of intrusive domes that have not been identified in remote sensing data. A closer observation of high-resolution DEMs and aspect maps may reveal new domes hidden in plain sight, like V3.

Intrusive domes are medium-sized structures that tend to occur in clusters, making the use of low-resolution data to study them limiting. Some datasets like the gravitational anomaly map derived from GRAIL are too coarse to retrieve meaningful information, but products with a medium resolution like M³ can be useful. Even if a spectral analysis of an intrusive dome will mainly return information on the covering units, some information can be derived from secondary structures. In the case of the Valentine system, the secondary structures were too small to use the spectral data of M³ as the primary means of classification. Nevertheless, with the aid of previously defined geomorphological units, it was possible to spot and contextualize clear differences between units using spectral indexes and clustering spectral parameters.

The intrusive system beneath the Valentine dome is bigger than previously estimated, the newly discovered dome V3 is the biggest in the system, and together with V1, they are part of a larger uplifted region. Some of the secondary structures on top of V1 are morphologically and compositionally different from the rim units, suggesting they are not kipukas; they are also aligned with each other and with the main rille on V1, which we propose was formed by a dyke stalled near the surface. Even though the compositional information about the secondary domes is not conclusive, we believe there is enough evidence to consider them as also igneous in origin. These structures record the history of an intrusive system that was active for several million years, after 2.98 ± 0.15 Ga and at least until 1.88 ± 0.5 Ga ago. The number of secondary domes, fault systems, and dyke networks interacting within the Valentine domes makes this location one of the most intriguing intrusive systems on the Moon, and thus an attractive target for future exploration.

3.9. Acknowledgments

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3.10. Open Research

The raw datasets used in this work (NAC and M³), can be accessed through the PDS (Robinson, 2009; Malaret, 2011). The ***MoonIndex*** software is available for Python 3.10 and higher in the PyPI repository. The source code, exemplary Jupyter notebooks, definition of functions, and workflows can be accessed via GitHub and Zenodo (Suárez-Valencia, 2024). The processed geospatial dataset, QGIS project, and final maps can also be accessed via Zenodo (Suárez-Valencia and Rossi, 2024).

3.11. Supporting Information

3.11.1. Introduction to supporting information

In this supplementary information we first present a table with all the data used to make the geomorphological maps. Next, we showcase the commands used in ISIS to process the RAW data to create interpretation-ready products. The first two supplementary figures illustrate minor analysis and discussions presented in the main text, while the last two are the full-size maps of the Valentine domes.

3.11.2. Dataset used

Name	Instrument/Mission	Data type
WAC_Mosaic (Speyerer et al., 2011)	WAC, LRO	Image
Bouger_Anomaly (Goossens et al., 2021)	GRAIL	Gravimetry
LRO_Kaguya_DEM (Barket et al., 2016)	Kaguya-LRO	DEM
Global_Plagioclase_Map (Lucey et al., 2021)	DIVINER, LRO	Radar
M3G20090204T233457	M ³ , Chandrayaan-1	Hyperspectral
M3G20090205T013151	M ³ , Chandrayaan-1	Hyperspectral
M1096429144le	NAC, LRO	Image
M1096429144re	NAC, LRO	Image
M1138844838le	NAC, LRO	Image
M1142369182LE	NAC, LRO	Image
M1142369182RE	NAC, LRO	Image
M1142376293LE	NAC, LRO	Image
M1142376293RE	NAC, LRO	Image
M1142383403LE	NAC, LRO	Image
M1142383403RE	NAC, LRO	Image
M1215373653le	NAC, LRO	Image
M1215373653re	NAC, LRO	Image
M1245960358le	NAC, LRO	Image
M1245960358re	NAC, LRO	Image

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M1249458276le	NAC, LRO	Image
M1249458276re	NAC, LRO	Image
M1258875804le	NAC, LRO	Image
M1258875804re	NAC, LRO	Image
M1289445702le	NAC, LRO	Image
M1289445702re	NAC, LRO	Image
M1323551881re	NAC, LRO	Image
M1335299652le	NAC, LRO	Image
M181095207le	NAC, LRO	Image
M181095207re	NAC, LRO	Image

Table 3.S1: List of the data used to perform the mapping.

3.11.3. Interpretation of indexes

Index Name	Interpretation
R540	High values (Higher than 0.03) → bright fresh material, plagioclase. Low values (Lower than 0.03) → dark terrain, pyroxene, and other mafic minerals.
BCI	Compositional variations of the principal mineralogical phases (pyroxenes, olivines, and plagioclases). Low-Ca pyroxenes have values lower than 0.99, high-Ca pyroxenes have values higher than 0.99.
BCII	If the band center is shifted to lower wavelengths, it may show abundance of low-Ca pyroxene. Low-Ca pyroxenes have values lower than 2.15, high-Ca pyroxenes have values higher than 2.15.
BDI	Abundance of the principal mineralogical phases and their grain sizes, also abundance of opaque phases. Values depend on the minerals involved and their proportions.
BDII	Abundance of the principal mineralogical phases and their grain sizes, also abundance of opaque phases. Values depend on the minerals involved and their proportions.
SS	Low values → fresh terrains, dark terrain. High values → older terrains, space weathering.
Clem RED	High values imply low titanium regions, or high glass contents.
Clem GREEN	High values show enrichment of iron in the surface, and mafic minerals.
Clem BLUE	Higher values imply high titanium content and bright slopes.
BD1900	Highlights differences in mafic compositions when combined with IBDI and IBDII.
IBDI	It shows high values when olivine and pyroxene are present. Values depend on the minerals involved and their proportions.

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IBDII	It shows high values when pyroxene is present. Values depend on the minerals involved and their proportions.
BAI	Useful to differentiate between mineral species. Bigger areas imply the presence of more mafic minerals. When plotted against the band center gives information about the mixture of mafic minerals.
BAII	Useful to differentiate between mineral species. Bigger areas imply the presence of more mafic minerals. When plotted against the band center gives information about the mixture of mafic minerals.
ASYI	Useful to identify glass-bearing mixtures with high asymmetries. Asymmetries higher than 15 points to the presence of glass. When plotted against the band center gives information about the mixture of mafic minerals.
ASYII	Useful to identify glass-bearing mixtures with high asymmetries. When plotted against the band center gives information about the mixture of mafic minerals.
OI	A higher value implies a major abundance of olivine. This index is only indicative, to properly quantify the amounts of olivine, the use of a radiative transfer model is suggested.
Sp1	A higher value implies a major abundance of spinel. This index is only indicative, it is not intended to be a quantitative tool.
Sp2	A higher value implies a major abundance of spinel. This index is only indicative, it is not intended to be a quantitative tool.
Px	A higher value implies a major abundance of pyroxene. This index is only indicative, it is not intended to be a quantitative tool.
An	A higher value implies a major abundance of anorthosite. This index is only indicative, it is not intended to be a quantitative tool.
BD950	While combined with other indexes to create the RGB6 composite is useful to study lunar maria. A higher value implies the presence of mafic minerals.
BD1050	While combined with other indexes to create the RGB6 composite is useful to study lunar maria. A higher value implies the presence of mafic minerals.
BD1250	While combined with other indexes to create the RGB6 composite is useful to study lunar maria. A higher value implies the presence of mafic minerals.
R1580	While combined with other indexes to create the RGB7 composite is useful to study lunar maria.

Fe	Higher values imply the presence of iron. The percentage of FeO in weight can be derived from the parameter: $wt\%FeO = 8.878 * Fe^{1.8732}$
Ti	Higher values imply the presence of titanium. The percentage of FeO in weight can be derived from the parameter: $wt\%FeO = 2.6275 * Ti^{4.2964}$
Cr	Higher values imply the presence of chromite. This index is only indicative, it is not intended to be a quantitative tool.

Table 3.S2: Table listing the spectral indexes used to perform the mapping.

3.11.4. ISIS commands

The processing of planetary data requires the use of the ISIS and GDAL software, which was done using the following commands:

Listing all files to do the batch processing

```
ls *.IMG | sed s/\.IMG// > Imputs.lis
```

Transformation from IMG to cubes

```
lronac2isis from=\$1.IMG to=\$1.cub -batchlist=Imputs.lis
```

Actualization of cubes kernels

```
spiceinit from=\$1.cub -batchlist=Imputs.lis
```

Calibrating for I/F

```
lronaccal from=\$1.cub to=\$1_lv1.cub -batchlist=Imputs.lis
```

NAC instrumental correction

```
lronacecho from=\$1_lv1.cub to=\$1_lv1echo.cub -batchlist=Imputs.lis
```

Map projection, a map template needs to be previously created

```
cam2map from=\$1_lv1echo.cub map=Equirectangular.map to=\$1_lv2.cub  
PIXRES=map -batchlist=Imputs.lis
```

Mosaic

```
noseam from=List2.txt to=Final.cub samples=333 lines=333
```

Translate

gdal_translate Final.cub Final.tif

After these steps, the data is ready for interpretation in a geoprocessing software.

3.11.5. Map of the Christiansen feature

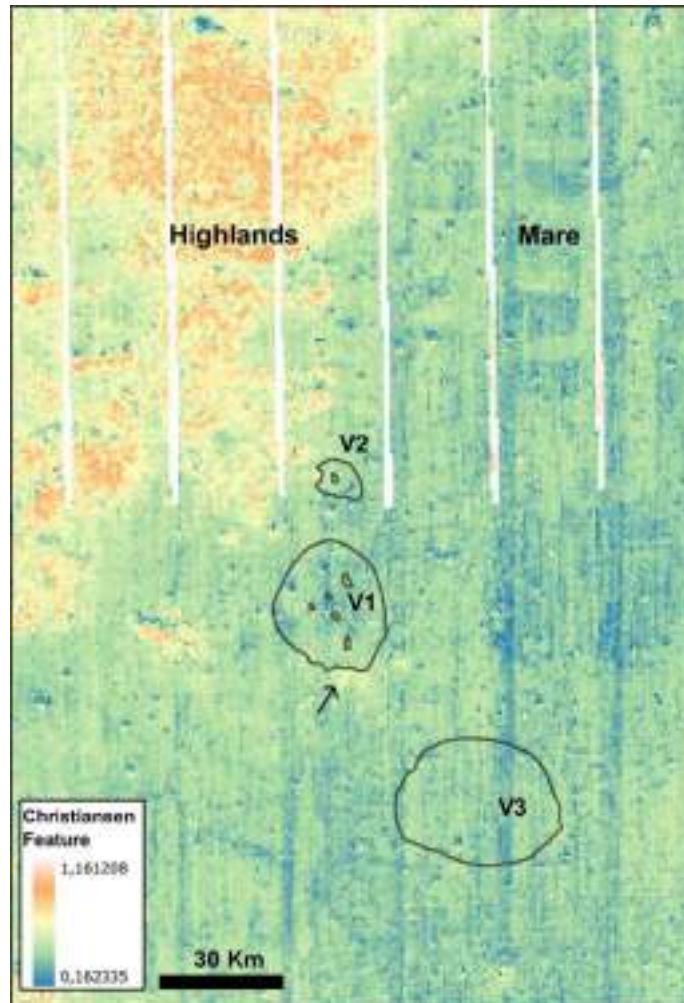


Figure 3.S1. Map of the Christiansen feature of the zone, values increase with the abundance of plagioclase. Higher values are found in the rim of the basin, and lower on the mare and the domes, which is consistent with the basaltic composition of the mare.

A region with intermediate values is found south of V1, which corresponds with the Kipukas (*Ik*) identified in this study (arrow).

3.11.6. Figure of the gravitational anomaly

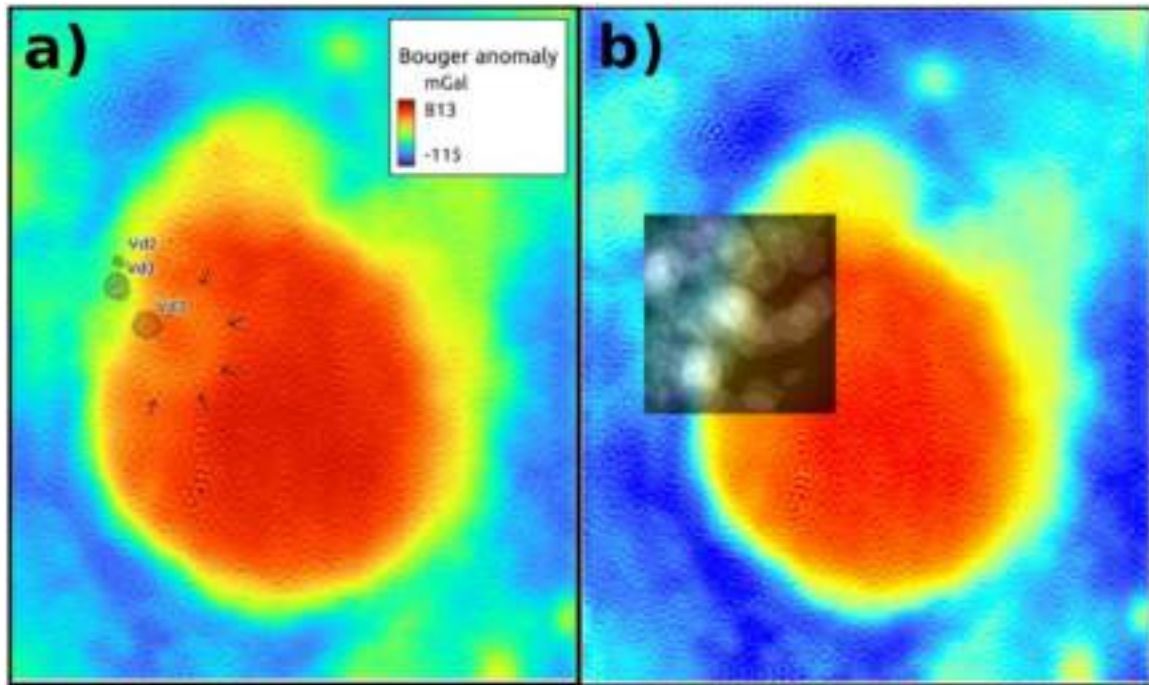
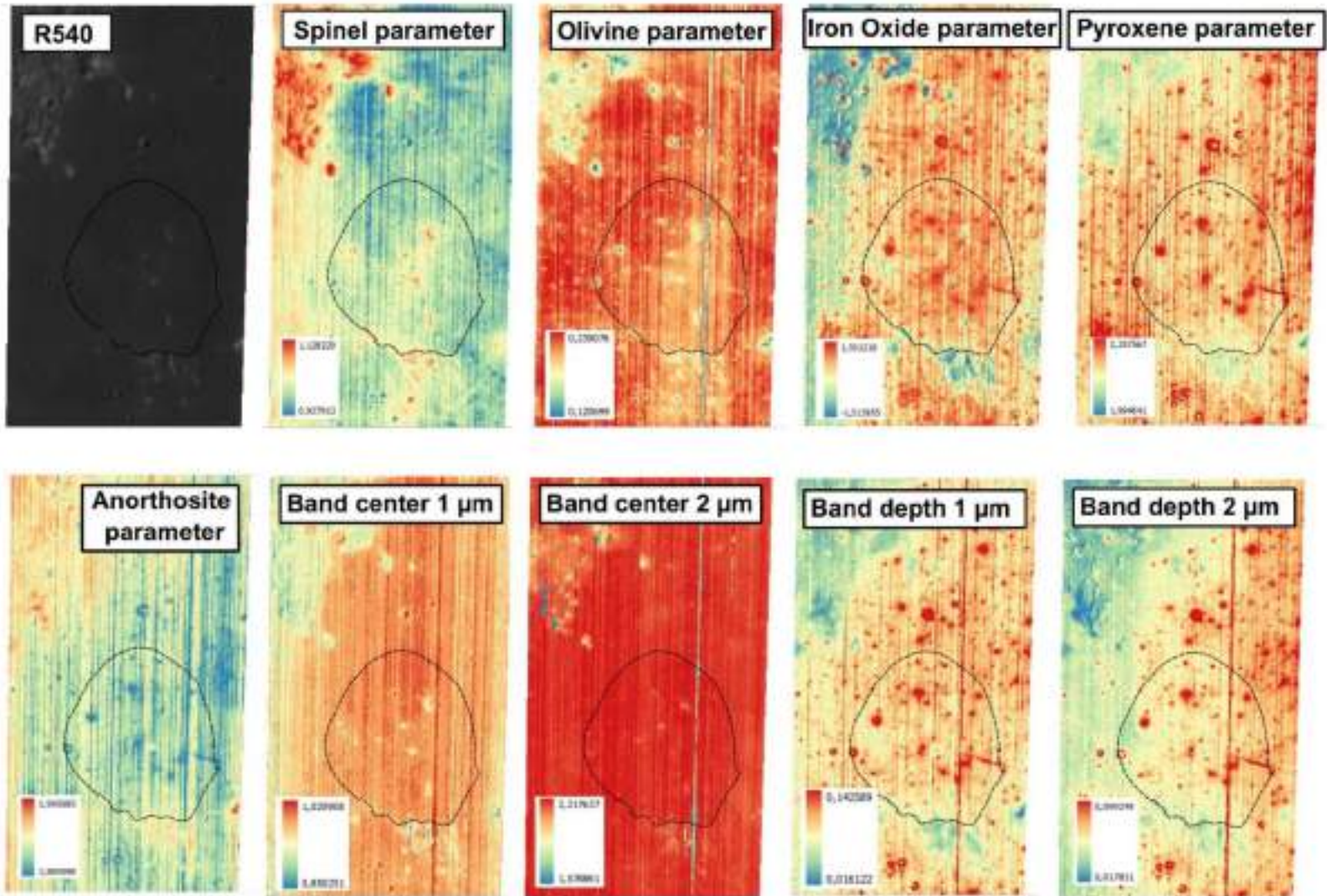


Figure 3.S2: Bouguer anomaly over the Valentine domes. a) The mare has a strong positive anomaly, but a ring-shaped structure with a lower anomaly is located near to the domes (black arrows). The position of the three domes is shown. b) Line density of the zone, lineaments are concentrated in the rim of the basin and the domes. The underlying structure might be a buried crater, which could have weakened the crust more in this location, allowing the emplacement of the intrusive system.

3.11.8. Spectral parameters



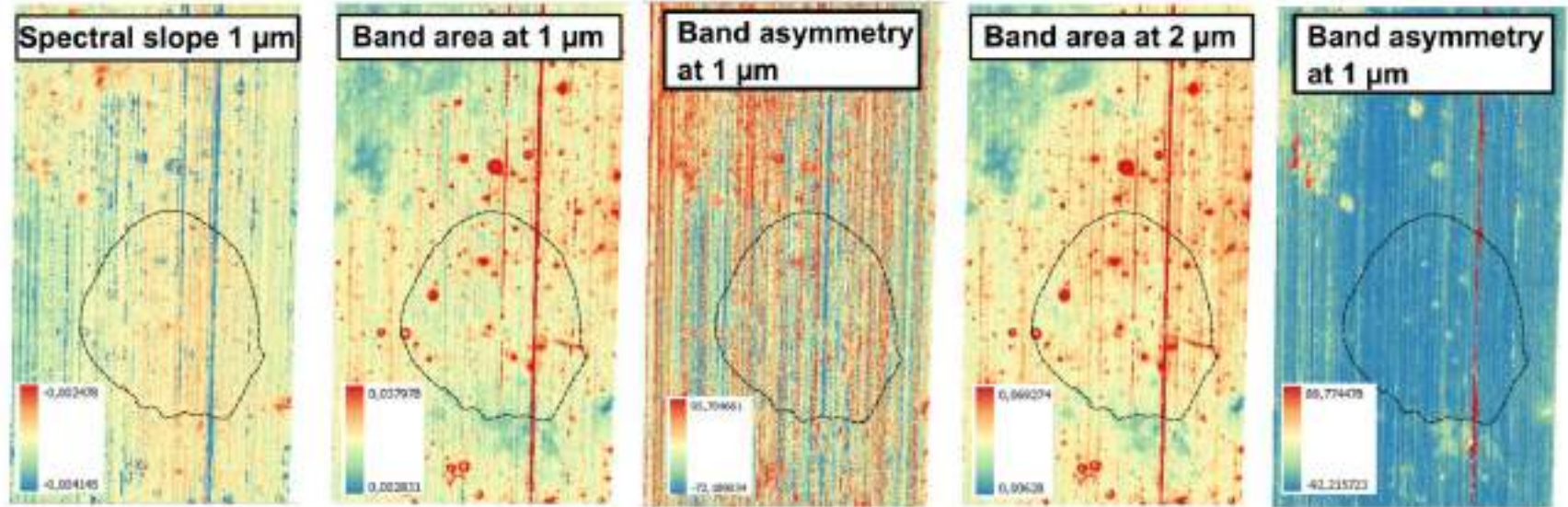


Figure 3.S5: Spectral indexes derived from M³.

Chapter 4: Origin of the dome field in western Utopia Planitia, on Mars

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4.1. Paper significance in the thesis

This paper constitutes the last stage of the research. As my intention was to analyze the behavior of intrusive systems across different planetary surfaces, I chose Mars as my second study target. The selected location was a dome field in western Utopia Planitia, a large area where small domes were emplaced across several geological units. This area was a big contrast with the Valentine Domes, since the domes were more numerous but also had a simpler structure. I followed the same methodology used in the lunar case, with some adjustments due to the quality of the data and the nature of the domes.

The results of this investigation represent another example of how intrusive system can be found in planetary surfaces and allowed me to analyze the similarities and differences with the lunar case.

4.2. Abstract

Hundreds of domes are scattered over a plain composed of different geological units in the western margin of Utopia Planitia, near the northern Martian dichotomy. These structures have traditionally been considered of igneous origin. In this work, we utilized recent data to study the geomorphological and compositional properties of the dome field in Utopia Planitia. We found that the domes originated from an intrusive-to-extrusive system, since they range from cryptodomes to volcanic domes. Each dome appears to represent a single magmatic event, indicating they formed in a monogenetic style. Two distinct groups of domes were identified according to their shapes and stratigraphic relationships with the floor units, which represent two different stages of igneous activity. From a lineament analysis it was established that the domes are preferentially aligned following a NW-SE trend, which is consistent with the regional faults and fractures. The domes field in Utopia Planitia was likely created by two monogenetic magmatic events at different ages, which took advantage of the tectonic configuration of the area to reach the surface. Some magmas were able to reach the surface creating extrusive structures, while the majority crystallized near the surface; of the last group, a small number of them remained trapped underground as cryptodomes, but eventually the majority were

uncovered. This scenario would explain the distribution and variety of domes we observe today.

4.3. Introduction

Martian landforms of volcanic origin are diverse and widely distributed across its surface. Many of them are located near the large volcanoes in the Tharsis region (e.g Williams et al., 2008, Mouginis-Mark, 2018), where lava flows, dyke swarms, calderas, cones, and several other structures are commonly found (e.g. Bleacher et al., 2007, Hynek et al., 2003). However, plutonic structures, particularly intrusive domes, have only been reported on a few instances.

Intrusive and extrusive domes are often harder to recognize than other igneous landforms, mainly because there are several geological processes on Mars that can result in dome-like structures. For example, fields of knobs, mesas, pingos, mud volcanoes, and mounds are found in the northern Martian plains, each with varied, non-igneous origins (eg. Zhang et al., 2023; Soare et al. 2013; Ivanov et al., 2014). Therefore, a detailed geomorphological and spectral analysis is needed to differentiate between these structures.

Two locations with potentially igneous domes were identified and studied by Rampey et al. (2007) and Farrand et al. (2011). One in Arcadia Planitia (between 34-46°N and 167-180°E), and the other in Utopia Planitia (between 37-46°N and 76-86°E), both places are located in the northern plains of Mars. In both cases, hundreds of domes are scattered across a large area, intersecting different geological units. This assemblage is called a “Dome field”. The individual domes are round-shaped and small-sized (on average 160 m high, and 1.5 km in diameter).

The dome field in Arcadia Planitia has been extensively studied before by Rampey et al. (2007), Farrand et al. (2011), and Farrand et al. (2021). While the one in Utopia Planitia received less attention and was only partially examined by Farrand et al. (2011). In this work, we analyzed the dome field in Utopia Planitia with recent data to understand how they formed, and to establish similarities and differences with the better understood dome field on Arcadia Planitia.

4.3.1. Location on Utopia Planitia

Utopia Planitia is one of the largest impact basins on Mars, situated in the northern plains of the planet, west of Elysium Mons and east of Nili Fossae. Ice-related and periglacial activity are thought to be important agents in the geologic evolution of the area, since thick ice-dust mantles and periglacial landforms are present across the basin (Soare et al., 2012).

The dome field lies along the western margin of the basin (between 37-46°N and 76-86°E). To the southeast are Nilosyrtris Mensae, a fretted terrain thought to be

formed by groundwater runoff (Bandfield & Amador, 2016), while to the northeast lies the extensive Vastitas borealis formation, a flat deposit of mixed sediments which origin is unclear but thought to be related to a hypothesized ancient ocean, outflow channels deposits or subsurface water sources (Liu et al., 2022). Most of the domes occur in a broad, nearly flat terrain, which gently slopes towards the northeast, to the center of the basin. The concentration of domes decreases gradually towards the east and south, where other dome-like structures also appear, like mesas or pingos (Mills et al., 2021). To narrow our research, we defined a study area of 141,000 Km², concentrating on the regions with the highest concentration of potential igneous domes (**Figure 4.1**).

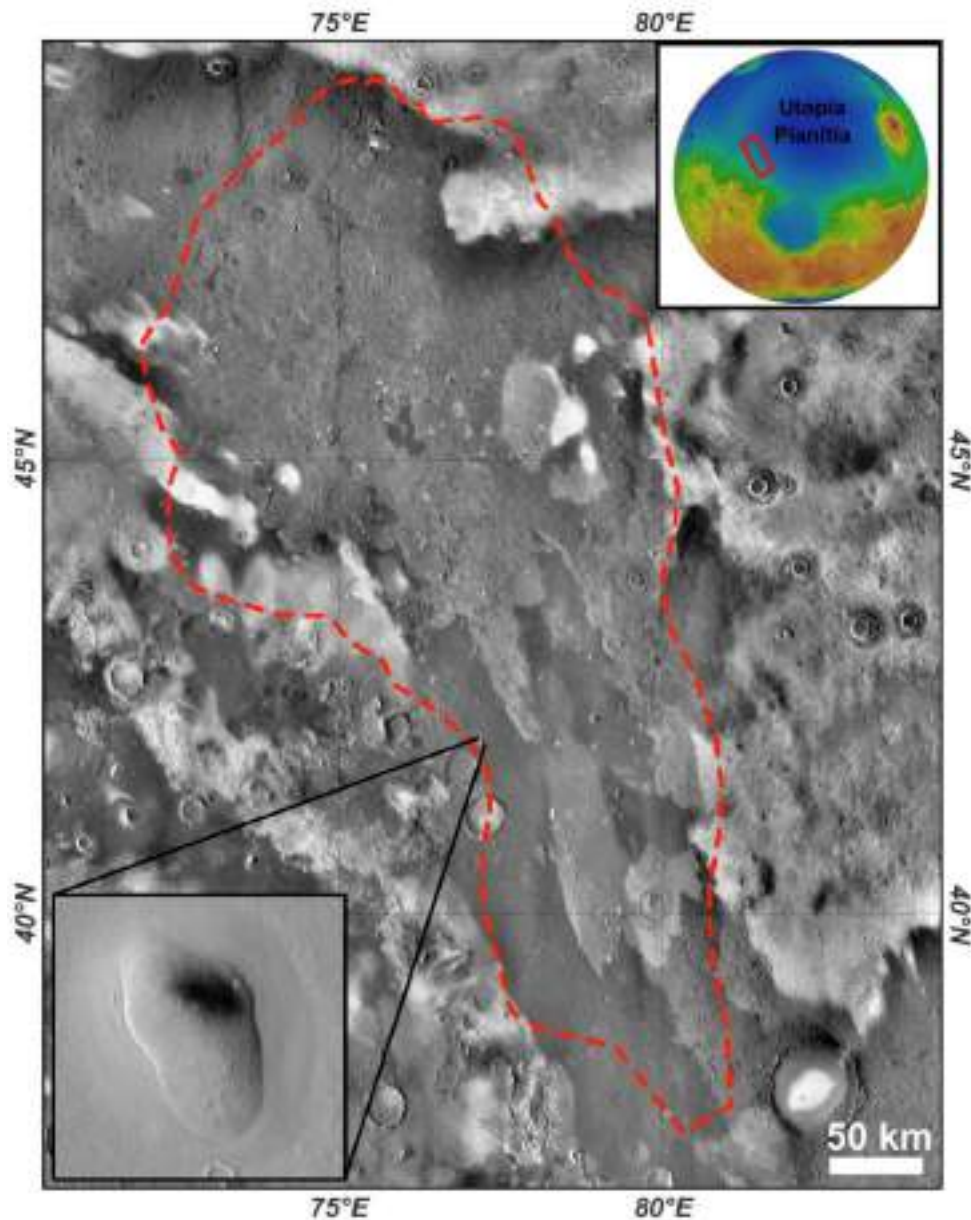


Figure 4.1: Location of the dome field on Utopia Planitia. The basemap is the THEMIS day infrared mosaic.

4.3.2. The dome field in Arcadia Planitia

The properties of the domes in Arcadia Planitia are relevant for this research due to their similarities to the ones in our area. As in Utopia Planitia, the domes are scattered over a vast and open plain. Numerous wrinkle ridges cross the area and are spatially related to the domes (Rampey et al., 2007). Each dome consists of a central core, radial aprons accumulated around them, and an aureole of light or dark-toned deposits (**Figure 4.2a**) (Farrand et al. 2011). The cores have a high thermal inertia, suggesting they are composed of solid rock, although their surface is covered by unconsolidated blocky materials. The aprons are sediments covering the flanks and surroundings of the domes, which would be consistent with debris falling from the cores, either by the action of mass waste or ice-related dynamics (Farrand et al., 2011). Finally, the aureole are distal zones with evidence of periglacial and sublimation textures. Aureole shows the particular “Brain terrain”, a texture thought to be formed by the cracking of ice-rich surfaces due to thermal and glacial stresses (Levy et al., 2009).

Farrand et al. (2021) used hyperspectral data to check the composition of the domes. They found strong absorptions at 1 and 2 μm , which would be consistent with a mixture of olivine, pyroxenes and glass (Burns, 1993; Sunshine et al., 1998). These authors also detected an anomalous absorption around 1.3 μm and a particular spectral convexity after 3 μm , which could be linked to the presence of Fe-rich plagioclase and alkali feldspar respectively (Brown, 1969). This mineralogy suggests an intermediate-to-felsic composition for the magmas that formed the domes.

Rampey et al. (2007) further classified the domes into two groups. The first type, the “core-annulus-aureole” (CCA) domes, is described above. These domes were interpreted as extrusive in origin, since they are clearly uncovered, and some show lobate structures and pitted summits. The second type, known as “Blister” or cryptodomes, appear as small bumps in the plain, with no aprons or aureole. Furthermore, these cryptodomes appear to be covered by the material that make up the plains, since they do not have any textural or spectral contrast with their surroundings. This lead Rampey et al. (2007) to classify these structures as intrusive domes that were emplaced near the surface. Farrand et al. (2011) proposed a formation model for the domes which involves several steps. First, the domes were emplaced near the surface, creating a fractured carapace rich in hyaloclastite breccia where the intrusions meet the host rock. Second, the domes were exhumated by erosion or tectonics, leading to the formation of the aprons from the hyaloclastite carapace. Finally, all the mobilized material underwent the effect of ice and wind, forming the distal aureole and their characteristic textures.

Many of the previous descriptions also apply for the domes on Utopia Planitia. However, there are some morphological differences compared to those on Arcadia

Planitia, which may be related to the distinct geological settings between the two locations (**Figure 4.2b**).

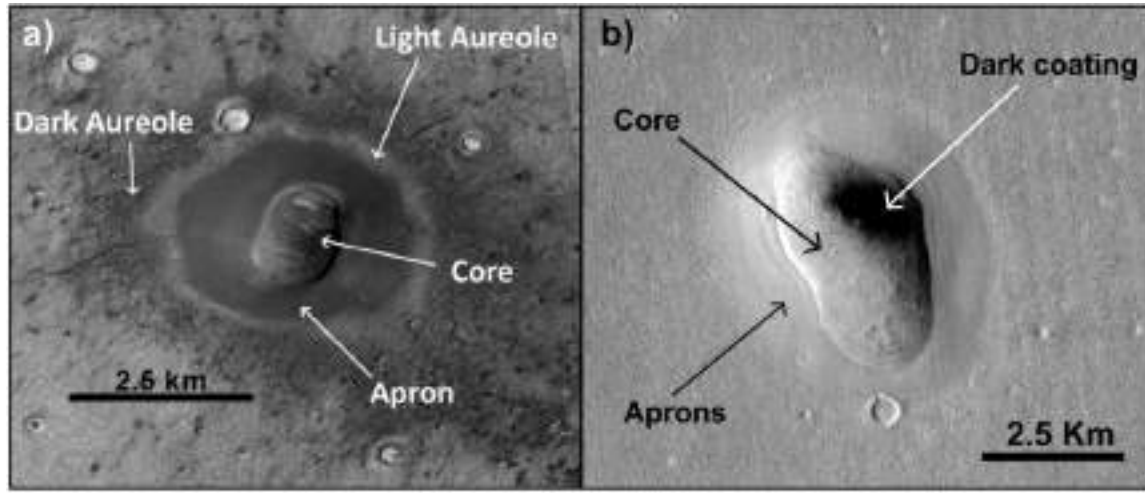


Figure 4.2: Structure of the domes. a) Typical structure of the domes in Arcadia Planitia, showing a core, aprons, and aureolae (Taken from Farrand et al., 2021). b) Typical structure of the domes in Utopia Planitia, showing a core, aprons, and a dark coating, but lacking aureole.

4.4. Data

Since the domes are spread over a large area, we used medium-resolution datasets to analyze the properties of the materials in which the domes are emplaced (here called floor units), and their stratigraphic relationships with the surrounding terrains. This was mainly done using the global mosaic derived from the Context Camera (CTX) onboard the Mars Reconnaissance Orbiter (MRO) (Malin et al., 2007). This panchromatic mosaic covers the area with an average resolution of 5 m/pixel (Dickson et al., 2024). Other global datasets used were the day and night thermal inertia mosaics derived from the Thermal Emission Imaging System (THEMIS) onboard Mars Odyssey, which have a spatial resolution of 100 m/pixel (Edwards et al., 2011). To gather terrain information, we used the global Digital Elevation Model (DEM) derived from the Mars Orbital Laser Altimeter (MOLA), offering a spatial resolution of 200 m/pixel (Fergason et al., 2018). In locations not well-covered by CTX data, multispectral images from the High Resolution Stereo Camera (HRSC) onboard Mars Express were used (Gwinner et al., 2016).

To study the individual domes and other small-scale features of the area, we used high resolution datasets, retrieved from the Planetary Data System (PDS). First, several panchromatic images captured by the High Resolution Imaging Science Experiment (HiRISE) onboard MRO were used; these images have an average spatial resolution of 50 cm/pixel (McEwen, 2007). Second, we utilized CRISM hyperspectral cubes to analyze the composition. We downloaded the Map-Projected Targeted Reduced Data Record (MTRDR) version of the cube, which is ready for analysis. The cubes have an average spatial resolution of 18 m/pixel,

and they cover the 436-3896nm spectral range across 489 bands (Seelos, 2016). An additional cube is also provided within the dataset, which contained 60 spectral indexes refined for mineral recognition (Viviano et al., 2014). Finally, we retrieved spectral signatures from the NASA RELAB spectral database to compare with samples taken from the CRISM cubes. A comprehensive list of all the data used can be found in **Table 4.S1**.

4.5. Methods

4.5.1. Data correction and projection

Datasets from other authors, such as the global mosaics, were ready for analysis, but the HiRISE and CTX images required processing. Both products were calibrated and map-projected using the Integrated Software for Imagers and Spectrometers (ISIS) (Laura et al., 2023), and the Geospatial Data Abstraction Library (GDAL) (Rouault et al., 2023). The steps of the image processing included: importing the data to ISIS, radiometric correction, noise correction, image stitching, map projection, and format transformation. A detailed description of the commands used in this process can be found in **Section 4.11.2**.

4.5.2. Spectral and clustering analysis

To obtain spectra from the CRISM cubes and compare them with laboratory-obtained spectra we used common Python libraries and jupyter notebooks. We tried to implement the signal-enhancing method suggested by Horgan et al. (2020), which consist of dividing the spectrum of the target by the one of a neutral area, this area is automatically defined by setting thresholds to the spectral parameters for certain minerals. Unfortunately, the CRISM cubes over Utopia Planitia show little spectral variation, so this method would diminish the spectral properties instead of enhancing them. We decided to take the data directly from the MTRDR reflectance cube. All the spectra used in this study were averaged using a 5x5 window. We also tried an unsupervised clustering analysis to obtain spectral endmembers, following the pipelines of Baschetti et al. (2024). However, the cubes were too noisy and homogeneous, so we did not obtain conclusive results. Nevertheless, we modified and used the pipelines of Baschetti et al. (2024) for plotting and analyzing the spectral signatures.

Given the large number of individual domes, we analyzed their spatial distribution in order to identify clusters and alignments that could suggest a tectonic control on the intrusions. We followed the methodology of Hencz et al. (2023) and Le Corvec et al. (2013), which involves several steps using the programming language Python and the geoprocessing software QGIS (**Section 4.11.3**). We used the global catalogue of Knapmeyer et al. (2006) to retrieve the faults in our region.

4.5.3. Mapping techniques

Given the size difference between the individual domes and the study area, we decided to map at two scales with different goals. The first objective was to create a regional map to describe the floor units across the area, allowing us to understand the geological setting of the location and how the domes interacted with it. Subsequently, a detailed mapping of a single dome was done, one which was covered by both HiRISE and CRISM datasets. Since the available spectral information was generally not conclusive, most of the units were mainly defined by their geomorphology. Nevertheless, when the spectra were clear and relevant, the units were first created as geomorphological, and later refined or modified according to the spectral information (e.g. Yingst et al., 2023; Wright et al., 2024). We defined the temporal relationships of the units by analyzing cross-cutting relationships, and when possible, we also used the crater size-frequency counting technique to obtain relative ages (Neukum et al., 2001; Yue et al. 2022). The analysis and mapping of the area were done in QGIS with the aid of the Mappy plug-in (Penasa and Brandt, 2023), the crater counting was performed with the CraterTools extension of ArcGIS (Kneissl et al., 2011), and the age determination was computed in the Python version of the software CraterStats (Michael, 2021).

4.6. Results

4.6.1. General details of the domes

The first step of this work was to identify all the domes within the area, describing their morphology and measuring their diameter and altitude. The distribution of the domes can be seen in **Figure 4.3**, and their measurements in the supplementary materials (Suarez-Valencia et al., 2024). The morphological classification of the domes and their aprons was done using the global CTX mosaic, and the measurement of altitude using the MOLA DEM.

General statistics for the domes can be seen in **Figure 4.4**. The mean diameter of the cores is 1.6 km, and they range normally between 300 m and 4.6 km (**Figure 4.4a**). As for the altitude, they are on average 33 m high (**Figure 4.4b**). Most of them are round or oval-shaped, while a minor number are irregular or rectangular-shaped, all of them have round edges (**Figure 4.4c**). There is a significant concentration of smaller domes to the south (around 20 m high), while to the north the domes are wider and larger (between 50 to 120 m high). An important difference with the domes on Arcadia Planitia is the lack of aureole, in this case the aprons rest next to the cores, but deposits located further away are not commonly present. “Brain terrain” is also widespread in the region, but they form directly over the aprons. On the other hand, the thermal response of the structures is like the domes on Arcadia Planitia, the cores have high thermal inertia, implying solid rock, while the aprons have a lower thermal inertia, even compared to the floor units, suggesting they are made of unconsolidated materials (**Figure 4.2b**). The domes are emplaced across several floor units, meaning their origin is

independent of them. Most of the domes have part of their flanks covered by a black coating, this material appears to be surficial, and mainly accumulates in the northeast-facing slope of the structures.

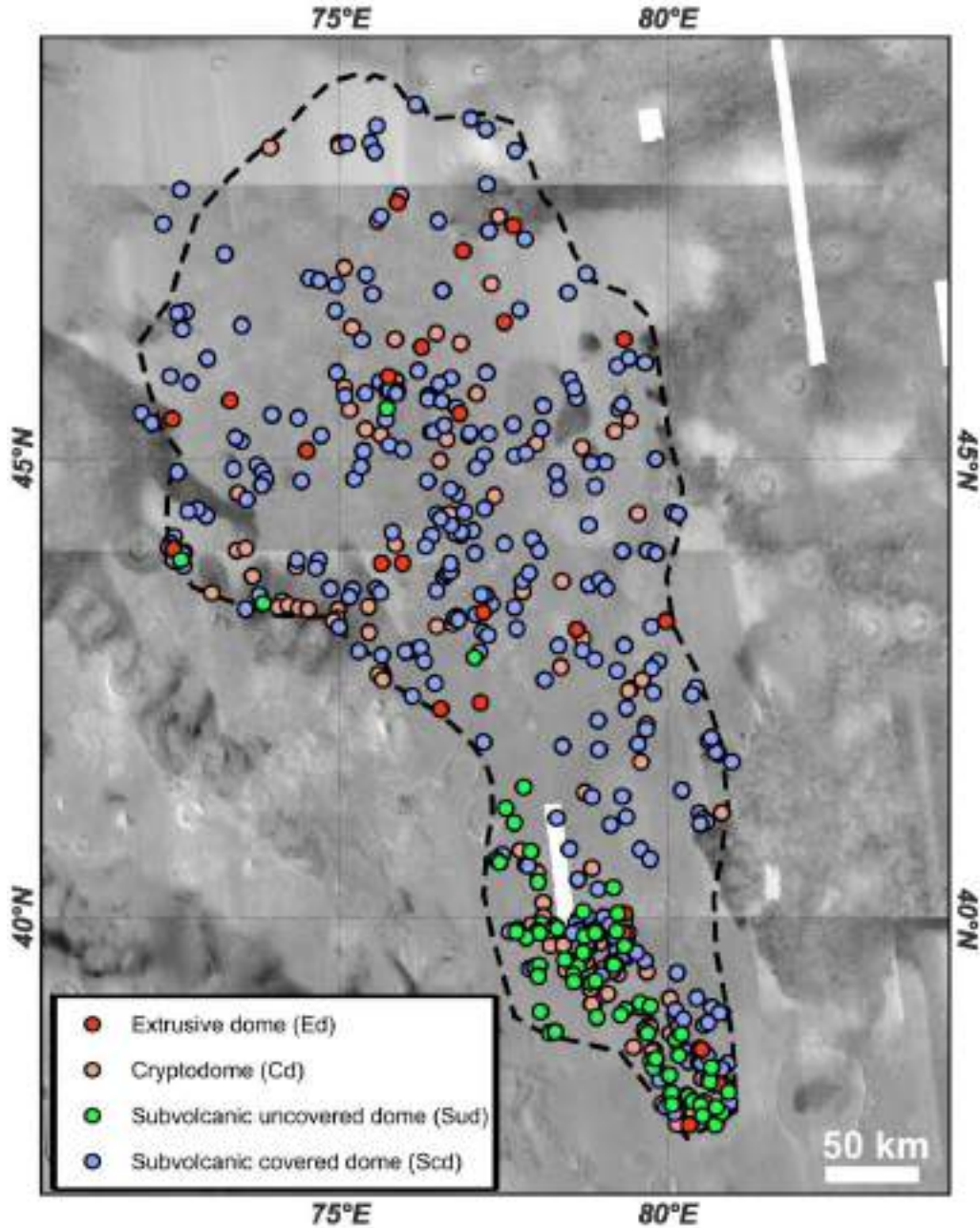


Figure 4.3: Distribution of domes in the area. The four types are represented in different colors. The basemap is the CTX mosaic.

A major question regarding the nature of igneous-originated domes is how to differentiate them from other processes that produce domes, to solve that, it was necessary to compare their morphological properties with other similar structures. Pingos (**Figure 4.5a**), and mud volcanoes (**Figure 4.5b**) are commonly found in these latitudes of Utopia Planitia, but they are considerably smaller than the candidate igneous domes. Furthermore, mud volcanoes have clear pits on their

summit (Ivanov et al., 2014), and pingos are flat-topped and have steep edges (Burr et al., 2009). These features are not shared by our candidate domes. The distinction from structures formed by erosion is more challenging. Mesas, like the ones in southern Utopia Planitia (Zhang et al., 2023), and mounds like the ones in Oxia Planum (McNeil et al., 2022), are particularly similar in size and texture to our candidate igneous domes, and they are also often accompanied by aprons. Nevertheless, these structures tend to have a more angular shape than igneous domes, they also have rough edges, flat summits and are usually made of multiple layers of rocks. Some stratification can also be identified on their walls and summits (**Figure 4.5c**). In contrast, the domes in Utopia Planitia have round edges, most of them are round-shaped, and they all have convex summits without any kind of stratification, which led us to classify them as igneous in origin (**Figure 4.5d**).

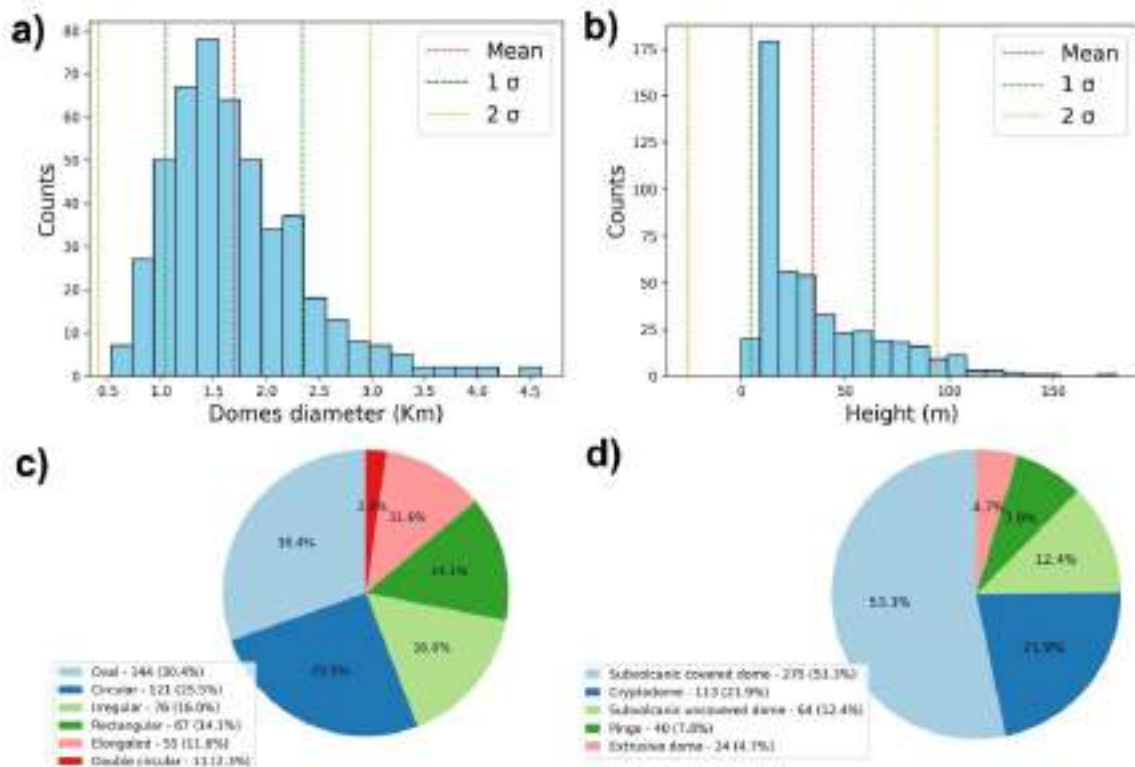


Figure 4.4: General statistics of the domes. a) Histogram showing the diameters of all the domes. b) Histogram showing the altitude of the domes. c) Pie chart showing the main shapes that the domes can have. d) Pie chart of the percentage of domes according to their type.

Although all the domes share the previous characteristics, they were classified in subclasses according to their morphological properties (**Figure 4.4d**). The most common type are the “subvolcanic covered domes” (**Scd**), these structures are like the ones studied in Arcadia Planitia by Farrand et al. (2021) (**Figure 4.6a**). They are the largest type of domes (larger than 1 Km), their cores are clearly distinguishable from the host units, and they are made of closely packed blocks

with diameters ranging from 3 to 6 m. They can have several shapes, from circular to irregular. The aprons are generally well-developed, extending hundreds of meters away from the cores. These domes do not have lobes or vents associated with them, and their texture is homogeneous. The “subvolcanic uncovered domes” (**Sud**) type is generally smaller (sizes less than 1 Km), their cores are partially removed, potentially uncovering the rocks below (**Figure 4.6b**). They are mainly circular-shaped, and sometimes oval-shaped. Some of them have large aprons like the previous domes, others have ejecta-like deposits around them, and others do not show aprons at all. “Extrusive domes” (**Ed**) are similar in size and texture to the subvolcanic covered ones, but they have well developed lobes next to the core, and/or summit pits. The lobes appear to be formed by viscous materials, since they do not spread far away from the domes or are clearly detached from them (**Figure 4.6c**). Finally, the “cryptodomes” (**Cd**) type are equivalent to the features of the same name described by Rampley et al. (2007) in Arcadia Planitia, these structures do not have cores or aprons, they are small and usually circular (**Figure 4.6d**). Cryptodomes have no effect on the continuity of the host unit, meaning the intrusive body is buried near the surface, like a laccolith (Schofield et al., 2021).

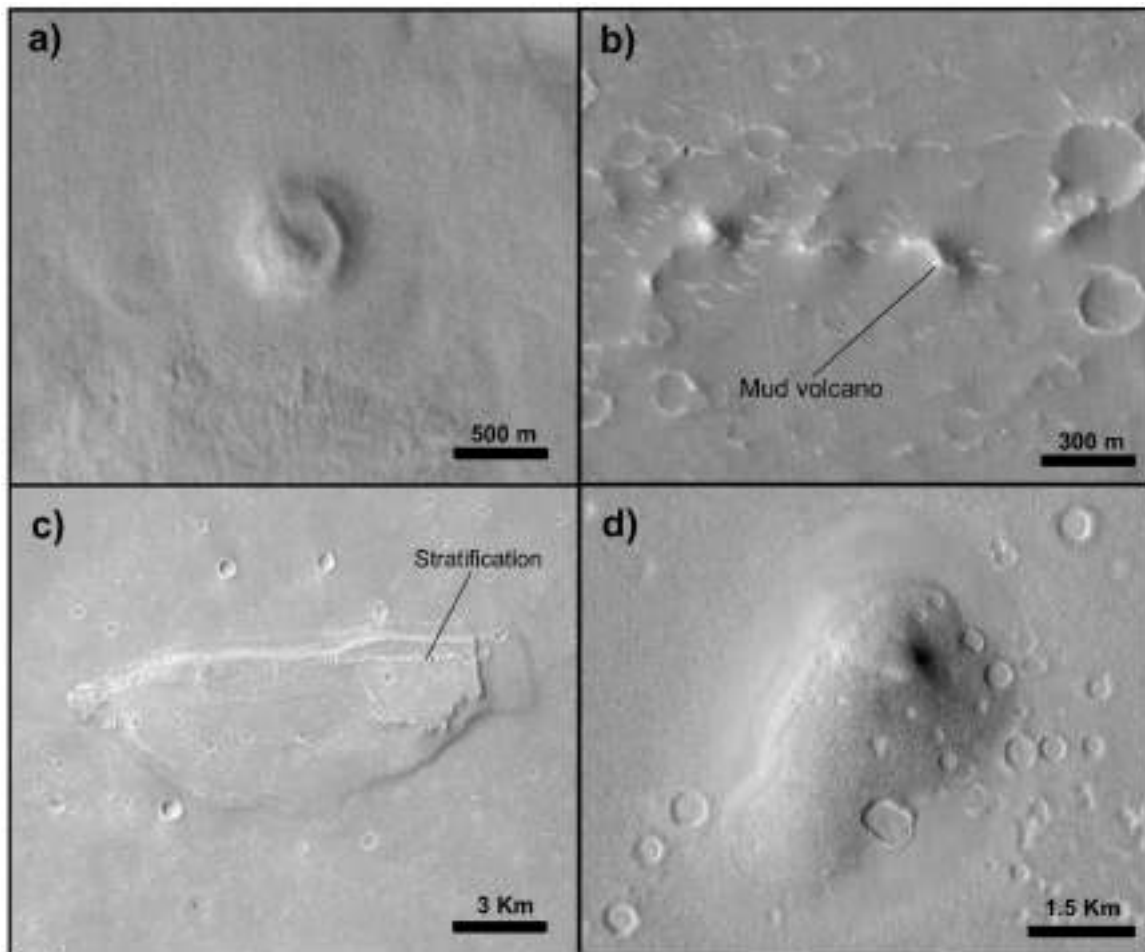


Figure 4.5: Different dome-like structures found across Utopia Planitia. a) Pingos (Ivanov et al., 2014), b) Mud volcanoes, c) Mesas, this one showing stratification (Zhang et al., 2023), d) the candidate intrusive domes in our study area.

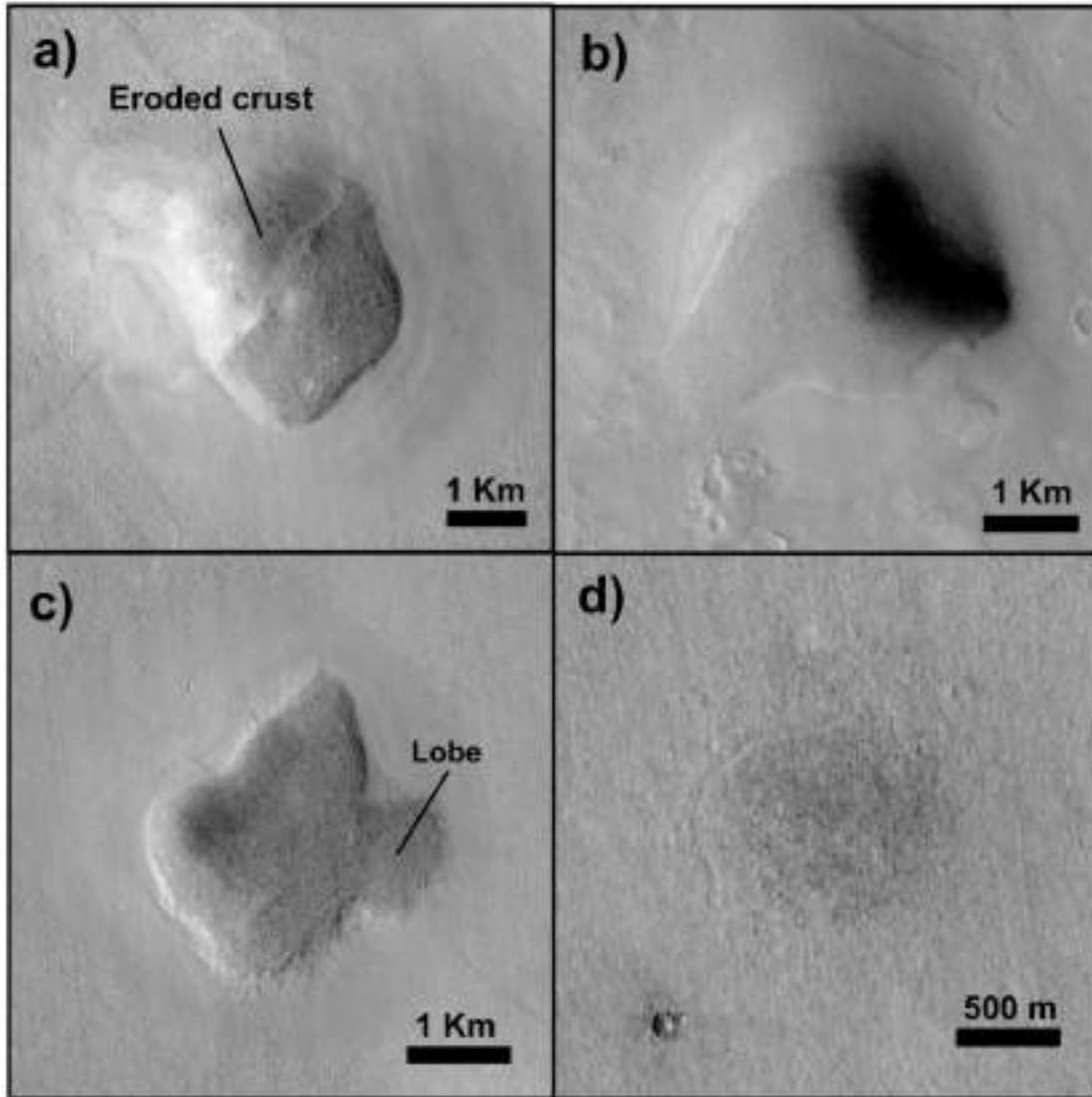


Figure 4.6: Different types of domes found in the area. a) Subvolcanic uncovered dome, with half of its crust eroded or removed. b) Subvolcanic covered dome, the covering crust is complete. c) Extrusive dome, with a lobe flowing over its east flank. d) Cryptodome, completely covered by the host unit.

4.6.2. Geomorphology of the floor units

The floor units in the study area have a diverse origin due to their position near the northern Martian dichotomy (Ballantyne et al., 2023). A map with the geomorphological units on the area is shown in **Figure 4.7**. The largest unit in the area is “Rugged materials” (*Rm*), it is characterized by a rugged texture, high albedo, and low thermal inertia. Periglacial landforms are common, including scallops, crevasses, polygons, large-scale pits, and occasionally brained terrain, the last mainly associated with the aprons of the domes. The aprons of the domes in this unit are usually incomplete due to the development of scallops or polygons over them. This unit correlates spatially to the Astapus Colles unit defined by Tanaka et al. (2005).

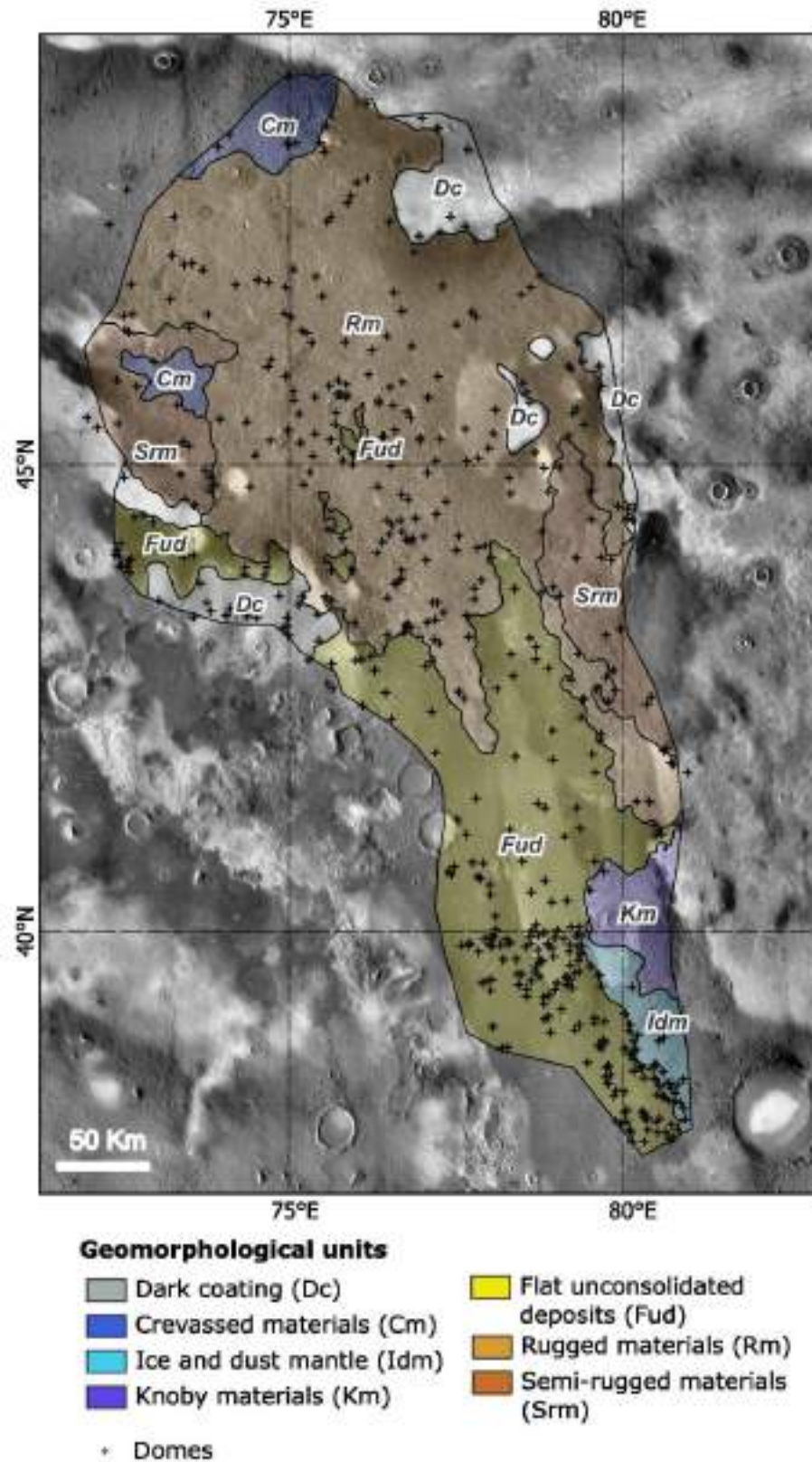


Figure 4.7: Geomorphological map of the floor units in the area. The basemap is the THEMIS day mosaic.

The second largest unit is the “Flat unconsolidated deposits” (**Fud**), it is located south of the **Rm** unit and extends to the outskirts of the Nilosyrtis Mensae. The unit is almost flat, although at a regional scale it is gently dipping towards the center of the basin. It has high albedo and the highest thermal inertia in the region. It is the lowest unit in the area, having discordant contacts with the surroundings ones, which suggests it is filling a local low. Internally, the unit is made of blocks ranging from 1 to 3 m in diameter, spread across a matrix of finer-grained material. Periglacial landforms are less common in this unit, which in turn allows the aprons of the domes to be well developed and continuous. Some sinuous rilles cross the area are filled by materials that are massive, or that have a grain size smaller than the image resolution (here denominated fine-grained materials). Some domes are superimposed to the rilles, locally interrupting their continuity (**Figure 4.8a**). We also identified the silhouettes of buried craters, meaning the unit may be covering a basement below. This unit correlates spatially with the Utopia Planitia 2 unit of Tanaka et al. (2005).

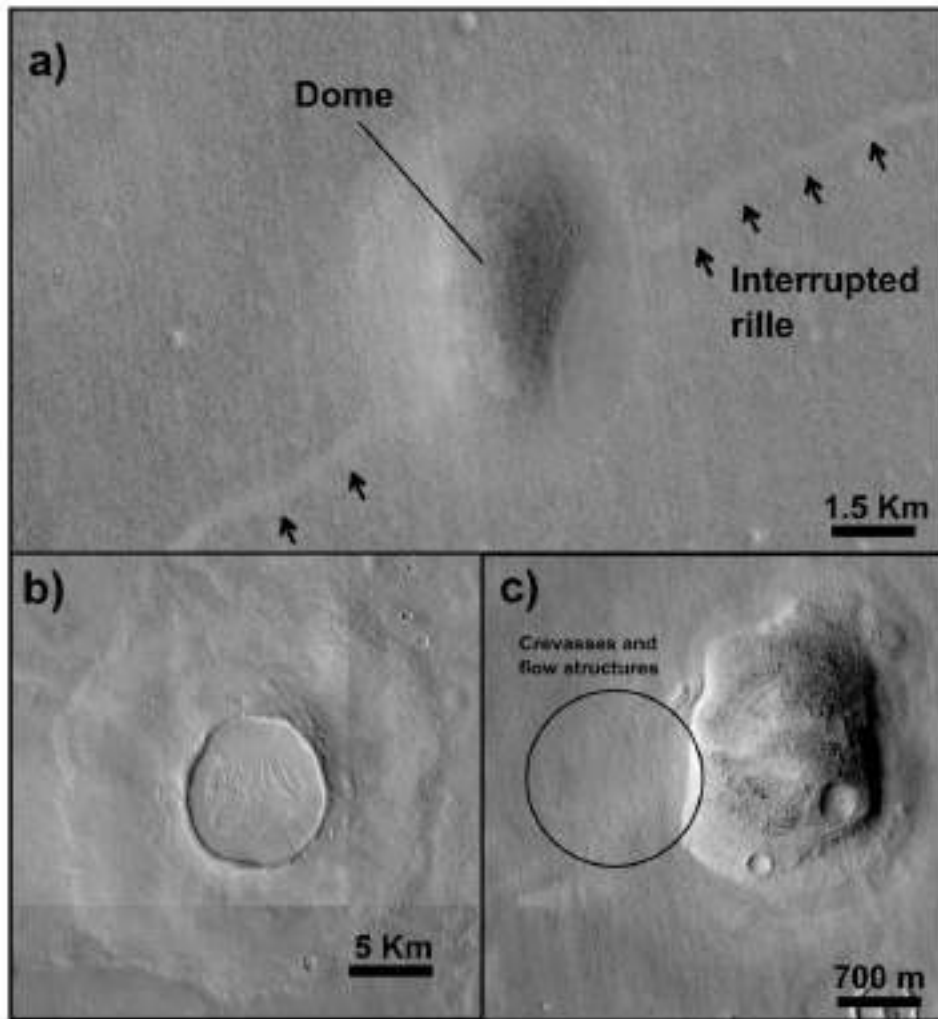


Figure 4.8: Outstanding landforms on the floor units. a) Dome superimposed to a rille in the **Fud** unit, suggesting the dome is younger. b) Pancake-type crater in the **ldm** unit. c) Flow structures surrounding a dome in the **ldm** unit.

To the southeast lies the “Ice and dust mantle” unit (**Idm**), it has the smoothest texture of the units in the area, high albedo, and high thermal inertia. Periglacial and sublimation landforms are common: Its surface is heavily pitted, and brain terrain develops frequently. It is composed of fine-grained or massive materials. It appears to be superimposed to the **Fud** unit, having lobate flow-like contacts with it. Crevasses are common, as well as large sublimation pits and polygons. The domes emplaced in this unit lack aprons, and some have flow structures surrounding them (**Figure 4.8c**). This unit matches the description of the Amazonian dust-ice mantle described by Soare (2011), as well as the Vastitas borealis marginal unit of Tanaka et al. (2005).

Another set of units seems to be modified portions of the **Rm** unit. The “Knobby materials” unit (**Km**) is just north of the **Idm** unit, it has a rough texture and high albedo. It contains large knobs that appear to be covered by a mantle of dust. Craters in this unit are usually pancake-type (**Figure 4.8b**). The unit “Semi-rugged materials” (**Srm**) appears at the west and east borders of the area. It has a rugged texture in some locations, and smooth texture in others. The unit “Crevassed materials” (**Cm**) is in the northernmost part of the area. It is characterized by the presence of large arc-shaped crevasses. The prior units are also spatially concordant with the Astapus Colles unit of Tanaka et al. (2005).

Finally, there are large areas covered by a “Dark coating” (**Dm**); these layers appear thicker than the ones over the flank of the domes. Apart from the lower albedo, the other morphological characteristics are like the **Fud** unit. In specific locations, “spiders” are formed within the dark coating materials (Reiss et al., 2013).

4.6.3. Crater counting

We performed a crater-counting analysis over the three larger floor units in the area: **Fud**, **Rm**, and **Idm**. The analysis retrieved an age of 1.25 ± 0.077 Ga for the **Fud** unit, 1.27 ± 0.19 Ga for the **Rm** unit, and 652 ± 94 Ma for the **Idm** unit (**Figure 4.9**).

The age obtained for the **Fud** unit is probably representing its formation age, since this unit does not appear to have been highly reworked by posterior process. That is not the case for the **Rm** and **Idm** units. Both units are characterized by the presence of glacial and periglacial features, these landforms appear to have modified the surface to a large degree, erasing a large number of craters from it. Hence, we consider these two estimations as resurfacing ages related to the beginning of large periglacial activity, and not the deposition ages of the materials that compose the bulk of these units.

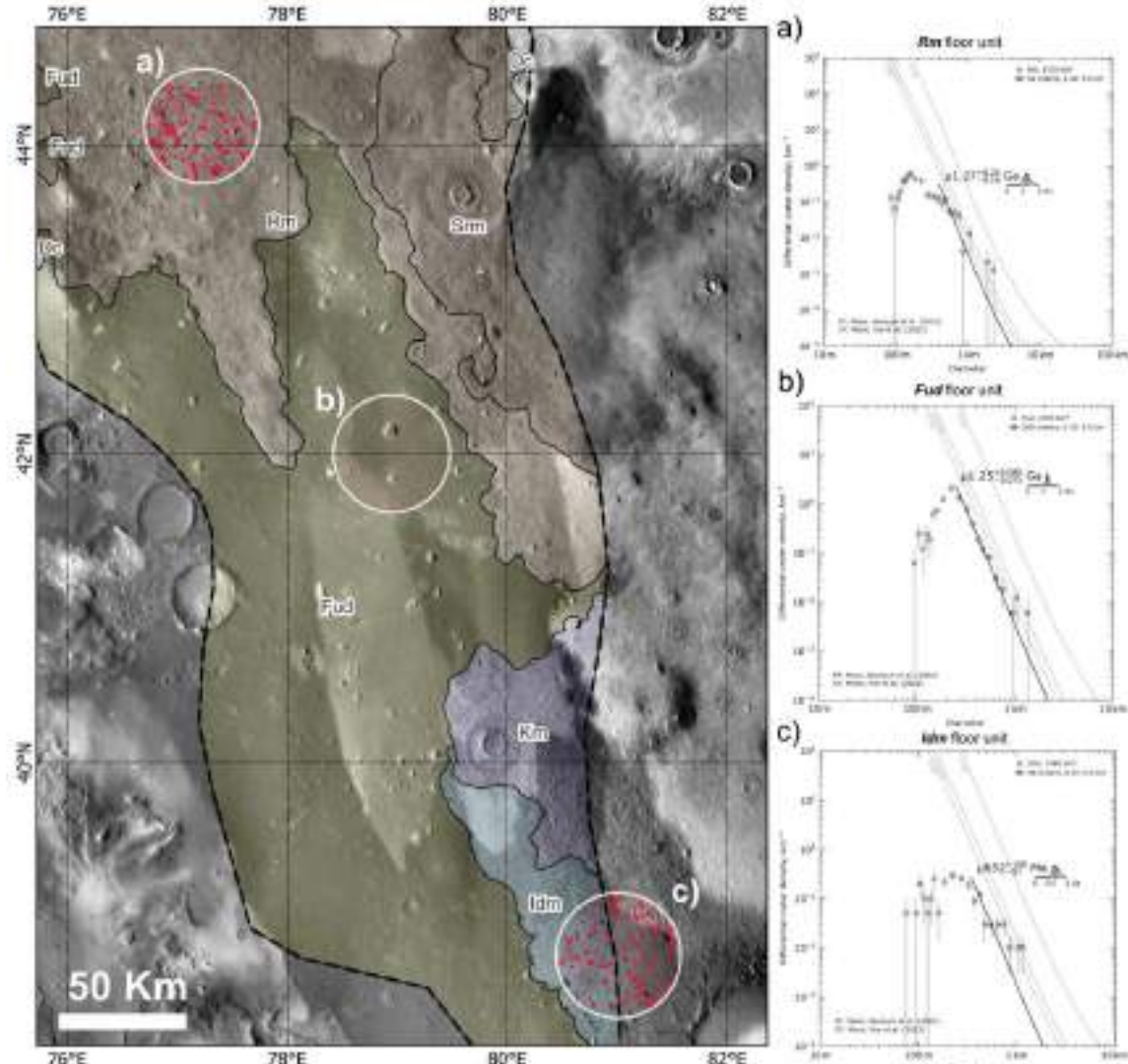


Figure 4.9: Crater counting analysis. a) The results for the **Rm** unit, retrieving an age of 1.27 ± 0.19 Ga. b) The results for the **Fud** unit, retrieving an age of 1.25 ± 0.077 Ga. c) the results for the **ldm** unit, retrieving an age of 652 ± 94 Ma.

4.6.4. Detailed map of a dome

We conducted a detailed mapping of an irregular dome and its surroundings in the **Rm** unit (**Figure 4.10**). It was selected because it is covered by both the ESP_016944_2255 HiRISE image and the Frt00017160 CRISM cube. The core of the dome is 5.44 Km in diameter in its largest direction, 2.54 Km in the shorter one, and it is 156 m high.

The Dome core (**Dc**) is an oval-shaped hill that stands out from the plain. Its texture is homogeneous. Its surface is dominated by blocks ranging from 3 to 6 m in diameter, closely packaged in a matrix of fine-grained materials (**Figure 4.11a**). The spectral signatures of the dome core show the three absorptions bands of olivine at 1 μ m (Burns, 1993), although the band are shifted to shorter wavelengths,

probably due to the presence of pyroxene (**Figure 4.12a**). This composition could correspond to basaltic rocks, but the signature on the surrounding units is the same, which indicates the measured spectra belong to a surficial unit that covers the whole area. Considering the presence of dunes and other aeolian features, this might be related to a general cover of basaltic sand. A small portion of the dome is covered by a fine-grained or massive homogeneous material (**Cd**), probably a shallow layer of dust and ice. To the south, braided terrain is developing over this unit. A small tongue-shaped lobe is visible in the left flank of the dome (**DI**), the materials flowed downslope a couple of meters. This is probably related to a gravitational process.

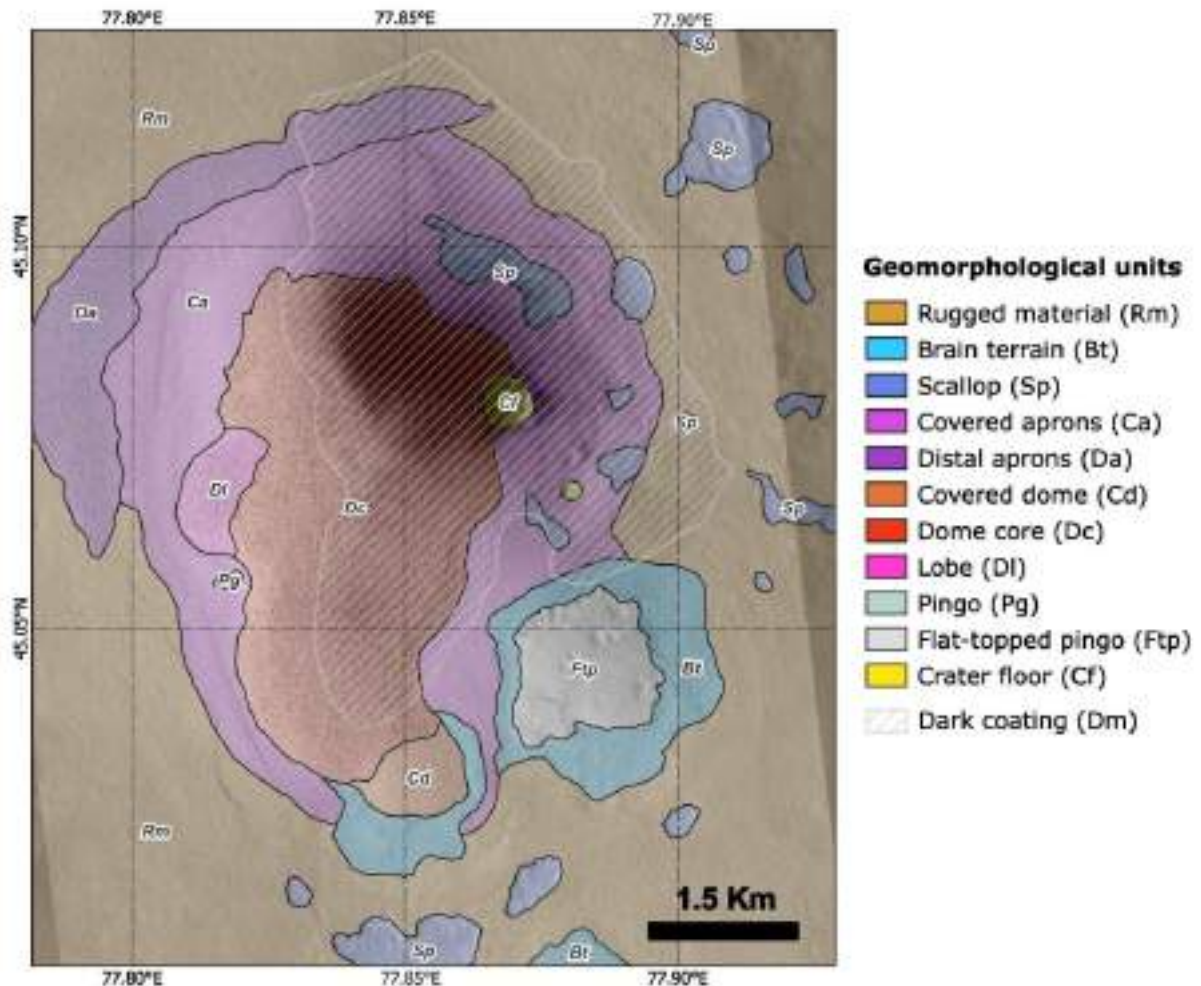


Figure 4.10: Geomorphological map of a subvolcanic covered dome in the **Rm** floor unit. The basemap is the ESP_016944_2255 HiRISE image.

The aprons of the dome are divided into two regions. First, next to the core, lies the Covered Aprons (**Ca**), this unit fully encircles the dome and it is located close to the slope break with the floor unit. The materials of the dome are not visible, instead a fine-grained material covers a slightly bulged terrain. Traces of sediments moving down the slope of the dome and incipient brain terrain are common in this unit. Further away is located the hardly distinguishable Distal

Aprons unit (**Da**), it is a semi-circular region outside of the **Ca** unit made of fragments that are 3 to 4 m wide, which are scattered over the floor unit. This region may be the equivalent to the aureole described by Farrand et al. (2021). Brain terrain can also be found over some aprons and parts of the floor unit (**Bt**) (**Figure 4.11b**). The polygons conforming the brain terrain are smaller near the boundary with the **Ca** unit, which appear to be gradually transforming into **Bt**.

The floor unit in this location is Rugged materials (**Rm**), its surface is characterized by polygonal structures and incipient brain terrain. There are no large sediments over it, the covering material is either fine-grained or massive. Its spectral signature is homogenous, it has a broad absorption at 1 μ m and no more clear absorptions, similar to the one of the dome core (**Figure 4.12a**). Over this unit several scallops develop (**Sp**), these landforms are made of a scarp on one side, and a gentle slope on the opposite one (**Figure 4.11c**) (Lefort et al., 2009). Brain terrain is commonly found in the inner part of the scallops. A couple of pingos were also identified in the location, one is a small tongue-shaped structure with steep edges (**Pg**), while the other is a flat-topped pingo (**Ftp**), more oval-shaped and with a smoother surface (Dundas and McEwen, 2010).

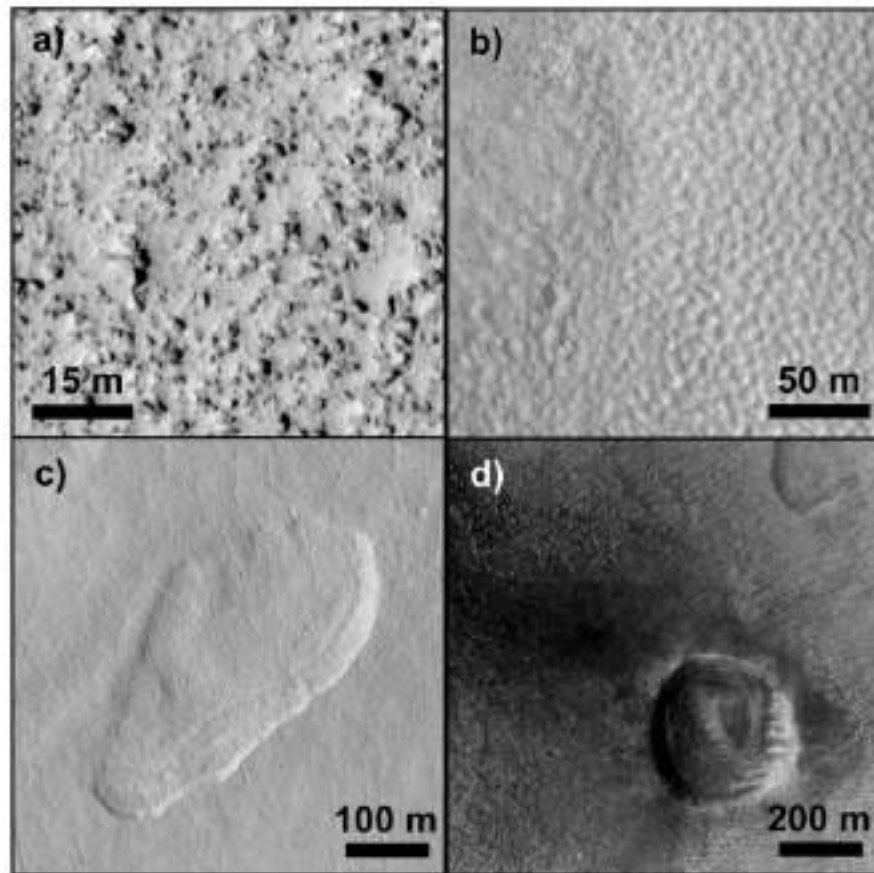


Figure 4.11: Outstanding landforms near the mapped dome. a) Texture of the dome core (**Dc**), made of closely packaged blocks, b) brain terrain advancing over the aprons (**Bt**), c) typical scallop (**Sp**), d) a crater visible through the dark coating (**Dm**).

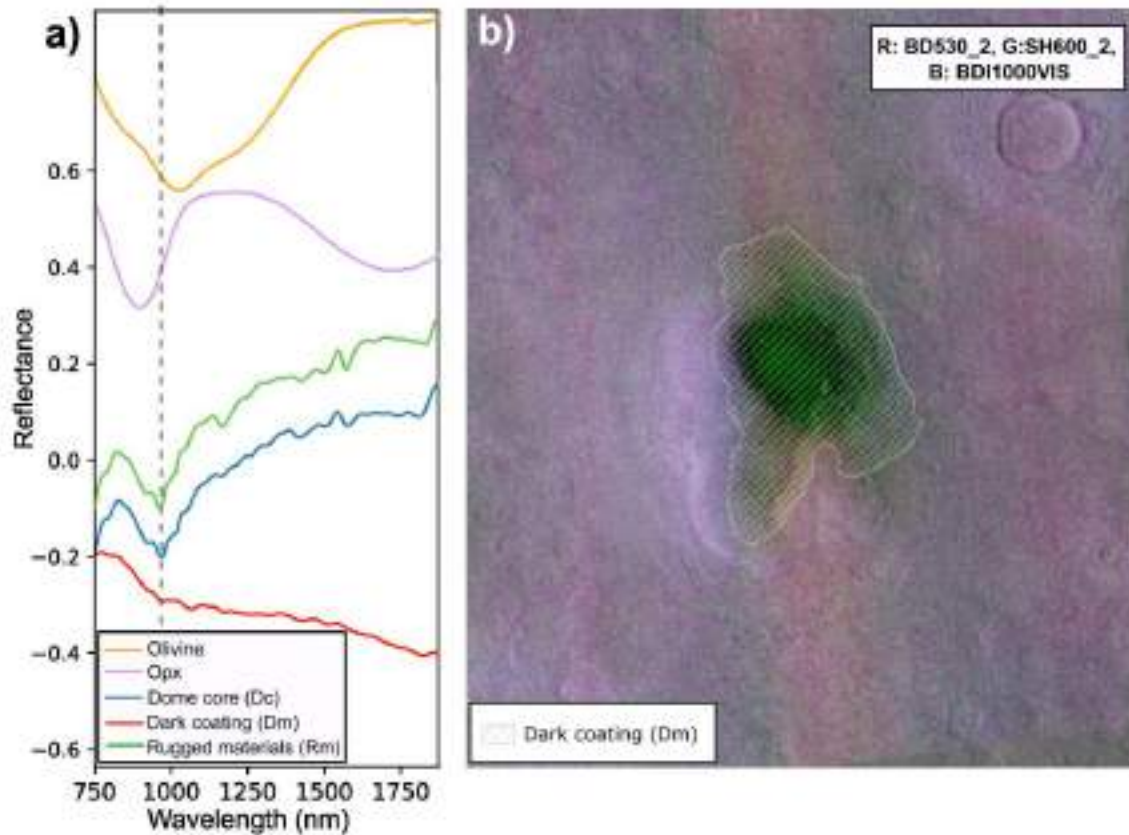


Figure 4.12: Spectral signatures of the main units from a CRISM cube. a) Comparison of the spectra of the units with the ones of olivine and orthopyroxene. The absorption at 1 μm of the units **Rm** and **Dc** show the three absorptions of olivine, but shifted to shorter wavelengths, probably due to the presence of orthopyroxene. The dark coating has a strong negative slope at 2 μm . b) FM2 RGB composite, the dark coating appears green, which is consistent with Fe minerals.

The most contrasting feature of the location is a dark coating that covers the northern part of the dome and some portions of the floor unit (**Dm**). The material is superficial, since scallops, rock fragments, and other underlying structures are visible through it (**Figure 4.11d**). This unit appears green in the FM2 RGB composite of Viviano-Beck et al. (2014), which suggests it contains coarse-grained Fe minerals (**Figure 4.11b**). Its spectral signature also has a negative slope after 1 μm (**Figure 12a**), which has been related to ferric coatings and nanoparticle iron (Viviano-Beck., 2014). Other domes in the region have similar accumulations of dark material, usually in the same northeast-facing flank. This implies that this material is being deposited by a regional process.

4.6.4. Distribution analysis of the domes

Volcanic fields are usually related to the tectonic configuration of the location they are intruding, since the upwelling magma would take advantage of faults and fractures to reach the surface. To evaluate if that was the case in Utopia Planitia,

we made a distribution analysis of the domes and compared it with the local faults. Before the analysis, one should determine if the domes are randomly scattered or clustered. This was done applying a Nearest Neighbor Analysis (NNA) to the domes (Le Corvec et al., 2013), which measures the distance between each dome and their closest neighbor, and then compares that distance with the expected one for a random distribution. The result of the NNA is interpreted with the statistical parameter R , which will be greater than 1 if the distribution is random, and smaller if they are clustered. The value of R for the domes in Utopia Planitia is 0.83, indicating that the domes are clustered. The code used for this process can be found in **Section 4.11.3**.

After confirming the clustered nature of the domes, the next step was the generation of a heatmap. This technique has been used before in volcanic settings to check for spatial concentrations of volcanic features (Trippanera et al., 2018). The heatmap in **Figure 4.13** was produced with the homonymous tool in QGIS, using a 50 km search radius. Two major dome clusters were found in the southern part of the region. Both clusters are dominated by the **Sud** type of domes, which are also almost restricted to this location. The clusters are located over the **Fud** unit. Smaller concentrations can be found in the northern part of the region, especially over the central **Rm** unit, in this case the dominant dome type is the **Scd**.

To identify if the domes are related to any tectonic pattern, it is necessary to check if they are aligned along preferential directions (e.g. Cañón-Tapia and Jacobo-Bojorquez, 2022). We followed the methodology of Hnecz et al. (2013), which consists of creating lines that connects each dome with the others, to later analyze the lines that connect more than two domes. The elongated shape of the dome field could affect this analysis, since the lines along the longer axis have a bigger chance of crossing more than two domes. To avoid this effect, we created three 100 km circles at the north, center and south parts of the area (**Figure 4.14**). Only the domes inside each circle were computed in the analysis, restraining the effect of long lines between far away domes. This process was done in Python and QGIS. Although not every three-dome alignment has to be necessarily related to a tectonic feature, multiple alignments on a large dataset may represent regional trends.

The obtained lines and rose diagrams for each sub-area are shown in **Figure 13**. Across the three groups, most of the lines follow a NW-SE trend. Since the direction is consistent across the spatially separated groups, it is possible to assume that this alignment is related to a geological feature. We have further evidence of this by considering the trend of the regional faults system derived from Knapmeyer et al. (2006), which also follows an NW-SE trend (**Figure 4.14**).

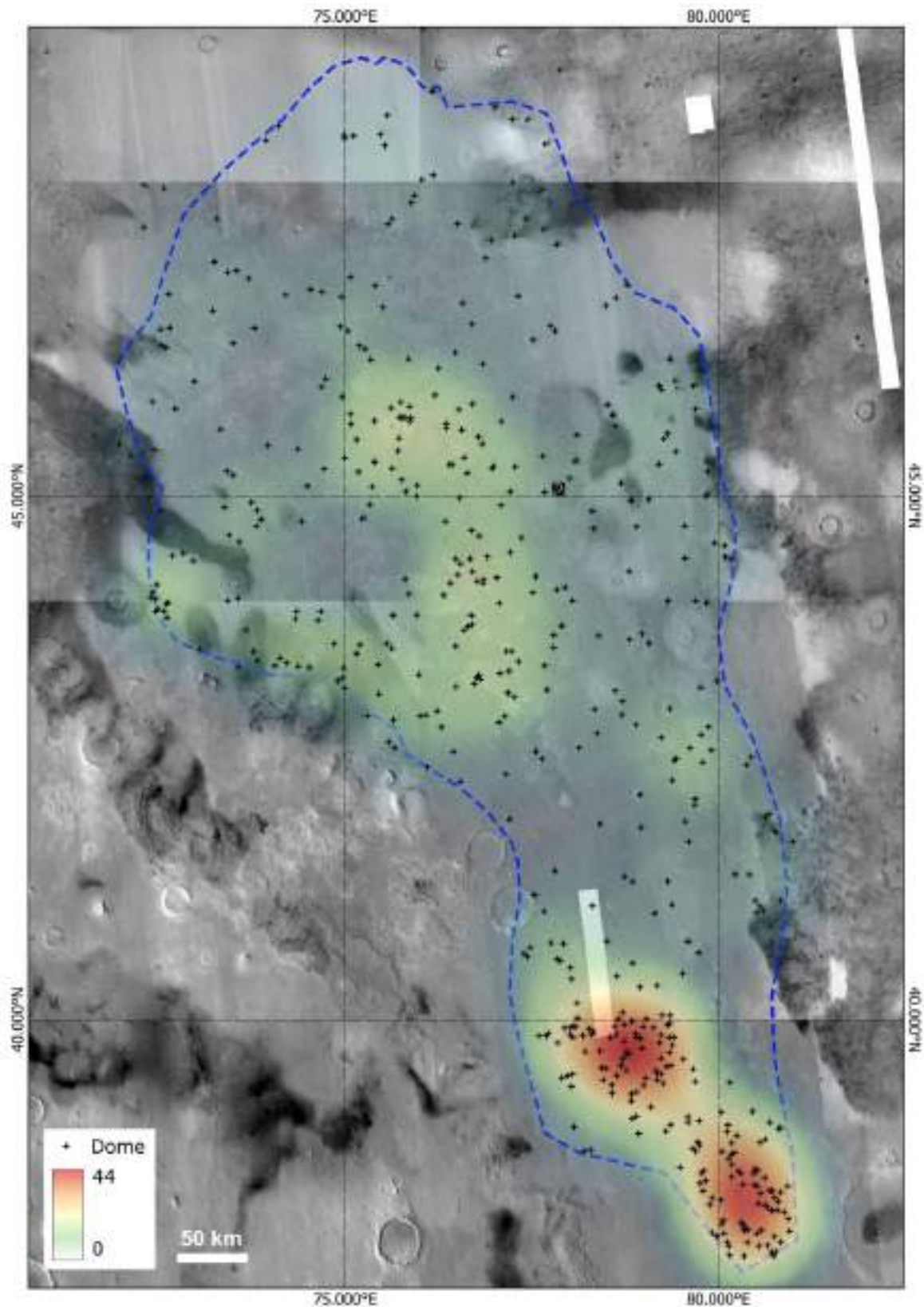


Figure 4.13: Heatmap showing the concentration of domes. There are two clusters to the south of the region (red). The basemap is CTX mosaic.

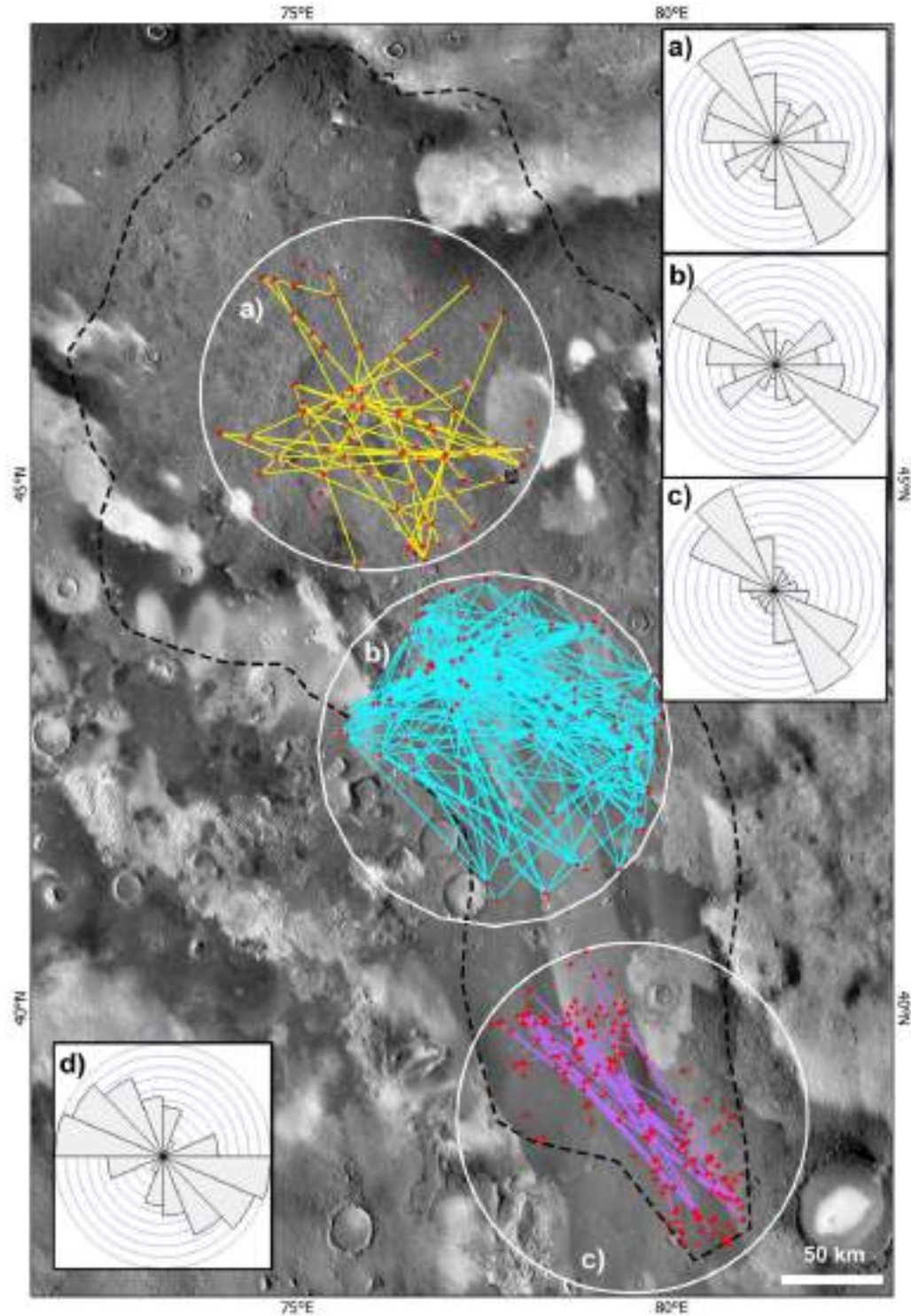


Figure 4.14: Alignment analysis for three zones to the north, center, and south of the area. The lines represent alignments of more than two domes. Only some of the lines are represented for clarity. All the regions have a preferential NW-SE trend. a) Northern area and its rose diagram, b) central area and its rose diagram, c) southern area and its rose diagram. d) Rose diagram of the regional faults of Knapmeyer et al. (2006), which also follows a NW-SE trend.

4.7. Discussion

4.7.1. Stratigraphic position of the domes

Since the domes are present all over the area, establishing their stratigraphic relationship with the floor units was challenging. However, we found that their relationships with minor structures and the status of the aprons were helpful clues. In the case of the domes located in the *Idm* unit, we found that the aprons are absent, they are more likely buried beneath deposits of ice and dust (**Figure 4.15a**). Flow patterns are seen around some domes, as well as crevasses and pits, this suggests that these flows are glacial masses that are pushing and embedding pre-existing domes (**Figure 4.8c**). The previous patterns would only be possible if the domes were older than the *Idm* unit.

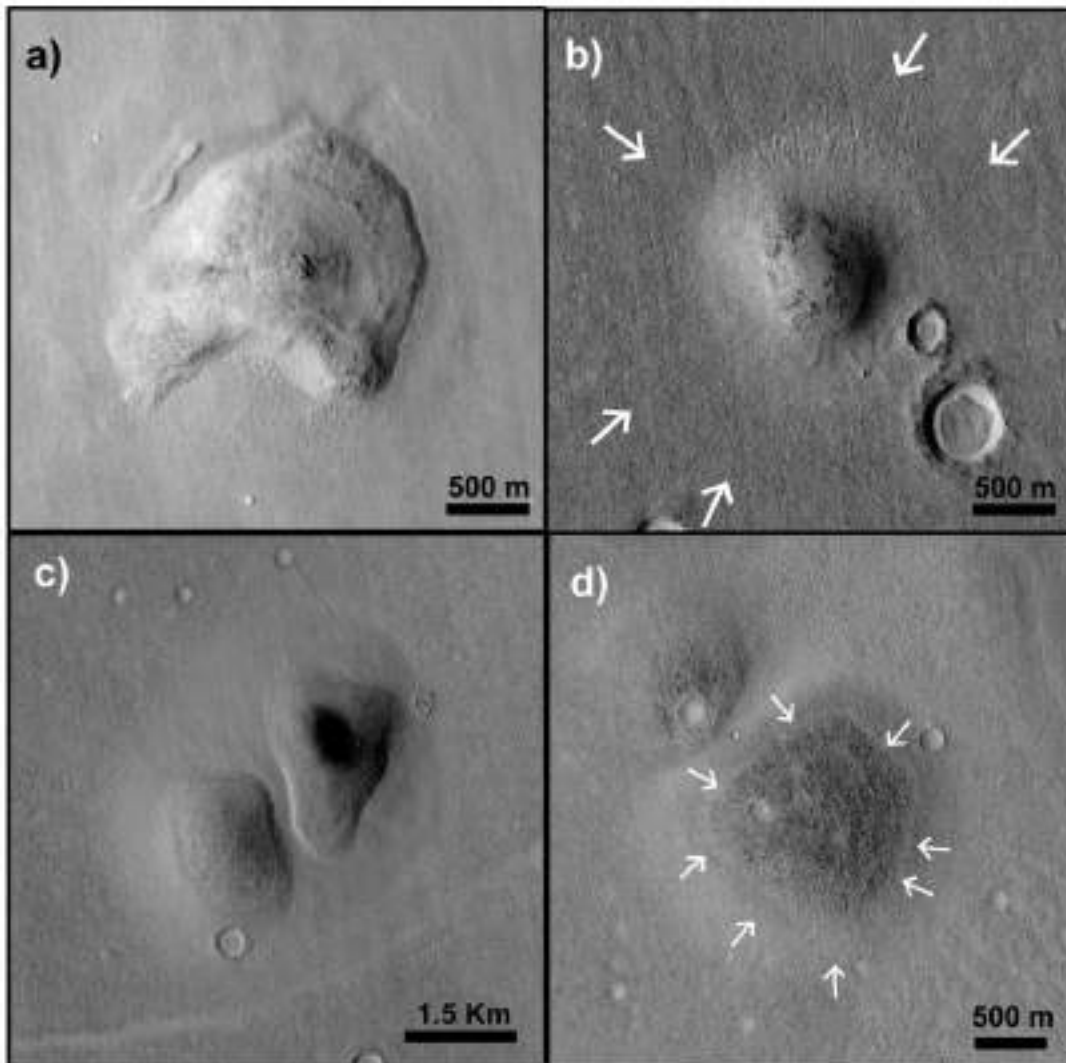


Figure 4.15: Different relationships of the aprons with the floor units. a) Aprons totally covered by the *Idm* unit. b) Ejecta-like deposits surrounding a subvolcanic uncovered dome. c) A pair of domes with well-developed aprons in the *Fud* unit. d) A pair of domes without aprons, the arrow points to materials of the *Fud* unit covering the structure.

The situation is more complex in the **Fud** unit. The **Sud** type of domes likely postdates its emplacement. The fact that their inner materials of these domes are uncovered implies that the topping unit was eroded or removed after their intrusion, regardless of if it was made of a hyaloclastite carapace, the **Fud** unit itself, or a combination of both (**Figure 15b**). Additionally, some **Sud** domes show ejecta-like deposits around them, possibly pyroclastic products (**Figure 4.15b**), while others are superimposed over the rilles that cross the unit (**Figure 4.8a**), further suggesting that these domes are younger than the **Fud** unit. Some domes of the **Scd** type also appear to postdate the **Fud** unit, since there are no flow structures around their cores and their aprons are fully developed and uninterrupted (**Figure 4.15c**). However, other domes of the same type have hardly visible aprons, instead, the materials of the **Fud** unit surround their cores, generating sharp contacts (**Figure 4.15d**). We propose that these domes were there before the **Fud** unit, which later embedded them. Cryptodomes are also common in this unit, they could be either pre-existing domes covered during the emplacement of the **Fud** unit, or posterior intrusions that stalled near the surface. We opt for the second option, since the cryptodomes are similar in size and are located in the same cluster as the **Sud** type, which postdates the **Fud** unit.

Finally, all the domes in the **Rm** unit appear to be younger than its formation. In most cases aprons are present (**Figure 4.6b**), and when they are not, it is usually because they were modified by more recent periglacial activity or covered by ice and dust. Furthermore, there are no signs of domes embedded by the materials of this unit.

4.7.2. Magmatic regime

The domes in Utopia Planitia are varied, they range from cryptodomes to extrusive domes, showing an intrusive-to-extrusive type of magmatism. Given these characteristics, the genetic model proposed by Farrand et al. (2011) for the domes in Arcadia Planitia could also be applied here. In that scenario, pockets of magma either reached the surface to create extrusive domes or stalled near it to form intrusive structures. Some among the latter were uncovered by erosion or by other uplifting processes, giving place to subvolcanic domes (**Sud** or **Scd** types), while the ones that remained trapped below the surface became cryptodomes (**Cd** type).

Regardless of the type, the domes are individual edifices with homogeneous shapes, even the extrusive ones show at most one lobate feature next to them. Therefore, we believe the magmatic activity on the area had a monogenetic behavior, meaning that every dome is a single eruption or intrusion, with no further events in the same spot (Smith & Németh, 2017). Monogenetic magmatism is usually related to depth and small-scale sources, these systems do not widely interact with the intruded crust, avoiding the formation of magma chambers or evolved magmas. In this case we would expect the domes to be mafic in composition, which aligns with the mineralogy observed in the CRISM cubes. It is

worth mentioning that the cubes over the zone were noisy and probably heavily influenced by dust, so we cannot rule out the presence of other species being masked by it. This contrasts with the results of Farrand et al. (2021) for the domes in Arcadia Planitia, which were classified as felsic-intermedium due to the detection of alkali feldspar.

From the heatmap, it was determined that a large cluster of domes is located south of the area, this cluster is also dominated by the **Sud** and **Cd** types of domes. Since they are spatially constrained and morphologically similar, this group of domes likely represents a different magmatic event compared to the **Scd** group. This event would have been weaker, since the resulting domes are smaller and concentrated in a reduced area.

The preferential trends of the alignments of the domes imply that the parental magmas took advantage of the regional faults and structures, with a NW-SE trend (**Figure 4.13**). Igneous systems commonly follow tectonic patterns when available, since they work as weak zones for the magma to rise (Mazzarini & Isola, 2024). Thus, we can assume that the domes in Utopia Planitia used pre-existing tectonic patterns as conduits to intrude. A diagram of how the intrusive system could work can be seen in **Figure 4.16**.

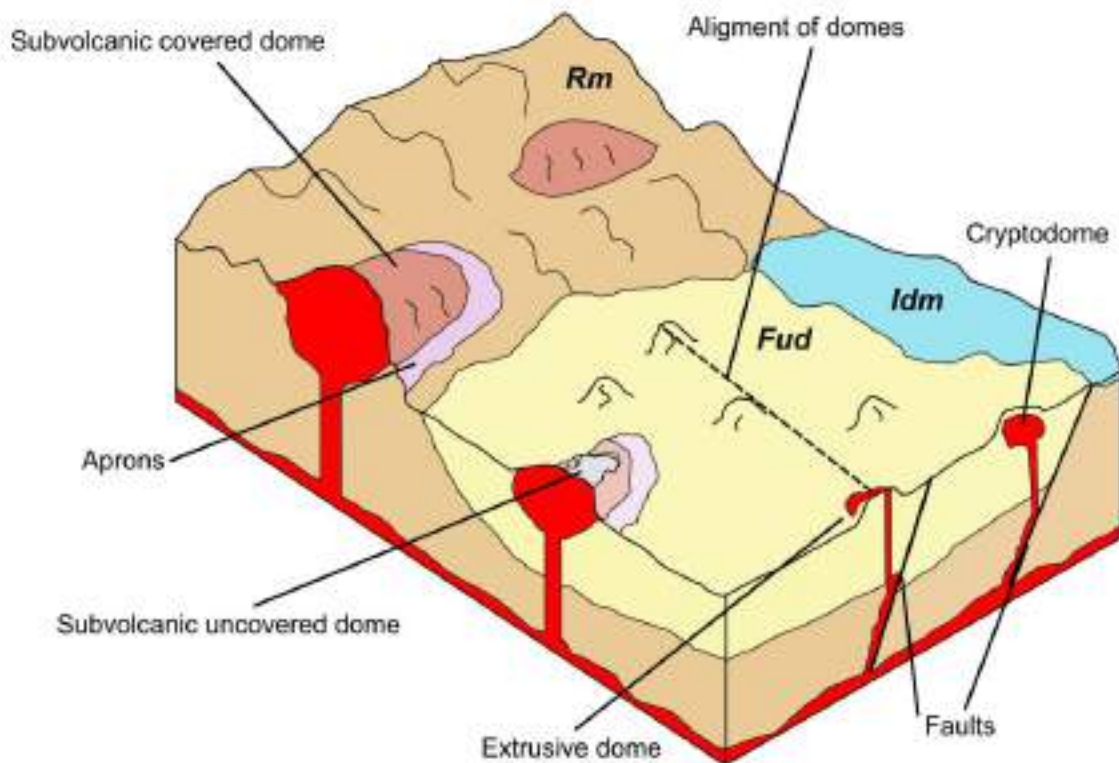


Figure 4.16: Sketch representation of the magmatic system under Utopia Planitia and the types of domes that it generated. The upwelling magma likely took advantage of the local fault system to reach the surface.

4.7.3. Geological history of the area

Since the number of magmatic events and their temporal span were already established, we defined the sequence of events that configured the area (**Figure 4.17**). The first event was the emplacement of the **Rm** unit, which is genetically related to the Vastitas Borealis unit described in other works (Tanaka et al., 2014; Liu et al., 2022). This unit is thought to be made of large-scale sedimentary deposits produced by an ancient ocean covering the lowlands, or by outburst flows originating in the lowlands. Given the regional nature of these deposits, it is possible that this unit also forms the basement of the whole region. According to Tanaka et al. (2014), these sequences were deposited in the Late Hesperian. After the emplacement of the **Rm** unit, a magmatic event produced the first set of domes, most of them reached the surface through time, making the bulk of the **Scd** type. The timing of their intrusion is uncertain. The aprons of the domes developed soon after their emplacement, driven by gravitational processes, atmospheric erosion, and glacial erosion. We found small distal aprons during our detailed analysis of the dome in the **Rm** unit. These deposits might correspond to the aureole described by Rampey et al. (2007), but it is unclear why they are underdeveloped in the Utopia Planitia region.

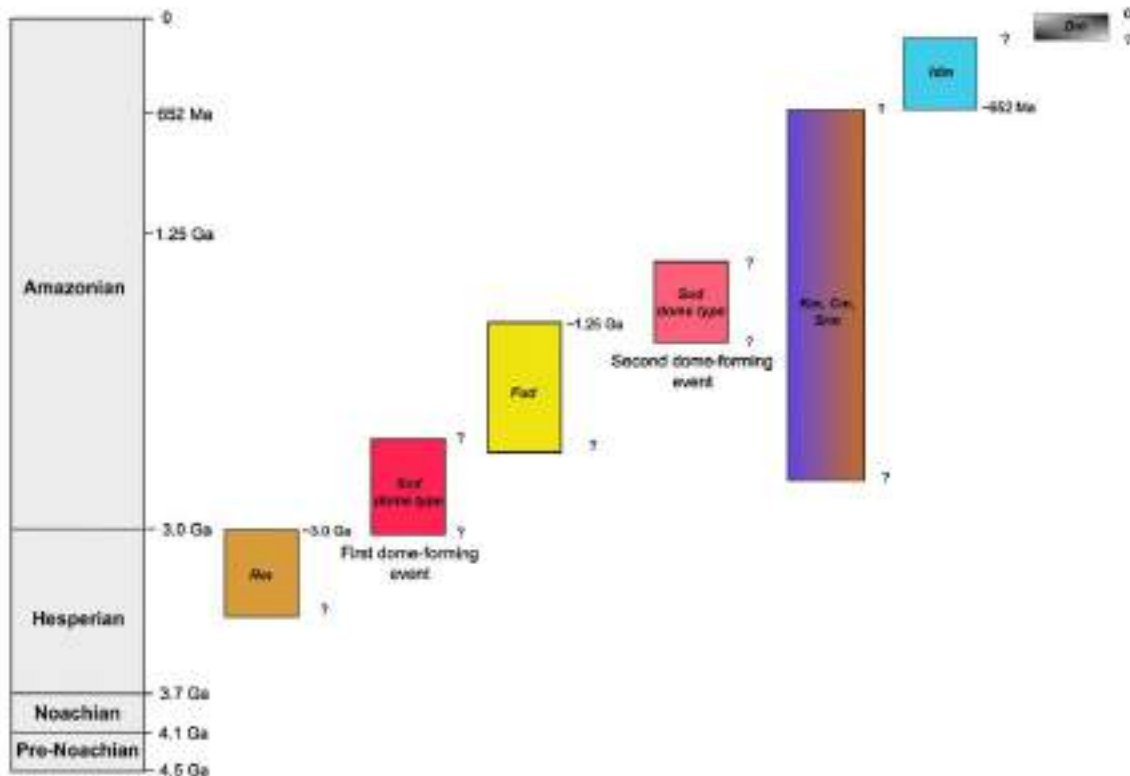


Figure 17: Geological evolution of the area. Most of the exact ages of the units are unknown, but the sequence of events was defined from stratigraphic relationships.

Next, the materials of the **Fud** unit were deposited around 1.25 ± 0.07 Ga. We believe this unit is made of sedimentary deposits linked to outburst flows from the

southern highlands, probably from Nilosyrtris Mensae (Bandfield & Amador, 2016). Nevertheless, those chaotic terrains could be also associated with older events, like the formation of the **Rm** unit. This unit mainly fills a large basin south of the **Rm** unit. From the analysis of the aprons we know that some domes existed before the emplacement of the **Fud** unit, since they were covered or surrounded by the filling material. A second magmatic event took place after, forming smaller domes that intruded through the already existing **Fud** unit. The sinuous rilles found in the area are probably formed by lava flows of this magmatic event.

Around this same time and onwards, periglacial activity greatly reworked the **Rm** unit, covering the aprons of some domes and generating subunits characterized by periglacial landforms (**Km**, **Srm**, **Cm**). Later, around 652 ± 94 Ma, the **Idm** unit was formed, likely due to large depositions of ice and dust (Soare et al., 2011), covering the prior units as well as the aprons of the domes in this location. Finally, the dark coatings (**Dm**), and other aeolian landforms are probably recent, since they are shallow and unconsolidated. The dark coatings usually appear in the NE-facing scarps of the domes, suggesting that they follow a regional wind trend.

4.8. Conclusions

The dome field in Utopia Planitia is likely igneous in origin, their morphological properties are different from other dome-like structures like pingos or mesas, and they share the general structure of the dome field in Arcadia Planitia. The edifices vary greatly in size and shape, some of them show the typical features of extrusive domes, such as lobes and summit pits, while others are buried and barely visible. This configuration indicates an intrusive-to-extrusive regime, one in which most of the domes were emplaced near the surface like laccoliths, while a smaller number of them reached the surface as extrusive domes. The magmatic regime is likely monogenetic, since the structures are homogeneous and do not show signals of recurrent eruptions or emplacements.

Two different intrusive stages were identified, which produced a set of domes with different characteristics. However, regardless of the type or timing of domes, the intruding magmas that formed them seem to have taken advantage of local faults and fractures. The domes are aligned in a NW-SE trend, which coincides with the trend of the regional faults. Unfortunately, the spectral information on the area has low quality, thus, further analysis will be needed to properly assess the composition of the domes and the properties of their parental magmas.

4.9. Acknowledgments

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the European Union's Horizon 2020 research and innovation programme under grant agreement No 871149.

4.10. Open research

The raw datasets used in this work can be accessed through the PDS. The processed geospatial dataset, QGIS project, statistics of the domes, and final maps can also be accessed via Zenodo (Suárez-Valencia et al., 2024b).

4.11. Supporting information

4.11.1. Table with the data

Sector	Name HiRISE	Name CRISM	Use
Northern area	ESP_016654_2260*	frt0001681e_07_sr167j_mtr3	Plains+crism
	ESP_016799_2260*	frt00016d23_07_sr167j_mtr3	Domes+crism
	ESP_016944_2255*	frt00017160_07_sr167j_mtr3	Dome+crism!
	ESP_026715_2285*		Cryptodomes
	ESP_068175_2280*		Linear dome
	ESP_077222_2255*		Crypto+stereo 1
	ESP_077354_2255*		Crypto+stereo 1
	ESP_078356_2280*		Regional stratigraphy
Central area	ESP_011775_2230*		Domes
	ESP_016021_2245*		Domes
	ESP_019779_2205*	frt0001b6a0_07_sr167j_mtr3	Crism+plains+stereo 2
	ESP_026504_2205*		Crism+plains+stereo 2
	ESP_081679_2210*		Crism+domes
	ESP_036341_2225*		Panckage+weird textured floor
	ESP_045374_2245*		Domes
	ESP_046495_2245*		Domes
	ESP_046706_2235*		Special dome
	ESP_055369_2210*		Pingos
	ESP_055857_2230*		Weird textured floor
	ESP_059431_2235*		Crater chain+pingos
	ESP_070866_2235*	hrl0000ab41_07_sr184j_mtr3	crism+domes+stereo 3

	PSP_008294_2235*		crism+plains+stereo 3
		hrs00018e1f_07_ sr176j_mtr3	crism
Southern area	ESP_033862_2235*		Structure+craters+stereo 4
	ESP_027071_2235*		Structure+craters+stereo 4
	ESP_027849_2220*		Structure+dome+stereo 5
	ESP_027981_2220*		Structure+dome+stereo 5
	ESP_028337_2215*		Fracture+dome
	ESP_028548_2210*		Small domes
	ESP_029326_2225*	frt0000a227_07_ r167j_mtr3	Structure+crism
	ESP_077723_2230*		Caldera+crism
	ESP_046007_2230*		Domes
	ESP_050411_2210*		Cryptodome
	ESP_059510_2215*		Sturcture+pingo
	ESP_061897_2245*		Fractures
	ESP_062108_2210*		Pingo
	ESP_066552_2215*		Ridge
	ESP_069112_2215*		Dark floor+dome
	ESP_069732_2210*		Pingo
	ESP_070022_2215*		Dark floor
	ESP_075771_2200*		Domes
	ESP_077235_2225*		Domes+structure
	ESP_077578_2245*		Domes+crater field
	PSP_009876_2190*		Domes
	ESP_042275_2190*		Domes
	ESP_042842_2185*		Domes
	ESP_046574_2185*		Domes
Sector	Name		Use
General	CTX mosaic		Morphological
General	HRSC_MOLA mosaic		Elevation
General	THEMIS DAYIR mosaic		Thermal
General	THEMIS NIGHTIR mosaic		Thermal

Table 4.S1: Table with all the data used.

4.11.2. Processing in ISIS

The processing of HiRISE images requires the use of the ISIS and GDAL software, which was done using the following commands:

Applying radiometrical and other corrections to the HiRISE data

```
hiedr2mosaic.py *RED* -w
```

##Projecting the images

```
cam2map from=data_ RED.mos_hijitreged.norm.cub map=HiRISE.map  
to=data_lv2.cub PIXRES=map
```

##Translate

```
gdal_translate data_lv12.cub data.tif
```

After these steps, the HiRISE data is ready for interpretation in a geoprocessing software. The other datasets were obtained in scientific-ready versions.

4.11.3. Lineament analysis

The alignment analysis was done following the methodology of Hencz et al. (2023). This included a first step in Python, and subsequent ones in QGIS. The jupyter notebook with the analysis done in Python can be found in the supplementary materials. Since our area was elongated, we conducted this analysis three times, for the north, central, and south areas.

- **Nearest neighbor analysis:** We calculated the ***R*** index for the NNA to determine if the distribution was random. This was done using the *Numpy* and *Geopandas* libraries of Python.
- **Alignments definition:** We created a list with the initial and final coordinates of all the possible alignments between domes, erasing repeated relations (e.g Dome A to Dome B is the same as Dome B to Dome A). This was done in Python using the *Geopandas* and *Itertools* libraries.
- **Lines creation in QGIS:** We imported the data QGIS, creating lines using the initial and final points (XY to line tool). We then created a buffer of 200 m for every line (Buffer tool). If three or more domes fell inside the buffer of the same line, it was counted as a valid alignment, if not it was discarded (Count points in polygon tool). Finally, the remaining buffers were converted back to lines (Polygon to line tool).
- **Visualizing:** The rose diagrams of the lines were created in the “Line direction histogram” extension for QGIS.

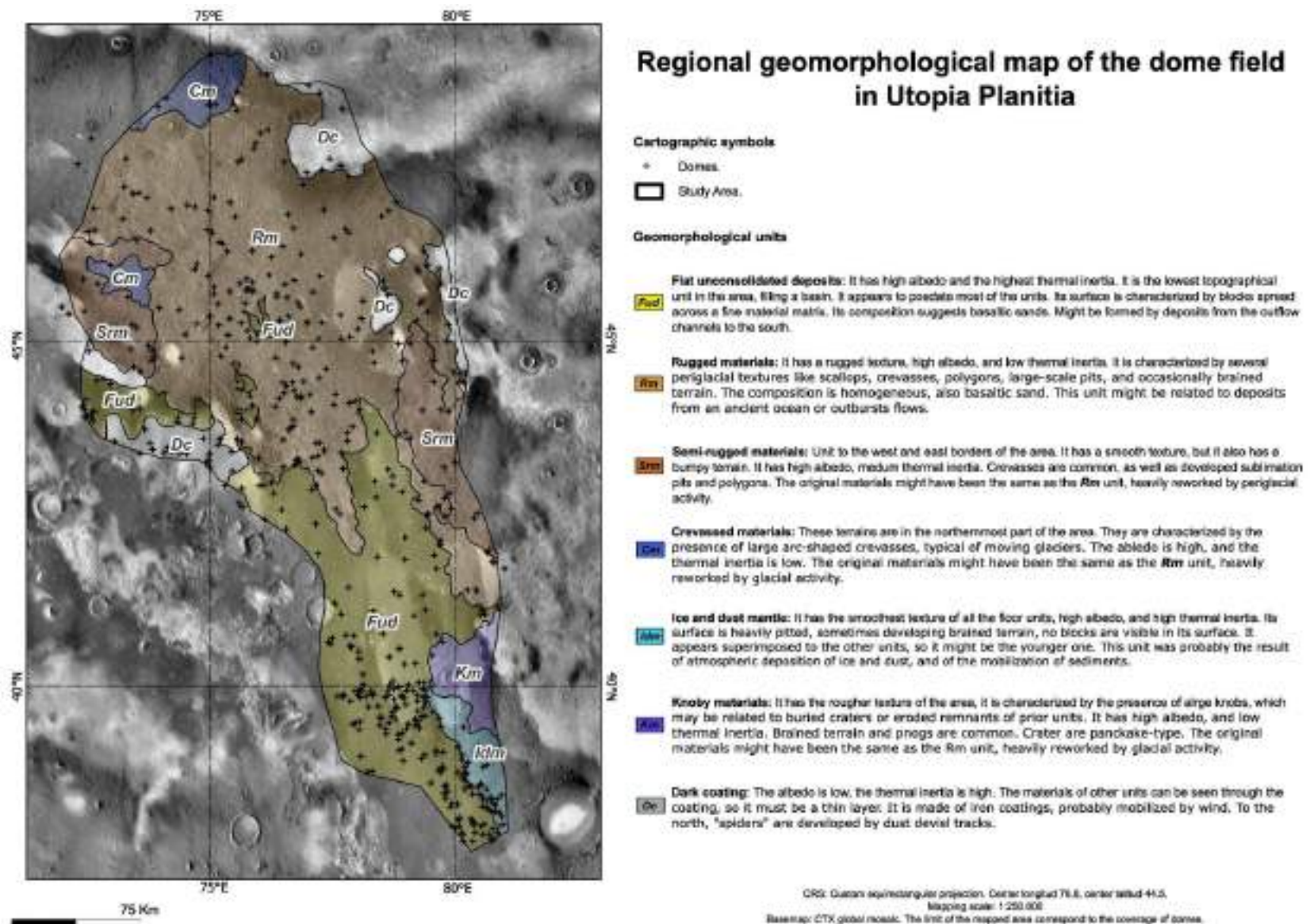


Figure 4.S1: Regional geomorphological map of the dome field in Utopia Planitia.

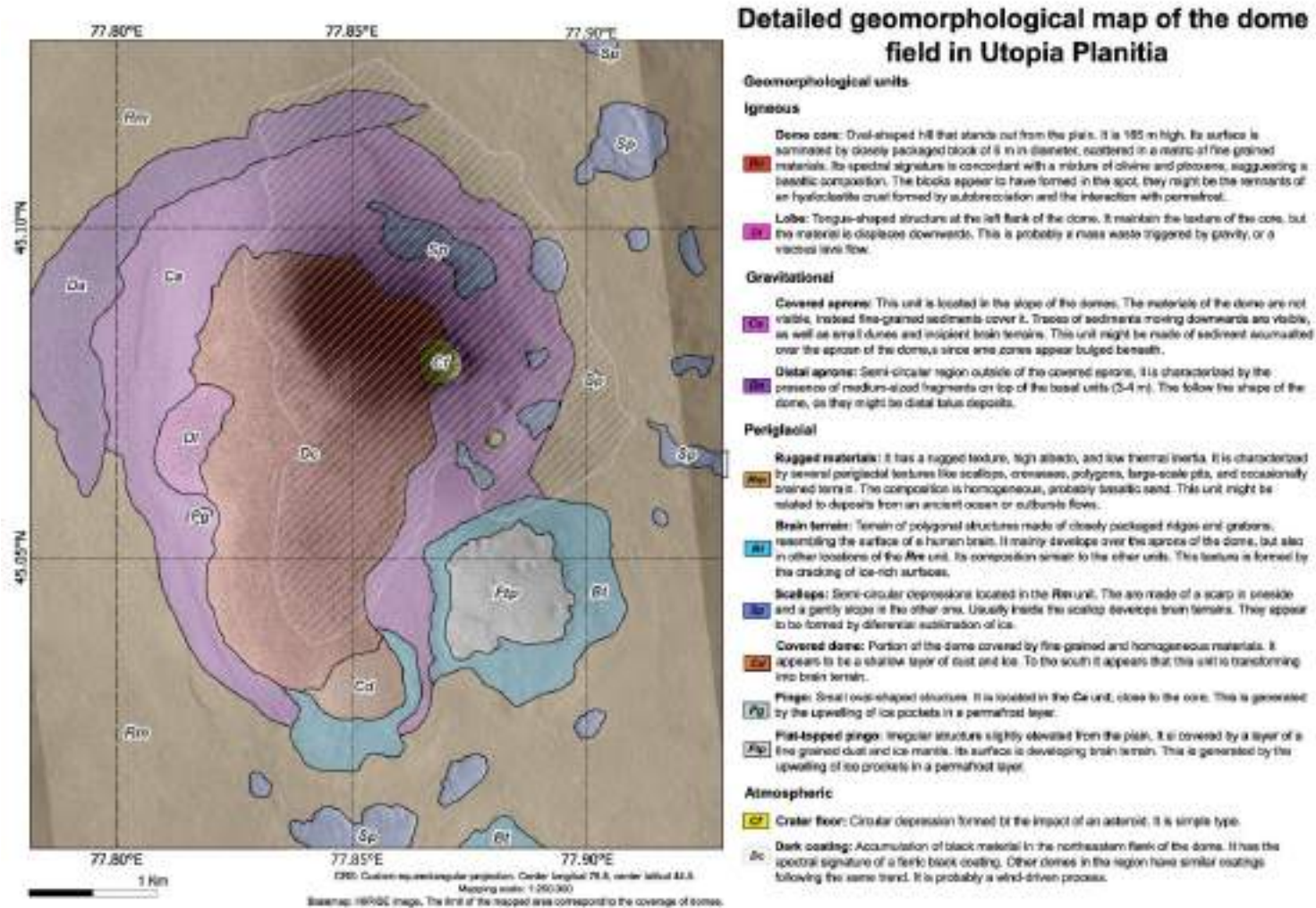


Figure 4.S2: Detailed geomorphological map of the dome field in Utopia Planitia.

Chapter 5: General discussion and conclusions

Across the three papers that made up the bulk of this thesis I explored the objectives that were originally formulated for this thesis: to explore techniques and methodologies to study intrusive domes, to use modern cartographic methodologies on them, and to discuss the importance of these locations for the understanding of these planetary bodies and for future space exploration. In this chapter I will discuss and summarize my results for these topics.

5.1. Identification and study of intrusive domes

One of the main challenges that I encountered during this research was identifying potential areas with intrusive domes. The reason for this varies between the Moon and Mars, but in both cases, it is related to the difficulty in finding them, and not necessarily because they are rare on planetary surfaces.

In the lunar case, intrusive domes are broad (span between 20 and 220 km), short (can be between 30 and 150 m high), have low slopes (lower than 3°), and lack distinguishable features like volcanic vents or lobes. These properties make them difficult to spot in global or regional datasets, since they do not produce a clear disruption on the surface. Furthermore, in most cases the intrusive magmas do not reach the surface, so the composition and the lateral continuity of the hosting units are not affected. In these circumstances, most panchromatic and spectral datasets are not optimal to identify these domes, although images with high incidence angles may be helpful to highlight their edges.

During this research I noticed that certain morphometric parameters are better for locating the domes, in particular, the aspect parameter turned out to be a valuable tool for this task. Since the aspect is a product that records the direction of the slope regardless of its magnitude, shorter landforms like intrusive domes are still detected. Its effectiveness was highlighted in Chapter 3 for the Valentine Domes, where I was able to discover a new dome, which went unnoticed in other datasets. To check that the advantage of using the aspect is not specific to the Valentine domes, I generated the aspect maps for other domes identified by Lena et al. (2009). As can be seen in **Figure 5.1**, the edges of the domes are greatly enhanced in the aspect map compared to the panchromatic image. It is likely that many lunar intrusive domes remain undiscovered, either near the ones already identified by previous authors or in other locations not considered before, even in the highlands. I believe the use of the aspect map could greatly improve the search of these structures, and its pairing with modern techniques like machine learning could lead to the discovery of many more domes.

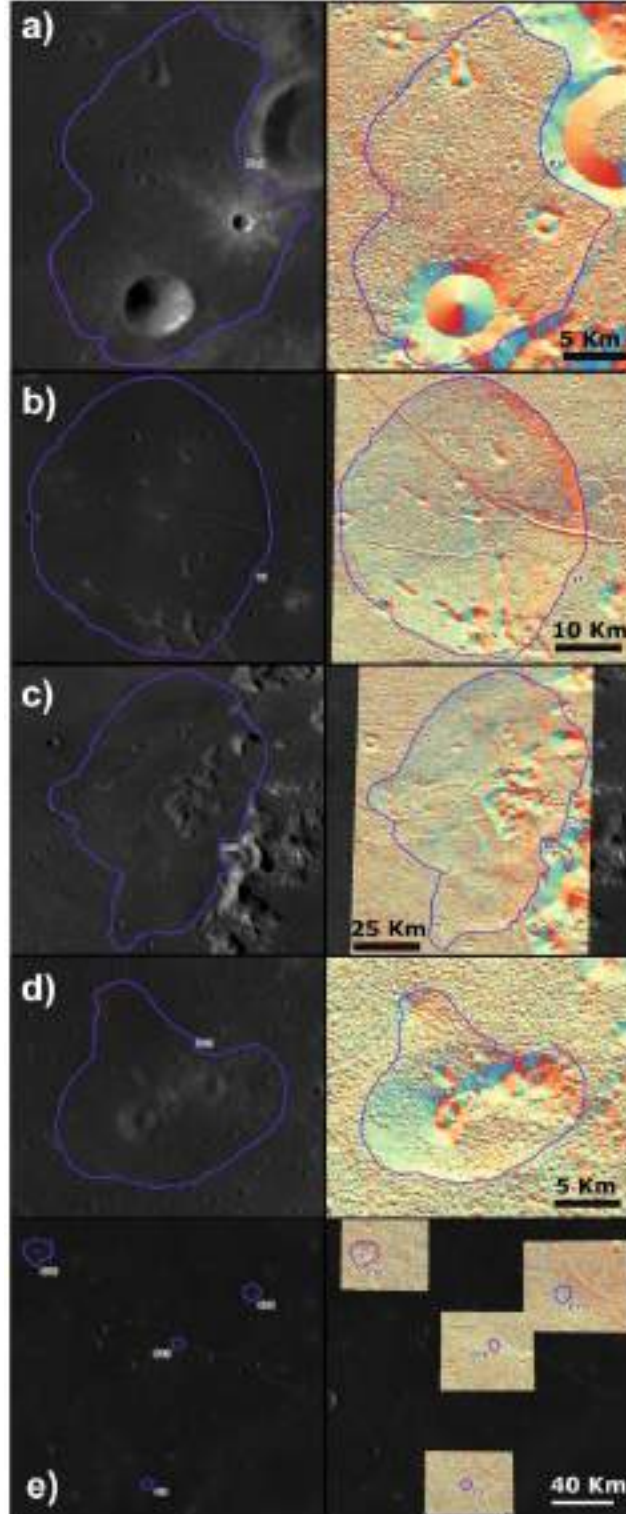


Figure 5.1: Selected examples of the lunar domes identified by Lena et al. (2009). To the left viewed in the WAC mosaic, and to the right in the aspect map. a) **Pa1** dome, intercepted by an impact crater. b) **V1** dome, well oval-shaped. c) **Ari1** dome, the biggest dome in the catalog. d) **Du3** dome, highly irregular. e) Agglomeration of the **C9**, **C10**, **C11** and **C16** domes, all of them are small and are closely packed.

For the Martian case, the difficulty in finding the domes was not that they were hardly visible, it was that they are not easily distinguishable from other landforms. The domes in Utopia Planitia are big, have consistent morphologies, and they show a great contrast with the surrounding units, making them more visible than the lunar domes. But, since they share morphological characteristics with other similarly shaped structures like mesas, pingos, and mounds, it is difficult to tell them apart from other landforms created by non-igneous processes. Unlike the Moon, Mars has undergone a wide variety of geological processes and has been shaped by several forces, usually more than one acting in the same location. Thus, dome-like structures can arise from the erosion of glaciers and water, tectonic uplift, changes in the permafrost, and many more. Given this complexity, a detailed geomorphological analysis is necessary to properly identify the origin of any group of domes. The main properties of igneous-formed domes are their round edges, oval shape, lack of stratification, rough surface, large-scale linear alignments, and discordant contacts with the surrounding units.

By using these criteria in Chapter 4, I was able to determine that the domes in Utopia Planitia originated from igneous activity. There are several locations on Mars with undefined dome-like structures, especially in the northern plains. I believe that the workflow followed here might prove helpful to study other similar areas, and to successfully identify other settings with the presence of intrusive domes.

5.2. Mapping techniques

Cartography was a recurrent and fundamental topic during this research, and some challenges related to it arose while studying both locations. The decision to map every area at two scales responded to the great difference in size in the phenomena involved. Even if the individual domes were no larger than 2 km, they could not be understood individually, since they are part of bigger intrusive systems, which cover large areas and have an effect in the regional geologic configuration. Therefore, the decision was to map at a regional scale to study the span of the intrusions and their stratigraphic relationships with other units, and to map at a detailed scale to define how they might have been emplaced and their evolution over time. This approach was effective, since in the lunar case it allowed the classification of a new domes; and in the Martian one, it was possible to establish the stratigraphic positions of the different types of domes and how they likely intruded following tectonic patterns.

The use of geostatigraphic units was also fundamental to define the course of actions during the mapping procedure. The analysis was first made upon geomorphological principles, giving me a general understanding of the formation process of the structures; and later, the analysis was complemented and modified with spectral information, which helped to further discriminate between units, especially in the lunar case. Nevertheless, the spectral information was not so useful in the studied areas, this is reflected in the definition of the units, which are

mainly geomorphological. This is mostly related to the quality of the hyperspectral data and the conditions of the locations. Most of the cubes over Utopia Planitia were noisy due to instrumental errors, restricting the amount of information that could be retrieved. Even the cubes without artifacts were not of much help, since the spectral signatures were homogeneous across the area, probably due to a widespread covering layer of dust and ice. In the lunar case, the resolution was also a limiting factor, many of the secondary domes were identified using the high-resolution NAC images due to their size, but they were covered by only a handful of pixels on the M³ cubes. Thus, for this kind of multiscale geological analysis, which includes a high-resolution component, geomorphological information will probably be the leading resource, while spectral one can be a valuable complementary tool to enhance the results, especially if the data and the location shows a broad mineralogical diversity.

5.3. Comparison of the magmatic regimes on the Moon and Mars

The locations studied in this research showcase two ways in which intrusive domes might be found on planetary surfaces. There are certain similarities between them: the composition of both systems appears to be basaltic; dykes and/or rilles commonly develop in conjunction with the domes; and tectonics may play an important role in the emplacement and evolution of the domes. Nevertheless, the genesis and most of the geologic properties of these systems are radically different, which to some degree might be related to the characteristics of the planetary body itself.

One way to categorize the type of volcanism of a system is to define the distribution of the intrusions and if they are recurrent or not, that is, if they are monogenetic or polygenetic. These definitions can be considered in a “volcanic architecture sense” or in a “petrogenetic sense” (Smith and Németh, 2017). The first one is related to the complexity of edifices produced, and the second one to the number of times that an event occurs in the same location. **Figure 5.2** shows the style of the areas studied here.

The Valentine Domes in the Moon fall into the polygenetic category in the petrogenetic sense, since the secondary domes were produced by different magmatic events in the same area as the main domes (**V1** and **V2**). In the architecture sense, the Valentine Domes are midway between monogenetic and polygenetic, since there are three main domes, and secondary ones modifying the main edifices. Polygenetic systems usually originate from a main magmatic chamber with a considerable supply (Walker, 2000), the involved magmas also interact with the host rock, allowing the formation of more silica-rich rocks. This scenario is plausible in the Valentine Domes, the domes **V1** and **V3** are large (15 to 20 Km in diameter) (**Figure 3.4**), so the intrusive body below should also be considerable. The composition of the domes is difficult to asset, but the spectral signatures suggest a minor concentration of mafic minerals compared with the

surroundings. The dome field in Utopia Planitia on Mars can be considered monogenetic in both senses. The individual edifices are scattered in a vast area, and most of the time they do not overlap. As for the petrogenetic sense, each dome has a simple structure, with no superposition of lobes, vents, or smaller domes, suggesting they were formed by a single magmatic pulse. These properties fit well in the monogenetic model, where the intruding magmas come from deep sources, rise through the surface in small pockets, and interact little with the host units, resulting in less evolved compositions (Smith and Németh, 2017).

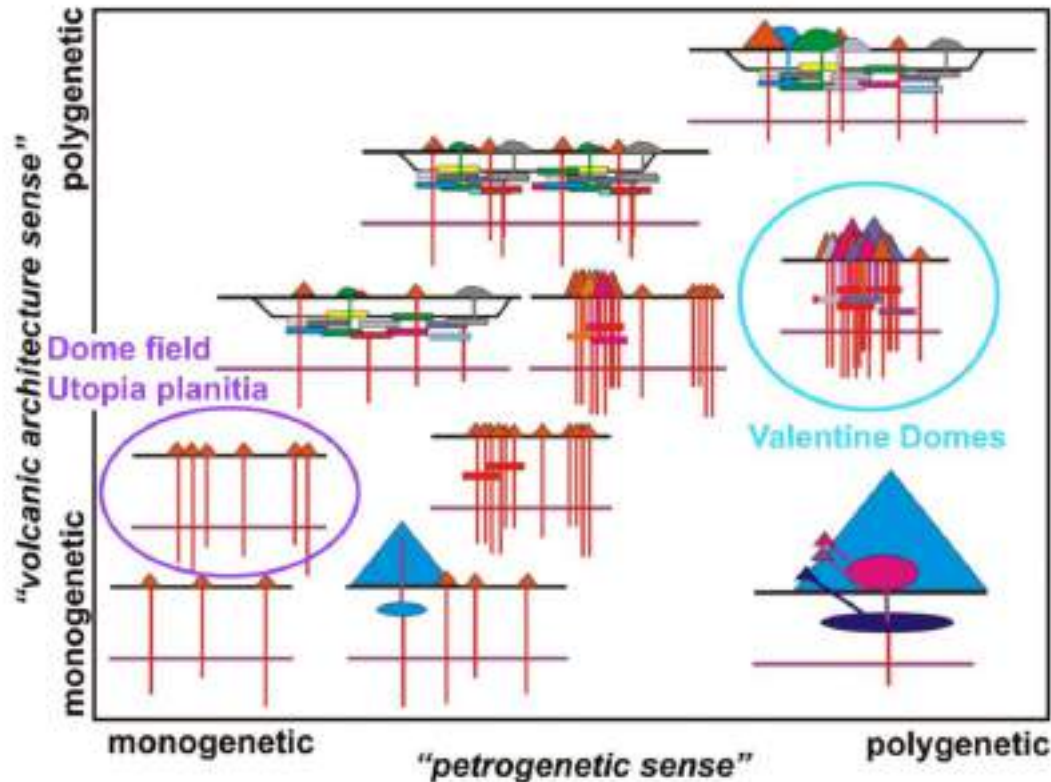


Figure 5.2: Magmatic style according to the architectural and petrogenetic sense. The dome field in Utopia Planitia is monogenetic in both senses, while the Valentine Domes is polygenetic in the petrological sense and intermediate in the architecture sense (Modified from Smith and Németh, 2017).

In this research we analyzed in detail only one location in the Moon, but it is notable how the other known intrusive domes share the same characteristic, they are laccoliths, are located in the maria, and are of the polygenetic type (Lena et al., 2009). Even if intrusive domes are difficult to find due to the reasons mentioned above, large dome fields like the one in Utopia Planitia should have been spotted before, so it is possible that this kind of monogenetic field did not develop on the Moon. Further research is needed to address why this is the case. As for Mars, Utopia Planitia is not the only location with dome fields, the system in Arcadia Planitia is remarkably similar (e.g. Farrand et al., 2021), and probably there are other ones not yet identified. Polygenetic type systems are also expected on Mars,

even if there are not known examples of laccoliths like the Valentine Domes, most of the Martian volcanoes are polygenetic (Krishnan & Kumar, 2023), so intrusive system of that type might have also developed.

5.4 Scientific interest of these locations

One of the initial ideas of this research was to assess the potential of intrusive igneous rock as space exploration targets, especially regarding their capacity of hosting ore minerals. There was an interest in contact metamorphism and the rocks and processes derived from it, which are usually related to intrusive bodies (Su and Leshner, 2012). There are some examples of these types of rocks in the lunar samples retrieved by planetary missions (Pernet-Fisher and Joy et al., 2021), but the assessment of these type of resources is difficult from orbital datasets. Although there are examples in Earth of deposits in ultramafic and mafic intrusive rocks (e.g. Page, 1977; Naldrett and Wilson, 1990), similar to what would be expected in the Moon and Mars, the nature of intrusive system hinders their survey, as the deposits would be mainly buried underground. Given this limitation, I decided to focus mainly on the scientific part of the study, since even if there are valuable ore minerals in these systems, there is no way to properly estimate their value apart from visiting them with robotic missions or recovering samples.

Still, I believe these locations are good candidates for future planetary missions. Intrusive systems can give us important knowledge about planetary interiors and how they evolved, since the composition and properties of the intruding magmas tell us about the processes in the crust and mantle. A NASA mission with a similar scope is already underway, a rover with land near the volcanic Gruithuisen domes in the Moon (Braden and Robinson, 2011), so a similar concept could also be developed for the basaltic intrusive system studied here. The Valentine Domes are good candidates for robotic exploration, they are located at medium latitudes, they have a complex geology that is likely representative of intrusive processes, and they should be easy to traverse. A missions like these should focus in the recovery of valuable samples from the secondary domes and the eastern scarp of V1, since an of their composition could reveal the properties of the intrusive system.

5.5. General conclusions

The main goal of this project was to characterize and understand the formation process of intrusive domes in the Moon and Mars, I believe this was fulfilled in both cases. As these landforms as not well known, it was necessary to apply new methodologies and techniques. This led to the creation of ***MoonIndex***, an open-source tool to create spectral indexes for the Moon, and that can be useful for a wide variety of lunar research. Furthermore, the techniques and procedures used in this work to detect and characterize the intrusive systems can be replicated in other locations.

The Valentine Domes on the Moon is a polygenetic system made of three large laccoliths, secondary domes and dykes, and a network of fractures and faults that likely controlled the emplacement of igneous bodies. The magmatic system was active between 2.98 ± 0.15 Ga until at least 1.88 ± 0.5 Ga, and it is likely the result of mantle magmas that rose through the weakened and thinned crust at the edge of the Serenitatis Basin.

The dome field in Utopia Planitia on Mars is geologically different, it is a monogenetic system, where hundreds of small domes are scattered over a large area. The geomorphological properties of the domes and how they interact with other units showed evidence about their origin, some of the domes were formed at the surface, while others cooled down near it, among the last, some remained underground and other were exhumated. This constitutes an intrusive-to-extrusive system. One group of the domes formed before 1.25 ± 0.07 Ga, and the other one before 652 ± 94 Ma. The intruding magmas came from deep and isolated sources, they used pre-existing fractures and faults to reach the surface.

Geological mapping is a necessary step to understand planetary landforms, especially the ones poorly explored. New methodologies, like the use of geostratigraphic units, are a clever way to overcome the difficulties of planetary mapping, and to get cartographic products that are closer to the geological reality of these locations. Hopefully this research will open the door to discovering new intrusive systems and to better understand the ones already known, these structures might be relevant in the future of space exploration, so studying them is valuable for the times to come.

Chapter 6: Additional work and collaborations

During the time in which my thesis was developed I had the opportunity to participate in several complementary activities. Although not necessarily related to the study of intrusive domes in other planets, these fieldtrips, projects, and workshops were all focused on planetary sciences, and greatly improved my knowledge and skills in the area. Many of these activities took place in Latin America, where I had the opportunity to connect with the local scientific community, and to share the knowledge I have obtained these years, which is also one of my goals as a Colombian scientist.

6.1. MIRACLES analogue mission

In June 2023 I participated in a lunar analog mission hosted by the ESA Analog-1 project (Carey et al., 2022). This exercise was an initiative to prepare Europe for future hybrid operations over the lunar surface. This was an interesting exercise for me, as I was able to experience a simulated robotic mission to the Moon. MIRACLES recreated an exploratory mission to a crater in the South pole Aitken basin (SPA). The robotic infrastructure consisted of two rovers equipped with scientific instruments, a larger one with multiple cameras and the ability to recover samples (Interact), and a smaller one capable of exploring difficult terrains (Scout). The human infrastructure consisted of teams dedicated to driving, safety, science, and an invited astronaut. Several preparatory sessions took place during the first semester of 2022, and an on-site test was carried out on Mount Etna at the end of June 2022.

The preparatory virtual simulations were run in the 3DROCKS software. On these occasions, I was part of the scientific team of the mission, which was responsible for selecting the scientifically interesting locations and the sampling points. To successfully locate these points, I used remote sensing data, including digital elevation models and morphometric parameters of Mount Etna recovered with drones. This helped me to define a traverse across the terrain, considering the rover limitations and the scientific objectives.

During the on-site mission I had the role of deputy scientist. My task was to discuss the information recovered during the missions with the scientific lead, so we could decide which samples to recover and what points of interest to visit. The simulation was successful overall, both rovers operated as expected, and several samples were recovered (**Figure 6.1**). We found that the most challenging part of the activity was the communication with other teams, especially during the sample recovery tasks, since the selection of a suitable rock was highly important for the scientific team, but the priority of the other teams was the safety of the rovers and the completion of the original traverse. Several protocols and improvements resulted from the missions, which will hopefully help advance Europe in upcoming missions to the Moon.

Overall, these activities helped me to experience the complexity and extensive planning related to exploratory missions, specifically in a volcanic environment like Mont Etna, which is like the geological setting of my study zones in the Moon and Mars. I also understood the relevance of geology in this kind of activity, and how I can contribute to them as a planetary scientist.

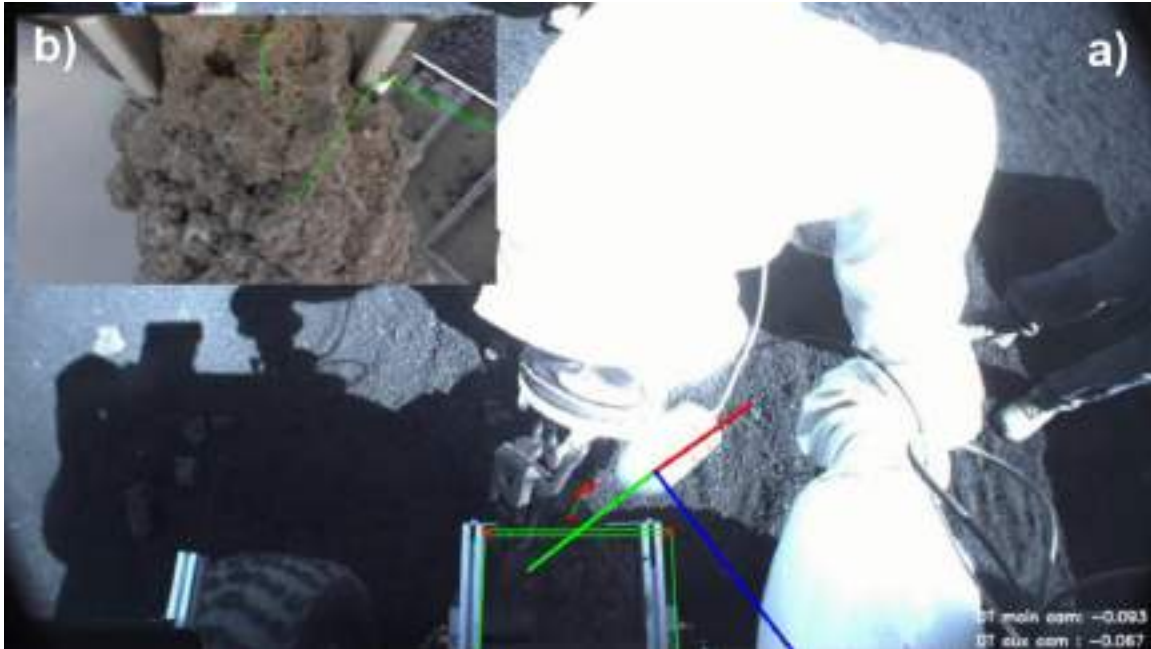


Figure 6.1: a) Image taken by the Interact rover across the terrain in Mount Etna. b) Sample recovered during the campaign (Taken from Suter, 2023).

6.2. EXPLORE project

The EXPLORE project was an initiative from several European institutions focused on the development of tools and workflows to support and promote the exploitation of space datasets. This thesis was done under the umbrella of the EXPLORE project, so part of my research was intended to feed and enhance the tools provided by it, especially the ones related to Lunar exploration. Two components of the EXPLORE project were made for this end, L-Explo and L-Hex. The objective of the first one was to create high-level products from remote sensing datasets and to deliver them in a user-friendly way to the scientific community. L-Hex wanted to build upon L-Explo, by using this data to enhance the study of prior and potential landing sites and evaluating potential rover traverses. To fulfill these objectives the EXPLORE team decided to develop a comprehensive Lunar web-browser, made of a robust backend hosting the datasets and pipelines, and an interactive frontend where the user can visualize the data over a Lunar basemap, request high-level datasets to the backend, or import their own data to make scientific interpretations (Nodjoumi et al., 2023). I contributed to this work mainly

by the collection, processing and ingestion of lunar data to the system, as well as the selection of interesting regions worth exploring with high-resolution datasets.

Within this framework, the hyperspectral datasets of M^3 and the derived spectral indexes generated by ***MoonIndex*** were perfect products to showcase in the EXPLORE ecosystem. Two methods were developed for this purpose. First, a spectral profiler was added to the web-browser, allowing the users to retrieve spectral signatures (before and after the continuum-removal) from M^3 cubes. And second, spectral indexes were computed and added to the backend for display (**Figure 6.2**). Several regions of interest were selected, including all the Apollo landing sites, the location of the potential intrusive domes defined by (Lena et al., 2013), and other relevant basins and craters.

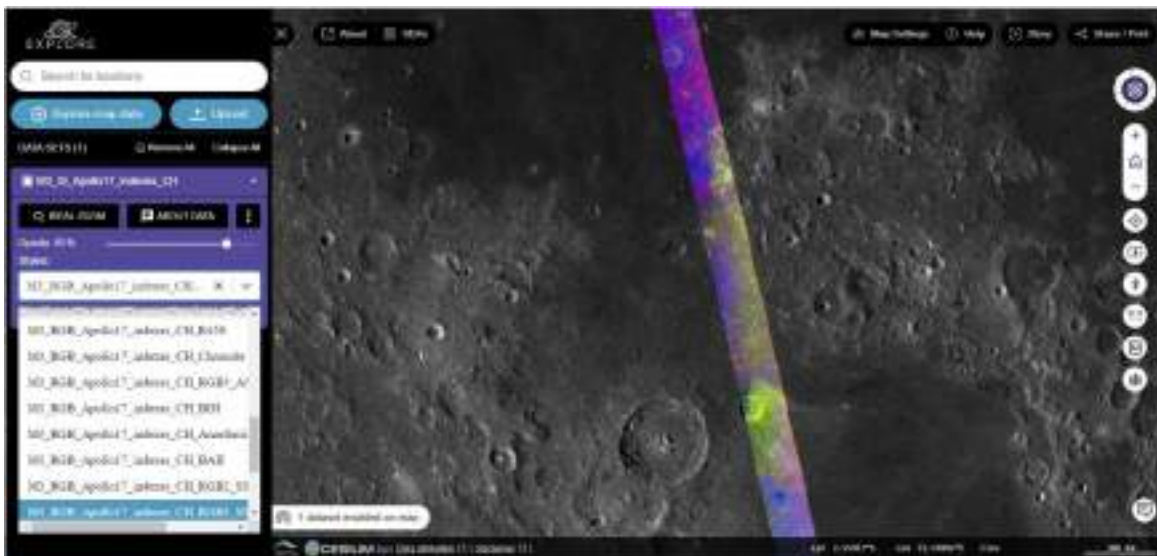


Figure 6.2: And RGB composite created by ***MoonIndex***, displayed in the EXPLORE web-browser.

I believe this platform is a good location to host and deliver the products of ***MoonIndex***, since it allows their use in connection to other lunar datasets in a user-friendly way, thus opening lunar science for a wider public. Although the EXPLORE project officially ended, all the infrastructure and pipelines are open-source and are available to the scientific community. This opens an opportunity for the project to be resumed and improved in the future.

6.3. Workshops and education

Over 2023 and 2024 I participated as a lecturer in several workshops and educational activities in Latin America. These events were organized by international organizations and were intended to train the local scientist in planetary sciences and to bring together the community.

6.3.1. COSPAR Data Analysis for Planetary Sciences

This event was held in Antofagasta, Chile, in January of 2023. It gathered early-career scientists from all the countries in South America and Mexico, which for two weeks attended lessons and training sessions guided by representatives of mission like Juno, ExoMars, and Hayabusa. I was invited as a lecturer to introduce the use of remote sensing products for cartographic purposes and to share workflows related to the processing and interpretation of planetary surfaces images. My intervention consisted of three theoretical sessions and the guidance of two groups of students interested in mapping polar deposits on Mars and craters in the asteroid Bennu.

I found this event to be successful, since the adopted methodology promoted longer working sessions with real data and close interactions between all the participants, including the lectures. The fact that the participants could use data from space missions along with senior scientists that participated in them allowed a deeper understanding of the datasets and their scientific goals. But most importantly, this was a unique space for Latin American early careers to meet and create solid networks for the future. The scientific community of the region is not as connected as in Europe and the United States, partly since there are not many strong organizations, but specially for the lack of resources, so the opportunities to gather are valuable. I still maintain contact with several of the participants from this event, and further collaboration and events emerged from it.

6.3.2. Europlanet events

After the COSPAR workshop, I participated as an instructor in other events in Latin America, this time sponsored by Europlanet. I went to La Paz, Bolivia on two occasions, in August 2023 and in February 2024 (**Figure 6.3**). The first time I visited the astronomical observatory of La Paz, where I trained for a couple of days university students and staff members of the Observatory. The activities carried out were similar to the ones during COSPAR, using remote sensing data of Mars for geological cartography. A bigger event was held next year, this time we organized a full workshop, hosting online talks with professional around Latin America, and a practical session of cartography, this time including Venus, the Mon, and Mars. These events had a greater impact in the community, since planetary sciences are a new topic in the country. The universities and institutes involved were very receptive and interested in the activity, and some of the students which participated in the workshops decided to create a Bolivian research group in the field of planetary sciences.

Finally, the first Europlanet Latin American Workshop was held in Buenos Aires, Argentine, in November 2023. This workshop brought together again the planetary community of the continent, this time including topics on astrobiology. I participated as a speaker, presenting some tools developed in the frame of the EXPLORE project, aimed at facilitating the process of working with planetary datasets.

These educational activities in Latin America have been relevant for my professional growth, since they allowed me to spread the knowledge I am getting to the scientific community of my continent. The lack of awareness and training has always been the biggest barrier for the development of planetary sciences in Latin America, so these workshops were helpful to provide tools to the new generation of planetary scientists on these countries, as well as to create a stable network that can foster future collaborations.



Figure 6.3: Workshop in Bolivia in January 2024.

6.4. Other publications

During my doctoral studies I contributed to other scientific publications, two of them as first author, and another one as a coauthor. They were not directly related to the topic of this thesis but were relevant to my growth as a planetary scientist.

6.4.1. Study of Martian deltas

When I was doing my master studies in Bogotá, I was also training a group of undergraduate students in the basics of planetary science. After some time, we decided to initiate a mapping project on Martian deltas, since they were interesting landforms and relatively easy to interpret. We checked the Martian deltaic features catalog of Di Achile and Kynek (2010), and ended up selecting two nearby deltas, associated with a system of lake chains near Ismenius Cavus, on Arabia Terra.

The objective of the research was to define the geological history of the zone, and to detail the processes that formed the deltas, especially since they were

notably different, even while being close to each other. To accomplish that, our approach was to make geomorphological maps, analyze the distribution of water-related landforms, and the cross-cutting relationships of the area. I was the first author of this paper and contributed to the entire process, mainly during the formulation of the project and the geomorphological mapping of the deltas with high-resolution datasets (**Figure 6.4**). The associated paper is called “Hydrologic evolution of two Martian deltas in the Ismenius Cavus system” and was published in the “Earth sciences research journal”.

Link to the paper: <https://doi.org/10.15446/esrj.v28n1.111269>

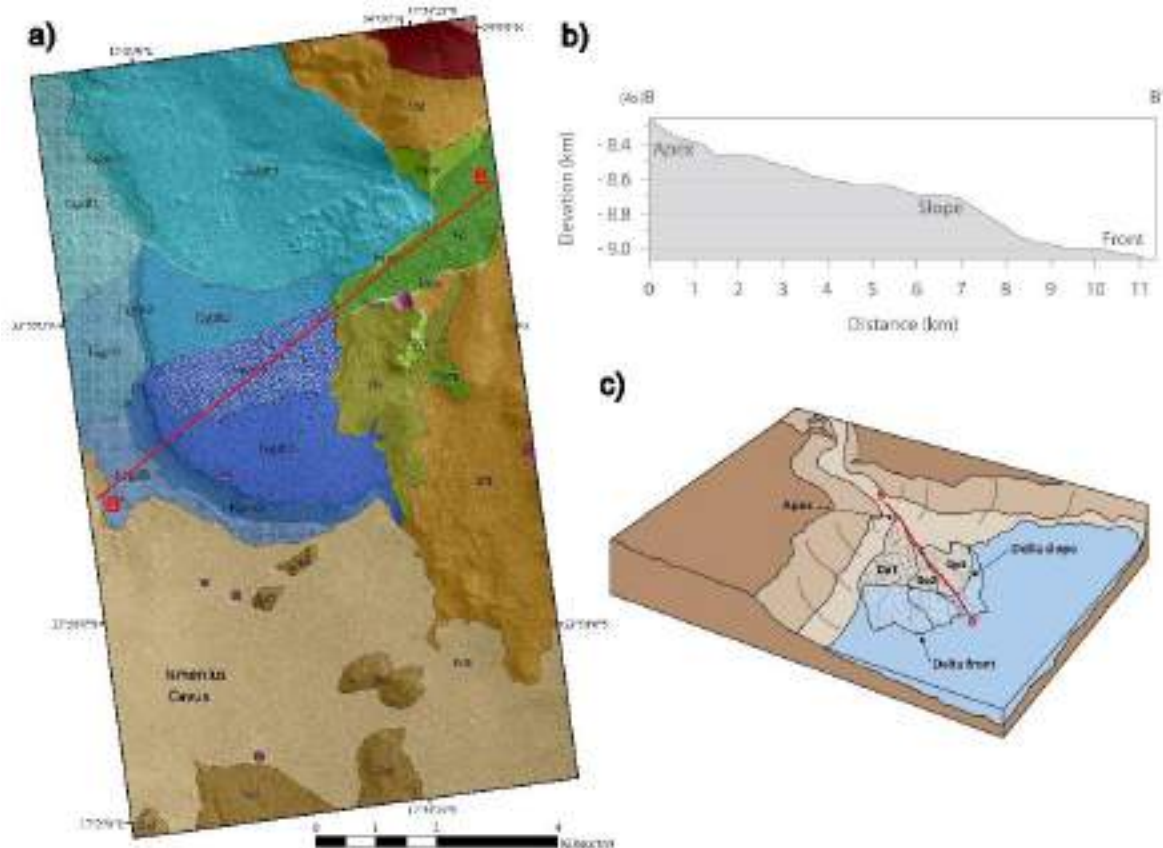


Figure 6.4: a) Geomorphological map of one of the studied deltas. b) Elevation profile of the delta taken from the HRSC DEM. c) Tridimensional interpretation of the river-dominated delta.

6.4.2. EXPLORE Machine learning data challenge

One of the activities developed by the EXPLORE project to promote the use of advanced tools for planetary exploration was the “EXPLORE Machine Learning Lunar Data Challenge”. This activity was open to all the scientific community, and the challenge consisted of using machine learning techniques to identify landforms that could be potential hazards for Lunar exploration, and the consequent creation

of an optimal traverse for a robotic or human mission. The location selected for this purpose was the Archytas Dome, one of the candidate intrusive domes of Lena et al. (2013).

The team that won the challenge achieved strong results, they used neural networks to automatically identify craters and boulders, and proximity algorithms to identify the optimal traverse across the target location. After the challenge was over, the EXPLORE team decided to write a scientific paper about the whole process, with the winning solution to the challenge as the main topic and the members of the winning team as the first authors. The paper called “Design of robotic traverses on the Archytas Dome on the Moon” was submitted to the “Open research Europe” journal. My contribution to this research was the preparation of the data used during the challenge, including a geomorphological map of the Archytas Dome (**Figure 6.5**).

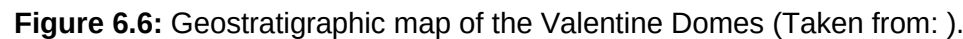
Link to the paper: <https://doi.org/10.12688/openreseurope.17424.1>

6.4.3. Atlas of planetary geological maps

The Atlas of Planetary Geological Maps was a compilation made by the Geological Survey of Italy during the second half of 2024. This publication was intended to highlight the cartographic products of planetary research, by focusing the volume on the maps themselves.

I contributed to the compilation as first author, with the piece called “Large scale geostratigraphic map of the lunar Valentine Domes”. This publication is derived from the second paper presented in this thesis, so their contents and scope are similar, with the difference that in this publication the map was more carefully schematized and fine-tuned (**Figure 6.6**).

Link to the contribution: Will be published at the end of 2024.



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