VISIBLE AND NEAR INFRARED SPECTROSCOPY OF MERCURY AND VENUS FROM ORBIT

PIERO D’INCECCO

Institute for Planetary Research
German Aerospace Center (DLR)
Berlin, Germany

Astronomy Research Unit
University of Oulu
Finland

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To my wife Szandra
Supervisors

Prof. Jürgen Schmidt
University of Oulu, Finland

Dr. Jörn Helbert
German Aerospace Center (DLR) in Berlin, Germany

Opponent

Dr. Johannes Benkhoff
European Space Research and Technology Centre (ESTEC), Noordwijk, Netherlands

Reviewers

Dr. Thomas Widemann,
Observatoire de Paris, Meudon, France

Dr. Colin Wilson
University of Oxford, UK

Custos

Prof. Jürgen Schmidt
University of Oulu, Finland

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Curriculum vitae

Personal information

address Kiefholzstrasse 412, 12435 – Berlin, Germany
phone +49 176 32 981 472
e-mail piero.dincecco@dlr.de
nationality Italian
place and date of birth Atri (Teramo - Italy), 09/05/1983
familiar status married

Education and professional activities

04/2011 – 03/2017 PhD at German Aerospace Center (DLR) in Berlin-Adlershof / University of Oulu (Finland), Department of Astronomy - Title of the PhD project: “Visible and near-infrared spectroscopy of Mercury and Venus from orbit”.

05/2007 – 10/2010 Master Degree – Geologic Sciences at “Università degli studi G. D’Annunzio” (Chieti, Italy) – Department of structural geology and geodynamics, of the Earth and planets. Title of the Master thesis: “Distinctive features of calderas on Venus”.

01/2008 – 08/2008 Erasmus project at University of Oulu (Finland), Department of Planetary Sciences (NRPIF) - Focus in planetary geology, Solar System.


Publications

Peer-reviewed Articles


Conference abstracts (as first author)


Abstract

The present thesis exposes methods and results obtained exploiting information provided by visible and near-infrared spectra over Mercury and Venus. We use information from different datasets to perform a geologically supervised investigation, in order to identify the presence of compositional heterogeneities and reconstruct the stratigraphy in the shallow crust of the two Terrestrial planets. We name these procedures “Datasets Fusion Techniques” (DFTs). We combine the MASCS dataset with the MDIS dataset from the MESSENGER mission to analyze the local and global crustal properties of Mercury. We select all MASCS observations contained within geologic units previously mapped using high-resolution MDIS NAC images. Similarly, we combine the Venus Express VIRTIS dataset with Magellan SAR imaging dataset for identifying location and extent of the recently active lava flows possibly responsible for the relatively high 1 μm emissivity anomalies observed by the VIRTIS instrument on Idunn Mons on Venus. Using a forward modeling-like procedure, we mapped a number of lava flows on Magellan SAR images, then assigning them a different value of simulated emissivity at each iteration. We found one non-unique solution which well approximates VIRTIS observations. This thesis is a comprehensive study which embraces three main research works performed during the current PhD project. The results show the occurrence of vertical and horizontal heterogeneities in the composition of the shallow crust of Mercury, providing as well important indications for the presence of N-S dichotomy. We also found that the recently active lava flows on Idunn Mons are most likely flank flows located on the eastern flank of the volcanic structure. We could finally reconstruct the stratigraphy beneath the local scale study areas of Mercury and Venus. This PhD thesis demonstrates that DFTs can be used as a powerful expedient for improving the quality of information we can achieve from remote sensing analyses.
1. Introduction

Planet Earth is only one among billions of terrestrial planets in the Universe. The very fast technological progress humanity went through after the Industrial Revolution and, more recently, the “Space Race”, opened new frontiers providing many answers and new important questions for the future evolution of the mankind. Planetary sciences are essential for extending our knowledge of geologic processes on terrestrial planets, in order to be able to find new potential homes in a distant future. This study should of course begin from our neighborhood, the Solar System.

For the moment, remote sensing is the only instrument we have for studying the crustal properties of extraterrestrial planets. Investigating the presence of vertical and horizontal heterogeneities in the composition is very important for understanding the basic properties of different environments, but it is doubtless very challenging. When working on Earth, we can use two principal methods for recognizing such variations. The in situ geological survey is the first resource for performing a direct analysis based on the outcrops. The second resource is characterized by the seismological investigations which can strongly help constraining the internal structure of our planet, indirectly providing information about the physical properties of all materials crossed by the seismic waves. Unfortunately, when working with other terrestrial planets, neither of these two approaches can be used. However, if we wisely use the whole amount of information collected about the geological processes on Earth, we have more chances for understanding similar processes on other planets. This concept is applicable also vice versa.

In the present work we are going to expose procedures and results from the fusion between different datasets of remotely sensed data. The first part of this thesis, exposed in chapter 2, will be focused on the local and global scale spectral analysis of a number of impact craters on Mercury. The spectral characteristics of impact deposits and their surroundings can provide useful information for identifying the eventual presence of compositional heterogeneities among different surface materials on Mercury. Using the dataset from the NASA MESSENGER mission, we combined high-resolution camera images with reflectivity spectra in the visible part of the electromagnetic spectrum. Chapter 2 is directly linked to the research work analyzed in two different manuscripts, produced during this PhD project:


- A geologically supervised spectral analysis over 121 globally distributed impact craters as a potential tool for identifying vertical and horizontal compositional heterogeneities in the crust of Mercury (doi:10.1016/j.pss.2016.08.004).
In the second part of this thesis, in chapter 3, we are going to expose the first results from the study we performed over Idunn Mons, a prominent volcano on Venus. The ESA Venus Express mission identified over this volcano emissivity anomalies that plausibly indicate the occurrence of recent volcanic activity on the surface of Earth’s twin planet. Hence we combined NASA Magellan high-resolution radar images with near-infrared 1µm emissivity data from the ESA Venus Express mission in order to localize the possible source of such anomalies. This study is the main focus of a third research manuscript:

- Idunn Mons on Venus: location and extent of recently active lava flows (http://dx.doi.org/10.1016/j.pss.2016.12.002).

This thesis is also an opportunity to demonstrate the efficiency of Datasets Fusion Techniques (DFTs) in the study of geological and spectral characteristics of Terrestrial planets.
2. Vertical and horizontal variations in the composition of the shallow crust of Mercury as revealed from a combination between high resolution images and near-infrared spectra from the MESSENGER mission.

2.1 The geology of Mercury after the Mariner 10 mission

Mercury is the innermost planet of the Solar System and it has been visited and studied for the first time by the Mariner 10 probe, launched by NASA on November 3, 1973. During the flybys around the planet, the Mariner 10 probe imagined about 45 % of the planetary surface at an average resolution of 1 km and less than 1 % of the planetary surface at a resolution of 500 meters (Murray et al., 1975). Mariner 10 had the great merit to be the first space mission allowing a comprehensive study of the magnetosphere and surface of Mercury. Before the three Mariner 10 flybys between the 1973 and 1974, in fact, very little was known about Mercury, since earth-based telescopes provided no better resolution than 300 km. The only available information was provided by astronomical observations showing faint albedo markings (e.g. Murray et al. 1972, Spudis and Guest, 1988) and polarimetric and photometric observations indicating the surface of Mercury as intensely cratered as the surface of the Moon (e.g. Lyot 1929; Hämeen-Anttila et al. 1967; Dollfus and Auriere 1974). With the first images provided by the Mariner 10 probe, Trask and Guest (1975) prepared the first geologic map of Mercury, paving the way to a new era of geologic studies and stratigraphic reconstructions which were totally unimaginable until few years before.

The geologic mapping deriving from the Mariner 10 dataset allowed recognizing a number of units such as heavily cratered terrain, intercrater plains, smooth plains a number of tectonic features (e.g., Gault et al. 1975; Strom 1979, 1984; Spudis and Guest 1988). Intercrater plains and heavily cratered terrain are older than the smooth plains, tough the stratigraphic relations between the different geologic units on Mercury are not very easy to interpret, and they were made even more intricate due to the relatively low resolution of the first Mariner 10 images.

The first geologic studies performed over the images provided by Mariner 10 immediately showed the surface of Mercury as heavily cratered (e.g. Murray et al. 1974; Gault et al. 1975). However, even if intensely cratered, at a more detailed analysis it was clear that Mercury’s surface was less densely cratered than the surface of the Moon (e.g. Spudis and Guest 1988). The reason for this difference is due to the presence of the so called intercrater plains, which were firstly defined as “the level to gently rolling terrain between and around the cratered terrain” (e.g. Trask and Guest 1975; Strom 1977). A lot of effort has been made by Mariner 10 geologic mappers in order to explain the stratigraphic relation occurring between heavily cratered terrain and intercrater plains, trying to establish the relative age of these two units. However, there is no unique answer to this question; Trask and Guest (1975) initially inferred that the majority of intercrater plains
would predate the formation of heavily cratered terrain, but this claim had to be partially reconsidered after Malin (1976), Guest and O’Donnell (1977) and Strom (1977) pointed out that several old impact craters on Mercury are embayed and covered by intercrater plains material. Furthermore, these authors observed that a number of secondary craters are actually superposed on the intercrater plains, making the stratigraphic interpretation even more difficult. Leake (1982) proposed a more articulated and complete solution, dividing craters in classes from 1 to 5 according to their degradation state, being class 1 craters more fresh and less degraded and class 5 craters more degraded. In the same way, she divided plains material in classes from 1 to 5, being class 1 plains those plains within class 1 craters or superposed on their ejecta blankets and so on for the older plains. On the basis of these assumptions, Leake (1982) suggested that class 5 through class 3 plains are equivalent to intercrater plains as intended by Trask and Guest (1975), while class 1 and class 2 plains should be younger than the intercrater plains. Therefore she argued that class 1 through class 3 craters are the likely sources of the secondary craters superposed on the intercrater plains.

Another unit representing plains material on Mercury is characterized by the intermediate plains, as it has been named by Mariner 10 geologic mappers (e.g. Schaber and McCauley, 1980; De Hon et al., 1981; Guest and Greeley, 1983; Grolier and Boyce, 1984; King and Scott, 1990). Mariner 10 geologic mappers did not provide a unique definition of this unit, making sometimes difficult to interpret its morphologic characteristics. The stratigraphic relation between intermediate plains and the other plain materials is not clear, though it seems intermediate plains are in some cases used as a stratigraphic unit connecting intercrater plains with smooth plains (e.g. Schaber and McCauley, 1980; De Hon et al., 1981; Guest and Greeley, 1983; Grolier and Boyce, 1984; King and Scott, 1990). Similarly to intercrater plains, the debate about the volcanic or impact related origin of intermediate plains did not lead to a definite response, so that both volcanic and impact related options were considered as plausible by Mariner 10 geologic mappers.

Smooth plains are instead considered by Mariner 10 geologic mappers as the stratigraphically youngest plains materials on Mercury (e.g. Schaber and McCauley, 1980; De Hon et al., 1981; Guest and Greeley, 1983; Grolier and Boyce, 1984; King and Scott, 1990). There is no unique definition for smooth plains, since this unit has been defined in slightly different ways from each author. For instance, De Hon et al. (1981) define them as “smooth, sparsely cratered surface occurring within craters and topographically low areas between craters and with intermediate albedo”, while according to King and Scott (1990) smooth plains are material “occurring within class 4 crater or older, characterized by a smooth, flat, sparsely cratered surface with few ridges”, reminding the stratigraphic classification provided by Leake (1982). Spudis and Guest (1988) instead more simply describe Mercurian smooth plains as “flat to gently rolling plains, possessing numerous lunar mare type wrinkle ridges, most strikingly exposed in a broad annulus around Caloris basin, filling depressions that range in size from regional troughs to craters floor”. Given these definitions,
it is clear there was a general accord about the basic morphologic features of the smooth plains. Another important scientific question is represented by the origin of plains materials. Some authors were better inclined to consider a volcanic origin (Strom, 1977; Kiefer and Murray 1987; Grolier and Boyce 1984; McGill and King 1983; Murray et al. 1974; Murray et al. 1975; Spudis and Guest 1988), while according to Wilhelms (1976) and Oberbeck (1977) the smooth plains surrounding Caloris basin could be considered as old basin-ejecta material. Wilhelms (1976) and Oberbeck (1977) pointed out that these plains materials are often associated with the hilly and lineated terrain as described by Trask and Guest (1975). Hilly and lineated terrain consists of parallel straight valleys with scalloped margins approximately 10 km across, and it disrupts both heavily cratered terrain and intercrater plains (Trask and Guest 1975; Spudis and Guest 1988). Using more detailed arguments, Leake (1982) observed that some class 3 craters and class 3 plains are modified by the lineated terrain, while class 2 craters and class 2 plains are not. It is important to note that hilly and lineated terrain is located at the antipodes of Caloris basin. Starting from this particular geographical position, Schultz and Gault (1975) proposed that seismic waves originated from Caloris basin impact concentrated at its surface antipodes generating the hilly and lineated terrain. As further evidence in support of the arguments proposed by Schultz and Gault (1975), the study of McCauley et al. (1981) inferred that Caloris basin impact should have taken place between the formation of class 3 and class 2 craters as defined by Leake (1982). These evidences led Leake (1982) to observe that Caloris basin formation event can be used as a “stratigraphic horizon” which allows to group geologic units into Post-Caloris units (classes 1 and 2), Caloris units (class 3) and Pre-Caloris units (classes 4 and 5), as described in table 2.1.1. Following these arguments, hilly and lineated terrain formation can be linked to that of large basins and consequently also plains materials can be interpreted as different facies of basin ejecta (e.g. Spudis and Guest 1988). Strom (1979) disagreed with this idea observing that there are not enough source basins for justifying the presence of such a widespread unit such as the intercrater plains. Mariner 10 team scientists (Murray et al. 1974, 1975; Strom et al. 1977) suggested a volcanic origin for the Mercurian smooth plains highlighting their similarities with lunar basins and maria, using similar arguments to those provided in support of a volcanic origin for Cayley plains surrounding the Imbrium basin on the Moon. Wilhelms (1976) however noted how the Apollo 16 Mission demonstrated that Cayley plains are actually impact deposits related to the formation of Imbrium basin. After these findings, Wilhelms (1976) for analogy speculated that also the smooth plains surrounding Caloris basin on Mercury would have the same origin, thus being an ejecta facies of Caloris basin. Spudis and Guest (1988) however have been more cautious, stating that there is no unambiguous evidence for volcanic landforms on Mercury. The first geologic studies performed over Mariner 10 images from the three flybys around Mercury allowed absolute dating estimates. The geologic history of Mercury is characterized by five chronostratigraphic systems: pre-Tolstojan (pre – 4.0 Gyr ago), Tolstojan (3.9 – 4.0 Gyr ago), Calorian (3.9
Gyr ago), Mansurian (3.0 – 3.5 Gyr ago) and Kuiperian (1.0 Gyr ago), as displayed in table 2.1.2.

Heavily cratered terrain and the approximately contemporaneous intercrater plains have been plausibly both emplaced during the pre-Tolstojan system. The impact event which formed the 390 km across Tolstoj basin (16.3° S; 163.5° W) and its deposits marks the beginning of the Tolstojan system. Tolstoj basin deposits, named “Goya Formation” by Spudis (1985), are characterized by distinctive lineated terrain. The crater density during the Tolstojan system is lower than that of the pre-Tolstojan system (e.g. Spudis and Guest 1988).

The Calorian system is instead characterized by the impact which formed the 1550 km across Caloris basin (30.5° N; 189.8° W) and its related deposits. Caloris basin’s impact deposits are supposed to have formed almost instantaneously in terms of geologic time, therefore these deposits are considered as an important marker horizon for Mercury (Guest and Gault 1976; Guest and O’Donnell 1977; Leake 1982) as much as Imbrium basin on the Moon (Shoemaker and Hackman 1962). As already mentioned above, the antipodes of Caloris basin are characterized by hilly and lineated terrain. Some authors (Schultz and Gault 1975; Hughes et al. 1977) linked the formation of this terrain to the propagation of seismic waves through the planet after Caloris basin’s impact event. Following this theory, the hilly and lineated terrain located at the antipodes of Caloris basin can be also used as a further stratigraphic marker indicating the base of the Calorian system. The Calorian system marked the end of the emplacement of the smooth plains, therefore the two most recent chronostratigraphic systems (Mansurian and Kuiperian) are exclusively characterized by the formation of impact craters.

The base of the Mansurian system is characterized by the impact which formed the 94 km across Mansur crater (47.8° N; 162.6° W), while the Kuiperian system has been named after the 62.3 km across Kuiper crater, whose formation signs the beginning of the most recent chronostratigraphic system of Mercury and whose detailed features will be discussed later in this chapter. Both systems are characterized by the emplacement of relatively fresh and slightly degraded craters, but only impact craters belonging to the Kuiperian system display bright rays patterns surrounding the rim (e.g. Spudis and Guest 1988).

The Mariner 10 mission granted scientists the possibility to improve our geologic knowledge of geologic history and surface structures of a previously unknown planet, marking the road for a new era of scientific investigations which is now making new steps with the NASA MESSENGER mission and with the coming ESA BepiColombo mission.
**Table 2.1.1** – Relative chronology of Mercury on the basis of the main geologic features identified after the Mariner 10 mission (from Leake, 1982).

<table>
<thead>
<tr>
<th>Era</th>
<th>Plains/Crater Class</th>
<th>Brief Description of Materials</th>
<th>% of mapped area covered&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Post Caloris</td>
<td>P&lt;sub&gt;1&lt;/sub&gt;</td>
<td>Very smooth plains material</td>
<td>0.9 (.01,.86)&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>C&lt;sub&gt;1&lt;/sub&gt;</td>
<td>Fresh and/or rayed craters</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td>P&lt;sub&gt;2&lt;/sub&gt;</td>
<td>Smooth plains material where thick, rougher where thin, burying rough topography</td>
<td>7.8 (2.7,5.1)</td>
</tr>
<tr>
<td></td>
<td>C&lt;sub&gt;2&lt;/sub&gt;</td>
<td>Moderately fresh craters</td>
<td>5.4</td>
</tr>
<tr>
<td>Caloris</td>
<td>P&lt;sub&gt;3&lt;/sub&gt;</td>
<td>Moderately smooth to hummocky plains</td>
<td>12.1 (9.6,2.5)</td>
</tr>
<tr>
<td></td>
<td>C&lt;sub&gt;3&lt;/sub&gt;</td>
<td>Moderately subdued craters, rounded rims</td>
<td>10.0</td>
</tr>
<tr>
<td>Pre Caloris</td>
<td>P&lt;sub&gt;4&lt;/sub&gt;</td>
<td>Moderately rough to hilly intercrater plains</td>
<td>9.6 (8.3,1.3)</td>
</tr>
<tr>
<td></td>
<td>C&lt;sub&gt;4&lt;/sub&gt;</td>
<td>Subdued, dissected craters</td>
<td>12.5</td>
</tr>
<tr>
<td></td>
<td>P&lt;sub&gt;5&lt;/sub&gt;</td>
<td>Very rough, knobby and pitted plains</td>
<td>15.7 (15.6,0.1)</td>
</tr>
<tr>
<td></td>
<td>C&lt;sub&gt;5&lt;/sub&gt;</td>
<td>Highly subdued craters</td>
<td>7.6</td>
</tr>
<tr>
<td></td>
<td>C&lt;sub&gt;5'&lt;/sub&gt;</td>
<td>Ancient circular depressions, vague rims</td>
<td>10.5</td>
</tr>
<tr>
<td>Hilly &amp; Lineated</td>
<td>plains</td>
<td>Hilly and lined material, large mas-</td>
<td>0.06</td>
</tr>
<tr>
<td></td>
<td>Lineated</td>
<td>sive hills and troughs</td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup> Total mapped area = 1.0284 x 10<sup>7</sup> km<sup>2</sup>.  
<sup>b</sup> In parentheses are % area of exterior and interior plains, respectively.  
<sup>c</sup> Crater area percentage = Σ(πD<sup>2</sup>N/100)/(4A) for each class crater over all diameter bins of geometric bin size D km >40 km. N craters per bin.

**Table 2.1.2** – Chronostratigraphic units of Mercury (from Spudis and Guest, 1988)

<table>
<thead>
<tr>
<th>System</th>
<th>Major Units</th>
<th>Approx. Age of Base of System&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Lunar Counterpart&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kuiperian</td>
<td>crater materials</td>
<td>1.0 Gyr</td>
<td>Copernican</td>
</tr>
<tr>
<td>Mansurian</td>
<td>crater materials</td>
<td>3.0–3.5 Gyr</td>
<td>Eratosthenian</td>
</tr>
<tr>
<td>Calorian</td>
<td>Caloris Group; plains, crater, small-basin materials</td>
<td>3.9 Gyr</td>
<td>Imbrian</td>
</tr>
<tr>
<td>Tolstojan</td>
<td>Goya Formation; crater, small-basin, plains materials</td>
<td>3.9–4.0 Gyr</td>
<td>Nectarian</td>
</tr>
<tr>
<td>pre-Tolstojan</td>
<td>Intercrater plains, multiring basin, crater materials</td>
<td>pre–4.0 Gyr</td>
<td>pre-Nectarian</td>
</tr>
</tbody>
</table>

<sup>a</sup>Approximate ages based on the assumption of a lunar-type impact flux history on Mercury.  
<sup>b</sup>Included for reference only; no implication of exact time correlation is intended.
2.2 The NASA MESSENGER mission: a more complete geologic view of Mercury

2.2.1 Main goals and instruments

The MErcury Surface, Space ENvironment, GEochemistry and Ranging (MESSENGER) probe was launched by NASA from Cape Canaveral (Florida, USA) on August 3, 2004 and entered orbit around Mercury on March 18, 2011. The MESSENGER mission has been thought to complete and improve the comprehensive study of Mercury begun by the Mariner 10 mission in 1975, providing the key for answering six fundamental questions: (1) What planetary formation processes led to Mercury's high ratio of metal to silicate? (2) What is the geological history of Mercury? (3) What are the nature and origin of Mercury's magnetic field? (4) What are the structure and state of Mercury's core? (5) What are the radar-reflective materials at Mercury's poles? (6) What are the important volatile species and their sources and sinks near Mercury? (Solomon et al. 2007). Among these key questions, the number 2 is particularly relevant for the procedures and results being exposed in this chapter.

The MESSENGER probe is composed by the following instruments: Mercury Dual Imaging System (MDIS), Gamma-Ray and Neutron Spectrometer (GRNS), X-Ray Spectrometer (XRS), Magnetometer (MAG), Mercury Laser Altimeter (MLA), Mercury Atmospheric and Surface Compositions Spectrometer (MASCS), Energetic Particle and Plasma Spectrometer (EPPS) and Radio Science (RS). For the purposes of this work we will shortly describe the characteristics of the MDIS instrument, the Gamma-Ray and Neutron Spectrometer, the X-Ray Spectrometer and the MASCS instrument.

The MDIS instrument (Fig. 2.2.1) consists of a monochrome narrow-angle camera (NAC) and a multispectral wide-angle camera (WAC). The camera system can image the surface of Mercury at an average resolution of 250 meters/pixel, while particular targets of interest (e.g. interesting geologic features) can be imaged at an approximate resolution of 30 meters/pixel (Hawkins et al. 2007).

The MASCS instrument (Fig. 2.2.2) consists of a Cassegrain telescope 257-mm effective focal length and a 50-mm aperture, and it contains two spectrometers: an UltraViolet and Visible Spectrometer (UVVS) and a Visible and InfraRed Spectrograph (VIRS). The UVVS instrument detects the ultraviolet light emissions in order to study the tenuous atmosphere of Mercury. This is possible thanks to three photomultiplier tube detectors that cover far ultraviolet (115-180 nm), middle ultraviolet (160-320 nm), and visible (250-600 nm) wavelengths with an average spectral resolution 0.6 nm (McClintock and Lankton 2007). The VIRS instrument is instead more specific for mineralogy investigations, analyzing the reflectance spectra from the surface of Mercury in the 300-1450 nm wavelength range with a 5 nm spectral resolution. The mineralogy maps provided by the VIRS instrument have an approximate spatial resolution of 5 km (McClintock and Lankton 2007).
The GRNS instrument and the XRS instrument are providing a map of the elemental composition of the surface of Mercury. The GRNS instrument detects the relative abundance of major elements such as H, O, Na, Mg, Si, Ca, Ti, Fe, K, and Th, measuring the gamma-ray emissions induced on the surface of Mercury by the incident solar flux (Goldsten et al. 2007). Similarly, the XRS instrument is currently measuring X-ray emissions in order to detect the relative abundance of Mg, Al, Si, S, Ca, Ti, and Fe will be (Schlemm et al. 2007).

We will discuss and analyze the data provided by these instruments (in particular MDIS and MASCs) later in this chapter, since they provided the necessary key of interpretation for the study which is going to be exposed.
Fig. 2.2.1 – Photograph of the Mercury Dual Imaging System (MDIS) instrument just prior to integration with the spacecraft (S/C). Redundant Data Processing Units (DPUs, not shown) connect to MDIS through the DPU Interface Switching Electronics (DISE). Red-tag covers were used to protect apertures during handling and were removed before flight. Some thermal blankets are not shown to reveal structure (from Hawkins et al., 2007).

Fig. 2.2.2 – MASCFS instrument image taken during instrument testing at the Laboratory for Atmospheric and Space Physics (LASP) at the University of Colorado (from McClintock and Lankton, 2007).
2.2.2 Geology of Mercury: previous studies from the MESSENGER team

The Mariner 10 mission unveiled for the first time the surface of Mercury, allowing the study of its geologic features and providing the possibility to reconstruct the chronostratigraphic history of the planet. However, many geologic questions remained unsolved whose answers may be found in the new dataset of the MESSENGER mission. The MESSENGER team is currently producing a huge effort for improving the definition criteria of the identified surface units in order to provide a better understanding of the geologic history of Mercury. The experimental approach we are going to expose in this chapter is thought to provide a possible key for distinguishing surface units through their morphologic and spectral characteristics, both on a local and global scale. The MESSENGER MDIS instrument recently achieved the 100% imaging coverage of the surface of Mercury, which along with the reflectance spectra provided by the MASCS instrument and with measurements from GRS and XRS instruments is providing a complete background dataset for building an exhaustive scientific investigation. We want to insert this project in continuity with the studies already performed by MESSENGER team. To do this, therefore, we will shortly summarize the results provided by the most relevant research works which focused their attention on the definition criteria and origin of the surface units of Mercury. The Mariner 10 team’s classification which morphologically divided Mercury’s plains material into intercrater plains, intermediate plains and smooth plains has been partially re-elaborated by MESSENGER team’s scientists. Robinson et al. (2008) and Denevi et al. (2009) analyzed the MDIS color images and defined a number of units on the basis of their relative reflectance, spectral slope and morphology. Building on the geologic classification provided by the Mariner 10 mappers, Denevi et al. (2009) defined three major MDIS color units: the smooth plains, the intermediate terrain (IT) and the low-reflectance material (LRM). These workers also defined three subclasses for the smooth plains: the high-reflectance red plains (HRP), characterized by a reflectance about 20% above the global mean and relatively steep spectral slopes; the intermediate plains (IP), characterized by reflectance and color properties similar to the global mean; the low-reflectance blue plains (LBP), characterized by a reflectance of about 15% below the global mean. According to the interpretation provided by Denevi et al. (2009), the IT unit displays reflectance and color properties similar to the global mean, and it approximately corresponds to the units previously mapped by Mariner 10 workers as heavily cratered terrain and intercrater plains. The LRM unit shows instead reflectance about 30% below the global mean and a spectral slope of about 5% lower than the HRP unit.

Despite this first classification, the real origin of plains material on Mercury is still object of discussion. Understanding the genetic processes behind the formation of the extensive plains has now a crucial importance for geologic mapping and for reconstructing the stratigraphic history of Mercury. Whitten et al. (2014) performed a global map of intercrater plains on Mercury, clarifying some ambiguous interpretations in the definition of the intercrater plains and intermediate plains ad defined by Mariner 10 mappers.
Intermediate plains unit in fact only appears in the Mariner 10 geologic maps, but it is never mentioned in previous geologic studies on the geology and stratigraphy of Mercury (e.g. Trask and Guest 1975; Spudis and Guest 1988). Whitten et al. (2014) suggest not to use intermediate plains unit for geologic mapping, stating that a part of these deposits should be referred to as intercrater plains while another part as smooth plains. We agree with this statement, as we think it is crucially important to define stratigraphic units in the best possible way for avoiding potential confusion and misinterpretations. However, even considering improves which have been made since the beginning of the MESSENGER mission, the question about the origin of plains material remains. Whitten et al. (2014) point out that at least a good part of intercrater plains should have a volcanic origin, though it is well possible that some intercrater plains have an impact related origin. In the same way, also the origin of the smooth plains has not been completely clarified from the MESSENGER dataset, though the identification of the so called northern volcanic plains may represent a key point in the whole debate.

The first high resolution NAC and WAC images from the MDIS instrument, along with the new data from GRNS and XRS instruments mounted on the MESSENGER probe showed the presence of extensive deposits at the northern latitudes of Mercury, which have been interpreted to be volcanically emplaced smooth plains postdating the formation of Caloris impact basin (e.g. Head et al. 2008, 2009a, 2009b, 2011). These findings somehow strengthen the opinion of those scientists supporting a volcanic origin for the smooth plains (Murray et al. 1974; Strom et al. 1977; Trask and Guest 1975; Trask and Strom, 1976). The identification of volcanic landforms not far from Caloris basin and the fact that smooth plains have been observed also far away from Caloris basin brought the MESSENGER team authors to favorite a volcanic origin for the majority of the smooth plains, suggesting that Mercurian smooth plains should be similar to the northern volcanic plains, sharing a magnesian alkali-basalt-like composition (e.g. Head et al. 2008, 2009a, 2009b, 2011; Denevi et al. 2013). Building on the data provided from the MESSENGER XRS instrument, these authors also inferred a similar composition between the Caloris plains and the northern volcanic plains, except for the fact that Caloris plains would show a lower K abundance. However, the real occurrence of such compositional similarities is still under debate.

Izenberg et al. (2014) in their study support the arguments provided by Denevi et al. (2013) about the compositional similarities between Caloris smooth plains and northern volcanic plains. These workers exploit three spectral parameters as RGB channels in order to divide Mercury’s surface into four broad VIRS spectral units: average, dark blue, red and bright. The three spectral parameters they use are: a) The reflectance at 575 nm wavelength (R575, red), b) the spectral slope at visible and infrared wavelengths, represented by the ratio of reflectance at 415 nm to that at 750
nm (VISr, green), c) the spectral slope at ultraviolet (UV) and visible wavelengths, represented by the ratio of reflectance at 310 nm to that at 390 nm (UVr, blue). The average unit is characterized by reflectance within 25% of the mean planetary reflectance, UVr value between 0.64 and 0.71, VISr value between 0.5 and 0.6 (Izenberg et al., 2013). The plains materials as defined during the analysis of MDIS color units by other workers (e.g. Robinson et al. 2008; Denevi et al. 2009; Denevi et al. 2013) fall into this spectral VIRS unit as defined by Izenberg et al. (2014). The Dark Blue VIRS spectral unit is characterized by spectra both darker than the planetary mean spectrum and less sloped or “bluer” (Izenberg et al., 2014). All areas identified as LRM and some areas defined as LBP from the MDIS dataset (e.g. Robinson et al., 2008; Denevi et al., 2009; Denevi et al. 2013) are included into this unit. The Red VIRS spectral unit is characterized by spectra that are both higher in reflectance and “redder” than the planetary mean spectrum, with low UVr (< 0.66) and low VISr (< 0.60) (Izenberg et al., 2014). This unit includes pyroclastic deposits whose origin is probably connected to explosive volcanism (e.g. Head et al., 2008). The bright spectral unit covers a wide range of UVr (0.60 – 0.74), and is generally brighter and have higher VISr value than the highest reflectance value of the average unit (Izenberg et al., 2014). Hollows (Blewett et al., 2011, 2013; Helbert et al., 2013) have spectral parameters that fall within the Bright VIRS spectral unit. Izenberg et al. (2014) inserted both northern plains and Caloris smooth plains in the same VIRS spectral average unit, displaying a general agreement between their observations and the results by Denevi et al. (2009).

Other studies carried out by the PEL group in Berlin (D’Amore et al., 2010, 2011, 2012, 2013a, 2013b; Helbert et al., 2013) used the DLR MASCS database to develop an unsupervised hierarchical clustering analysis which is able to group pixels sharing similar spectral characteristics. Using this methodology, they have divided the surface of Mercury into two main global units: an Equatorial Region (ER) extending at middle latitudes, and a Polar Region (PR) which is instead covering the two poles. These two mega-regions display moderate spectral heterogeneities, whose origin still has to be identified. In case these spectral heterogeneities are caused by the presence of real differences in the average composition between the two mega-regions, these results would be in contrast with the scenario proposed by Izenberg et al. (2014) and by Denevi et al. (2013).

Building on the previous studies mentioned above, we expose in this chapter a new approach consisting of a geologically supervised spectral analysis, directly complementary to the unsupervised hierarchical clustering analysis exposed by D’Amore et al. (2010, 2011, 2012, 2013a, 2013b) and Helbert et al. (2013). Our approach allows identifying the presence of eventual spectral heterogeneities occurring between two or more previously mapped geologic units and it can be used both on a local and on a global scale.
2.3 Impact craters as a window on the subsurface layers of Mercury

In the section 1.2 we already mentioned how none of most common methods used for investigating the internal structure of the Earth can be applied to other terrestrial planets as well. However, an alternative method of analysis can be used for identifying the eventual presence of horizontal and vertical variations in the composition of the shallow crust of Mercury. Impact craters can be considered as a natural window on the interiors of a terrestrial body. Melosh (1989) performed one of the most comprehensive studies on the formation processes and morphology of impact craters in the Solar System. Before introducing the approach we have used, it is better to shortly summarize the main morphological features we can observe on impact craters. Melosh (1989) divided all the impact structures of terrestrial bodies into four main morphologic categories in order of increasing diameter: a) simple craters, characterized by smooth, bowl-shaped interiors b) complex craters, characterized by flat floors, terraced walls and a central peak c) peak-ring basins, with terraced walls and one ring of massive peaks emplaced on a flat floor, d) multi-ring basins, characterized by flat floors and two or more concentric rings of peaks (Fig. 2.3.1a-d). In this regard, one important argument provided by previous studies on impact craters (i.e., Melosh 1989; Ernst et al. 2010) is that some craters with complex morphology or larger diameters excavated enough through the surface to expose material coming from greater depths in the crust (Fig. 2.3.2). Mercury is characterized by a heavily cratered surface, so that a deep analysis of its impact structures and related deposits is possible. For this reason, analyzing the spectral properties of materials exposed by large and fresh (well visible) craters can give us an indication of the eventual presence of compositional heterogeneities in the shallow crust of Mercury. Building on these arguments, in the following sections we will expose two similar approaches for identifying the eventual presence of compositional diversities both on a local scale and on a global scale using impact deposits as a window on the shallow crust of Mercury.
Fig. 2.3.1 – Impact crater morphology as a function of increasing size. (a) Simple crater: 2.5 km diameter crater Linné on the Moon (Apollo 15 Panometric Photo strip 9353). (b) Complex crater with central peak: 102 km diameter crater Theophilus on the Moon (Apollo 16 Hasselblad photo 0692). (c) Complex crater with internal ring: Mercurian craters Strindberg (165 km diameter) to the lower right and Ahmad Baba (115 km) to the upper left (Mariner 10 FDS 150, rectified). (d) Multiring basin: 620 km diameter (of most prominent ring) Orientale basin on the Moon (LROC WAC mosaic. Full width of image PIA13225 is 1350 km. NASA/GSFC/ASU), from Melosh, 2011.
Fig. 2.3.2 – Schematic illustration of how craters of different sizes can reveal clues to the subsurface stratigraphy. In all cases, the black unit represents impact melt and the dashed line indicates the pre-impact ground surface. (a) A crater too small to penetrate the surface layer (Layer 1) can be used to constrain the minimum thickness of this layer. (b) A crater that penetrates through the top layer and excavates underlying material constrains the maximum thickness of the top layer and reveals underlying layers (in this example, Layer 2). (c) A crater revealing a third stratigraphic layer (Layer 3) in a central structure can additionally constrain the thickness of the second layer, from Ernst et al., 2010.
2.4 Local scale study of Kuiper and Waters craters

The local scale approach has been tested using two of the youngest impact craters on the surface of Mercury, both belonging to the Kuiperian system (1.0 Gyr ago): Waters crater (106 W; 9 S, Figs. 2.4.1, 2.4.2), 15 km diameter and Kuiper crater (30 W; 11 S, Figs. 2.4.1, 2.4.3), 62.3 km diameter. In the following sections we will outline the geologic background of the two craters, focusing on previous maps and studies of the respective areas, for then describing the methods used for data processing. In the end we will expose and discuss the obtained results.

2.4.1 Geologic background of the study area

The 62.3 km diameter Kuiper crater and the 15 km diameter Waters crater are located in the region shown in Fig. 2.4.1. This region includes parts of two different quadrangles of Mercury which have been geologically mapped by Mariner 10 workers, the H06-Kuiper quadrangle (De Hon et al. 1981) and the H07-Beethoven quadrangle (King and Scott 1990).

The two craters share some important morphological similarities which make them good terms for a direct comparison. Kuiper crater lies in fact over the rim of the preexisting Murasaki crater and a similar situation is observable over Waters crater. It seems that in the case of Kuiper crater preexisting topography has played a key role in affecting the direction of melt outflowing, which is oriented toward the interior of the underlying Murasaki crater (Hawke and Head 1977). A totally similar scenario is observable over Waters crater, which is lying over the rim of a preexisting crater and it also shows a certain quantity of outflowed melt.

Kuiper crater gives its name to the H06 quadrangle where this crater is located, and it is definitely one of the youngest craters on Mercury. The most recent chronostratigraphic system of Mercury, the Kuiperian system, is in fact also named after Kuiper crater which is therefore an important marker horizon for global stratigraphy. Similarly to Leake (1982), Mariner 10 geologic mappers divided all impact craters on Mercury into five classes according to their degradation state, inserting into class 1 the oldest and most eroded craters and into class 5 the youngest and morphologically best preserved craters. Waters crater and Kuiper crater have been both classified as c5 craters, so their morphology is really fresh and well exposed. Kuiper crater is located over a heavily cratered portion of the H06 quadrangle, its deposits directly overlap the older deposits from Murasaki crater and, at greater depths, an alternation of intercrater plains and plains terra material (De Hon et al. 1981). De Hon et al. (1981) defined plains and terra material as “mostly cratered and intercrater plains materials, which may include some smooth plains and rough terra deposits”, basically interpreting it as a unit mixed between intercrater plains and smooth plains. This unit extends westward to Waters crater, whose deposits directly overlap plains and terra material (King and Scott 1990). A “bright ray or halo material around of emanating from c5 craters” consisting of thin layer of fresh ejecta deposits surrounds Waters crater’s rim as proposed in the interpretation provided by King and Scott (1990). The most recent XRS data (Nittler et al., 2013) show...
some differences in the elemental composition between Waters crater and Kuiper crater surroundings; from a Al/Si and Mg/Si ratios maps, it is clear how Kuiper crater’s surrounding deposits are relatively richer in Al in comparison with Waters crater’s surroundings, while Waters crater’s surrounding deposits show a content in Mg higher than Kuiper crater’s surroundings. The values of Al/Si and Mg/Si ratios observed over the deposits surrounding Waters crater are consistent with the average content observed for intercrater plains, confirming the morphologic interpretation made by Mariner 10 mappers which interpreted Waters crater to be located in an area of Mercury dominated in fact by intercrater plains. The regional area including Kuiper crater and Waters crater falls completely within the Equatorial Region (ER) as defined by workers of PEL group at DLR in Berlin (D’Amore et al. 2010; D’Amore et al. 2011; D’Amore et al. 2012; D’Amore et al. 2013a; D’Amore et al. 2013b; Helbert et al. 2013). Izenberg et al. (2014) instead defined Waters crater’s ejecta as fresh crater material and Waters crater’s surroundings as Low-reflectance Blue Plains (LBP), following the same nomenclature provided in the analysis of MDIS color images (Robinson et al. 2008; Denevi et al. 2009). Whitten et al. (2014) mapped an area including Waters crater, defining its ejecta as crater material and its surroundings as intercrater plains.

2.4.1 Methods and procedure

The local scale procedure we are going to describe is a complement of the unsupervised hierarchical clustering analysis technique used by D’Amore et al. (2010, 2011, 2012, 2013a, 2013b) and Helbert et al. (2013), and it can be divided into three main steps: 1) geologic mapping of the two analyzed impact structures; 2) extraction of the MASCS observations falling within each of the mapped units; and 3) approximate reconstruction of the local scale stratigraphy beneath the two analyzed craters.

2.4.1.1 Geologic mapping of the two analyzed impact structures.

The nomenclature used for defining the units mapped over Waters crater and Kuiper crater has been defined building on the nomenclature provided by Mariner 10 workers (i.e. De Hon et al. 1981, King and Scott, 1990). The following units have been mapped: crater peak material (cpm), crater floor and terraces (cft), crater melt material located within the crater rim (cmm_a), crater melt material outflowed from the crater rim (cmm_b) for both Waters crater (Fig. 2.4.4a) and Kuiper crater (Fig. 2.4.5a), characterizing each unit with a multipolygonal shapefile. Waters crater shows no clear central peak, as this crater is at the transition between simple and complex morphology. However, an area which can be considered as a proto central peak has been mapped. Building on previous studies which highlighted how proximal continuous ejecta on the Terrestrial planets of the Solar System extend at a distance between 1 and 2 radii from the crater rim (Melosh, 1989; Osinski et al. 2011), we defined an annulus extending at 1 radius from the rim of Waters crater and Kuiper crater, named crater fresh ejecta (cfe) unit. The cfe unit does not consider areas which are partially or completely covered by overlying cmm_b unit, since according to our interpretation cmm_b unit
stratigraphically postdates cfe unit. Due to the particular topographic configuration of the two craters, we could not precisely distinguish wall deposits and slump deposits from floor deposits. Moreover, in the case of Waters crater, the simpler and bowl shaped morphology did not allow a real separation between wall and floor.

For facilitating the differentiation of the units mapped over the two craters, we have added the prefix “w-“ to the units mapped at Waters crater, while we have added the prefix “k-“ to the units mapped at Kuiper crater. In this way, for instance, the unit cpm will be w-cpm for Waters crater and k-cpm for Kuiper crater.

In order to quantify and compare the spectral heterogeneities observed between the mapped units, we have defined an external reference area (era) unit, centered at 2.4°N, 83.3°W (Figs. 2.4.1, 2.4.6a). This unit is 100 km x 70 km in size and lies over an area of Mercury which has been previously mapped by King and Scott (1990) as “intercrater plains”, thus the reference spectra extra extracted from this region (Figs. 2.4.6b, 2.4.7, 2.4.8 and 2.4.9) act like a good term of comparison for defining the spectral differences between the units mapped for the two craters.

For mapping consistency, we relate the nomenclature of our mapped units to that used by Mariner 10 mappers for the H06 Kuiper and Beethoven quadrangles (e.g. De Hon et al. 1981; King and Scott, 1990). This nomenclature is more properly suited to geologic mapping than the nomenclature more recently proposed by Denevi et al. (2009) and Denevi et al. (2013), which is instead based on the spectral properties of the defined units. However, the w-cmm_a and w-cmm_b units were not mapped by King and Scott (1990). The two units together form a lobate melt flow which moves from the internal (w-cmm_a) to the external (w-cmm_b) surface of Waters crater. As far as Kuiper crater is concerned, De Hon et al. (1981) mapped the units we identified respectively as k-cmm_a and k-cmm_b, as “smooth plains materials”. In particular, k-cmm_b is not a typical lobate flow extending from the internal to the external region of the crater of origin. Within the Kuiper crater’s rim, deposits collapsed mostly from the north-western portion of the wall, and the maximum accumulation of k-cmm_a and the melt ejecta of k-cmm_b all point in the same SE direction. These factors indicate that Kuiper crater’s SE margin collapses towards Murasaki crater. In fact, the whole k-cmm_b unit is emplaced over the floor of Murasaki, and there is no trace of melt in other directions around the rim of Kuiper crater. This implies that k-cmm_b is just emplaced where it would be expected to be emplaced if k-cmm_b were impact melt flowing from Kuiper crater. Though we can’t exclude a volcanic origin for k-cmm_b within Murasaki crater, there are no visible eruption vents to support a volcanic origin. For these reasons, we interpret k-cmm_b as an impact melt ejected at a certain distance from - rather than flowing as a continuous unit out of - the rim of Kuiper crater. In order to avoid confusion between w-cmm_b, that is a common lobate outflowed melt, and k-cmm_b, we represent these two units with different colors, respectively brown and black (Figs. 2.4.4a, 2.4.5a).
2.4.1.2 Data selection and processing

The DLR MASCS database currently contains over 4 million spectra. Since a complete photometric correction was not performed on MASCS data, we applied normalized the MASCS spectra in order to reduce phase angle effects (i.e., D’Amore et al., 2012, 2013a, 2013b; D’Incecco et al. 2015; Helbert et al., 2013). To do this, we normalized the values of reflectance of each spectrum to its mean value of reflectance in the 700-750 nm range. This means that the normalized reflectance of all spectra is ~1 in the 700-750 nm range. We used the 700-750 nm range for the normalization as we noticed it is less affected by instrumental effects and we have chosen a relatively wide wavelength interval in order to increase the signal to noise ratio. After defining each of the units mentioned above as multypoligons in a GIS software, we are able to select from the DLR MASCS database only those spectral observations which completely fall within each of the previously defined units, and we do this using SQL spatial queries. Considering that we represent each MASCS observation as a polygon with four external vertices and one center vertex which represents the central field of view, with our SQL queries we expressly ask to select only those observations (polygons) whose all four external vertices (and consequently also the central vertex) are completely included within each multypolygon defined or mapped with GIS software. In this way we have extracted from the DLR MASCS database all observations falling within all units defined for Waters crater (Fig. 2.4.4b), Kuiper crater (Fig. 2.4.5b) and for the era unit (Fig. 2.4.6b). When applying the selection procedure, we have initially filtered the data to considered only MASCS observations with incidence angle < 72°, instrument temperature between 10 °C and 30 °C and with average 700 – 750 nm reflectance > 0. Using the filtered data, we calculated the mean values of normalized reflectance for all available observations at each wavelength. We iterated this procedure, getting a single mean normalized spectrum for each unit mapped over Waters crater (Fig. 2.4.7a) and over Kuiper crater (Fig. 2.4.8a). Since none of the normalized mean spectra from Waters crater (Fig. 2.4.7a) and Kuiper crater (Fig. 2.4.8a) show clear absorption bands and both the mean spectra are affected by noise, we decided to apply a smoothing function with a 55 points interval over both the mean normalized spectra from Waters crater (Fig. 2.4.7b) and Kuiper crater (Fig. 2.4.8b). We applied the smoothing in order to calculate the spectral slope from the mean normalized smoothed spectrum of each defined unit, since the smoothing function can help avoiding noise effects to reduce reliability of spectral slope calculations. We calculated the spectral slope for two different intervals, the 350-450 nm wavelength interval (Fig. 2.4.9a) and the 450-650 nm wavelength interval (Fig. 2.4.9b). We preferred not to select an interval too close to the normalization point at 700 nm, since near this point all spectra approximately converge to one nullifying the relative differences in spectral slope occurring between the mapped units.

We have also used the values of absolute 700-750 nm reflectance as a secondary parameter. Before extracting absolute 700-750 nm reflectance spectra we have applied an additional filter, considering only observations with incidence angles between 25° and 35° and with emission angles
between 40° and 50°. We did this because absolute reflectance still didn’t pass through an accurate photometric correction, so we decided to carefully constrain incidence and emission angles within a maximum range of variation of 10° so that absolute reflectance data would not be dramatically affected by geometry of observation. Unit $w-cmr_m-a$ represents the only exception to our filtering, since the only three MASCS observations falling within this unit were obtained at incidence angles of 46° and emission angles between 32° and 33°.

2.4.1.3 Pre-impact stratigraphy beneath the two analyzed craters.

The third step of this local scale approach is that of reconstructing the relative thickness and depth of origin of each spectrally heterogeneous and possibly compositionally different layer excavated by Water crater and Kuiper crater impact events. Ernst et al. (2010) combined analytical methods with spectral information from MESSENGER MDIS color images to obtain a reconstruction of the local stratigraphy beneath a number of impact structures on Mercury, getting an approximate estimation for the “maximum excavation depth of ejecta” and for the “maximum depth of melting” which corresponds to the “minimum depth of origin of central peak”.

The “maximum excavation depth of ejecta” is usually considered to be equal to one tenth of the transient crater diameter ($D_{tc}$), so these authors used the visible rim-to-rim crater diameter ($D_r$) to derive the transient crater diameter ($D_{tc}$) and consequently they estimated the “maximum excavation depth of ejecta” for each analyzed impact structure. Ernst et al. (2010) displayed three analytical methods for relating $D_r$ to $D_{tc}$ (Croft, 1985; Melosh, 1989; Holsapple, 1993), but they selected the most recent of the three methods (Holsapple, 1993) for their calculations.

The other layer whose depth was estimated by Ernst et al. (2010), the “maximum melting depth” or “minimum depth of origin of the central peak” represents the maximum depth where impact melt from each impact structure should originate. This layer is supposed to directly overlie the layer of origin of central peak material. This is the reason for the double name given to this estimated depth. Ernst et al. (2010) displayed three different analytical methods for estimating the “maximum melting depth” from the transient crater diameter ($D_{tc}$), the first from Cintala (1992) and Cintala and Grieve (1998a, 1998b), the second from Pierazzo et al. (1997) and the third method from Watters et al. (2009), but also in this case they selected only the method from Watters et al. (2009) for their calculations.

The plot of Fig. 2.4.10 shows the relationship between $D_r$, $D_{tc}$ and maximum excavation depth of ejecta, while the analytical relationship between $D_{tc}$ and the maximum depth of melting is shown in Fig. 2.4.11.

Building on the work performed by Ernst et al. (2010), we also selected the method from Holsapple (1993) for deriving $D_{tc}$ and consequently the maximum depth of origin of ejecta for both Waters crater and Kuiper crater, as shown in Fig. 2.4.10, and we selected the analytical method from Watters et al. (2009) for estimating the maximum melting depth (minimum depth of origin for the central peak) for the two analyzed craters (Fig. 2.4.11). The
use of these analytical methods allowed us to approximately reconstruct the local scale stratigraphy beneath Waters crater (Fig. 2.4.12a,b) and Kuiper crater (Fig. 2.4.13).

2.4.2 Results

From a first look at both the plots in Fig. 2.4.9a,b, we note that Waters crater’s units and Kuiper crater’s units are well localized in spectral reflectance space and not randomly arranged, even assuming that the average 700–750 nm reflectance is partially affected by phase angle effects. The units of Kuiper crater all lie up towards the upper right (high 700-750 nm reflectance and high 350-450 nm and 450-650 nm slope), while the units of Waters crater are all located towards the lower left (low 700-750 nm reflectance and low 350-450 nm and 450-650 nm slope) of the two plots in Fig. 2.4.9a,b. The era unit exhibits a spectral slope and average reflectance at 700–750 nm that is characteristic of typical intercrater plains. The units of the Kuiper crater show a 350-450 spectral slope and 700-750 nm reflectance higher than the era unit, while the units of Waters crater (except for w-cfe) display a lower 350-450 spectral slope and a lower 700-750 nm reflectance. Besides compositional variations and phase angle effects, the spectral differences between two or more materials can be caused by several factors. Previous studies on Lunar deposits (i.e., Fischer and Pieters, 1994) have demonstrated that space weathering acts reddening the spectral slope of more mature deposits, if iron is abundant. However, recent studies on the elemental composition of Mercury (i.e., Riner and Lucey, 2012; Izenberg et al., 2014; Weider et al., 2015) showed that the abundance of iron on Mercurian surface is not high enough to justify alone the reddening of spectra due to iron nanophase particles. Hence, we can’t exclude the occurrence of the spectral reddening due to space weathering effects on Mercury, but it must work differently than on the Moon. On the other hand, previous studies on the spectra of experimentally shocked enstatite in the 350-2500 nm wavelength range (Adams et al., 1979) and plagioclase feldspars in the 400-2500 nm wavelength range (Johnson and Hoerz, 2003), have shown that impact metamorphism induces an overall decreases in reflectance with increasing shock pressures, with only minor variations in the absorption bands or spectral slope. Finally, in the 700-750 nm wavelength range, reflectance decreases with increasing grain size (i.e., Hapke, 1993; Clark and Roush, 1984). Assuming that both Waters and Kuiper craters expose material relatively fresher and less mature than the surrounding intercrater plains (era unit), the position of the units of Waters crater on both Fig. 2.4.9a,b is consistent with space weathering being the dominant cause of the spectral differences observed between the deposits of Waters crater and the External Reference Area (era) deposits. The fresh deposits of Waters crater are generally characterized by spectral slope lower than or similar to that of the more mature deposits of the era unit (Fig. 2.4.9a,b), as would be expected if space weathering is the dominant process affecting the spectral slope, though we cannot exclude the presence of compositional heterogeneities.
Looking at the mapped units of Waters crater more in detail (Fig. 2.4.9b), we notice that in the 450–650 nm wavelength range the crater’s units exhibit significantly bluer spectral slopes than the era unit: in the case of w-cpm, w-cft and w-cfe units, this is most likely due to shorter exposure to space weathering effects. The absolute 700–750 nm reflectance of w-cpm, w-cft and w-cmm_b is generally similar to that of the era unit. This might indicate that the peak shock pressures reached during Waters crater’s impact were not so high to strongly affect the spectral characteristics of these three units compared to era unit. Moreover, the spectral outputs of w-cft and w-cmm_b are not given by one single material, but most likely represent a mixture of different materials.

The unit w-cfe displays instead higher absolute reflectance than the era unit. Assuming that Waters crater’s impact did not excavate deep into the shallow crust of Mercury, k-cfe might be composed of intercrater plains (era unit) material that has experienced low degree of impact metamorphism. In comparison with the pro-genitor regolith of intercrater plains (era unit), w-cfe is less mature and might have been even more finely powdered after the impact. This might explain the higher absolute reflectance of w-cfe compared to that of era unit. A different argument can be made for w-cmm_a, which displays a lower spectral slope and a relatively lower absolute average 700–750 nm reflectance compared to the era unit (Fig. 2.4.9a,b). Since for w-cmm_a we have included absolute 700-750 nm reflectance values with incidence angles of 46° and emission angles between 32° and 33° - we tested whether phase angle effects are likely to be the cause of the low reflectance of w-cmm_a. In particular, we applied a much broader incidence angle filter of < 72° also to absolute mean 700-750 nm reflectance. As illustrated in Fig. 2.4.9c,d, the relative positions of the mapped units remain similar to those in the corresponding plots in Fig. 2.4.9a,b. This suggests that the values of absolute reflectance are not dramatically affected by the variations in incidence angle and emission angle across the two analyzed craters and across the era unit. Hence, assuming that phase angle effects are not involved, the low reflectance of w-cmm_a can be caused by textural changes with genesis of glasses after the melting process (i.e., Johnson et al., 2003), without any direct relation between crystal size and mineral species of the pro-genitor material of w-cmm_a. In this case, all the units of Waters crater would originate from the same surface layer, with an average composition very similar to that of the era unit (intercrater plains) (Fig. 2.4.12a).

However, given its extremely low spectral slope and absolute 700-750 nm reflectance, we can’t either exclude a case where w-cmm_a originates from relatively shallow intrusions of dark material, possibly LRM, compositionally different from the surrounding intercrater plains (era unit) (Fig. 2.4.12b). In this case, Waters units w-cmm_a and w-cmm_b would thus represent the compositional continuum of a single unit, where the spectral differences we observe between w-cmm_a and w-cmm_b would be mainly due to the greater mixing of w-cmm_b with the external surface deposits such as w-cfe and intercrater plains (era unit). Hence, w-cmm_a should
display spectral characteristics more consistent with the real composition of Waters crater impact melt than w-cmm_b.

The interpretation of the spectral characteristics of the units mapped across Kuiper crater is made more challenging and intriguing by the larger size and penetration depth of this crater. Unlike the units at Waters crater, the units of Kuiper crater display similar or higher absolute relative 700–750 nm reflectance to the era unit (Fig. 2.4.9a,b). Overall, Kuiper’s normalized spectra display a generally redder slope than the external reference area in the 350-450 nm window, while they display a generally bluer slope than the external reference area in the 450-650 nm interval. More specifically, in the 350–450 nm interval all units of Kuiper crater show a spectral slope redder than the era unit, with k-cpm being the unit with the largest deviation from the spectral slope of the era unit (Fig. 2.4.9a). In the 450–650 nm interval, k-cmm_b is the only unit displaying slightly redder spectral slope than that of the era unit (Fig. 2.4.9b). During the stratigraphic and compositional interpretation of the units of Kuiper crater we will principally refer to the slope values in the 350–450 nm wavelength range, since this window is farther from the normalization point (700 nm).

Kuiper crater’s deposits are surely less mature than the surrounding intercrater plains (era unit), but the spectral slopes of Kuiper crater’s units in the 350–450 nm wavelength range are much higher than the spectral slope of the era unit (Fig. 2.4.9a). Given the results from the recent studies on the elemental composition of Mercury (i.e., Riner and Lucey, 2012; Izenberg et al., 2014; Weider et al., 2015), space weathering is unlikely to be the dominant process producing the differences in spectral slopes between the deposits of Kuiper crater and the era unit. Rather, this may imply that Kuiper crater excavated material that is compositionally distinct from the intercrater plains (era unit). Additional evidence for compositional heterogeneities between the units exposed by Kuiper crater and the surrounding intercrater plains (era unit) can be found by examining the individual units at Kuiper crater.

The k-cpm unit is composed by the deepest material uplifted during the impact that formed Kuiper crater. This unit displays a much higher 700–750 nm reflectance than the era unit, as shown in Fig. 2.4.9a,b. The high reflectance, spectral slope, and depth of origin of this material suggests that the process which caused the observed spectral configuration of k-cpm was not space weathering. Impact metamorphism might play a role in determining the final spectral output of k-cpm. However, on the basis of previous studies (i.e., Adams et al., 1979; Johnson and Hoerz, 2003), if the metamorphosed k-cpm unit would be characterized by the same composition as the powdered regolith of the era unit, it should display absolute 700-750 reflectance lower than that of the era unit. For this reason we infer that k-cpm is compositionally different from the surrounding intercrater plains (era unit). A spectrally comparable unit, characterized by relatively high albedo and relatively high spectral slope, has been identified and named red material (RM) on the basis of Mariner 10 (Rava and Hapke, 1987; Dzurisin, 1977; Schultz, 1977), and MESSENGER (Robinson et al., 2008; Murchie et al., 2008; Head et al., 2008; Blewett et al., 2009; Kerber et al., 2009) data.
Like \( k \)-cpm, \( k \)-cmm\(_a\) also displays higher absolute 700-750 nm reflectance than the \( era \) unit and significant variability in spectral slope as its mean normalized spectrum approaches the normalization point at 700 nm. The \( k \)-cmm\(_a\) unit originated at shallower depths and likely experienced even higher shock pressures than \( k \)-cpm. Johnson and Hoerz (2003) demonstrated that, for the same pro-genitor material, reflectance at extremely high and melt generating shock pressures (like for \( k \)-cmm\(_a\) unit) should be expected to be lower than reflectance at lower shock pressures that only trigger metamorphism without noticeable melting (like for \( k \)-cpm). As \( k \)-cmm\(_a\) is characterized by absolute 700-750 nm reflectance that is even slightly higher than that of \( k \)-cpm, this implies that \( k \)-cmm\(_a\) could be compositionally different from the \( era \) unit, as well as from \( k \)-cpm. Alternatively, \( k \)-cmm\(_a\) might be composed by a mixture between \( k \)-cpm and other material that is compositionally different from \( k \)-cpm. However, texture might play a role as well.

The MDIS color unit “high-reflectance red plains” (HRP), which corresponds with many of the smooth plains on Mercury (Robinson et al. 2008; Denevi et al. 2009), exhibits spectral characteristics similar to the spectral features of the unit \( k \)-cmm\(_a\). Similar to \( w \)-cmm\(_a\) and \( w \)-cmm\(_b\), the spectral differences between \( k \)-cmm\(_a\) and \( k \)-cmm\(_b\) may be caused by increased mixing with the surrounding surface materials (\( era \) and \( k \)-cfe units). Together with \( k \)-cfe, \( k \)-cmm\(_b\) has an average 700–750 nm reflectance that is more similar to that of the \( era \) unit. Though \( k \)-cmm\(_b\) was mapped to represent the external impact melt of Kuiper crater, MASCS footprints partially include some \( k \)-cfe deposits and the older (more mature) external deposits from Murasaki crater’s floor. The MASCS resolution does not allow small-scale variations in surface materials to be discerned, especially if we try to spectrally differentiate melt veneers (like for \( k \)-cmm\(_b\)) from other surrounding materials. Moreover, the lower thickness of \( k \)-cmm\(_b\) (characterized by very thin melt flows, ponds and veneers), compared to the higher thickness of \( k \)-cmm\(_a\), may negatively affect the reliability of the spectral output of \( k \)-cmm\(_b\). For this reason, the spectral characteristics of \( k \)-cmm\(_b\) should not be directly linked to compositional heterogeneities resulting from a single geologic unit. Geologically, \( k \)-cmm\(_b\) should in fact represent a compositional continuum with the \( k \)-cmm\(_a\). Hence, we infer the same depth of origin and composition for both \( k \)-cmm\(_a\) and \( k \)-cmm\(_b\) (Fig. 2.4.9a).

Of all units mapped in Kuiper crater, \( k \)-cfe is spectrally the most similar to the \( era \) unit (Fig. 2.4.9a,b). However, it is important to note that the spectral slope of \( k \)-cfe remains (as for all the other units of Kuiper crater) considerably higher in the 350–450 nm wavelength range, despite being very similar to that of \( era \) unit in the 450–650 nm range. The absolute 700-750 nm reflectance of \( k \)-cfe is lower than that of the other units of Kuiper crater, but higher than that of the \( era \) unit. This implies that, as for the other units of Kuiper crater, impact metamorphism cannot be the dominant process in determining the observed spectral differences between \( k \)-cfe and the \( era \) unit (Adams et al., 1979; Johnson and Hoerz, 2003). Similarly, if grain-size effects would be the dominant process affecting the observed spectral
differences between *k-cfe* and *era* unit, *k-cfe* should display lower reflectance than the *era* unit since the latter is likely made up of finely powdered regolith whereas the former is composed by fragmental material ejected immediately after the impact. As we observe the opposite situation, we exclude also the grain-size effects and we must infer a compositional difference between *k-cfe* and *era* units. It is not possible to determine if *k-cfe* and *k-cpm* are compositionally different since the *k-cfe* material could acquire a different 700-750 reflectance with respect to *k-cpm* on the basis of the diverse metamorphic degree (i.e. higher metamorphism =lower reflectance) and texture (i.e. finer grain size = higher reflectance).

The spectral characteristics of *k-cft*, as for *k-cmm_b*, are unlikely to represent a single distinct composition that was exposed in the impact event. Impact craters walls usually expose the different subsurface layers penetrated by the impact, thus the spectral characteristics of *k-cft* are interpreted as a mixture of the spectral features of the different excavated layers exposed at the crater wall. The relative position of *k-cft* in the two plots of Fig. 2.4.9a,b appears to be consistent with our interpretation.

Building on the work of Ernst et al. (2010), and given the spectral characteristics of the mapped units, we approximated the vertical stratigraphy beneath Waters crater and Kuiper crater. Using the same analytical methods as Ernst et al. (2010), we calculated a maximum excavation depth of ejecta of ~ 1 km for Waters crater and ~ 4.1 km for Kuiper crater (Holsapple, 1993), while we calculated a maximum melting depth (minimum depth of origin for the central peak) of ~ 1 km for Waters crater (Figs. 2.4.10, 2.4.11, 2.4.12a,b) and ~ 6 km for Kuiper crater (Watters et al. 2009), as displayed in the Figs. 2.4.10, 2.4.11, 2.4.13.

On the basis of our spectral study, we propose that at least two layers with distinctive composition are present beneath Kuiper crater (Fig. 2.4.13). In particular we propose two layers beneath the relatively thin surface coverage of intercrater plains. The middle layer, which may extend to a depth of ~4.1 km, may have a distinct composition or may represent a mixed composition between that of the overlying and underlying layers. The *k-cfe* unit possibly originated from this layer. The depth of ~ 6 km represents the maximum melting depth and also the minimum depth of origin for *k-cpm*. Thus, we assume that *k-cmm_a* and *k-cmm_b* originated from the range of depths between ~ 4.1 and ~ 6 km. Beneath the depth of ~ 6 km (minimum depth of origin for the central peak of Kuiper crater), we are not able to constrain any other limit. From the analysis of the spectral features of *k-cpm*, we infer that material at this depth is characterized by a different composition than surface intercrater plains (*era* unit). In contrast, the spectral differences observed between *k-cpm*, *k-cmm_a* and *k-cfe* do not need to necessarily reflect compositional heterogeneities, as they might be at least partially attributed to other factors like the different grain size and the different shock pressures experienced by these materials during and after the impact process.
Fig. 2.4.1 - Regional area of study, including Waters crater, 15 km diameter, centered at 8.9 S, 105.4 W and Kuiper crater, 62.3 km diameter, centered at 11.3 S, 31.3 W. MDIS monochrome global mosaic at 250 mpp resolution.
Fig. 2.4.2 - Location area of the 15 km diameter Waters crater on Mercury, centered at 8.9 S, 105.4 W. The MDIS NAC image EN0229495136M at 44 mpp is overlain on the MDIS monochrome global mosaic at 250 mpp.
Fig. 2.4.3 - Location area of the 62.3 km diameter Kuiper crater on Mercury, centered at 11.3 S, 31.3 W. This figure is composed of the MDIS NAC images EN0223659984M, EN0228372224M, EN0228372226M, EN0228372268M and EN0228372270M overlain on MDIS WAC image EW0223443634I.
Fig. 2.4.4 - a) Waters crater (8.9 S, 105.4 W) geologic map. The mapped units are: Waters crater peak material (w-cpm), Waters crater floor and terraces (w-cft), Waters crater internal melt material (w-cmm_a), Waters crater external melt material (w-cmm_b) and Waters crater fresh ejecta (w-cfe). b) MASCS coverage over Waters crater (8.9 S, 105.4 W). Moreover, Waters crater rim (w-cr) is defined. Polygons represent MASCS footprints and have been color coded to match the different geologic units displayed in Fig. 2.4.4a. Both panels use MDIS NAC image EN0229495136M at 44 mpp overlain on the MDIS monochromie global mosaic at 250 mpp as their background.
Fig. 2.4.5 - a) Kuiper crater (11.3 S, 31.3 W) geologic map. The mapped units are: Kuiper crater peak material (k-cpm), Kuiper crater floor and terraces (k-cft), Kuiper crater internal melt material (k-cmm_a), Kuiper crater external melt material (k-cmm_b) and Kuiper crater fresh ejecta (k-cfe). Moreover, Kuiper crater rim (k-cr) and Murasaki crater rim (mr) are defined. b) MASCS coverage over Kuiper crater (11.3 S, 31.3 W). Polygons represent MASCS footprints and have been color coded to match the different geologic units displayed in Fig. 2.4.5a. Both panels use MDIS NAC images EN0223659984M, EN0228372224M, EN0228372226M, EN0228372268M and EN0228372270M overlain on MDIS WAC image EW0223443634I as their background.
**Fig. 2.4.6 - a)** External reference area (era), centered at 2.4 N, 83.3 W. This area is 70 km x 100 km in size and is located in a representative region of intercrater plains between Waters crater and Kuiper crater. **b)** MASCS coverage over the external reference area (era), centered at 2.4 N, 83.3 W. Polygons represent MASCS footprints.
Fig. 2.4.7 - MASCS mean normalized spectra for Waters crater (8.9 S, 105.4 W). The spectra have been normalized at 700 nm as an approximate photometric correction. Each mean spectrum is color coded to match the units displayed in Fig. 2.4.4a and the MASCS footprints displayed in Fig. 2.4.4b. a) MASCS mean normalized spectra without smoothing. b) MASCS mean normalized spectra smoothed with a 55 points sampling interval.
Fig. 2.4.8 - MASCS mean normalized spectra for Kuiper crater (11.3 S, 31.3 W). The spectra have been normalized at 700 nm as an approximate photometric correction. Each mean spectrum is color coded to match the units displayed in Fig. 2.4.5a and the MASCS footprints displayed in Fig. 2.4.5b. a) MASCS mean normalized spectra without smoothing. b) MASCS mean normalized spectra smoothed with a 55 points sampling interval.
Fig. 2.4.9 - Absolute average MASCS reflectance in the 700 – 750 nm wavelength range, plotted against the spectral slope calculated from the mean smoothed spectra (Figs. 2.4.7b, 2.4.8b) for each mapped unit. Squares represent Kuiper crater’s units, triangles represent Waters crater’s units, the circle represents the external reference area (era). All units are color coded as in the Figs. 2.4.4a, 2.4.5a, 2.4.6a. a) Absolute average 700 – 750 nm reflectance filtered selecting only MASCS observations with incidence angles between 25° and 35°, and with emission angles between 40° and 50° plotted against the spectral slope in the 350 – 450 nm wavelength window. b) Absolute average 700 – 750 nm reflectance filtered selecting only MASCS observations with incidence angles between 25° and 35°, and with emission angles between 40° and 50° plotted against the spectral slope in the 450 – 650 nm wavelength window. c) Absolute average 700 – 750 nm reflectance filtered selecting all MASCS observations with incidence angles < 72° plotted against the spectral slope in the 350 – 450 nm wavelength window. d) Absolute average 700 – 750 nm reflectance filtered selecting all MASCS observations with incidence angles < 72° plotted against the spectral slope in the 450 – 650 nm wavelength window.
Fig. 2.4.10 - Relationship between rim to rim diameter, transient crater diameter and maximum depth of excavation of ejecta for impact craters on Mercury, according to the analytical method proposed by Holsapple (1993) and used by Ernst et al. (2010). The figure is modified from Ernst et al. (2010). The small triangle indicates the position of Waters crater, the small square indicates the position of Kuiper crater.
Fig. 2.4.11 - Relationship between maximum depth of melting (minimum depth of origin of the central peak) and transient crater diameter for impact craters on Mercury, according to the analytical method proposed by Watters et al. (2009) and used by Ernst et al. (2010). The figure is modified from Ernst et al. (2010). The small triangle indicates the position of Waters crater, the small square indicates the position of Kuiper crater.
Fig. 2.4.12 - Pre-impact stratigraphy beneath Waters crater, reconstructed using the analytical methods of Holsapple (1993) and Watters et al. (2009). a) First possible scenario, where all of the units of Waters crater originate from the same surface layer, with an average composition very similar to that of the \textit{era} unit (intercrater plains). b) Second possible scenario, where \textit{w-cpm}, \textit{w-cft} and \textit{w-cfe} would originate from a uniform layer with composition similar to that of the \textit{era} unit, while the units \textit{w-cmm\_a} and \textit{w-cmm\_b} would originate from shallow intrusions of dark material with a composition different from that of the units \textit{w-cpm}, \textit{w-cft}, \textit{w-cfe} and different from that of the \textit{era} unit.
Fig. 2.4.13 - Pre-impact stratigraphy beneath Kuiper crater, reconstructed using the analytical methods by Holsapple (1993) and Watters et al. (2009). The relative depth of origin of each unit mapped beneath Kuiper crater is displayed to the right of the stratigraphic column. The different scales of grey indicate material with different composition.
2.5 Global scale analysis of 121 globally distributed impact craters

Building on the procedure developed for the local scale approach focused on the combined study between Waters crater and Kuiper crater on Mercury (D’Incecco et al., 2015; sec. 2.4), we set up a procedure for simultaneously retrieving MASCS spectra on a global scale. We defined this approach as a geologically supervised global scale investigation of the spectral characteristics of the shallow crust of Mercury as appears from the exposure of fresh impact related material on Mercury.

2.5.1 Methods and procedure

2.5.1.1 Impact craters’ selection criteria

For the global scale analysis we have selected 121 impact craters which are globally distributed across the surface of Mercury, between 60° N and 60° S latitude (Fig. 2.5.1). We selected the craters on the basis of the following morphologic and morphometric criteria: a) between 20 km and 100 km in diameter, the approximate dimensional range for complex morphology on Mercury (Melosh, 1989; Osinski et al., 2011), b) relatively prominent central peaks, c) fresh morphology, with relatively little affected by the superimposition of smaller (and more recent) primary and secondary craters. We selected craters with complex morphology and relative central peaks the main goal of this study is to identify the vertical and horizontal spectral heterogeneities in the distribution of materials from the subsurface of Mercury. Central peaks are in fact excavated from subsurface layers, so their spectral characteristics can display such compositional heterogeneities. Moreover, selecting craters of the same morphologic class allows the definition of a single set of morphologic units. The quality of the spectral information also plays a key role in the reliability of the generated final results. The resolution of the MASCS instrument is much lower than the resolution of the MDIS camera. For this reason, we selected craters with the freshest (youngest) possible morphology in order to increase the possibilities of observing the real characteristics of impact deposits when analyzing the related MASCS spectra. When analyzing central peaks, we have only very few MASCS observations available covering those small areas. Selecting craters with fresh morphology and prominent central peaks increases the probability that the limited number of spectra we retrieve can fully reflect the composition of the peak materials.

In the case of surrounding ejecta, the problem is not represented by the limited number of MASCS observations (like in the case of central peak materials) but from the gradual transition between the different types of impact ejecta. Previous studies (Melosh, 1989; Osinski et al., 2011), in fact, identified the presence of a thin layer of ejecta blanket (between 1 and 2 crater radii from the point of impact), proximal ejecta (< 5 crater radii from the point of impact) and distal ejecta (between 5 and 10 crater radii from the point of impact). Moreover, space weathering effects tend to uniform the spectral characteristics of all surface materials, making it impossible to identify eventual compositional heterogeneities. For these reasons, selecting
craters with fresh morphology can help identifying the spectral differences occurring between the different types of impact ejecta, reducing the eventual influence of space weathering effects.

2.5.2.2. Units’ definition and nomenclature

Building on the nomenclature provided by Mariner 10 geologic mappers (e.g., Schaber and McCauley, 1980; De Hon et al., 1981; Guest and Greeley, 1983; Grolier and Boyce, 1984; King and Scott, 1990) and more directly on the nomenclature introduced in sec. 2.4.1.1 (D’Incecco et al., 2015), we defined the following units: crater peak material (cpm), crater floor material (cfm), and crater fresh ejecta (efe) at a distance of 1 radius from the crater rim (1 to 2 crater radii from the point of impact). Unlike in sec. 2.4.1.1 (D’Incecco et al., 2015), we defined two additional annuli respectively at 4 to 5 radii (unit 5 R) and 9 to 10 radii distance (unit 10 R) from the crater rim (or 5 to 6 crater and 10 to 11 crater radii from the point of impact, respectively), as shown in Figs. 2.5.2a and 2.5.3a.

Central peaks usually cover small areas and very few MASCS observations are available. Approximating the shape of a central peak to that of a circle increases the number of MASCS observations which would effectively fall within the central peak area. One example is given by the 88 km diameter C030 unnamed crater (23.5° N, 18.2° E), whose central peak is characterized by an extremely irregular shape (Fig. 2.5.4a-c). Mapping the central peak of C030 crater as a circle which includes the whole peak, we selected three MASCS observations (Fig. 2.5.4b). When we precisely mapped the peak approximating its irregular shape, we noticed that only one MASCS observation is really contained within the borders of the peak (Fig. 2.5.4e), while the other two observations do not actually belong to the cpm unit of C030 crater. Performing the calculations on the basis of three observations instead of one – as we see in the case of C030 crater - can lead to a big error in the resulting values. Therefore, in order to preserve the data quality, we use multipolygonal shapefiles to reproduce the real (2D) shape of each central peak.

We defined crater floor material (cfm) as in sec. 2.4.1.1 (D’Incecco et al., 2015). Unlike what we did for cpm units, we have approximated the external borders of cfm units to ellipses, while the internal borders were defined by clipping the area of the cpm units. We did this because we observed that the real external borders of the floor materials are generally less irregular than the borders of cpm units. Furthermore, cfm units contain a much greater number of MASCS observations than cpm units. When considering broader areas and a greater number of MASCS observations falling within these areas, the error is limited. Therefore, cfm units are more suitable than cpm units for being approximated with more geometrical shapes such as ellipses. Moreover, approximating to simpler geometries also helps simplifying and fastening the GIS data processing. We directly experienced the difficulties of GIS software in managing spatial queries when the use of multipolygonal shapefiles with relatively complex (irregular) boundaries is involved, especially if these join analyses have to be performed simultaneously on many units distributed across the planet.
During some preliminary tests where we used complex geometries to reproduce the real borders of cfm unit, the execution of the spatial query halted in the middle of the data processing. We defined cfm units as ellipses, clipping the area of the cpm units from the central portion of each ellipsis. Being simultaneously performed over the 121 craters, this procedure also avoids mapping a big number of units, and makes our analysis more efficient in terms of ratio between reliability of final results and mapping plus data processing time.

Previous studies on the distribution of impact ejecta showed that a layer of continuous fresh ejecta generally surrounds all the fresh impact craters between 1 and 2 crater radii from the crater rim (Melosh, 1989; Osinski et al., 2011). Analyzing the characteristics of impact deposits on Terrestrial planets in the Solar System, Osinski et al. (2011) distinguished between proximal ejecta, within 5 crater radii from the point of impact, and distal ejecta at distances greater than 5 crater radii from the point of impact. For this reason, we have simultaneously created – for all the 121 selected craters - the three annuli extending until 1 radius (cfe unit), 5 radii (5 R unit) and 10 radii (10 R unit) distance from the crater rim. In this way, we can better analyze the variations in the spectral signatures as we move outward from the point of impact to proximal ejecta and distal ejecta (Melosh, 1989; Osinski et al., 2011). Unit cfe can reveal the spectral characteristics of the continuous layer of fresh proximal ejecta. Unit 5 R is located in the zone of transition between proximal and distal ejecta, hence it can provide a spectral characterization of this transition zone. Unit 10 R can instead provide a full spectral characterization of distal ejecta.

We used the same external reference area (era unit) already defined by D’Incecco et al. (2015) for the local scale analysis over Waters crater and Kuiper crater (Fig. 2.4.6a). This area, centered at 2.4°N, 83.3°W and 100 km x 70 km in size, is situated within a region previously mapped by King and Scott (1990) as intercrater plains. Given that era unit encloses a portion of intercrater plains, this area can be used as an absolute term of comparison when analyzing the spectral characteristics of all the other defined units.

2.5.2.3 MASCS observations selection procedure

For this analysis, we used MASCS spectra with the same normalization process described in sec. 2.4.1.2. Due to the great quantity of data, we used only six values per spectrum, where each value represents the mean normalized reflectance of a 10-nm wide interval. The six windows are 345-355 nm, 445-455 nm, 495-505 nm, 545-555 nm, 595-605 nm and 645-655 nm. We have also extracted the mean values of absolute reflectance in the 700-750 nm range. Since multiple observations were available for each defined unit, we calculated the mean of all the values for each of the six intervals to get a single mean normalized spectrum, and we also got a single mean value of absolute reflectance in the 700-750 nm range for each defined unit. After obtaining a single mean spectrum for each defined unit, we calculated a value of spectral slope for the 350-450 nm and 450-650 nm ranges. In the case of the 350-450 nm range, we calculated the spectral slope from the 345-355 nm and 445-455 nm intervals. In the case of the 450-650
nm range, we calculated the spectral slope from the 445-455 nm, 495-505 nm, 545-555 nm, 595-605 nm and 645-655 nm intervals. Before starting the spatial join procedure, we applied a number of preliminary filters to the MASCS dataset.

In order to use the absolute reflectance from data with no preliminary photometric correction, we selected only observations with incidence angles $< 72^\circ$. When comparing Waters and Kuiper craters, we initially selected only observations with incidence angles between 25$^\circ$ and 35$^\circ$ (D’Incecco et al., 2015; sec. 2.4.1.2). However, applying such a narrow filter in the current study would have resulted in too few craters to perform a global study of crustal heterogeneities. We already tested the influence of incorporating incidence angles up to 72$^\circ$ by comparing the results with those of a narrower filter, which includes only incidence angles between 25$^\circ$ and 35$^\circ$ for Waters and Kuiper craters. This test showed that - at least in the case of Waters and Kuiper craters - the final results were not affected by using a broader filter to include all incidence angles $< 72^\circ$ (D’Incecco et al., 2015; sec. 2.4.2).

As a secondary filter for reducing the influence of phase angle effects, we have selected only impact craters between 60$^\circ$ N and 60$^\circ$ S. Hence, we excluded the polar regions where incidence angles are usually higher than in the equatorial region and may potentially lead to a greater influence of phase angle effects when analyzing the absolute 700-750 nm mean reflectance.

We filtered our data also basing on the MASCS instrument operating temperature. During the calibration process, the MASCS instrument operating temperature range was set between -30 °C and +30 °C (i.e., McClintock et al., 2004; McClintock and Lankton, 2007). Sensitivity calculations on the VIRS instrument showed that a signal to noise ratio greater than 200 can be reached at 20 °C (McClintock et al., 2004). Subsequently, during the MESSENGER mission, the MASCS instrument operating temperature range was slightly changed, varying from +10 °C to $> 50$ °C (i.e., Izenberg et al., 2014). In order to be more conservative and optimize the signal to noise ratio, we included only MASCS observations with instrument temperature between 10 °C and 30 °C.

We applied an additional filter to the spatial query we used for retrieving MASCS observations contained within the defined classes of morphologic units. In the GIS software we used, all MASCS observations are in fact represented as diamond-shaped multipolygons with four external vertices, plus a fifth central vertex (i.e., Fig. 2.5.4a-c). To be more conservative, we decided to select only the MASCS observations whose five vertices were all completely contained within the multipolygons representing the defined morphologic units (i.e., Fig. 2.5.4b-e).

When performing the spatial join between all the defined classes of morphologic units with the preliminarily filtered MASCS observations, we used two different approaches.

In the first and more conservative approach (Figs. 2.5.2b,c, 2.5.3b,c), before running the spatial query, we excluded all areas shared by multiple craters. So, after deleting all intersecting areas from the morphologic units defined for the 121 selected impact craters (Figs. 2.4.15b, 2.4.16b), we joined all
MASCS observations completely contained within the non-intersecting areas (Figs. 2.5.2c, 2.5.3c).

In the second and less conservative approach, we also included MASCS observations completely contained within the areas shared by multiple craters (Figs. 2.5.2a, 2.5.3a, 2.5.5a,b). In the case one observation is shared by more craters, we applied the relation “one to many”. Following the “one to many” relation, as many copies of one observation are created as many craters (and morphologic units) that observation is shared by. For example, given two impact craters “Cx” and “Cy”, if a MASCS observation “Z” is found which belongs to both Cx’s 5 R unit and Cy’s 10 R unit, our query will create two copies of the MASCS observation Z, “Zx” and “Zy”: Zx will be included into Cx’s 5 R unit, and Zy will be included to Cy’s 10 R unit. This means that the total number of MASCS observations retrieved with this less conservative approach is actually higher than the real number of MASCS observations effectively contained within all the defined morphologic units, as the observations shared by multiple craters are counted more times. Intersecting areas with relative shared observations can be seen in detail in Fig. 2.5.5b.

We plotted spectral slope from normalized spectra in the 350-450 nm and 450-650 nm intervals, respectively, against the MASCS absolute mean reflectance in the 700-750 nm interval, and spectral slope from normalized spectra in the 350-450 nm interval against that in the 450-650 nm interval. We did this considering for both the used approaches. We initially considered all units containing at least one MASCS observation (Figs. 2.5.6a-c, 2.5.7a-c). Subsequently, we considered only craters with complete dataset, that is only the craters who had at least one available MASCS observation for each of its related morphologic units, from cpm to 10 R units. In the case of the first approach (without shared areas), 34 craters out of the 121 initially selected have a complete dataset (Figs. 2.5.8, 2.5.9a-c, Table 2.5.1). In the case of the second approach (with shared areas), 45 craters out of the 121 initially selected have a complete dataset (Figs. 2.5.11, 2.5.12a-c; Table 2.5.2). For both the 34 craters with complete dataset resulting from the first approach and for the 45 craters with complete dataset resulting from the second approach, we also analyzed longitudinal and latitudinal trends of the spectral slope (normalized to that of unit era) in the 350-450 nm and 450-650 nm ranges, respectively (Figs. 2.5.10a-d, 2.5.13a-d).

Table 2.5.3 displays the values of areal extent and number of observations for both approaches described above, with the relative differences between the two approaches. All quantities are indicated both in terms of absolute values and percentage.

We analyzed the trend of the spectral slope of all craters with complete dataset retrieved using the two different approaches of data selection (Tables 2.5.1, 2.5.2), both in the 350-450 nm and 450-650 nm ranges. On the basis of their spectral characteristics (spectral slope and absolute reflectance), we have selected the following three impact craters for a detailed analysis: a) the 54.9 km diameter C007 (Degas) crater, centered at 37.1° N 127.2° W (Figs. 2.5.8, 2.5.11 and 2.5.14a; Tables 2.5.1, 2.5.2), b)
the 66 km diameter C078 (unnamed) crater, centered at 13.2° S, 89.7° W (Figs. 2.5.8, 2.5.11 and 2.5.14b; Tables 2.5.1, 2.5.2), c) the 71.5 km diameter C064 (unnamed) crater, centered at 0.7° S, 108.3° W (Figs. 2.5.8, 2.5.11 and 2.5.14c; Tables 2.5.1, 2.5.2). The values of normalized slope and absolute reflectance of the three craters (Fig. 2.5.15a-c) are those calculated following the first and more conservative approach.

We display the range of mean values of normalized reflectance in the 345-355 nm, 445-455 nm, 495-505 nm, 545-555 nm, 595-605 nm, 645-655 nm intervals and the range of absolute 700-750 nm mean reflectance, with the relative range of standard deviations from the mean values, for each of the five classes of units (Table 2.5.4), and for the era unit (Table 2.5.5). Table 2.5.5 also displays the total number of MASCS observations contained within the era unit.

2.5.2 Results

The main goal of this work is that of identifying the presence of compositional heterogeneities in the shallow crust of Mercury by analyzing the spectral differences between central peaks, external impact deposits and the surrounding intercrater plains. Following the first and the second approach, respectively, we plotted the spectral slope calculated in the two windows 350-450 nm and 450-650 nm ranges against the absolute 700-750 nm mean reflectance, and the 350-450 nm against the 450-650 nm spectral slopes for: a) all units with available MASCS observations (Figs. 2.5.6a-c, 2.5.7a-c); b) the 34 craters with complete dataset resulting from the first approach (Figs. 2.5.8, 2.5.9a-c); c) the 45 craters with complete dataset resulting from the second approach (Figs. 2.5.11, 2.5.12a-c). As we can see on the plots of Figs. 2.5.6a-c, 2.5.7a-c, 2.5.9a-c and 2.5.12a-c, there is no evident dependency between the results and the two different approaches we have used. For this reason, the results we are going to discuss are valid for both approaches.

The class of cpm units exhibits a relatively wide spectral heterogeneity both compared to the more external classes of units and within the class of cpm units themselves (Figs. 2.5.6a-c, 2.5.7a-c, 2.5.9a-c and 2.5.12a-c). In general, the larger the distance from the crater, the more the spectral signatures of the external units tend to be clustered. The class of units 10 R is the most clustered and its spectral characteristics are similar to those of the unit era (Figs. 2.5.6a-c, 2.5.7a-c, 2.5.9a-c and 2.5.12a-c). Although the values of absolute 700-750 nm mean reflectance may be partially affected by phase angle effects, these results seem to indicate that there is a relatively large spectral diversity among central peaks (unit cpm) and intercrater plains (unit era), while the spectra from more external units (i.e., unit 10 R) are more similar to the mean spectra of the intercrater plains (unit era). In sec. 2.4.2, we already mentioned how recent studies on the elemental composition of Mercury (i.e., Riner and Lucey, 2012; Izenberg et al., 2014; Weider et al., 2015) showed that the abundance of iron on Mercurian surface is not high enough to justify the reddening of spectra due to iron nanophasic particles. For this reason, the wide range of spectral variety found among cpm units, and between the class of cpm units and the more
external classes, reflect the occurrence of compositional heterogeneities in the shallow crust of Mercury. This result is fully consistent with the indications we get from the models of formation of impact craters with complex morphology on Terrestrial planets, which demonstrate that central peaks expose materials from greater depths (i.e., Melosh, 1989; Osinski et al., 2011), with composition eventually different from that of surrounding surface deposits.

The analysis of eventual dependencies of the spectral slope (of each class of units) in the 350-450 nm and 450-650 nm ranges, that we performed both on the 34 craters with complete dataset resulting from the first approach (Fig. 2.5.10a-d) and on the 45 craters with complete dataset resulting from the second approach (Fig. 2.5.13a-d), show that there is no dependency of the spectral slope (in the 350-450 nm and 450-650 ranges) from the longitude (Figs. 2.5.10a,c, 2.5.13a,c). On the other hand, we note a certain dependence of the spectral slope from the latitude (Figs. 2.5.10b,d, 2.5.13b,d). In the 350-450 nm range (Figs. 2.5.10b, 2.5.13b), the trend lines of the spectral slope get steeper as we move from the class of cpm units to the most external class of 10 R units. In the 450-650 nm range (Figs. 2.5.10d, 2.5.13d) we observe a similar scenario, with the only difference that the trend line of the class of 5 R units is steeper than that of the class of 10 R units. In general, the spectral slope of all classes of units decreases with increasing latitudes (from S to N). This result indicates the presence of a global N-S dichotomy in the composition of the shallow crust of Mercury. This compositional dichotomy is better displayed by the cpm units. Space weathering effects eventually mitigate the differences in spectral slope between the more external units (in particular 5 R and 10 R units) and the unit era (Figs. 2.5.10b,d, 2.5.13b,d).

As we mentioned above - analyzing the two lists of craters with complete dataset resulting from the two approaches we have used (Tables 2.5.1 and 2.5.2, respectively) - we notice a general similarity in the results from we get by including or excluding MASCS observation contained within the areas shared by multiple units, with some small differences. In order to better highlight similarities and differences between the two approaches, we looked for craters with constantly increasing as well as decreasing spectral slope from cpm unit to 10 R units, in both the 350-450 nm and 450-650 nm ranges. The main differences we can find regard the C010 (unnamed) crater, the C057 (Tansen) crater, the C047 (Yeats) crater, the C079 (Moody) crater, the C084 (unnamed) crater and the C093 (unnamed) crater. The C057 (Tansen) crater displays a constantly decreasing spectral slope in the 350-450 nm range in the first approach (Table 2.5.1), while it doesn’t in the second approach (Table 2.5.2). The C010 and C047 (unnamed) craters displays a constantly decreasing spectral slope in the 450-650 nm range with the second approach (Table 2.5.2) but not with the first approach (Table 2.5.1). The C079 (Moody), the C084 (unnamed) and the C093 (unnamed) craters, instead, display a constantly decreasing slope in the 450-650 nm range, a constantly decreasing slope in both ranges, and a constantly increasing slope in both ranges with, respectively, but they only have a
complete dataset with the second approach (Table 2.5.2), so they are not included in Table 2.5.1.

The similarities in the results between the two approach are shown by the C004, C105, the C024 and C078 (unnamed) craters, and the C007 (Degas) crater. The C004 unnamed crater displays a constantly increasing spectral slope in the 350-450 nm range with both approaches (Tables 2.5.1, 2.5.2). Similarly, the C105 (unnamed) crater displays a constantly increasing slope in the 450-650 nm range, with both approaches (Tables 2.5.1, 2.5.2). With both approaches the C024 and the C078 (unnamed) craters display constantly decreasing slope in the 350-450 nm and 450-650 nm range, respectively (Tables 2.5.1, 2.5.2). The most interesting is C007 (Degas) crater, which displays a constantly increasing spectral slope in both (350-450 nm and 450-650 nm) wavelength ranges with both approaches (Tables 2.5.1, 2.5.2). From the two lists in Tables 2.5.1 and 2.5.2, we display and discuss with more detail the spectral characteristics of three sample craters with three different spectral configurations: the C007 (Degas) crater, the C078 (unnamed) crater and the C064 (unnamed) crater. The values of normalized slope and absolute reflectance in Figs. 2.5.15a-c and 2.5.16a-c are those calculated following the first and more conservative approach.

The 54.9 km diameter (Degas) crater is centered at 37.1° N 127.2° W (Figs. 2.5.8, 2.5.11, and 2.5.14a; Tables 2.5.1, 2.5.2). As we mentioned above, this is the only craters whose units display – on both the 350-450 nm and 450-650 nm ranges and using both approaches – a constantly increasing spectral slope moving outward from cpm unit to 10 R unit (Fig. 2.5.15a; Tables 2.5.1, 2.5.2). Moreover, all the defined units of this crater display a shallower spectral slope than that of unit era (Fig. 2.5.15a). We can observe a gradual transition from the relatively shallow spectral slope of cpm unit to the steepest slope of unit era (Fig. 2.5.15a). The values of absolute 700-750 nm mean reflectance for the units of this crater are generally much lower than those of unit era (Figs. 2.5.15a-c, 2.5.16a-c). In terms of absolute 700-750 nm mean reflectance and spectral slope, units cpm and cfm of C007 (Degas) crater are the most different from unit era (Fig. 2.5.16a-c). This likely indicates that cpm and cfm units, on C007 (Degas) crater, are compositionally different from the surrounding deposits and from unit era. Given their relatively low values of absolute 700-750 nm mean reflectance, all deposits of C007 (Degas) crater, and in particular cpm and cfm units, might be compared to the Low Reflectance Material (LRM) as defined on the basis of the studies performed on the MDIS dataset (i.e., Robinson et al., 2008; Denevi et al., 2009) and with the dark blue VIRS spectral unit as defined by Izenberg et al. (2014) on the basis of the MASCS dataset.

The 66 km diameter C078 (unnamed) crater is centered at 13.2° S, 89.7° W (Figs. 2.5.8, 2.5.11, and 2.5.14b). All its units display spectral slopes and absolute 700-750 nm mean reflectances similar to those of unit era (Figs. 2.5.15b, 2.5.16a-c). Given their spectral output, all units of C078 (unnamed) crater are compositionally similar to unit era. In this case, we might compare the units of C078 crater with the intermediate plains as defined by Denevi et al. (2009) on the basis of the MDIS dataset or with the average unit defined by Izenberg et al. (2014).
The 71.5 km diameter C064 (unnamed) crater is centered at 0.7° S, 108.3° W (Figs. 2.5.8, 2.5.11 and 2.5.14c). The units of this crater are all characterized by steeper spectral slopes and higher absolute 700-750 nm reflectances than unit *era* (Figs. 2.5.15c, 2.5.16a-c). Given their spectral characteristics, materials from the units *cpm*, *cfm* and *cfe* (1 R) of C064 crater have a high probability to be compositionally different from unit *era* material. The relatively high absolute 700-750 nm mean reflectance and the relatively steep spectral slope characterizing the *cpm*, *cfm* and *cfe* units of C064 crater make these units a possible term of comparison with the High Reflectance Plains (HRP) materials as defined on the basis of the studies of the MDIS dataset (i.e. Robinson et al., 2008; Denevi et al., 2009) or eventually with the bright MASCS VIRS spectral unit from Izenberg et al. (2014).

The three selected craters are located relatively close to each other, all being enclosed in an area of 41° in longitude x 54° in latitude (15°S-39°N; 129°W-88°W) (Figs. 2.5.8, 2.5.11). Since the three craters are also comparable in size, their maximum excavation depth must be also similar (i.e., Ernst et al., 2010; D’Incecco et al., 2015; secs. 2.4.1.3, 2.4.2). This means that the materials of the *cpm* units of the three craters originated from similar depths. If the presence of spectral differences between central peaks and surrounding deposits generally indicates the occurrence of vertical heterogeneities in the composition of the shallow crust of a planet, the differences in spectral characteristics observed between the *cpm* and *cfm* units of the three sample craters reflect as well the presence of short-range horizontal heterogeneities in the composition of the shallow crust of Mercury.
Fig. 2.5.1 - The 121 selected impact craters plotted over the MDIS monochrome global mosaic at 250 mpp resolution. The selection considered only complex and morphologically fresh impact craters between 60° N and 60° S.
Fig. 2.5.2 – a) Global view of the units defined for each of the 121 selected impact craters on the basis of morphologic criteria, b) Global view of the units defined in Fig. 2.5.2a, where areas shared by multiple craters have been eliminated, c) MASCS coverage over the defined units as in Fig. 2.5.2b. We excluded MASCS observations covering areas shared by multiple craters. Polygons represent MASCS footprints and have been color coded to match the different units.
Fig. 2.5.3 – a) Detailed view of a sample area showing the units as defined in Fig. 2.5.2a. b) Same sample area as in Fig. 2.5.3a, after eliminating the areas shared by multiple craters. c) MASCS coverage of the units as shown in Fig. 2.5.3b. MASCS observations covering areas shared by multiple craters are not included.
Fig. 2.5.4 – Detail of the central peak of the 88 km diameter unnamed crater on Mercury, centered at 23.5° N, 18.2° E, identified as C030. MDIS monochrome global mosaic at 250 mpp. a) MASCS coverage (blue polygons). b) MASCS observations completely contained (red polygons) within a circle (white polygon) roughly approximating the central peak of the crater. c) MASCS observation completely contained (red polygon) within the irregular shape more closely reproducing the real boundaries of the central peak of the crater.
Fig. 2.5.5 – a) MASCS coverage of the units as defined in Fig. 2.5.2a. Here we include MASCS observations of areas shared by multiple craters. Polygons represent MASCS footprints and have been color coded to match the different units. b) Detailed view of the MASCS coverage of units as shown in Fig. 2.5.3a. MASCS observations of areas shared by multiple craters are included.
Fig. 2.5.6 – MASCS absolute mean reflectance in the 700-750 nm interval and slope from spectra (normalized at 700 nm) in the 350-450 nm and 450-650 nm intervals, respectively, for all units with available observations, are plotted above. Calculations were made using the first approach, which excludes areas shared by multiple units. a) absolute reflectance vs 350-450 nm slope, b) absolute reflectance vs 450-650 nm slope, c) 350-450 nm slope vs 450-650 nm slope.
Fig. 2.5.7 – MASCS absolute mean reflectance in the 700-750 nm interval and slope from spectra (normalized at 700 nm) in the 350-450 nm and 450-650 nm intervals, respectively, for all units with available observations, are plotted above. Calculations were made using the second approach, which includes areas shared by multiple units. a) absolute reflectance vs 350-450 nm slope, b) absolute reflectance vs 450-650 nm slope, c) 350-450 nm slope vs 450-650 nm slope.
Fig. 2.5.8 – The figure displays the location of 34 out of the 121 initially selected craters which are characterized by a complete dataset. For this selection, MASCS observations of areas shared by multiple craters were excluded as in Fig. 2.5.2b,c and 2.5.3b,c. The 34 craters are plotted over an MDIS monochrome global mosaic at 250 m/pixel resolution.
Fig. 2.5.9 – MASCS absolute mean reflectance in the 700-750 nm interval and slope from spectra (normalized at 700 nm) in the 350-450 nm and 450-650 nm intervals, respectively, of all units defined for each of the 34 craters represented in Fig. 2.5.8, are plotted above. a) absolute reflectance vs 350-450 nm slope, b) absolute reflectance vs 450-650 nm slope, c) 350-450 nm slope vs 450-650 nm slope.
Fig. 2.5.10 – The spectral slope (normalized to that of era unit) of all units defined for the 34 craters in Fig. 2.5.8 - calculated in the 350-450 nm and 450-650 nm intervals, respectively - is plotted against Latitude and Longitude. Trend lines are also indicated.
Fig. 2.5.11 – Location of the 45 craters out of the 121 initially selected, which are characterized by a complete dataset. For this selection, we used the approach which includes MASCS observations of areas shared by multiple craters as in Fig. 2.5.5a,b. The 45 craters are plotted over an MDIS monochrome global mosaic at 250 m/pixel resolution.
Fig. 2.5.12 – MASCS absolute mean reflectance in the 700-750 nm interval and slope from spectra (normalized at 700 nm) in the 350-450 nm and 450-650 nm intervals, respectively, of all units defined for each of the 45 craters represented in Fig. 2.5.11, are plotted above. a) absolute reflectance vs 350-450 nm slope, b) absolute reflectance vs 450-650 nm slope, c) 350-450 nm slope vs 450-650 nm slope.
Fig. 2.5.13 – The spectral slope (normalized to that of era unit) of all units defined for the 45 craters in Fig. 2.5.11 - calculated in the 350-450 nm and 450-650 nm intervals, respectively - is plotted against Latitude and Longitude. Trend lines are also indicated.
Fig. 2.5.14 – a) The 54.9 km diameter Degas crater on Mercury, centered at 37.1° N, 127.2° W. MDIS monochrome global mosaic at 250 mpp. b) A 66 km diameter unnamed crater on Mercury, centered at 13.2° S, 89.7° W, identified as C078. MDIS monochrome global mosaic at 250 mpp. c) A 71.5 km diameter unnamed crater on Mercury, centered at 0.7° S, 108.3° W, identified as C064. MDIS monochrome global mosaic at 250 m/pixel.
Fig. 2.5.15 – MASCS mean reflectance normalized at 700 nm of the three selected craters shown in Fig. 10a-b-c, calculated on six different windows: 345-355 nm, 445-455 nm, 495-505 nm, 545-555 nm, 595-605 nm and 645-655 nm. Mean normalized spectra from: a) Degas crater (37.1° N, 127.2° W), b) C078 unnamed crater (13.2° S, 89.7° W), and c) C064 unnamed crater (0.7° S, 108.3° W).
Fig. 2.5.16 – MASCS absolute mean reflectance in the 700-750 nm interval and slope from spectra (normalized at 700 nm) in the 350-450 nm and 450-650 nm intervals, respectively, of all units defined for each of the 3 selected craters shown in Fig. 2.5.14a,b,c, respectively, are plotted above. a) absolute reflectance vs 350-450 nm slope, b) absolute reflectance vs 450-650 nm slope, c) 350-450 nm slope vs 450-650 nm slope.
Table 2.5.1 – Location, name and size of the 34 impact craters with complete dataset resulting from the more conservative approach which excludes MASCS observations contained within areas shared by multiple craters. The list displays also the craters with slope constantly increasing from \( cpm \) to \( 10 \, R \) unit in the 350-450 nm interval (light green), in the 450-650 nm interval (dark green) and in both intervals (highlighted in green), as well as those with constantly decreasing slope in the 350-450 nm interval (light red) and in the 450-650 nm interval (dark red).

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<td>-123,7</td>
<td>Cezanne</td>
<td>67,4</td>
</tr>
<tr>
<td>C075</td>
<td>-10</td>
<td>121,9</td>
<td>Enwonwu</td>
<td>37,7</td>
</tr>
<tr>
<td>C078</td>
<td>-13,2</td>
<td>-89,7</td>
<td>unnamed</td>
<td>66</td>
</tr>
<tr>
<td>C087</td>
<td>-17,2</td>
<td>58,4</td>
<td>unnamed</td>
<td>66,8</td>
</tr>
<tr>
<td>C095</td>
<td>-22,7</td>
<td>-90,8</td>
<td>unnamed</td>
<td>95,4</td>
</tr>
<tr>
<td>C097</td>
<td>-23,3</td>
<td>112,2</td>
<td>unnamed</td>
<td>71,3</td>
</tr>
<tr>
<td>C101</td>
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<td>80,2</td>
<td>unnamed</td>
<td>75,7</td>
</tr>
<tr>
<td>C105</td>
<td>-32,4</td>
<td>-170,4</td>
<td>unnamed</td>
<td>36</td>
</tr>
<tr>
<td>C107</td>
<td>-33,6</td>
<td>-39,4</td>
<td>unnamed</td>
<td>74</td>
</tr>
<tr>
<td>C114</td>
<td>-42,5</td>
<td>-124</td>
<td>unnamed</td>
<td>??</td>
</tr>
<tr>
<td>C118</td>
<td>-48,1</td>
<td>132,4</td>
<td>unnamed</td>
<td>63</td>
</tr>
<tr>
<td>C120</td>
<td>-49,6</td>
<td>-63,1</td>
<td>unnamed</td>
<td>24,2</td>
</tr>
</tbody>
</table>
Table 2.5.2 – Location, name and size of the 45 impact craters with complete dataset resulting from the less conservative approach which counts also MASCS observations contained within areas shared by multiple craters. The list displays also the craters with slope constantly increasing from $cpm$ to $10 R$ unit in the 350-450 nm interval (light green), in the 450-650 nm interval (dark green) and in both intervals (highlighted in green), as well as those with constantly decreasing slope in the 350-450 nm interval (light red), in the 450-650 nm interval (dark red) and in both intervals (highlighted in red).

<table>
<thead>
<tr>
<th>Crater ID</th>
<th>Center Lat</th>
<th>Center Lon</th>
<th>Feature name</th>
<th>Diameter (km)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>C002</td>
<td>49,1</td>
<td>-107,5</td>
<td>unnamed</td>
<td>42,4</td>
</tr>
<tr>
<td>C004</td>
<td>42,7</td>
<td>89,3</td>
<td>unnamed</td>
<td>55</td>
</tr>
<tr>
<td>C007</td>
<td>37,1</td>
<td>-127,2</td>
<td>Degas</td>
<td>54,9</td>
</tr>
<tr>
<td>C008</td>
<td>36,9</td>
<td>-58,4</td>
<td>unnamed</td>
<td>33,7</td>
</tr>
<tr>
<td>C010</td>
<td>36,3</td>
<td>-115,7</td>
<td>unnamed</td>
<td>59,6</td>
</tr>
<tr>
<td>C016</td>
<td>31,5</td>
<td>88,7</td>
<td>unnamed</td>
<td>29</td>
</tr>
<tr>
<td>C018</td>
<td>30,6</td>
<td>-62,7</td>
<td>unnamed</td>
<td>52,4</td>
</tr>
<tr>
<td>C024</td>
<td>27,4</td>
<td>-117,2</td>
<td>unnamed</td>
<td>49,2</td>
</tr>
<tr>
<td>C026</td>
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<td>-75,1</td>
<td>unnamed</td>
<td>35,2</td>
</tr>
<tr>
<td>C028</td>
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<td>106,3</td>
<td>unnamed</td>
<td>50,6</td>
</tr>
<tr>
<td>C030</td>
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<td>18,2</td>
<td>unnamed</td>
<td>88</td>
</tr>
<tr>
<td>C031</td>
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<td>-103,1</td>
<td>Mickiewicz</td>
<td>85,7</td>
</tr>
<tr>
<td>C036</td>
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<td>-103,8</td>
<td>unnamed</td>
<td>27</td>
</tr>
<tr>
<td>C038</td>
<td>17</td>
<td>58</td>
<td>unnamed</td>
<td>44</td>
</tr>
<tr>
<td>C039</td>
<td>15,7</td>
<td>93,7</td>
<td>unnamed</td>
<td>91</td>
</tr>
<tr>
<td>C040</td>
<td>15,6</td>
<td>39,9</td>
<td>unnamed</td>
<td>35,1</td>
</tr>
<tr>
<td>C044</td>
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<td>-144,7</td>
<td>Balzac</td>
<td>64,8</td>
</tr>
<tr>
<td>C046</td>
<td>9,8</td>
<td>41,8</td>
<td>unnamed</td>
<td>60,1</td>
</tr>
<tr>
<td>C047</td>
<td>9,5</td>
<td>-34,9</td>
<td>Yeats</td>
<td>94,3</td>
</tr>
<tr>
<td>C050</td>
<td>8,4</td>
<td>-67,8</td>
<td>unnamed</td>
<td>20,3</td>
</tr>
<tr>
<td>C052</td>
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<td>-23,5</td>
<td>unnamed</td>
<td>61,6</td>
</tr>
<tr>
<td>C053</td>
<td>5,9</td>
<td>-132,5</td>
<td>Thoreau</td>
<td>68,7</td>
</tr>
<tr>
<td>C056</td>
<td>4,7</td>
<td>155,8</td>
<td>unnamed</td>
<td>54,9</td>
</tr>
<tr>
<td>C057</td>
<td>4,1</td>
<td>-71,6</td>
<td>Tansen</td>
<td>26</td>
</tr>
<tr>
<td>C059</td>
<td>2,9</td>
<td>-47,3</td>
<td>unnamed</td>
<td>51</td>
</tr>
<tr>
<td>C060</td>
<td>2,2</td>
<td>121,3</td>
<td>unnamed</td>
<td>51</td>
</tr>
<tr>
<td>C064</td>
<td>-0,7</td>
<td>-108,3</td>
<td>unnamed</td>
<td>71,5</td>
</tr>
<tr>
<td>C073</td>
<td>-8,5</td>
<td>-123,7</td>
<td>Cezanne</td>
<td>67,4</td>
</tr>
<tr>
<td>C075</td>
<td>-10</td>
<td>121,9</td>
<td>Enwonwu</td>
<td>37,7</td>
</tr>
<tr>
<td>C078</td>
<td>-13,2</td>
<td>-89,7</td>
<td>unnamed</td>
<td>66</td>
</tr>
<tr>
<td>C079</td>
<td>-13,3</td>
<td>145</td>
<td>Moody</td>
<td>82,5</td>
</tr>
<tr>
<td>C084</td>
<td>-15,6</td>
<td>84,9</td>
<td>unnamed</td>
<td>59</td>
</tr>
<tr>
<td>C087</td>
<td>-17,2</td>
<td>58,4</td>
<td>unnamed</td>
<td>66,8</td>
</tr>
<tr>
<td>C090</td>
<td>-19,1</td>
<td>-63,3</td>
<td>Repin</td>
<td>95,4</td>
</tr>
<tr>
<td>C093</td>
<td>-21,3</td>
<td>-76,6</td>
<td>unnamed</td>
<td>43,8</td>
</tr>
<tr>
<td>C095</td>
<td>-22,7</td>
<td>-90,8</td>
<td>unnamed</td>
<td>71,3</td>
</tr>
<tr>
<td>C097</td>
<td>-23,3</td>
<td>112,2</td>
<td>unnamed</td>
<td>75,7</td>
</tr>
<tr>
<td>C100</td>
<td>-24,7</td>
<td>-78</td>
<td>unnamed</td>
<td>31,7</td>
</tr>
<tr>
<td>C101</td>
<td>-27,1</td>
<td>80,2</td>
<td>unnamed</td>
<td>36</td>
</tr>
<tr>
<td>C105</td>
<td>-32,4</td>
<td>-170,4</td>
<td>unnamed</td>
<td>74</td>
</tr>
<tr>
<td>C107</td>
<td>-33,6</td>
<td>-39,4</td>
<td>unnamed</td>
<td>??</td>
</tr>
<tr>
<td>C110</td>
<td>-37,4</td>
<td>45,5</td>
<td>unnamed</td>
<td>59,4</td>
</tr>
<tr>
<td>C114</td>
<td>-42,5</td>
<td>-124</td>
<td>unnamed</td>
<td>63</td>
</tr>
<tr>
<td>C118</td>
<td>-48,1</td>
<td>132,4</td>
<td>unnamed</td>
<td>24,2</td>
</tr>
<tr>
<td>C120</td>
<td>-49,6</td>
<td>-63,1</td>
<td>unnamed</td>
<td>51,5</td>
</tr>
</tbody>
</table>
Table 2.5.3 – Areal extent of the five classes of units defined and number of MASCS observations completely contained within each of them. Both approaches – without (Figs. 2.5.2a-c, 2.5.3a-c) and with (Fig. 2.5.5a,b) shared areas, respectively - are considered, with relative difference values between the two approaches. All calculations are performed on the craters with complete dataset only and on the total number of craters with available values, respectively.

<table>
<thead>
<tr>
<th>Classes of units</th>
<th>Approach without shared areas</th>
<th>Approach with shared areas</th>
<th>Difference between the two approaches</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Area (km²)</td>
<td>n. of MASCS observations within each class of unit</td>
<td>Area (km²)</td>
</tr>
<tr>
<td>34 craters with complete dataset</td>
<td>4650</td>
<td>221</td>
<td>250</td>
</tr>
<tr>
<td>Total unshared</td>
<td>46270</td>
<td>89518</td>
<td>4403</td>
</tr>
<tr>
<td>45 craters with complete dataset</td>
<td>303546</td>
<td>631836</td>
<td>14689</td>
</tr>
<tr>
<td>Total unshared</td>
<td>57653</td>
<td>1480882</td>
<td>2833975</td>
</tr>
<tr>
<td>Complete list of 121 craters</td>
<td>6792750</td>
<td>5236177</td>
<td>96012</td>
</tr>
<tr>
<td>Total</td>
<td>1588637</td>
<td>3794247</td>
<td>52231</td>
</tr>
<tr>
<td>SUM (X)</td>
<td>2906422</td>
<td>6720939</td>
<td>102241</td>
</tr>
</tbody>
</table>
Table 2.5.4 – The table displays the range of (minimum and maximum) mean values of normalized and absolute reflectances observed within each of the five defined classes of units, and the relative standard deviations (minimum and maximum) from the mean values.

<table>
<thead>
<tr>
<th>Type of approach</th>
<th>Types of reflectance</th>
<th>Wavelength intervals</th>
<th>Classes of units</th>
<th>Range of mean values of reflectance observed within each class of units [min-max]</th>
<th>Range of standard deviations from the mean values of reflectance observed within each class of units [min-max]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>cpm</td>
<td>cfm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>345-355 nm</td>
<td></td>
<td>0.43–0.65</td>
<td>0.39–0.62</td>
</tr>
<tr>
<td></td>
<td></td>
<td>445-495 nm</td>
<td></td>
<td>0.61–0.78</td>
<td>0.57–0.76</td>
</tr>
<tr>
<td>Approach without shared areas</td>
<td>Normalized reflectance</td>
<td>495-505 nm</td>
<td></td>
<td>0.69–0.83</td>
<td>0.67–0.82</td>
</tr>
<tr>
<td></td>
<td></td>
<td>545-555 nm</td>
<td></td>
<td>0.77–0.88</td>
<td>0.75–0.87</td>
</tr>
<tr>
<td></td>
<td></td>
<td>595-605 nm</td>
<td></td>
<td>0.83–0.91</td>
<td>0.83–0.91</td>
</tr>
<tr>
<td></td>
<td></td>
<td>645-655 nm</td>
<td></td>
<td>0.90–0.98</td>
<td>0.90–0.95</td>
</tr>
<tr>
<td></td>
<td>“Absolute” reflectance</td>
<td>700-750 nm</td>
<td></td>
<td>0.02–0.10</td>
<td>0.02–0.07</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>345-355 nm</td>
<td>0.42–0.65</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>445-495 nm</td>
<td>0.59–0.78</td>
</tr>
<tr>
<td>Approach with shared areas</td>
<td>Normalized reflectance</td>
<td>495-505 nm</td>
<td></td>
<td>0.68–0.83</td>
<td>0.67–0.82</td>
</tr>
<tr>
<td></td>
<td></td>
<td>545-555 nm</td>
<td></td>
<td>0.77–0.88</td>
<td>0.75–0.87</td>
</tr>
<tr>
<td></td>
<td></td>
<td>595-605 nm</td>
<td></td>
<td>0.83–0.91</td>
<td>0.83–0.92</td>
</tr>
<tr>
<td></td>
<td></td>
<td>645-655 nm</td>
<td></td>
<td>0.90–0.98</td>
<td>0.90–0.95</td>
</tr>
<tr>
<td></td>
<td>“Absolute” Reflectance</td>
<td>700-750 nm</td>
<td></td>
<td>0.02–0.10</td>
<td>0.02–0.10</td>
</tr>
</tbody>
</table>
Table 2.5.5 – The table displays the mean values of normalized and absolute reflectances observed within the *era* unit, and the relative standard deviations from the mean values. The total number of MASCS observations contained within the era unit is also indicated.

<table>
<thead>
<tr>
<th>Types of reflectance</th>
<th>Wavelength intervals</th>
<th>Mean</th>
<th>Standard deviation from the mean</th>
<th>n. of MASCS observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normalized reflectance</td>
<td>345-355 nm</td>
<td>0.46</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td></td>
<td>445-495 nm</td>
<td>0.64</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td></td>
<td>495-505 nm</td>
<td>0.72</td>
<td>0.01</td>
<td></td>
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<tr>
<td></td>
<td>545-555 nm</td>
<td>0.80</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td></td>
<td>595-605 nm</td>
<td>0.87</td>
<td>0.01</td>
<td>441</td>
</tr>
<tr>
<td></td>
<td>645-655 nm</td>
<td>0.92</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>“Absolute” reflectance</td>
<td>700-750 nm</td>
<td>0.05</td>
<td>0.01</td>
<td></td>
</tr>
</tbody>
</table>
2.6 Overview

As a complement of the previous studies performed by the Planetary Emissivity Laboratory (PEL) Group at DLR in Berlin (D’Amore et al. 2010; D’Amore et al. 2011; D’Amore et al. 2012; D’Amore et al. 2013a; D’Amore et al. 2013b; Helbert et al. 2013; Ferrari et al. 2014), in this chapter we exposed procedures and results from a study which uses the MESSENGER dataset to combine visible and near-infrared spectra retrieved from the DLR MASCS database with high-resolution images from the MDIS instrument. Using impact craters as a window to the subsurface layers, we used both a local and a global scale approach in order to identify the eventual presence of vertical and horizontal heterogeneities in the composition occurring between the shallow crust and surface weathered deposits (intercrater plains) on Mercury.

The two approaches allowed identifying the presence of compositional heterogeneities in the shallow crust of Mercury. These compositional heterogeneities are particularly evident when comparing the spectral characteristics of central peaks with those of external deposits, such as intercrater plains (e.g., Trask and Guest, 1975; De Hon et al. 1981; King and Scott, 1990). The spectral characteristics of central peaks are in fact consistent with the models of formation for complex impact craters, which indicate a deeper origin for central peak materials.

The local scale approach also allowed the reconstruction of the pre-impact stratigraphy beneath the study areas, Waters and Kuiper craters. The geologically supervised spectral analysis over these two craters identified spectral and compositional heterogeneities in the shallow crust of Mercury. In particular, this analysis clearly indicated the occurrence of compositional heterogeneities between all materials exposed by Kuiper crater and the surrounding intercrater plains. Two intriguing units, k-cmm_a and w-cmm_a, show spectral characteristics comparable to those of HRP and LRM units, respectively, as identified by Denevi et al. (2009).

The results from the global scale approach indicate that the class of central peaks is the morphologic class which is spectrally and compositionally the most heterogeneous than all the other defined classes. As we move outward from the central peaks to external deposits, the other morphologic classes tend to be more and more spectrally and compositionally homogenous and more similar to intercrater plains. We also identified a dependency of the spectral slopes from latitude. The spectral slopes of the analyzed deposits tend to decrease at increasing latitudes. This result might indicate the presence of a global N-S dichotomy in the composition of the shallow crust of Mercury.

Thanks to its MDIS and MASCS instruments, the MESSENGER mission has revolutionized our global understanding of the geologic and spectral properties of the shallow crust of Mercury. This path will be soon continued by the ESA BepiColombo mission. The MERcury Thermal Infrared Spectrometer (MERTIS), the Spectrometers and Imagers for MPO BepiColombo Integrated Observatory SYStem (SIMBIO-SYS) and the Mercury Imaging X-ray Spectrometer (MIXS) mounted on the
BepiColombo spacecraft, are particularly relevant for this study as they will map morphology, spectral characteristics and elemental composition of the surface of Mercury with higher level of detail compared to MESSENGER MDIS, MASCs and XRS instruments. MERTIS will cover a wavelength interval between 7 µm and 14 µm, globally mapping the mineralogical composition of the surface of Mercury with a spatial resolution of 500 m (i.e., Hiesinger and Helbert, 2010). SIMBIO-SYS will study geology, stratigraphy and global tectonics of Mercury (i.e., Flamini et al., 2010, 2016). This instrument will perform a global mapping in stereo and color imaging as well as in high spatial resolution imaging. The Stereo Channel of SIMBIO-SYS (STC) will provide global color coverage of Mercury at a resolution < 110 m. The High spatial Resolution Imaging Channel (HRIC) will reach a spatial resolution of 5 m/pixel for specific targets of interest. SIMBIO-SYS will also perform imaging spectroscopy in the 400-2000 nm interval. The MIXS instrument will produce global elemental abundance maps of key rock-forming elements to an accuracy of 5-50% (i.e., Fraser et al., 2010). The data retrieved from MERTIS, SIMBIO-SYS and MIXS will allow a likely complete definition of the global morphology and chemical composition of the shallow crust of Mercury. However, the high potential of the instruments mounted on the BepiColombo spacecraft requires comparably efficient techniques of data processing and analysis. The methodologies shown in this chapter are an example of how important it is to be able to efficiently handle global data, and display what can be done in the future with the higher resolution dataset from the BepiColombo mission.
3. Location and extent of recently active lava flows on Venus resulting from the combination between high resolution Magellan radar images and Venus Express 1 μm emissivity data.

3.1 Exploration of Venus prior to Venus Express

Except for a short flyby operated by the Mariner 5 (1967) and Mariner 10 (1974) NASA probes, an extensive exploration of Venus really begun with the Soviet Venera program from 1961 to 1985. Despite the first attempts to reach the orbit of Venus were not successful (Venera 1-3), Venera 4 on June 1967 was the first probe to enter the atmosphere of another planet transmitting data back to Earth. Venera 4 was followed by Venera 5 and 6, which also returned data from the atmosphere of Venus. Venera 7 on August 1970 was instead the first probe to land on another planet being able to transmit data directly from its surface. Venera 8-14 also successfully landed on Venus, with constantly increasing survival times on its surface. While Venera 10 in October 1975 returned the first black and white image, Venera 13 on March 1982 was able to return to Earth the first ever color images from the surface of Venus. The Venera 13 lander also detected the presence of leucite basalts, while the Venera 14 lander identified what has been interpreted to be tholeiitic basalt. The last two probes of the Venera program, Venera 15 and 16, were launched in June 1983 and consisted of two orbiters equipped with special radar able to penetrate the thick cloud coverage of Venus atmosphere. These two probes mapped the northern hemisphere of Venus imaging the whole surface of the planet from the North Pole down to 30° N at a resolution of 1-2 km.

NASA Pioneer Venus 1 and 2 were two twin probes launched in May 1978 to perform different kind of analyses on Venus. Pioneer Venus 1 consisted of an orbiter equipped with a radar mapper which allowed to realize a topographical map of the surface of the planet from 73° N to 63° S with a resolution of 75 km. Pioneer Venus 1 found that Venus was much more spherical than Earth, identifying in Maxwell Montes the highest point of the planet, rising 10.8 km above the planetary datum. Pioneer Venus 2 was instead equipped with four atmospheric probes, a 1.5 meters large probe which was first released into Venusian atmosphere, and three 76 cm diameter smaller probes released immediately after the bigger one. Finally, also the Pioneer Venus 2 main bus entered the atmosphere of Venus. Despite the probes were not projected for it, two of the three smaller probes survived the impact sending data from the surface too. All the four atmospheric probes together with the main bus provided significant data about the atmosphere of Venus.

The Soviet program Vega, consisting of two twin spacecraft launched on December 1985 had the double goal to analyze atmosphere and surface of Venus and to operate a flyby around the Comet Halley. The two spacecraft were both equipped with a lander and with an atmospheric balloon which would have been released by the mother bus during the Venus flyby. Both
the balloons mounted on Vega 1 and 2 provided reliable data during their
descent into the atmosphere, while only the Vega 2 lander was able to
perform a complete analysis of the surface of Venus, identifying a
composition which reminds that of anorthosites of the lunar highlands.
The NASA Magellan orbital probe was launched on May 1989 and its main
goals were a) to realize a global high resolution radar mapping of at least the
70% of the surface of the planet, b) to perform global altimetry
measurements and c) to perform global measurements of the gravitational
field of Venus. Through three cycles of left, right and stereo looking
geometries, the Magellan radar sensor obtained high-resolution images of
the 98% of the surface, 22% of which were stereo images, with a resolution
better than 300 meters (Saunders et al., 1992). The high-resolution radar
images provided by the Magellan mission showed a planet dominated by
volcanism, tectonism, extensive lava flows, and turbulent wind activity on
the surface of Venus. Further studies performed on the impact cratering
record on the surface of Venus allowed establishing that the crust of Venus
is relatively young, it is covered for the 85% by volcanic flows and it
experienced a global resurfacing event around 300 m. y. ago (Strom et al.,
1994). This is another important discover achieved thanks to the data
provided by the Magellan mission.
More recently, the first Europe’s mission to Venus was launched on
November 2005 under the name of Venus Express. The European Space
Agency’s (ESA) Venus Express can be considered as a twin probe of the
previous ESA Mars Express, despite the fact that also other instruments
from other deep space missions like the ESA Rosetta have been used for
designing the Venus Express mission. One of the most relevant scientific
achievements of this mission is that of having showed evidences of recent
volcanic activity, suggesting that volcanism on Venus may have been active
in the last 3 m. y. (i.e. Smrekar et al., 2010).
3.2 Space missions instruments involved in the present study

In the present work we combine data from two instruments mounted on two different spacecraft, the Magellan Radar System sensor used in Synthetic Aperture Radar (SAR) mode and the Venus Express Visible InfraRed and Thermal Imaging Spectrometer (VIRTIS) instrument. Before entering in the details of our study, we will shortly describe the characteristics of both these instruments.

3.2.1 The Magellan Radar System in the SAR mode

The Magellan mission was launched from Cape Canaveral on May 4, 1989. The main goals of the mission were: (1) to provide a global characterization of landforms and tectonic features, (2) to distinguish and understand impact processes, (3) to define and explain erosion, deposition, and chemical processes, (4) to model interior density distribution.

The Magellan Radar System sensor is a single instrument which is able to acquire data in three different modes: SAR imaging mode, radiometer mode and altimeter mode (Fig. 3.2.1). In the SAR and radiometer modes, the Magellan sensor was connected to a large High-Gain Antenna (HGA) dish which also served for communications with Earth. The SAR and radiometer modes operate at a wavelength of 12.6 cm with horizontal parallel transmit/receive polarization (HH). This is in fact the way how microwaves can penetrate the thick layer of Venusian clouds, allowing to collecting data from the surface of Venus (i.e. Ford et al., 1993). While the SAR mode was explicitly used for geologic observations, the radiometer mode was instead used for recording the radio-thermal emission in order to extrapolate the surface temperature of Venus. In the altimeter mode, the sensor was connected to a smaller, nadir-directed horn antenna (ALTA). The altimeter mode was used for topography. The Magellan Radar System interleaved its observations in cycles of SAR, radiometer and altimeter modes respectively (Fig. 3.2.1). More details about the system design have been provided by Johnson et al. (1991) and Saunders et al. (1992).

The Magellan spacecraft scanned approximately the 98% of the surface of Venus during the first three cycles of radar mapping, while a fourth cycle was dedicated to gravity measurements. SAR images reach a spatial resolution of about 300 meters or a pixel resolution of 75 m/pixel. During the three cycles of radar mapping the SAR moved from north to south, being “left-looking” when pointed to east and “right-looking” when pointed to west. Cycle 1 was left-looking and mapped the 83.7% of the planet, with incidence angles ranging between 45° at periapsis and 16° at high latitudes. Cycle 2 was right-looking, and it was devoted to filling gaps left during Cycle 1 mapping and to obtaining radar images from different viewing angles and directions. Cycle 2 covered about the 54.5% of the surface of the planet. Cycle 1 and 2 provided a cumulative coverage of 96%. The target of Cycle 3 was that of acquiring stereo image coverage of the surface. This cycle was left-looking with incidence angles mostly smaller than in the previous two cycles. Moreover, Maxwell Montes underwent a specific mapping during Cycle 3, with incidence angles larger than those of Cycle 1. The 21.3% of the planetary surface was mapped during Cycle 3, raising the
cumulative surface coverage to the actual 98%. The Magellan SAR incidence angles during the three mapping cycles as a function of the latitude are shown in Fig. 3.2.2 (Ford et al., 1993).

3.2.3 The Venus Express mission and the VIRTIS instrument

The European Space Agency’s (ESA) Venus Express mission, launched on November 9, 2005, was devoted to unveil some aspects of the Venusian atmosphere, like the interactions between upper atmosphere and solar wind and the interactions between the lower atmosphere and the surface. The scientific goals of the mission were focused on studying (1) atmospheric structure, (2) atmospheric dynamics, (3) atmospheric composition and chemistry, (4) cloud layer and hazes, (5) energy balance and greenhouse effect, (6) plasma environment and escape processes, and (7) surface properties and geology (i.e. Svedhem et al., 2009). Despite the fact that the study of the atmosphere of Venus was the main scientific target of this mission, in this work we are particularly interested on the point (7) of those mentioned above.

The instruments mounted on the Venus Express orbiting probe in order to achieve such goals are the following (fig. 3.2.3): UV and IR Spectrometer for solar/stellar occultation and Nadir Observations (SPICAV/SOIR), UV-visible-near-IR imaging spectrometer (VIRTIS), Analyzer of Space Plasma and Energetic Atoms (ASPERA), Venus Radio Science (VeRa), Venus Monitoring Camera (VMC), Magnetometer (MAG).

The VIRTIS instrument (Fig. 3.2.3) is an imaging spectrometer which is able to observe in the near-ultraviolet, visible and infrared portions of the electromagnetic spectrum. This instrument is identical to that mounted on the ESA Rosetta spacecraft. For the purposes of our study, we focus on the emissivity data at 1 µm wavelength (infrared) obtained by the VIRTIS instrument.

Fig. 3.2.1 – Magellan observing geometry in the SAR imaging, altimeter, and radiometer modes of operation. Cross-track resolution is obtained from the time-delay (range) coordinate. Along-track resolution comes from Doppler-frequency analysis. Resolution in the radiometer mode is determined from the high-gain antenna pattern (from Ford et al., 1993).
Fig. 3.2.2 – Magellan SAR incidence angles as a function of latitude for the three imaging cycles (from Ford et al., 1993).

Fig. 3.2.3 – Cutaway diagram showing size and location of the instruments mounted on the Venus Express spacecraft. (Copyright: ESA)
3.3 Background

3.3.1 Large volcanic rises on Venus

Large volcanic rises on Venus are characterized by a broadly uplifted topography (i.e., Stofan et al., 1995; Stofan & Smrekar, 2005). Those regions, generally over 1000 km in diameter, have been associated as the surface expression of Earth-like hotspots and mantle upwelling (i.e., Stofan et al., 1995; Stofan & Smrekar, 2005). Nine major Regions have been surely identified and described as large volcanic rises on Venus: Atla Regio (Phillips and Malin, 1984; Senske et al., 1992), Beta Regio (McGill et al., 1981; Campbell et al., 1984), Bell Regio (Basilevsky and Janle, 1987; Janle et al., 1987), Dione Regio (Keddie and Head, 1995), eastern, center and western Eistla Regio (Senske et al., 1992; Grimm and Phillips, 1992; McGill, 1994), Imdr Regio (Stofan et al., 1995; Stofan & Smrekar, 2005). On the basis of the dominant structures characterizing each Regionem, Stofan et al. (1995) divided the volcanic rises into three different morphologic classes: rift-dominated, volcano-dominated and corona-dominated.

Atla and Beta are rift-dominated rises. Both Regiones are cut by 50 to 100 km wide and up to 2 km deep rift valley, extending for thousand kilometers (i.e., Solomon et al., 1992; Smrekar et al., 1997). The rift-dominated are the topographically highest topographic rises and are characterized by large apparent depth of compensation. A minor distribution of large shield volcanoes and coronae has been on on Atla and Beta Regiones (i.e., Smrekar et al., 1997).

Themis, central Eistla and eastern Eistla Regiones have been classified as corona-dominated topographic rises. Those Regiones are contain coronae 200 to approximately 500 km diameter with associated widespread volcanism (i.e., Stofan et al., 1995; Smrekar et al., 1997). Western Eistla, Bell, Dione and Imdr Regiones have been classified as volcano-dominated rises. Volcano-dominated rises are characterized by the presence of one or more volcanic structures large shield volcanoes as defined by Head et al. (1992).

Schaber (1982) observed that the rift-dominated rises (Atla and Beta Regiones) are located on the junction of regional chasmata systems which have been interpreted by Stofan et al. (1995) to be the surface expression of extensional stress state. Corona-dominated rises are instead associated with breakup of a plume or secondary convection (i.e., Stofan et al., 1995; Smrekar et al., 1997). The volcano-dominated rises have been instead associated with mantle plumes comparable with Terrestrial hotspots (McGill et al., 1981; Phillips and Malin, 1984; Smrekar, 1994; Stofan et al., 1995; Smrekar & Parmentier, 1996; Stofan & Smrekar, 2005).

3.3.2 Magmatic centers

Building on the results from the Venera 15 and 16 missions (Barsukov et al., 1986; Slyuta and Kreslavsky, 1990), Head et al. (1992) performed the first global scale classification of volcanic centers on Venus, using the higher spatial resolution provided by the Magellan probe. Head et al. (1992)
divided the magmatic centers on Venus into two main categories: those characterized by surface volcanic accumulation (extrusive centers), and those associated with emplacement and transport of magma at depths (intrusive centers). Large volcanic rises contain morphologies from both categories (Head et al., 1992). For the purposes of this paper, we provide a short outline of the extrusive volcanic centers, ignoring the intrusive members.

Extrusive volcanic centers are characterized by two subunits, the volcanic vents and the volcanic shield fields (i.e., Head et al., 1992). Following the classification from Head et al. (1992), volcanic vents can be further divided into: large volcanoes, ≥ 100 km diameter; intermediate volcanoes, ≥ 20 km and < 100 km; small volcanoes, < 20 km diameter. Head et al. (1992) classified 550 shield fields (concentrations of small volcanoes), 274 intermediate volcanoes, 156 large volcanoes and 86 calderic structures of 60-80 km diameter. We focus on the previous classifications of large volcanoes, as this is relevant for the present work.

Head et al. (1992) observed that large volcanoes are often characterized by circular or concentric central features, and more rarely by radial patterns. Another indication that allows identifying large volcanoes is by their positive topography with a number of lava flows radially distributed around the center of the volcanic edifice (Head et al., 1992). These authors also established the criteria for calculating the width of a large volcano, which can be measured to the distal end of the average associated digitate lava flows, excluding the flow fields spreading in only one direction from the volcanic center.

Crumpler et al. (1997) provided both a morphometric and morphologic classification of large volcanoes on Venus. Crumpler et al. (1997) observed that the main variations in slope on large volcanoes usually occur at the summit area. The summit of large volcanoes can be characterized by circular and radial fractures, complex calderas or caldera-like features, or parasitic smaller edifices (Crumpler et al., 1997). Building on these observations, Crumpler et al. (1997) distinguished three main types of altimetric profiles: 1) straight-sloped cone or shield, 2) straight-sloped cone or shield with a) truncated, b) shallow upper flank slope, or c) depressed summit area, 3) irregular, asymmetric or domic.

Crumpler et al. (1997) also elaborated a morphologic classification of the main structural characteristics of large volcanoes, from simple to more complex ones. Crumpler et al. (1997) distinguish nine different morphologic classes, that we entirely quote in order to avoid ambiguous interpretations: Class I: simple large edifices characterized by a relatively symmetrical outline and distribution of radial flows extending away from a summit region. Class II: edifice surmounted by central caldera(s); Class III: edifice with one or more flanking rift zones arrayed generally radially to the edifice, resembling the flanking rift zones seen on Terrestrial volcanoes such as Kilauea; Class IV: edifice with elongated summit, often with multiple caldera-like features (i.e., Gula Mons); Class V: edifice with multiple or steep topographic summits, which may contain parasitic intermediate volcanoes (i.e., Sapas Mons); Class VI: edifice surrounded by an exterior set
of fractures that generally appear to be radial to the volcanic edifice and commonly predate many of the flow units making up the central part of the edifice (i.e., Sekmet Mons); Class VII: edifice arranged along the axis of a rift trend. Distinguished from Class III by association with large regional rift zones (i.e., Gula Mons and Guor Linea) or through-going rift zones (i.e., Theia Mons and Devana Chasma); Class VIII: radial fractures occur at the center of topographic summit of some volcanoes, frequently with a very high density; Class IX: large volcanoes characterized by corona-like interiors. This class might represent the morphologic term of transition between large volcanoes and coronae that Head et al. (1992) pointed out in their first classification of large volcanoes on Venus.
3.4 Recent volcanism on Idunn Mons

3.4.1 Geologic overview of the study area

Imdr Regio is one of the volcano-dominated rises of Venus, along with Western Eistla Regio, Dione Regio and Bell Regio (Stofan et al., 1995). According to the previous observations by Stofan et al. (1995), Imdr Regio is regionally crossed by wrinkle ridge patterns which indicate a minimum uplift of 200 m. Imdr Regio has been described by Stofan et al. (1995) as being characterized by the least complex morphology of all volcanic rises, with no associated coronae and a relatively small volume of volcanics (48 x \(10^6\) km\(^3\)). On the other hand, Stofan et al. (1995) observed that Imdr Regio is characterized by the highest apparent depth of compensation of all volcanic rises, with its 260 km.

We focus on the analysis of the summit and eastern flank of Idunn Mons (46\(\text{S}; 146\text{W}\)) - a 200 km diameter volcanic structure (Fig. 3.4.1a,b) – where the VIRTIS data show positive variations in the 1 \(\mu\)m emissivity (Mueller et al., 2008; Stofan et al. 2009; Smrekar et al., 2010; Fig. 3.4.2).

The positive variations in the VIRTIS 1 \(\mu\)m emissivity recently observed over the eastern flank of Idunn Mons (Mueller et al., 2008; Stofan et al. 2009; Smrekar et al., 2010) provide a further confirmation to the observations made by Crumpler et al. (1997). Crumpler et al. (1997) proposed that Imdr Regio is likely to be an intermediate stage of evolution, with an active plume.

Idunn Mons (46\(\text{S}; 146\text{W}\), Fig. 3.4.1a,b) is the major volcanic edifice of Imdr Regio. According to the the classification provided by Head et al. (1992), Idunn Mons is a large volcano. We mapped the lineaments for better studying the structural characteristics of the local study area (Fig. 3.4.3). Idunn Mons lies South-East of Olapa Chasma, a long and steep-sided depression whose morphology is similar to that of rifts, and it is surrounded by a set of NW-SE trending wrinkle ridges that most likely predate the latest stage of Idunn Monn volcanism, as we observed no wrinkle ridges on the visible flows associated with Idunn Mons (Fig. 3.4.3). The highest point of the volcano touches the 4335 m above the planetary datum. It is not possible to observe the contacts of the lava flows in proximity of the summit of Idunn Mons, due to the relatively high radar backscattering. However, we can recognize a number a calderic collapses on its top (Fig. 3.4.4). On the basis of the morphologic classification elaborated by Crumpler et al. (1997), outlined in sec. 3.3.2, we might define Idunn Mons as a Class VII volcano. This class includes all volcanic edifices arranged along the axis of a rift trend. In the case of Idunn Mons, the rift trend is represented by Olapa Chasma. Around the volcanic edifice, the local stress-field of Idunn Mons interacts with the regional stress-field of Olapa Chasma to arrange the fractures in a characteristic hourglass pattern (i.e, Lopez et al., 2008). The W-E altimetric profile of Idunn Mons (Fig. 3.4.5) shows a slightly truncated summit area, with gently sloping sides. Building on the morphometric classification of Crumpler et al. (1997), we might describe the profile of Idunn Mons at the transition between a simple straight-sloped cone and a
straight-sloped cone with truncated summit (sec. 3.3.2). On the other hand, we can observe a number of lava flows originating from the flanks of the large volcano, whose contacts and source vents are instead better visible (Fig. 3.4.1a,b). The lowermost lava flows are located ~ 1500 m above the planetary datum. These lava flows are radially distributed around the volcano within an approximate distance of 200 km from the peak of Idunn Mons (Fig. 3.4.1a,b). The only exception is represented by the south-eastern lava flow which is located ~ 900 m above the planetary datum and reaches a distance of ~ 300 km from the Idunn Mons summit area (Figs. 3.4.1a,b). Because of the intense flank eruption activity characterizing its style of volcanism, we might compare Idunn Mons to Gula, Sif and Kunapipi Montes (Stofan et al., 2001). However, the lava flows with digitate morphology characterizing in particular the eastern flank of Idunn Mons and the summit calderas on its top make our study area more suitably comparable to Gula Mons. In any case, the truncated profile of Idunn Mons differs from that of all three volcanic structures analyzed by Stofan et al. (2001).

3.4.2 Methods and procedure

In the present study we combine information from two different datasets: a) thermal emissivity data from the ESA Venus Express VIRTIS (Piccioni et al., 2007) in the atmospheric window at 1 μm (Helbert et al., 2008; Mueller et al., 2008) b) Magellan SAR images at the highest available resolution (75 m/pixel) (Saunders et al., 1992). The procedure we used can be divided into three main steps: a) background SAR image selection, b) geologic mapping of the lava flows on the eastern flank of Idunn Mons c) search for the configuration with the smallest root-mean-square (RMS) error between the simulated the 1 μm emissivity assigned to the mapped lava flows and the VIRTIS observations.

3.4.2.1 Background SAR image selection

We analyzed both left-look and right-look SAR images to achieve as much information as possible from the observable differences in radar backscattering. Variations in radar backscattering can be caused by three main processes: 1) topographic effects, 2) surface roughness, and 3) electrical properties. Topographic effects cause terrains that slope toward the sensor to appear radar brighter and spatially compressed and terrains that slope away from the sensor appear radar darker and spatially extended. Surface roughness has also an effect on radar backscattering. Relatively rough surfaces are characterized by more enhanced radar backscattering than smoother surfaces. Topographic effects are usually the dominant in radar backscattering when Magellan SAR incidence angles are < 20°, while for incidence angles between 20° and 60° surface-roughness effects are the main factors influencing such variations (i.e., Ford et al., 1993). In addition to topographic and surface roughness effects, the intrinsic electrical properties can also affect the radar brightness of a certain terrain. High dielectric constants (depending on composition and/or bulk density) enhance radar backscatter (i.e., Ford et al., 1993).
When choosing between left-look and right-look SAR images we have initially paid attention to the Magellan SAR incidence angles as a function of the latitude. The aim was that of trying to avoid as much as possible the influence of local topography, selecting the radar image with higher incidence angle. However at 46° S, the latitude of Idunn Mons, both left-look and right-look SAR images have been taken with equal incidence angles of approximately 24°. There is not a noticeable difference in backscattering over the eastern side of Idunn Mons between left and right looking images (Fig. 3.4.1a,b). Nevertheless, the left-look image (Fig. 3.4.1a) is less affected than the right-look image (Fig. 3.4.1b) by diffuse scattering in the summit area of Idunn Mons, and it allows a slightly better differentiation of the contacts between the mapped lava flows. Moreover, on the left-look image (Fig. 3.4.1a) we could easily distinguish and map the calderic collapses on the top of Idunn Mons (Fig. 3.4.4). For these reasons, we favored the left-look over the right-look image for our geologic mapping.

3.4.2.2 Geologic mapping

We use the VIRTIS dataset for estimating the variations in emissivity at 1 μm wavelength and the Magellan SAR images for visual interpretation and geologic mapping. Using common GIS software, we create a map from the Magellan SAR images (Fig. 3.4.3), highlighting the main lineaments and the lava flow units characterizing Idunn Mons’ summit area and its eastern flank, where the 1 μm emissivity anomalies are higher.

We mapped the flow units observing variations in radar brightness, visible source vents and slope. We create a polygon from each lava flow unit outline and we insert it as a parameter into the model of top of atmosphere brightness together with a 1 μm emissivity value assigned to this unit.

We defined five lava flow units (lfu) classified with letters from a to e. Lfu-a covers the summit area of Idunn Mons, while lfu-b, lfu-c, lfu-d and lfu-e cover its eastern flank (Fig. 3.4.6). To get more information, for all five mapped lava flows we have also calculated: 1) uppermost elevation, 2) lowermost elevation, 3) average slope, 4) visible extent, 5) average distance from the Idunn Mons’ summit peak (Table 3.4.1).

3.4.2.3 Search of the configuration best approaching VIRTIS observations

We wanted to find the best possible configuration for the five mapped lava flows. We tested eight different scenarios (Figs. 3.4.7 I-VIII, 3.4.8 I-VIII), calculating the value of RMS error for each of them (Table 3.4.2).

We inserted the polygonal shapefiles representing the mapped lava flows as parameters into the model of top of atmosphere brightness, assigning each polygon a simulated value of 1 μm emissivity. At the end of every iteration, the software used for the 1 μm emissivity modeling creates the following output products: a) the 1 μm emissivity map used as input (Fig. 3.4.7 I-VIII); b) the overlay of Magellan left-look image, unit outlines, and separate isolines of the 1 μm top of atmosphere relative brightness as observed by VIRTIS and the modeled relative brightness (Fig. 3.4.8 I-VIII); c) a value of
RMS error between the observed and modelled brightness for each configuration we try (Table 3.4.2). In the configurations I to V we alternatively assign a high value of simulated emissivity to one single lava flow unit, respectively from a to e (Table 3.4.2). In configuration VI we assigned the same value of moderately high simulated 1 μm emissivity to all mapped lava flows. In configuration VIII we assigned instead high values of 1 μm simulated emissivity to lfu-a and lfu-e. In the next section we are going to discuss results and implications related to data showed in Table 3.4.2.

3.4.3 Results

3.4.3.1 VIRTIS 1 μm emissivity modeling

The scenario with the lowest RMS, which best approximates the VIRTIS observations, is the number VII in Figs. 3.4.7, 3.4.8 and in Table 3.4.2. This configuration was obtained assigning extremely high values of simulated emissivity to lfu-b, lfu-c, lfu-d, while assigning very low values of simulated emissivity (close to the background value) to lfu-a, lfu-e. We also tried to find a good fit with the VIRTIS observations by assigning higher values of simulated emissivity to lfu-a and lfu-e which, especially in the SAR left-look image (Fig. 3.4.1a), appear brighter than the other mapped units (scenario VIII in Table 3.4.2). After a number of attempts, the lowest RMS we could obtain in this case is anyway higher than the RMS obtained for configuration VII (Table 3.4.2).

Configuration VI, where we assigned the same moderately high value of simulated emissivity to all the mapped lava flows, is characterized by a relatively low RMS value, slightly higher than that of configuration VII but lower than that of configuration VIII (Table 3.4.2). Configurations I to V instead all display values of RMS error higher than the values of configurations VI to VIII.

3.4.3.2 Radar properties and relations of the mapped flow units

VIRTIS data show a relatively high 1 μm emissivity over the eastern flank of Idunn Mons (Smrekar et al., 2010), and the main target of our study was that of understanding which units could be responsible for this relatively high 1 μm emissivity. We identified five lava flow units, where lfu-a is the summit composite unit of Idunn Mons and lfu-b, lfu-c, lfu-d and lfu-e are flank flows which likely originate from the several fissures situated on the eastern flank of the volcanic edifice (Fig. 3.4.9). Lfu-a is the summit unit (Fig. 3.4.10) with the largest visible extent of all mapped units with its 14458 km², it is characterized by relatively high backscattering, an average slope of 1.1 % and a value of average microwave emissivity of 0.80. (Table 3.4.1). This unit contains the summit area of Idunn Mons that appears to be disrupted by a number of calderic collapses (Fig. 3.4.4). However, due to very uniform radar backscattering characterizing the Idunn Mons’ summit area, lfu-a is most likely a composite unit.

On the north-eastern boundary, separating the summit composite lfu-a from the flank unit lfu-c, a number of fractures with length variable between ~ 10 km and ~ 50 km were identified and mapped (Figs. 3.4.6, 3.4.9). With a
total extent of 1274 km², $Lfu$-c likely originated from this set fractures (Fig. 3.4.9). This unit is characterized by an average slope of 2.4 %, it ranges between 4000 m and 3100 m in elevation and it is 66.7 km distant from the summit peak of Idunn Mons (Fig. 3.4.10; Table 3.4.1). This unit is also characterized by an average microwave emissivity of 0.80 (Table 3.4.1).

$Lfu$-b extends for 1280 km² from the north-eastern boundaries of $Lfu$-c. We identified only two fractures located on the northernmost boundary of this unit, respectively 7 km and 17 km long. $Lfu$-b slopes down from the flank of Idunn Mons with SW-NE direction, with an average slope of 2.5 % and an average microwave emissivity of 0.85 (Table 3.4.1). This unit ranges 3200 m and 2000 m above the planetary datum (Fig. 3.4.10), and it has a 43.8 km average distance from the summit peak of Idunn Mons. The two fractures are therefore located near the lowest point of $Lfu$-b, so they can’t be the source of this lava flow (Fig. 3.4.9). It is instead more likely that $Lfu$-b originates from the same fractures as $Lfu$-c, but from a previous eruption. Alternatively, the source fractures of $Lfu$-b may have been buried by the following eruption that originated lava flow unit c. In both cases $Lfu$-b eruption event predates the formation of $Lfu$-c. Moreover, if $Lfu$-b originated from the same fissures as $Lfu$-c, then the $Lfu$-b eruption event is likely to postdate the eruption which formed the summit composite unit $Lfu$-a. This is clear as the set of fractures that originated $Lfu$-c - and in this case also lava flow unit b - disrupts $Lfu$-a (Figs. 3.4.5, 3.4.9).

$Lfu$-d extends for 2119 km² and it constantly slopes down from the flank of Idunn Mons with a W-E direction. $Lfu$-d is characterized by a slope of 1.7 % (Table 3.4.1), it ranges in elevation between 3000 m and 1900 m above the planetary datum (Fig. 3.4.10), and its distance from the summit peak is 79.2 km. Along with $Lfu$-e, $Lfu$-d is characterized by the highest average microwave emissivity of all mapped units, with a value of 0.86 (Table 3.4.1). There is a ~ 5 km long fracture extending just on the boundary between $Lfu$-a and $Lfu$-d (Fig. 3.4.9). Given its position, it possible to identify this fracture as the potential source of eruption for the $Lfu$-d. There are other two additional fractures of ~ 8 km located on the lowest part of the unit (Fig. 3.4.9). Following the same considerations we made above for the $Lfu$-b, these fractures can’t be the eruption source of this lava flow. While it is clear that lava flow unit d postdates the formation of the summit composite $Lfu$-a, the stratigraphic relation between $Lfu$-c and $Lfu$-d is not clear due to the absence of direct contacts.

With its 4464 km², $Lfu$-e is the most extensive of the flank flows mapped on the eastern side of Idunn Mons (Table 3.4.1). $Lfu$-e is also the most distant and the lowermost of the mapped units from the peak of Idunn Mons (Fig. 3.4.10; Table 3.4.1). This unit is characterized by a very low slope of 1.4 % and its lowermost point reaches a distance of 98 km from the peak of Idunn Mons (Table 3.4.1). $Lfu$-e is crossed by a number of fractures of variable length between 5 km and 36 km (Fig. 3.4.9). This set of fractures is concentrated in the central part of the flow, and most likely they postdate the emplacement of lava flow unit e (Fig. 3.4.9). $Lfu$-e is partially overlain by and thus predates the emplacement of $Lfu$-b, $Lfu$-c and $Lfu$-d. Following this whole discussion, it was possible to reconstruct the post-eruption local
scale stratigraphy beneath the eastern flank of Idunn Mons, relative to the five mapped lava flow units (Fig. 3.4.9). The flank units \textit{lfu-b}, \textit{lfu-c} and \textit{lfu-d} are stratigraphically younger than \textit{lfu-a} and \textit{lfu-e} (Fig. 3.4.11). Idunn Mons was imaged by both left-looking and right-looking geometries at incidence angles of 24°. At this incidence angle, surface roughness is the dominant parameter to affect the resulting radar backscatter. Previous studies (i.e., Pettengill et al., 1992; Wilt, 1992) highlighted how the microwave emissivity of the lava flows of a number of volcanoes on Venus suddenly drops above a certain “critical radius”, for then increasing again at higher altitudes. The critical radius varies from feature to feature, but on average it lies at a planetary radius of about 6054 km (Wilt, 1992). Among the lava flow units we mapped on Idunn Mons, only two \textit{lfu-a} and \textit{lfu-c} lie above 6054 km. In fact, \textit{lfu-a} and \textit{lfu-c} are the units with the lowest observed values of microwave emissivity than all other lava flows mapped on Idunn Mons (Table 3.4.1). However, the microwave emissivity of the lava flow units mapped over the eastern flank of Idunn Mons varies between 0.80 and 0.86. Hence, all values are close to the global mean value of 0.845 seen using horizontal polarization (the same we use in this work), as found by Pettengill et al. (1992). For comparison, Pettengill et al. (1992) observed a much bigger gap between the minimum and the maximum microwave emissivity of Ozza Mons, 0.34 and 0.92, and Sapa Mons, 0.46 and 0.70, respectively. Following those arguments, the relatively high radar backscatter and low microwave emissivity characterizing the \textit{lfu-a} and \textit{lfu-c} might be partially correlated with the decrease in microwave emissivity above the critical radius observed over several Montes across Venus (i.e., Pettengill et al., 1992; Wilt, 1992; Campbell et al., 1997). Chemical weathering on highlands and Montes should act ubiquitously and on a short time scale, causing a general increase in the dielectric constant (i.e, Cambell et al, 1997 and references therein). Basing on this assumption, we can imagine chemical weathering to have partially affected \textit{lfu-a} and \textit{lfu-c} increasing their dielectric constant and radar backscatter, and decreasing their microwave emissivity. However, the drop in microwave emissivity which characterized \textit{lfu-a} and \textit{lfu-c} is limited if compared to that observed on other volcanic structures such as Ozza Mons and Sapa Mons (Pettengill et al., 1992). For this reason, we can consider \textit{lfu-a} and \textit{lfu-c} just beneath the critical radius, and only limitedly affected by chemical weathering. The values of microwave emissivity of the units mapped across Idunn Mons are close to the global average value of 0.845 indicated by Pettengill et al. (1992). Those values are consistent with a dielectric permittivity of ~4.0, which is typical of dry basaltic minerals (i.e., Pettengill et al., 1992).
Fig. 3.4.1 – The figures shows Idunn Mons (46 S; 146 W), a 200 km across volcanic edifice located at Imdr Regio on Venus. a) Magellan left-look SAR image. b) Magellan right-look SAR image.
Fig. 3.4.2 – Magellan SAR image overlain on VIRTIS emissivity anomaly (see color bar) observed by the VIRTIS instrument over the summit area and eastern flank of Idunn Mons (46 S; 146 W). From Smrekar et al. (2010).
Fig. 3.4.3 – Structural map of the 200 km diameter volcano Idunn Mons (46 S; 146 W). Magellan SAR image with left-looking view at 75 m/pixel.
Fig. 3.4.4 – Detailed look of Idunn Mons (46 S; 146 W), displaying the summit caldera and the inferred flat top (Magellan left-look SAR image).
Fig. 3.4.5 – Altimetric profile of Idunn Mons, showing an intermediate morphology between a simple straight-sloped cone and a straight-sloped cone with truncated summit area (Crumpler et al., 1997).
Fig. 3.4.6 – Geologic map of the eastern flank of Idunn Mons (46 S; 146 W), displaying the five lava flow units (lfu) identified during the mapping process. Lfu are classified from a to e. Lfu-a represents the summit composite unit of Idunn Mons, while the Lfu-b, Lfu-c, Lfu-d and Lfu-e are flank units of the volcanic edifice. (Magellan left-look SAR image).
Fig. 3.4.7 – Grayscale image showing the emissivity assigned to the mapped lava flow units in eight different configurations (I-VII). The images are scaled linearly from black indicating 1 μm emissivity = 1 to white indicating 1 μm emissivity = 0.
Fig. 3.4.8 – Overlay of the Magellan SAR image with the mapped unit outlines and isolines for the 1 μm relative brightness as observed by VIRTIS (colored continuous lines) and the simulated brightness as resulting from the eight model 1 μm VIRTIS emissivity maps displayed in Fig. 3.4.7 I-VII (dashed lines).
Fig. 3.4.9 – Detail composite map displaying the overlay between the five lava flow units mapped on the eastern flank of Idunn Mons (Fig. 3.4.5) and related fractures (Fig. 3.4.2).
Fig. 3.4.10 – Overlay between the five mapped lava flow units (lfu) and the elevation map from the Magellan Global Topographic Data Record (GTDR).
Fig. 3.4.11 – Post-eruption stratigraphy of the eastern flank of Idunn Mons. The stratigraphic columns displays the relative position of the five lava flow units (Ifu) mapped on the eastern flank of Idunn Mons.
Table 3.4.1 – The table displays uppermost elevation, lowermost elevation, slope, extent, average distance from the peak and average microwave emissivity for all five lava flow units mapped on the eastern flank of Idunn Mons.

<table>
<thead>
<tr>
<th>Units</th>
<th>Uppermost elevation (m)</th>
<th>Lowermost elevation (m)</th>
<th>Slope (%)</th>
<th>Extent (km²)</th>
<th>Avg. distance from peak (m)</th>
<th>Avg. Microwave Emissivity (ε = 1-R)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lfu-a</td>
<td>4300</td>
<td>2900</td>
<td>1.1</td>
<td>14458</td>
<td>-</td>
<td>0.8</td>
</tr>
<tr>
<td>Lfu-b</td>
<td>3200</td>
<td>2000</td>
<td>2.5</td>
<td>1280</td>
<td>43.8</td>
<td>0.85</td>
</tr>
<tr>
<td>Lfu-c</td>
<td>4000</td>
<td>3100</td>
<td>3.5</td>
<td>1274</td>
<td>66.7</td>
<td>0.80</td>
</tr>
<tr>
<td>Lfu-d</td>
<td>3000</td>
<td>1900</td>
<td>1.7</td>
<td>2119</td>
<td>79.9</td>
<td>0.86</td>
</tr>
<tr>
<td>Lfu-e</td>
<td>3400</td>
<td>1600</td>
<td>1.4</td>
<td>4464</td>
<td>98</td>
<td>0.86</td>
</tr>
</tbody>
</table>

Table 3.4.2 – This table displays the values of simulated 1 μm VIRTIS emissivity assigned to each mapped lava flow. The eight configurations indicated in the table by roman numerals from I to VIII respectively correspond to the eight configurations indicated in Figs. 3.4.7 and 3.4.8 by letters from a to h. The RMS of each non-unique solution is expressed by both the absolute value and the percentage indicating the difference relative to configuration I, the highest obtained RMS.

<table>
<thead>
<tr>
<th>Lava flows</th>
<th>I RMS error = 0.0116</th>
<th>II RMS error = 0.0114</th>
<th>III RMS error = 0.0113</th>
<th>IV RMS error = 0.0112</th>
<th>V RMS error = 0.0114</th>
<th>VI RMS error = 0.0110</th>
<th>VII RMS error = 0.0108</th>
<th>VIII RMS error = 0.0112</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>0.93</td>
<td>0.61</td>
<td>0.61</td>
<td>0.61</td>
<td>0.61</td>
<td>0.78</td>
<td>0.70</td>
<td>0.78</td>
</tr>
<tr>
<td>b</td>
<td>0.61</td>
<td>0.93</td>
<td>0.61</td>
<td>0.61</td>
<td>0.61</td>
<td>0.78</td>
<td>0.93</td>
<td>0.70</td>
</tr>
<tr>
<td>c</td>
<td>0.61</td>
<td>0.61</td>
<td>0.93</td>
<td>0.61</td>
<td>0.61</td>
<td>0.78</td>
<td>0.95</td>
<td>0.70</td>
</tr>
<tr>
<td>d</td>
<td>0.61</td>
<td>0.61</td>
<td>0.61</td>
<td>0.93</td>
<td>0.61</td>
<td>0.78</td>
<td>0.93</td>
<td>0.70</td>
</tr>
<tr>
<td>e</td>
<td>0.61</td>
<td>0.61</td>
<td>0.61</td>
<td>0.61</td>
<td>0.93</td>
<td>0.78</td>
<td>0.61</td>
<td>0.93</td>
</tr>
</tbody>
</table>
4. Conclusions

The present thesis exposed the comparable procedures (DFTs) we used for analyzing the surface characteristics of two different terrestrial planets such as Mercury and Venus in the visible and near-infrared portion of the electromagnetic spectrum. We used visible and near-infrared spectroscopy for identifying the vertical and horizontal heterogeneities in the composition of the shallow crust of Mercury, as well as for localizing the source and extent of the lava flows responsible of the relatively high 1 μm emissivity anomalies observed over the eastern flank of Idunn Mons. The use of DFTs also allowed us the stratigraphic reconstruction of the local study areas of Mercury and Venus.

On Mercury, we used fresh impact craters with complex morphology as a window in the subsurface of the planet. Both the local and global scale approaches confirm that the spectral characteristics of surface deposits tend to be more homogenous as we move from the center of a fresh complex crater to the external areas. Moreover, the global scale study likely identified the presence of a global N-S dichotomy in the composition of the shallow crust of Mercury.

The combination between Venus Express VIRTIS 1 μm emissivity data and Magellan SAR images at the highest resolution, allowed calculating location and extent of the recently active lava flows on Idunn Mons. The results show that flank eruptions are the likely cause of the relatively high 1 μm emissivity anomalies observed by the VIRTIS instrument on the eastern flank of Idunn Mons. The values of microwave emissivity of the lava flows we mapped on Idunn Mons indicate the presence of dry basaltic minerals.

The next ESA BepiColombo mission represents a huge step forward in terms of amount and quality of the data we will be able to retrieve and analyze on Mercury. Similarly, the ESA EnVision, the NASA’s Venus Emissivity, Radio Science, InSAR, Topography, and Spectroscopy (VERITAS) and Deep Atmosphere Venus Investigation of Noble gases, Chemistry, and Imaging (DAVINCI) or comparable proposals represent a great chance to go back to and unveil the secrets of Venus. These future missions will guarantee the possibility of analyzing the chemical and mineralogical composition of the two planets, with a level of precision which has been never reached so far. However, the higher resolution and greater amount of data which are going to be provided by these missions also constitutes a big challenge for the computer techniques we exploit for data processing.

The next goals might be summarized into the following key points: a) identification of the diagnostic spectral features that can be used for distinguishing between volcanically emplaced materials and impact melts using DFTs as the driving tool, and b) improving the synergy between the different constituents of DFTs, managing in the best way the interactions between hardware, OS, GIS software, SQL spatial queries and database.

For this reason, also the efficiency of DFTs has to be improved in order to fit the specific requirements of the future missions.
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Paper I

Shallow crustal composition of Mercury as revealed by spectral properties and geological units of two impact craters.

Credit:

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We have performed a combined geological and spectral analysis of two impact craters on Mercury: the 15 km diameter Waters crater (106°W; 9°S) and the 62.3 km diameter Kuiper crater (30°W; 11°S). Using the Mercury Dual Imaging System (MDIS) Narrow Angle Camera (NAC) dataset we defined and mapped several units for each crater and for an external reference area far from any impact related deposits. For each of these units we extracted all spectra from the MESSENGER Atmosphere and Surface Composition Spectrometer (MASCS) Visible-InfraRed Spectrograph (VIRS) applying a first order photometric correction. For all the mapped units, we analyzed the spectral slope in two wavelength ranges, 350–450 nm and 450–650 nm, and the absolute reflectance in the 700–750 nm range. Normalized spectra of Waters crater display a generally bluer spectral slope than the external reference area over both wavelength windows. Normalized spectra of Kuiper crater generally display a redder slope than the external reference area in the 350–450 nm window, while they display a bluer slope than the external reference area in the 450–650 nm wavelength range. The combined use of geological and spectral analyses enables reconstruction of the local scale stratigraphy beneath the two craters, providing insight into the properties of the shallower crust of Mercury. Kuiper crater, being ~4 times larger than Waters crater, exposes deeper layers with distinctive composition, while the result for Waters crater might indicate substantial compositional homogeneity with the surrounding intercrater plains, though we cannot exclude the occurrence of horizontal compositional heterogeneities in the shallow sub-surface.

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2. Background

2.1. Geology of Mercury after the Mariner 10 mission

The Mariner 10 spacecraft imaged approximately 40% of the surface of Mercury at a resolution more or less comparable to that of Earth-based observations of the Moon (Murray et al., 1974). In the mid-1970s, Mariner 10 science team members identified and divided Mercury’s surface into morphologic and physiographic units such as intercrater plains, heavily cratered terrain and smooth plains (e.g., Trask and Guest, 1975; Gault et al. 1975; Trask, 1976; Strom, 1977; Kiefer and Murray, 1987; Spudis and Guest, 1988). Intercrater plains and heavily cratered terrain represent the oldest units of Mercury and their origins and chronostratigraphic relations have been studied by various authors (e.g., Strom, 1977; Trask and Guest, 1975; Trask and Strom, 1976).

In contrast to the intercrater plains, the smooth plains are characterized by a relatively low density of impact craters and by a smoother surface morphology. In accordance with the studies of Leake (1982), smooth plains have been interpreted by Mariner 10 geologic mappers to be stratigraphically younger than the intercrater plains (i.e., Schaber and McCauley, 1980; De Hon et al., 1981; Guest and Greeley, 1983; Grolier et al., 1660; King and Scott, 1990).

Intercrater plains, heavily cratered terrains and smooth plains were all plausibly emplaced during a very early phase of Mercury’s surface history. The most recent chronostratigraphic periods, the Mansurian (which began between 3.0 and 3.5 Ga) and the Kuiperian (1.0 Ga), are mainly characterized by the emplacement of impact craters and related material (Spudis and Guest, 1988).

2.2. MESSENGER’s studies

Data acquired by the MESSENGER spacecraft have allowed key questions such as the origin of smooth plains to be revisited. The MDIS instrument has imaged 100% of Mercury’s surface at a spatial resolution better than 200 m/pixel. Coupled with new spectra

| Table 1 | MDIS color units (in the center) are compared with global units defined on the basis of geologic interpretation (on the left) and with MASCS VIRS spectral units (on the right). The correspondence is not total, but in some cases the overlap is possible. |
|-----------------------------------------------|
| **GLOBAL GEOLeGIC UNITS** (Mancinelli et al., 2014) | **MDIS COLOR UNITS** (Robinson et al., 2008; Genniti et al. 2009, 2013; Ernst et al., 2010) | **MASCS VIRS UNITS** (Izenberg et al., 2014) |
| Smooth Plains | Smooth Plains | High Reflectance Red Plains (HRP) |
| Intercrater Plains (IP) | Intermediate Terrain (IT) | Intermediate Plains (IP) |
| Bright Intercrater Plains (BIP) | Low Reflectance Material (LRM) | Low Reflectance Blue Plains (LBP) |
| Odin Formation | Bright Crater-Floor Deposits (BCFDs) | Bright |
| Caloris Rough Ejecta (CRE) | Pyroclastic Deposits | Red |
| Dark Material (DM) | | |
| Ejecta Material (EM) | | |
| Red Material (RM) | | |
| Immature Ejecta | | |
provided from both MDIS color data and the MASCS instrument, a more complete and detailed investigation of the crustal properties of Mercury is now possible. Robinson et al. (2008) and Denevi et al. (2009) analyzed the MDIS color images identifying a number of units on the basis of their spectral slope and relative reflectance (Table 1). Denevi et al. (2009) went further linking color units to the morphologic units previously defined using Mariner 10 data. On the basis of MESSENGER flyby data, Denevi et al. (2009) subdivided the former Mariner 10 units into additional units that take into considerations enhanced colors: the smooth plains, the intermediate terrain (IT) and the low-reflectance material (LRM) (Table 1). They also divided the smooth plains into three color subunits: the high-reflectance red plains (HRP), the intermediate plains (IP) and the low-reflectance blue plains (LBP) (Table 1). It is important to note that the intermediate plains as defined by Denevi et al. (2009) and intermediate plains as defined by Mariner 10 authors (e.g., Gröllier et al., 1660; Spudis and Prosser, 1984; King and Scott, 1990) are not the same unit. To avoid any misunderstanding, Whitten et al. (2014) suggested remapping the whole unit, subdividing it into two different parts: intercrater plains and smooth plains.

Mancinelli et al. (2014) performed a comprehensive local scale geologic study of a portion of Raditladi quadrangle. Given the downsampling nature of their approach, these authors used already existing global units such as smooth plains and Odin Formation as defined by Denevi et al. (2013) and also defined a number of new global units. In particular, on the global scale, they defined: bright intercrater plains (BIP), the oldest mapped unit; intercrater plains (IP), including all LRM from Denevi et al. (2009) and ”intermediate plains” from Trask and Dzurisin (1984); material ballistically ejected by the major impacts (EM); Caloris rough ejecta (CRE), covering deposits of Caloris rim and undulated deposits east of Caloris; dark material (DM), characterized by patches of low reflectance material located near or within impact craters (Table 1).

Building on the first findings of Robinson et al. (2008) and Denevi et al. (2009), other important color units have been classified by Ernst et al. (2010), including fresh (immature) crater ejecta, bright crater-floor deposits (BCFDs), and red material (RM) (Table 1). In most cases, fresh crater ejecta are characterized by brighter reflectance and slightly bluer spectral slopes, suggesting that the ejecta has been less affected by space weathering but that it is otherwise compositionally similar to the more mature surrounding deposits (Ernst et al., 2010). BCFDs, now referred to as hollows (Blewett et al., 2010), exhibit significantly higher reflectance and bluer slopes than their surroundings, possibly indicating compositional heterogeneities between the hollows and their surrounding deposits (Blewett et al. 2010). RM units (e.g., Robinson et al. 2008; Ernst et al. 2010) can be associated with central peaks and are characterized by relatively red spectra and high reflectance.

The wealth of orbital data from MESSENGER has allowed the origin of the smooth plains to be investigated in greater detail. Volcanic landforms such as shield volcanoes and volcanic vents had been initially identified within Caloris basin and smooth plains units occur also far away from large basins particularly in the northern hemisphere (e.g., Head et al., 2008, 2009a, 2009b, 2011; Denevi et al., 2013). On the other hand, Rothery et al. (2014) showed that Caloris basin vent floors are not situated at the summit of significant edifices, discounting the occurrence of shield volcanoes in Caloris basin. A subsequent study from Thomas et al. (2014) also showed similar lack of edifices outside of Caloris too. Weider et al. (2015) observations from MESSENGER’S X-Ray Spectrometer (XRS) revealed that Caloris exhibits similar Mg/Si, Ca/Si, and Al/Si values to the northern plains, suggesting that the deposits in Caloris as well as other HRP might share a magnesian alkali-basalt-like composition.

A recent study from Byrne et al. (2015) determined crater size–frequency distributions for six smooth plains units on Mercury, showing that they are comparable to the values obtained by other authors for other smooth plains units (i.e., Denevi et al. 2013) and lower than the values obtained for intercrater plains (i.e., Whitten et al., 2014). Hence, this analysis provided further evidence that smooth plains are stratigraphically younger than intercrater plains. Izenberg et al. (2014) used MASCS data to explore the global spectral properties of Mercury. To visualize the spectral diversity of the planet, they selected three spectral parameters: a) The reflectance at 575 nm wavelength (R575, red), b) the spectral slope at visible and infrared wavelengths, represented by the ratio of reflectance at 415 nm to that at 750 nm (VISr, green), c) the spectral slope at ultraviolet (UV) and visible wavelengths, represented by the ratio of reflectance at 310 nm to that at 390 nm (UVr, blue). Using these parameters, they divided Mercury’s surface into four broad MASCS Visible and Infrared (VIRS) spectral units: average, dark blue, red and bright (Table 1). The average unit is characterized by reflectance within 25% of the mean planetary reflectance, an UVr value between 0.64 and 0.71, and a VISr value between 0.5 and 0.6 (Izenberg et al., 2014). The plains as defined by MDIS color units (e.g., Robinson et al. 2008; Denevi et al. 2009, 2013) fall into this spectral VIRS unit (Izenberg et al. 2014). The dark blue VIRS spectral unit is characterized by spectra both darker than the planetary mean spectrum and less sloped or “bluer” (Izenberg et al., 2014). This unit includes all areas identified as LRM and some areas defined as LBP from the MDIS dataset (i.e., Robinson et al., 2008; Denevi et al., 2009; Denevi et al. 2013). The Red VIRS spectral unit is characterized by spectra that are both higher in reflectance and “redder” than the planetary mean spectrum, with a low UVr (<0.66) and a low VISr (<0.50) (Izenberg et al., 2014). This unit includes pyroclastic deposits defined on the basis of morphology and visible color as having formed through explosive volcanism (e.g., Head et al., 2008; Kerber et al., 2011; Goudge et al., 2014). The bright spectral unit covers a wide range of UVr (0.60–0.74), and it has a higher VISr value and is brighter than the highest reflectance values of the average unit (Izenberg et al., 2014). Hollows (Blewett et al., 2011, 2013; Helbert et al., 2013) have spectral parameters that fall within the bright VIRS spectral unit.

All the units defined above are displayed into Table 1, which compares the MDIS color units defined by Robinson et al. (2008), Denevi et al. (2009, 2013) and Ernst et al. (2010) with the global geologic units defined by Mancinelli et al. (2014) and the MASCS VIRS spectral units defined by Izenberg et al. (2014), respectively.

As a first-order classification, Helbert et al. (2013) have distinguished two mega-regions on the surface of Mercury: an Equatorial Region (ER) encompassing primarily middle latitudes, and a Polar Region (PR) that covers the two poles. Performing a comparative study between the smooth plains within Caloris basin and the smooth plains within Rembrandt basin, they noted that Caloris infill deposits belong mostly to the ER, with some scattered spot of PR, while Rembrandt’s deposits are spectrally more similar to the PR. This is in contrast to earlier findings that suggested that the Caloris basin fill is spectrally similar to the northern plains (e.g., Denevi et al., 2013; Izenberg et al., 2014). The most recent XRS data show only partial similarities between the Caloris plains and the Northern plains, without confirming a complete compositional match (Weider et al., 2015).

3. Regional context

We selected two craters, both located near 10° south of the equator of Mercury, for geological and spectral analyses (Fig. 1a).
This area includes part of two quadrangles: the 15 km diameter Waters crater (106°W, 9°S; Fig. 1b) is located in the H07-Beethoven quadrangle (King and Scott, 1990), while the 62.3 km diameter Kuiper crater (30°W, 11°S; Fig. 1c) falls within the H06-Kuiper quadrangle (De Hon et al., 1981). Since the present study area has been already imaged by the Mariner 10 spacecraft, we build our...
regional overview on the geologic maps created by De Hon et al. (1981) for the H06-Kuiper quadrangle and by King and Scott (1990) for the H07-Beethoven quadrangle.

Kuiper crater represents one of the youngest impact craters on Mercury (De Hon et al., 1981). For this reason, the youngest chronostratigraphic system of Mercury, the Kuiperian system (1.0 Ga ago), is named after this crater (e.g., Spudis and Guest, 1988). Waters crater is also very young, so that both Kuiper crater and Waters crater were classiﬁed by the geologic mappers of the H06 (De Hon et al. 1981) and H07 quadrangles (King and Scott, 1990) as “c5” class craters (with “c5” deﬁned as the class that includes the morphologically and stratigraphically youngest craters on the surface of Mercury).

Waters crater and Kuiper crater are suitable for a direct comparison because they share a number of similarities, such as a young relative age and a certain quantity of external impact melt. Kuiper crater lies on the topographic rim of the preexisting Murasaki crater, and Waters crater similarly lies on the rim of an older unnamed impact basin. For this, the actual morphologic conﬁguration of each of the two craters was inﬂuenced by preexisting topography, causing impact melt to be ejected out of the crater rims (Beach et al., 2012; D’Incecco et al., 2012, 2013; Hawke and Head, 1977; Ostrach et al., 2012).

Kuiper crater is located in a heavily cratered region of the Kuiper quadrangle. At shallow depths, its deposits directly overlap older deposits from Murasaki crater and, at greater depths, an alternation of intercrater plains and “plains and terra material” (De Hon et al., 1981). The unit “plains and terra material” is described by De Hon et al. (1981) as “mostly cratered and intercrater plains materials, which may include some smooth plains and rough terra deposits”, and it extends until Waters crater, which lies directly over these very ancient deposits (King and Scott, 1990). Waters crater is instead surrounded by a thin layer deﬁned as “bright ray or halo material around or emanating from c5 craters”, and was interpreted as fresh ejecta by King and Scott (1990).

Al/Si and Mg/Si ratios from the most recent XRS data (Weider et al., 2015) show that the surroundings of Kuiper crater are richer in Al than the surroundings of Waters crater, while Waters crater is beyond the southern limit of the high-Mg region. XRS data support the Mariner 10 morphologic observation that Waters crater is located on ancient deposits as the values Al/Si and Mg/Si near Waters are consistent with the average composition of intercrater plains and heavily cratered terrain materials (Weider et al., 2015).

An area of Mercury’s surface which includes Waters crater was examined by Izenberg et al. (2014) using the three spectral parameters described in the previous section. They deﬁned the ejecta of Waters crater as fresh crater materials, while they categorized the surrounding area as low-reflectance blue plains (LBP), using the same nomenclature as MDIS color units (Robinson et al. 2008; Denevi et al. 2009). Whitten et al. (2014) mapped a region of Mercury’s surface that includes Waters crater. They deﬁned its ejecta as crater materials, mapping its surroundings as intercrater plains, in partial modiﬁcation of the nomenclature previously established by Mariner 10 authors (De Hon et al. 1981; King and

Fig. 2. (a) Waters crater (8.9 S, 105.4 W) geologic map. The mapped units are: Waters crater peak material (w-cpm), Waters crater floor and terraces (w-cft), Waters crater internal melt material (w-cmm_a), Waters crater external melt material (w-cmm_b) and Waters crater fresh ejecta (w-cfe). (b) MASCS coverage over Waters crater (8.9 S, 105.4 W). Moreover, Waters crater rim (w-cr) is deﬁned. Polygons represent MASCS footprints and have been color coded to match the different geologic units displayed in 2a. Both panels use MDIS NAC image EN0229495136M at 44 mpp overlain on the MDIS monochrome global mosaic at 250 mpp as their background.
The smooth plains mapped by Denevi et al. (2013) do not include Waters crater, Kuiper crater, or their respective surroundings. Thus, the LBP designation assigned by Izenberg et al. (2014) to the region surrounding Waters crater in their spectral Red-Green-Blue map is not consistent with the geological definition of LBP of Denevi et al. (2009).

4. Methods and procedure

To complement the unsupervised hierarchical clustering analysis technique used by D’Amore et al. (2013a,b) and Helbert et al. (2013), we here perform a direct cross-correlation between geological and spectral characteristics through independent geologic mapping and supervised spectral analysis. In contrast to the methods of Izenberg et al. (2014), in which spectral units were defined by spectral parameterization, we define units by identifying geological boundaries in image data and then performing a supervised spectral analysis of these units. Such a geologically supervised analysis can be very effective for a local scale spectral correlation. Our procedure is characterized by three main steps: 1) geologic classification of the two analyzed impact structures with related mapping; 2) extraction of the MASCS observations falling within each of the mapped units; and, 3) approximate reconstruction of the local scale stratigraphy beneath the two analyzed craters.

4.1. Geologic mapping

We defined the following units for both Waters (Fig. 2a) and Kuiper (Fig. 3a) craters: crater peak material (cpm), crater floor and terraces (cft), crater melt material located within the crater rim (cmm_a), crater melt material external to the crater rim (cmm_b). Despite MDIS NAC images show no unequivocal indication of a developed central peak at Waters crater, it is clear the presence of a proto-central peak as Waters crater is at the transition between simple and complex crater morphology.

Considering that previous studies on the distribution of proximal impact ejecta in the Solar System (Melosh, 1989; Osinski et al. 2011) showed that a layer of continuous fresh ejecta generally surrounds all the fresh impact craters within a distance between 1 and 2 crater radii from the crater rim, we defined an annulus extending from the crater rim until a distance of 1 crater radius for both craters. This annulus is mapped as the unit “crater fresh ejecta” (cfe). The unit “cfe”, excludes the areas partially covered by external impact melt (cmm_b) because we interpret the external melt as a unit which postdates and covers the underlying “cfe”. For this reason, the unit “cfe” is partially erased over both Waters and Kuiper craters.

Due to the particular topographic configuration of the two craters, we could not precisely distinguish wall deposits and slump deposits from floor deposits. Moreover, in the case of Waters...
crater, the simpler and bowl shaped morphology did not allow a real separation between wall and floor.

In order to facilitate the differentiation of the units of the two craters, we have added the prefix "w-" to the units mapped at Waters crater, while we have added the prefix "k-" to the units mapped at Kuiper crater. In this way, for instance, the unit cpm will be w-cpm for Waters crater and k-cpm for Kuiper crater.

We have defined an external reference area (era), centered at 2.4° N, 83.3° W (Figs. 1a and 4a), that we use as a comparison for interpreting the spectral characteristics of the units mapped at Kuiper crater and Waters crater. This area, 100 km x 70 km in size, is located between Kuiper crater and Waters crater, within a region previously mapped by King and Scott (1990) as intercrater plains. The reference spectra extracted from this region (Figs. 4b and 5–7) allow us to quantify relative spectral differences between the units mapped for the two craters.

For mapping consistency, we relate the nomenclature of our mapped units to that used by Mariner 10 mappers for the H06 Kuiper and Beethoven quadrangles (e.g. De Hon et al. 1981; King and Scott, 1990). This nomenclature is more properly suited to geologic mapping than the nomenclature more recently proposed by Denevi et al. (2009) and Denevi et al. (2013), which is instead based on the spectral properties of the defined units. However, the w-cmm_a and w-cmm_b units were not mapped by King and Scott (1990). The two units together form a lobate melt flow which moves from the internal (w-cmm_a) to the external (w-cmm_b) surface of Waters crater. As far as Kuiper crater is concerned, De Hon et al. (1981) mapped the units we identified respectively as k-cmm_a and k-cmm_b, as "smooth plains materials". In particular, k-cmm_b is not a typical lobate flow extending from the internal to the external region of the crater of origin. Within the Kuiper crater’s rim, deposits collapsed mostly from the north-western portion of the wall, and the maximum accumulation of k-cmm_a and the melt ejecta of k-cmm_b all point in the same SE direction. These factors indicate that Kuiper crater’s SE margin collapses towards Murasaki crater. In fact, the whole k-cmm_b unit is

![Fig. 4.](image-url) (a) External reference area (era), centered at 2.4 N, 83.3 W. This area is 70 km x 100 km in size and is located in a representative region of intercrater plains between Waters crater and Kuiper crater. (b) MASCS coverage over the external reference area (era), centered at 2.4 N, 83.3 W. Polygons represent MASCS footprints.

![Fig. 5.](image-url) MASCS mean normalized spectra for Waters crater (8.9 S, 105.4 W). The spectra have been normalized at 700 nm as an approximate photometric correction. Each mean spectrum is color coded to match the units displayed in Fig. 2a and the MASCS footprints displayed in Fig. 2b. (a) MASCS mean normalized spectra without smoothing. (b) MASCS mean normalized spectra smoothed with a 55 points sampling interval.
emplaced over the floor of Murasaki, and there is no trace of melt in other directions around the rim of Kuiper crater. This implies that $k$-cmm$_b$ is just emplaced where it would be expected to be emplaced if $k$-cmm$_b$ were impact melt flowing from Kuiper crater. Though we can’t exclude a volcanic origin for $k$-cmm$_b$ within Murasaki crater, there are no visible eruption vents to support a volcanic origin. For these reasons, we interpret Murasaki crater, there are no visible eruption vents to support a volcanic origin. For these reasons, we interpret

4.2. MASCS observations selection procedure

Exploiting the capabilities of specific spatial queries in the DLR MASCS database (D’Amore et al. 2013a,b; Helbert et al. 2013), we selected MASCS observations whose footprints are completely included within the boundaries of each of the units mapped at Waters crater (Fig. 2a and b), Kuiper crater (Fig. 3a and b) and the External Reference Area (Fig. 4a and b). We then calculated spectral slopes and extracted the absolute average reflectance in the 700–750 nm wavelength window. Before calculating the spectral slopes, we applied an additional filter to the data, selecting only the MASCS observations with incidence angle $<72^\circ$, instrument temperature between 10°C and 30°C and with average 700–750 nm reflectance $>0$. To calculate the spectral slope, we normalized the spectra at 700 nm. As our data were not photometrically corrected, we used this normalization as an approximate photometric correction that strongly reduces phase angle effects (D’Amore et al., 2013a,b). Using the filtered data, we calculated the mean values of normalized reflectance for all available observations at each wavelength. We iterated this procedure for each of the units and for the external reference area (era), getting a single mean normalized spectrum for each unit mapped over Waters crater (Fig. 5a) and over Kuiper crater (Fig. 6a). No clear absorption bands are discernible in the shown spectra. Thus, we focus our discussion on the analysis of the spectral slopes. However, the spectra in Fig. 5a and b exhibit relatively high noise, which may potentially affect the calculations of spectral slopes. For this reason, before calculating spectral slopes, we decided to apply a smoothing function with a sampling interval of 55 points to each mean normalized spectrum belonging to each unit of Waters crater (Fig. 5b) and Kuiper crater (Fig. 6b). We have then calculated two different slope values in % for each smoothed mean spectrum: the first slope value was calculated in the 350–450 nm wavelength window (Fig. 7a and c), while the second value was calculated in the 450–650 nm wavelength window (Fig. 7b and d). We selected the upper limit of 650 nm for the second wavelength window in order to avoid getting too close to the normalization point at 700 nm, since near the normalization point all spectra approximately converge to one, nullifying the relative differences in spectral slope occurring between the mapped units.

For extracting the average 700–750 nm reflectance, we have applied another filter. Since the average 700–750 nm reflectance is not photometrically corrected, we selected only observations with incidence angles between 25° and 35° and with emission angles between 40° and 50° (Fig. 7a and b). While this may not remove all phase angle effects, it does eliminate the more extreme viewing geometries. The only exception is represented by the Waters crater internal melt material (w-cmm$_a$), since the only three MASCS observations falling within this unit were obtained at incidence angles of 46° and emission angles between 32° and 33°. We decided to include these observations in our analysis, though we will consider the viewing geometry limitations in our discussion.

However, over the small range of phase angles observed by the MASCS instrument, there is no evidence of a correlation between spectral slope and incidence, emission, or phase angles (Izenberg et al., 2014). Thus, in this work we base our conclusions mainly on observed differences in spectral slope occurring between the analyzed units; we discuss the values of average 700–750 nm reflectance only as a secondary parameter to be investigated in more detail once a photometric correction is available.

4.3. Local scale stratigraphy beneath Waters crater and Kuiper crater

The last step of our analysis is to estimate the relative thickness and depth of origin of the layers excavated by the impact events.

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**Fig. 6.** MASCS mean normalized spectra for Kuiper crater (11.3 S, 31.3 W). The spectra have been normalized at 700 nm as an approximate photometric correction. Each mean spectrum is color coded to match the units displayed in Fig. 3a and the MASCS footprints displayed in Fig. 3b. (a) MASCS mean normalized spectra without smoothing. (b) MASCS mean normalized spectra smoothed with a 55 points sampling interval.
which formed Waters and Kuiper craters. We apply similar methods to those of Ernst et al. (2010), who combined geological mapping with semi-analytical crater scaling rules to estimate the depth of origin of spectrally distinct surface material exposed by impact craters on Mercury. Considering that the maximum excavation depth of ejecta is approximately equal to one-tenth of the transient crater diameter \(D_{tc}\), they used the visible rim to rim diameter \(D_{r}\) to derive the transient crater diameter. Ernst et al. (2010) present three analytical methods for relating \(D_{r}\) to \(D_{tc}\) (Croft, 1985; Melosh, 1989; Holsapple, 1993), but selected the most recent of the three methods (Holsapple, 1993) for their calculations as it is the most comprehensive study and incorporated also experimental observations.

Ernst et al. (2010) also estimated the “maximum depth of melting”, which is the maximum depth of origin of the melt material within and outside of impact craters such as Kuiper and Waters. One important observation made by Ernst et al. (2010) is that the maximum depth of melting can be taken as the minimum depth of origin for the central peaks, since central peaks are made of solid material which arises from greater depths directly penetrating the layer of more liquid impact melt.

The relationship between \(D_{r}\), \(D_{tc}\) and maximum excavation depth of ejecta we found for Kuiper and Waters craters is shown in Fig. 8a, while Fig. 8b shows the analytical relationship between \(D_{tc}\) and the maximum depth of melting. For consistency with the work of Ernst et al. (2010), we have chosen the method from Holsapple (1993) for calculating \(D_{tc}\) and consequently the maximum excavation depth of ejecta for the two craters and we used the method from Watters et al. (2009) for calculating the “maximum melting depth” (minimum depth of origin for the central peak) for Waters and Kuiper crater. These calculations have allowed us to partially reconstruct the local stratigraphy in the crust beneath the two craters, as it was before Waters crater (Fig. 9a and b) and Kuiper crater (Fig. 10) formations.

5. Results

From a first look at both the plots in Fig. 7a and b, we note that Waters crater’s units and Kuiper crater’s units are well localized in spectral reflectance space and not randomly arranged, even assuming that the average 700–750 nm reflectance is partially...
affected by phase angle effects. The units of Kuiper crater all lie up towards the upper right (high 700–750 nm reflectance and high 350–450 nm and 450–650 nm slope), while the units of Waters crater are all located towards the lower left (low 700–750 nm reflectance and low 350–450 nm and 450–650 nm slope) of the two plots in Fig. 7a and b. The era unit exhibits a spectral slope and average reflectance at 700–750 nm that is characteristic of typical intercrater plains. The units of the Kuiper crater show a 350–450 spectral slope and 700–750 nm reflectance higher than the era unit, while the units of Waters crater (except for w-cfe) display a lower 350–450 spectral slope and a lower 700–750 nm reflectance.

Besides compositional variations and phase angle effects, the spectral differences between two or more materials can be caused by several factors. Space weathering acts reddening (steepening) the slope and decreasing the absolute reflectance of the spectra (Fischer and Pieters, 1994; Ernst et al., 2010). On the other hand, previous studies on the spectra of experimentally shocked enstatite in the 350–2500 nm wavelength range (Adams et al., 1979) and plagioclase feldspars in the 400–2500 nm wavelength range (Johnson and Hoerz, 2003), have shown that impact metamorphism induces an overall decreases in reflectance with increasing shock pressures, with only minor variations in the absorption bands or spectral slope. Finally, in the 700–750 nm wavelength range, reflectance decreases with increasing grain size (i.e., Hapke, 1993; Clark and Roush, 1984). Assuming that both
Waters and Kuiper craters expose material relatively fresher and less mature than the surrounding intercrater plains (era unit), the position of the units of Waters crater on both Fig. 7a and b is consistent with space weathering being the dominant cause of the spectral differences observed between the deposits of Waters crater and the External Reference Area (era) deposits. The fresh deposits of Waters crater are generally characterized by spectral slope lower than or similar to that of the more mature deposits of the era unit (Fig. 7a and b), as would be expected if space weathering is the dominant process affecting the spectral slope, though we cannot exclude the presence of compositional heterogeneities.

Looking at the mapped units of Waters crater more in detail (Fig. 7b), we notice that in the 450–650 nm wavelength range the crater’s units exhibit significantly bluer spectral slopes than the era unit: in the case of w-cpm, w-cft and w-cfe units, this is most likely due to shorter exposure to space weathering effects. The absolute 700–750 nm reflectance of w-cpm, w-cft and w-cmm_b is generally similar to that of the era unit. This might indicate that the peak shock pressures reached during Waters crater’s impact were not so high to strongly affect the spectral characteristics of these three units compared to era unit. Moreover, the spectral outputs of w-cft and w-cmm_b are not given by one single material, but most likely represent a mixture of different materials.

The unit w-cfe displays instead higher absolute reflectance than the era unit. Assuming that Waters crater’s impact did not excavate deep into the shallow crust of Mercury, k-cfe might be composed of intercrater plains (era unit) material that has experienced low degree of impact metamorphism. In comparison with the progenitor regolith of intercrater plains (era unit), w-cfe is less mature and might have been more finely powdered after the impact. This might explain the higher absolute reflectance of w-cfe compared to that of era unit.

A different argument can be made for w-cmm_a, which displays a lower spectral slope and a relatively lower absolute average 700–750 nm reflectance compared to the era unit (Fig. 7a and b). Since for w-cmm_a we have included absolute 700–750 nm reflectance values with incidence angles of 46° and emission angles between 32° and 33° – we tested whether phase angle effects are likely to be the cause of the low reflectance of w-cmm_a. In particular, we applied a much broader incidence angle filter of < 72° also to absolute mean 700–750 nm reflectance. As illustrated in Fig. 7c and d, the relative positions of the mapped units remain similar to those in the corresponding plots in Fig. 7a and b. This suggests that the values of absolute reflectance are not dramatically affected by the variations in incidence angle and emission angle across the two analyzed craters and across the era unit. Hence, assuming that phase angle effects are not involved, the low reflectance of w-cmm_a can be caused by textural changes with genesis of glasses after the melting process (i.e., Johnson and Hoerz, 2003), without any direct relation between crystal size and mineral species of the pro-genitor material of w-cmm_a. In this case, all the units of Waters crater would originate from the same surface layer, with an average composition very similar to that of the era unit (intercrater plains) (Fig. 9a).

However, given its extremely low spectral slope and absolute 700–750 nm reflectance, we cannot either exclude a case where w-cmm_a originates from relatively shallow intrusions of dark material, possibly LRM, compositionally different from the surrounding intercrater plains (era unit) (Fig. 9b). In this case, Waters units w-cmm_a and w-cmm_b would thus represent the compositional continuum of a single unit, where the spectral differences we observe between w-cmm_a and w-cmm_b would be mainly due to the greater mixing of w-cmm_b with the external surface deposits such as w-cfe and intercrater plains (era unit). Hence, w-cmm_a should display spectral characteristics more consistent with the real composition of Waters crater impact melt than w-cmm_b.

The interpretation of the spectral characteristics of the units mapped across Kuiper crater is made more challenging and intriguing by the larger size and penetration depth of this crater. Unlike the units at Waters crater, the units of Kuiper crater display similar or higher absolute relative 700–750 nm reflectance to the era unit (Fig. 7a and b). Overall, Kuiper’s normalized spectra display a generally redder slope than the external reference area in the 350–450 nm window, while they display a generally bluer slope than the external reference area in the 450–650 nm wavelength window. More specifically, in the 350–450 nm wavelength window all units of Kuiper crater show a spectral slope redder than the era unit, with k-cpm being the unit with the largest deviation from the spectral slope of the era unit (Fig. 7a). In the 450–650 nm wavelength window, k-cmm_b is the only unit displaying slightly redder spectral slope than that of the era unit (Fig. 7b). During the stratigraphic and compositional interpretation of the units of Kuiper crater we will principally refer to the slope values in the 350–450 nm wavelength range, since this window is farther from the normalization point (700 nm).

As in the case of our analysis of Waters crater, we apply the same logic that given two materials with a similar starting composition, space weathering acts to redden (steepen) and often darken the spectra of the more mature material (Fischer and Pieters, 1994; Ernst et al., 2010). Kuiper crater’s deposits are surely less mature than the surrounding intercrater plains (era unit), but the spectral slopes of Kuiper crater’s units in the 350–450 nm wavelength range are much higher than the spectral slope of the era unit (Fig. 7a). This suggests that space weathering cannot be the dominant process producing the differences in spectral slopes between the deposits of Kuiper crater and the era unit. Rather, this may imply that Kuiper crater excavated material that is compositionally distinct from the intercrater plains (era unit). Additional evidence for compositional heterogeneities between the units exposed by Kuiper crater and the surrounding intercrater plains (era unit) can be found by examining the individual units at Kuiper crater.

The k-cpm unit is composed by the deepest material uplifted during the impact that formed Kuiper crater. This unit displays a much higher 700–750 nm reflectance than the era unit, as shown in Fig. 7a and b. The high reflectance, spectral slope, and depth of origin of this material suggests that the process which caused the observed spectral configuration of k-cpm was not space weathering. Impact metamorphism might play a role in determining the final spectral output of k-cpm. However, on the basis of previous studies (i.e., Adams et al., 1979; Johnson and Hoerz, 2003), if the metamorphosed k-cpm unit would be characterized by the same composition as the powdered regolith of the era unit, it should display absolute 700–750 reflectance lower than that of the era unit. For this reason we infer that k-cpm is compositionally different from the surrounding intercrater plains (era unit). A spectrally comparable unit, characterized by relatively high albedo and relatively high spectral slope, has been identified and named red material (RM) on the basis of Mariner 10 (Rava and Hapke, 1987; Dzurisin, 1977; Schultz, 1977), and MESSENGER (Robinson et al., 2008; Murchie et al., 2008; Head et al., 2008; Blewett et al., 2009; Kerber et al., 2009) data.

Like k-cpm, k-cmm_a also displays higher absolute 700–750 nm reflectance than the era unit and significant variability in spectral slope as its mean normalized spectrum approaches the normalization point at 700 nm. The k-cmm_a unit originated at shallower depths and likely experienced even higher shock pressures than k-cpm. Johnson and Hoerz (2003) demonstrated that, for the same pro-genitor material, reflectance at extremely high and melt generating shock pressures (like for k-cmm_a) should be expected.
to be lower than reflectance at lower shock pressures that only trigger metamorphism without noticeable melting (like for k-cpm). As k-cmm_a is characterized by absolute 700–750 nm reflectance that is even slightly higher than that of k-cpm, this implies that k-cmm_a could be compositionally different from the era unit, as well as from k-cpm. Alternatively, k-cmm_a might be composed by a mixture between k-cpm and other material that is compositionally different from k-cpm. However, texture might play a role as well. The MDIS color unit “high-reflectance red plains” (HRP), which corresponds with many of the smooth plains on Mercury (Robinson et al. 2008; Denevi et al. 2009), exhibits spectral characteristics similar to the spectral features of the unit k-cmm_a.

Similar to w-cmm_a and w-cmm_b, the spectral differences between k-cmm_a and k-cmm_b may be caused by increased mixing with the surrounding surface materials (era and k-cfe units). Together with k-cfe, k-cmm_b has an average 700–750 nm reflectance that is more similar to that of the era unit. Though k-cmm_b was mapped to represent the external impact melt of Kuiper crater, MASCS footprints partially include some k-cfe deposits and the older (more mature) external deposits from Murasaki crater’s floor. The MASCS resolution does not allow small-scale variations in surface materials to be discerned, especially if we try to spectrally differentiate melt veneers (like for k-cmm_b) from other surrounding materials. Moreover, the lower thickness of k-cmm_b (characterized by very thin melt flows, ponds, and veneers), compared to the higher thickness of k-cmm_a, may negatively affect the reliability of the spectral output of k-cmm_b. For this reason, the spectral characteristics of k-cmm_b should not be directly linked to compositional heterogeneities resulting from a single geologic unit. Geologically, k-cmm_b should in fact represent a compositional continuum with the k-cmm_a. Hence, we infer the same depth of origin and composition for both k-cmm_a and k-cmm_b (Fig. 7a).

Of all units mapped in Kuiper crater, k-cfe is spectrally the most similar to the era unit (Fig. 7a and b). However, it is important to note that the spectral slope of k-cfe remains (as for all the other units of Kuiper crater) considerably higher in the 350–450 nm wavelength range, despite being very similar to that of era unit in the 450–650 nm range. The absolute 700–750 nm reflectance of k-cfe is lower than that of the other units of Kuiper crater, but higher than that of the era unit. This implies that, as for the other units of Kuiper crater, impact metamorphism cannot be the dominant process in determining the observed spectral differences between k-cfe and the era unit (Adams et al., 1979; Johnson and Hoberz, 2003). Similarly, if grain-size effects would be the dominant process affecting the observed spectral differences between k-cfe and era unit, k-cfe should display lower reflectance than the era unit since the latter is likely made up of finely powdered regolith whereas the former is composed by fragmental material ejected immediately after the impact. As we observe the opposite situation, we exclude also the grain-size effects and we must infer a compositional difference between k-cfe and era units. It is not possible to determine if k-cfe and k-cpm are compositionally different since the k-cfe material could acquire a different 700–750 reflectance with respect to k-cpm on the basis of the divergent metamorphic degree (i.e. higher metamorphism = lower reflectance) and texture (i.e. finer grain size = higher reflectance).

The spectral characteristics of k-cft, as for k-cmm_b, are unlikely to represent a single distinct composition that was exposed in the impact event. Impact craters walls usually expose the different subsurface layers penetrated by the impact, thus the spectral characteristics of k-cft are interpreted as a mixture of the spectral features of the different excavated layers exposed at the crater wall. The relative position of k-cft in the two plots of Fig. 7a and b appears to be consistent with our interpretation.

Building on the work of Ernst et al. (2010), and given the spectral characteristics of the mapped units, we approximated the vertical stratigraphy beneath Waters crater and Kuiper crater. Using the same analytical methods as Ernst et al. (2010), we calculated a maximum excavation depth of ejecta of ~1 km for Waters crater and ~4.1 km for Kuiper crater (Holsapple, 1993), while we calculated a maximum melting depth (minimum depth of origin for the central peak) of ~1 km for Waters crater (Figs. 8 and 9a and b) and ~6 km for Kuiper crater (Watters et al. 2009), as displayed in the Fig. 8a and b and 10.

On the basis of our spectral study, we propose that at least two layers with distinctive composition are present beneath Kuiper crater (Fig. 10). In particular we propose two layers beneath the relatively thin surface coverage of intercrater plains. The middle layer, which may extend to a depth of ~4.1 km, may have a distinct composition or may represent a mixed composition between that of the overlying and underlying layers. The k-cfe unit possibly originated from this layer. The depth of ~6 km represents the maximum melting depth and also the minimum depth of origin for k-cpm. Thus, we assume that k-cmm_a and k-cmm_b originated from the range of depths between ~4.1 and ~6 km. Beneath the depth of ~6 km (minimum depth of origin for the central peak of Kuiper crater), we are not able to constrain any other limit. From the analysis of the spectral features of k-cpm, we infer that material at this depth is characterized by a different composition than surface intercrater plains (era unit). In contrast, the spectral differences observed between k-cpm, k-cmm_a and k-cfe do not need to necessarily reflect compositional heterogeneities, as they might be at least partially attributed to other factors like the different grain size and the different shock pressures experienced by these materials during and after the impact process.

6. Discussion

The present study uses geologic interpretation and spectral analysis to provide a local scale characterization of two fresh impact craters of Mercury. The spectral analysis highlighted striking differences between Waters crater units and Kuiper crater units: the first being characterized by lower spectral slope and average 700–750 nm reflectance than the second. Furthermore, Kuiper crater’s mean spectra (Fig. 6a and b) display a redder spectral slope than Waters crater’s mean spectra over both the analyzed wavelength windows, while they display a spectral slope redder than the mean spectrum of the era unit in the 350–450 nm wavelength window and a slope bluer than the mean spectrum of the era unit in the 450–650 nm wavelength window. The spectral differences between the units mapped on Waters crater and the surrounding intercrater plains (era unit) do not necessarily need to be linked to compositional heterogeneities and can be explained assuming the dominance of other factors like space weathering and shock metamorphism. However, given the extremely low absolute 700–750 nm reflectance and spectral slope of w-cmm_a, we cannot exclude the occurrence of compositional heterogeneities between this unit and the era unit. For this reason we proposed two different scenarios. A first scenario where Waters crater impact melt (w-cmm_a and w-cmm_b) is compositionally homogeneous with the other units mapped over Waters crater and with the surrounding intercrater plains (unit era). A second scenario where Waters crater’s impact melt (units w-cmm_a and w-cmm_b) is compositionally different from the other units of Waters crater and from the surrounding intercrater plains. In the latter case, we suggest a similarity between with the MDIS color LRM unit (Robinson et al. 2008; Denevi et al. 2009) and the Waters crater impact melt.
Kuiper crater's units display instead a much more variable spectral slope, as all its units in the 350–450 nm range are characterized by much higher values than that of the era unit, while almost the opposite happens in the 450–650 nm range. Given that a) spectral slope increases with space weathering (Fischer and Pieters, 1994), b) in the 700–750 nm range, absolute reflectance of experimentally shocked impact deposits generally decreases with increasing shock pressures (Adams et al., 1979; Johnson and Hoerz, 2003), and c) in the 700–750 nm range, absolute reflectance decreases with increasing grain size, we assume the occurrence of compositional heterogeneities between the units of Kuiper crater (in particular k-cpm, k-cmm_a and k-cfe) and the surrounding intercrater plains (era unit). We also infer the possible occurrence of compositional heterogeneities between k-cpm, k-cmm_a and k-cfe. However, we cannot exclude that k-cpm, k-cmm_a and k-cfe are characterized by materials of the same compositions looking spectrally different due to Kuiper-impact and post-impact processes (impact melting and metamorphism).

7. Conclusions

The geosupervised spectral analysis over Watera and Kuiper crater identified spectral and compositional heterogeneities in the shallow crust of Mercury. In particular, this analysis clearly indicated the occurrence of compositional heterogeneities between all materials exposed by Kuiper crater and the surrounding intercrater plains. Two intriguing units, k-cmm_a and w-cmm_a, show spectral characteristics comparable to those of HRP and LRM units, respectively, as identified by Denevi et al. (2009). The higher spectral resolution of the future ESA BepiColombo mission will provide an even deeper look into the crustal properties of Mercury, with its Spectrometers and Imagers for Mercury Planetary Orbiter (MPO) BepiColombo Integrated Observatory System (SIMBIO-SYS) and Mercury Thermal Infrared Spectrometer (MERTIS) instruments. Both SIMBIO-SYS and MERTIS will allow discerning with improved precision among the various factors (i.e., chemical composition, texture, degree of metamorphism) affecting the spectral output of materials within the shallow crust of Mercury, especially those exposed by impact craters. Waiting for the new BepiColombo dataset, we are currently extending this geosupervised supervised procedure to include many more fresh impact craters in order to realize a global-scale stratigraphic investigation of the shallow crust of Mercury using the MDS dataset and the capabilities of the DLK MASCs database.

Acknowledgments

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Paper II

A geologically supervised spectral analysis of 121 globally distributed impact craters as a tool for identifying vertical and horizontal heterogeneities in the composition of the shallow crust of Mercury.

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A geologically supervised spectral analysis of 121 globally distributed impact craters as a tool for identifying vertical and horizontal heterogeneities in the composition of the shallow crust of Mercury

Piero D’Incecco a, b, Jörn Helbert a, Mario D’Amore a, Sabrina Ferrari a, James W. Head b, Alessandro Maturilli a, Harald Hiesinger c

a Institute of Planetary Research, German Aerospace Center, Rutherfordstrasse 2, D-12489 Berlin, Germany
b Department of Geological Sciences, Brown University, Providence, RI 02912, USA
c Westfälische Wilhelms-Universität Münster, Institut für Planetologie, Wilhelm-Klemm Str. 10, D-48149 Münster, Germany

**Abstract**

In the present work, we expose procedures and results from a global scale geologically supervised spectral analysis of 121 impact craters on Mercury, selected on the basis of specific morphologic criteria. Using the capabilities of DFTs developed by PEL researchers at DLR, we combined MASCS spectra from the DLR database with MDIS high-resolution images. We use impact structures as a window for identifying vertical and horizontal compositional heterogeneities in the shallow crust of Mercury. Using specific GIS queries on a global scale, we defined five morphologic classes of units for each of the 121 impact craters, moving outward from the central peak to deposits at ten radii distance from the crater rim. We also used an external reference area as a term of comparison to represent intercrater plains. We then retrieved all the available MASCS spectra contained within each of those units. We analyzed the spectral slopes in the 350–450 nm and 450–650 nm ranges and reflectances in the 700–750 nm range using two different approaches, the first one being more conservative than the second one. The results indicate that the central peaks class is spectrally the most homogeneous compared to all the other defined classes. As we move outward from the central peaks to external deposits, the other morphologic classes tend to get more and more spectrally and compositionally homogeneous and more similar to intercrater plains. We identified a dependency of the spectral slopes from latitude. The spectral slopes of the analyzed deposits tend to decrease at increasing latitudes. This result might indicate the presence of a global N–S dichotomy in the composition of the shallow crust of Mercury. The detailed analysis of three impact craters with distinctive spectral characteristics revealed as well the occurrence of short-range horizontal heterogeneities in the composition of the shallow crust of Mercury.

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**1. Introduction**

This study is focused on the global spectral analysis of the surface and subsurface of Mercury by simultaneously selecting all the available spectral observations contained within a number of previously defined morphologic units. The Planetary Emissivity Laboratory (PEL) group at DLR has been working in the last years on the development of techniques which allow the fusion of different planetary datasets in order to improve the ratio between quality of results and data processing time for both local and global scale supervised classifications. We name these procedures (here for the first time) as “Datasets Fusion Techniques” (DFTs) (D’Incecco et al., 2015).

Building on the results obtained through the global scale unsupervised clustering (D’Amore et al. 2012, 2013a,b; Helbert et al., 2013) and local scale geologically supervised studies performed by the D’Incecco et al. (2012, 2013, 2015), we used DFTs to perform a global scale geologically supervised spectral study of Mercury. In this study, we combine Mercury Atmospheric and Surface Composition Spectrometer (MASCS) Visible and Infrared Spectrograph (VIRS) data with Mercury Dual Imaging System (MDIS) images, both acquired from orbit by the Mercury Surface, Space Environment, Geochimistry, and Ranging (MESSENGER) spacecraft. This global scale analysis is the direct continuation of the local scale geologically supervised spectral study of Waters and Kuiper craters by D’Incecco et al. (2012, 2013, 2015). The morphologic units we have defined for our global scale analysis follow the same approach used for the nomenclature of the units in the local scale study of Waters crater and Kuiper crater by D’Incecco et al. (2012,
2013, 2015), with some adaptations due to special needs for the global scale approach. After the results from the local scale analysis by D’Incecco et al. (2015), this study highlights again the potential of using DFTs as a tool for both local and global scale studies in many different contexts.

2. Background studies

2.1. Geology of Mercury after the Mariner 10 mission

In the mid-1970s, the Mariner 10 science team divided Mercury’s surface into three morphologic units: intercrater plains, heavily cratered terrain and smooth plains (e.g., Trask and Guest, 1975; Gault et al. 1975; Trask and Strom, 1976; Strom, 1977; Kiefer and Murray, 1987; Spudis and Guest, 1988). Intercrater plains and heavily cratered terrain represent the oldest unit of Mercury (e.g., Strom, 1977; Trask and Guest, 1975; Trask and Strom, 1976), and their origins and chronostratigraphic relations have been debated by various authors.

Compared to heavily cratered terrain and intercrater plains, the smooth plains are characterized by lower density of impact craters and smoother surface morphology. Hence, smooth plains were interpreted to be stratigraphically younger than intercrater plains (i.e., Schaber and McCauley, 1980; De Hon et al., 1981; Guest and Greeley, 1983; Grolier and Boyce, 1984; King and Scott, 1990).

Since no relevant geologic activity has been recorded on the surface of Mercury during the last 3 Ga, intercrater plains, heavily cratered terrains and smooth plains were all plausibly emplaced during a very early phase of Mercury’s geologic history.

2.2. MESSENGER’s studies

Using MDIS images with enhanced colors, Denevi et al. (2009) subdivided the former Mariner 10 units into the following units: the smooth plains, the intermediate terrain (IT) and the low-reflectance material (LRM). These authors also divided the smooth plains into three color subunits: the high-reflectance red plains (HRP), the intermediate plains (IP) and the low-reflectance blue plains (LBP). More recently, Whitten et al. (2014) suggested that intermediate plains by Denevi et al. (2009) can be completely remapped either as intercrater plains or as smooth plains units.

Izenberg et al. (2014) used MASCS VIRS data for analyzing the spectral variations on the surface of Mercury. They selected three spectral parameters: (a) The reflectance at 575 nm wavelength (R575, red), (b) the spectral slope at visible and infrared wavelengths, represented by the ratio of reflectance at 415 nm to that at 750 nm (VISr, green), (c) the spectral slope at ultraviolet (UV) and visible wavelengths, represented by the ratio of reflectance at 310 nm to that at 390 nm (UVr, blue). On the basis of these three spectral parameters, Izenberg et al. (2014) divided Mercury’s surface into four VIRS spectral units: average, dark blue, red and bright. The average unit includes the plains as defined by MDIS color units (e.g., Robinson et al. 2008; Denevi et al. 2009, 2013). The dark blue spectral unit is characterized by spectra both darker than the planetary mean spectrum and less sloped or bluer (Izenberg et al., 2014). All areas identified as LRM and some areas defined as LBP from the MDIS dataset (i.e., Robinson et al., 2008; Denevi et al., 2009; Denevi et al. 2013) fall within this unit. The Red VIRS spectral unit is characterized by higher in reflectances and redder spectra than the planetary average (Izenberg et al., 2014). This unit includes pyroclastic deposits formed through explosive volcanism (i.e., Head et al., 2008; Kerber et al., 2011; Goudge et al., 2014). The bright spectral unit is characterized by higher VISr value and reflectances compared to the average unit (Izenberg et al., 2014). This unit includes hollows (Blewett et al., 2011, 2013; Helbert et al., 2013).

Using the same normalization approach we describe in this manuscript (Section 3.3), Helbert et al. (2013) performed a global scale unsupervised classification on MASCS VIRS spectra. They divided the surface of Mercury into two mega-regions: an
Fig. 2. (a) Global view of the units defined for each of the 121 selected impact craters on the basis of morphologic criteria. (b) Global view of the units defined in a, where areas shared by multiple craters have been eliminated. (c) MASCPS coverage over the defined units as in b. We excluded MASCPS observations covering areas shared by multiple craters. Polygons represent MASCPS footprints and have been color coded to match the different units.
Fig. 3. (a) Detailed view of a sample area showing the units as defined in Fig. 2a. (b) Detailed view of the same sample area as in a, after eliminating the areas shared by multiple craters. (c) Detailed view of the MASCS coverage of the units as shown in b. MASCS observations covering areas shared by multiple craters are not included.
3. Methods and procedure

The results obtained from the local scale geologically supervised spectral analysis of Waters and Kuiper craters (D’Incecco et al., 2012, 2013, 2015) encouraged us to extend that study and define a global scale procedure for simultaneously comparing morphology and spectral characteristics across multiple impact craters.

3.1. Impact craters selection criteria

For the global scale analysis we have selected 121 impact craters which are globally distributed across the surface of Mercury, between 60° N and 60° S latitude (Fig. 1). We selected the craters on the basis of the following morphometric and morphologic criteria: (a) between 20 km and 100 km in diameter, the approximate dimensional range for complex morphology on Mercury (Melosh, 1989; Osinski et al., 2011), (b) relatively prominent central peaks, (c) fresh morphology, relatively little affected by the superimposition of smaller (and more recent) primary and secondary craters.

We selected craters with complex morphology and prominent central peaks because the main goal of this study is to identify vertical and horizontal spectral heterogeneities in the subsurface of Mercury. Central peaks are in fact excavated from subsurface layers, so their spectral characteristics can help to display vertical heterogeneities in the composition of the shallow crust of Mercury. Moreover, selecting craters of the same morphologic class allows the definition of a single set of morphologic units.

The quality of the spectral information also plays a key role in the reliability of the generated final results. The resolution of the MASCS instrument is much lower than the resolution of the MDIS camera. For this reason, we selected craters with the freshest (youngest) possible morphology in order to increase the possibilities of observing the characteristics of impact deposits when analyzing the related MASCS spectra.

When analyzing central peaks, we have only very few MASCS observations available covering those small areas. Selecting craters with fresh morphology and prominent central peaks increases the probability that the limited number of spectra we retrieve can fully reflect the composition of the peak materials.

In the case of surrounding ejecta, the problem is not represented by the limited number of MASCS observations (like in the case of central peak materials) but by the gradual transition between the different types of impact ejecta. Previous studies (Melosh, 1989; Osinski et al., 2011) identified the presence of a thin layer of ejecta blanket (between 1 and 2 crater radii from the point of impact), proximal ejecta (<= 5 crater radii from the point of impact) and distal ejecta (between 5 and 10 crater radii from the point of impact). Moreover, space weathering effects tend to uniform the spectral characteristics of all surface materials, making it impossible to identify eventual compositional heterogeneities. For these reasons, selecting craters with fresh morphology can help identifying the spectral differences occurring between the different types of impact ejecta, reducing the eventual influence of space weathering effects.

3.2. Units’ definition and nomenclature

Building on the nomenclature provided by Mariner 10 geologic mappers (e.g., Schaber and McCauley, 1980; De Hon et al., 1981; Guest and Greeley, 1983; Grolier and Boyce, 1984; King and Scott, 1990) and more directly on the nomenclature used by D’Incecco et al. (2015), we defined the following units: crater peak material (cpm), crater floor material (cfm), and crater fresh ejecta (cfe) at a distance of 1 radius from the crater rim 1–2 crater radii from the point of impact). Furthermore, unlike D’Incecco et al. (2015), we defined two additional annuli respectively at 4–5 radii (unit 5 R).
and 9–10 radii distance (unit 10 R) from the crater rim (or 5–6 crater and 10–11 crater radii from the point of impact, respectively), as displayed in Figs. 2a and 3a.

During the data processing, we select only MASCS observations whose all vertices are included contained within each defined unit and we calculate the average reflectance of these observations (Section 3.3). For this reason, we had to map cpm differently from all the other classes of units. Central peaks usually cover small areas and very few MASCS observations are thus available. Approximating the shape of a central peak to that of a circle can lead us to include more observations than those which would effectively fall within the real borders of the central peak area. One example is given by the 88 km diameter C030 unnamed crater (23.5°N, 18.2°E), whose central peak is characterized by an extremely irregular shape (Fig. 4a–c). Mapping the central peak of C030 crater as a circle which includes the whole peak, we would include three MASCS observations (Fig. 4b), from which we would calculate the average reflectance. Mapping more precisely the peak to reproduce its irregular shape, we see that only one MASCS observation is really contained within the real borders of the central peak (Fig. 4c), while the other two observations do not actually belong to the cpm unit of C030 crater. Calculating the average reflectance of three observations, two of which are not really contained within the peak area – as we see in the case of C030 crater – can lead to a significant

Fig. 5. Detail of the external reference area (era) unit in Fig. 1, centered at 2.4°N, 83.3°W. This area is 70 km × 100 km in size and is located in a region representative of intercrater plains. The MASCS observations contained within this area are represented as blue polygons. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 6. (a) Full average MASCS normalized spectrum of k-cfe (1 R) unit, analyzed by D’Incecco et al. (2015). (b) Average MASCS normalized spectrum of k-cfe (1 R) unit obtained by calculating the mean value of normalized reflectance in the 345–355 nm, 445–455 nm, 495–505 nm, 545–555 nm, 595–605 nm, 645–655 nm windows, respectively.
difference in the results. Therefore, we use multipolygonal shape-files to reproduce the real (2D) shape of the central peaks in order to preserve the data quality.

We defined Crater Floor Material (cfm) as in D’Incecco et al. (2015). Unlike what we did for cpm units, we have approximated the external borders of cfm units to ellipses, while the internal borders were defined by clipping the area of the cpm units (i.e., Fig. 3a). We did this because we observed that the real external borders of the floor materials are generally less irregular than the borders of cpm units. Moreover, all the defined classes of units other than cpm have broader areas and contain a much larger number of MASCS observations than cpm units. When we consider broader areas, the number of MASCS observations (located on the borders) which might not really belong to a certain unit (if we would precisely map its borders) is very small compared to the total number of selected observations. For this reason, the relatively small number of MASCS observations on the borders of the classes of units other than cpm have a very limited influence on the final average values. Therefore, all the defined classes of units – except cpm – are suitable for being approximated with more geometrical shapes such

Fig. 7. (a) MASCS coverage of the defined units as in Fig. 2a. Here we include MASCS observations of areas shared by multiple craters. Polygons represent MASCS footprints and have been color coded to match the different units. (b) Detailed view of the MASCS coverage of units as shown in Fig. 3a. MASCS observations of areas shared by multiple craters are included.
Fig. 8. MASCS absolute mean reflectance in the 700–750 nm interval and slope from spectra (normalized at 700 nm) in the 350–450 nm and 450–650 nm intervals, respectively, for all units with available observations, are plotted above. Calculations were made using the first approach, which excludes areas shared by multiple units.

(a) absolute reflectance vs 350–450 nm slope, (b) absolute reflectance vs 450–650 nm slope, (c) 350–450 nm slope vs 450–650 nm slope.
Fig. 9. MASCS absolute mean reflectance in the 700–750 nm interval and slope from spectra (normalized at 700 nm) in the 350–450 nm and 450–650 nm intervals, respectively, for all units with available observations, are plotted above. Calculations were made using the second approach, which includes areas shared by multiple units. (a) absolute reflectance vs 350–450 nm slope, (b) absolute reflectance vs 450–650 nm slope, (c) 350–450 nm slope vs 450–650 nm slope.
as circles or ellipses. Approximating to simpler geometries helped simplifying and speeding up the GIS data processing. We directly experienced the difficulties of GIS software in managing spatial queries when the use of multipolygonal shapefiles with relatively complex (irregular) boundaries is involved, especially if these join analyses have to be performed simultaneously on many units distributed across the planet. During some preliminary tests where we used complex geometries to reproduce the real borders of cfe units, the execution of the spatial query halted in the middle of the data processing. Being simultaneously performed over the 121 craters, this procedure also avoids mapping a large number of units, and makes our analysis more efficient in terms of ratio between reliability of final results and mapping plus data processing time.

Previous studies on the distribution of impact ejecta showed that a layer of continuous fresh ejecta generally surrounds all the fresh impact craters between 1 and 2 crater radii from the crater rim (Melosh, 1989; Osinski et al., 2011). Analyzing the characteristics of impact deposits on Terrestrial planets in the Solar System, Osinski et al. (2011) distinguished between proximal ejecta, within 5 crater radii from the point of impact, and distal ejecta at distances greater than 5 crater radii from the point of impact. For this reason, we have simultaneously created – for all the 121 selected craters – the three annuli extending until 1 radius (cfe unit), 5 radii (5 R unit) and 10 radii (10 R unit) distance from the crater rim. In this way, we can better analyze the variations in the spectra as we move outward from the point of impact to proximal ejecta and distal ejecta (Melosh, 1989; Osinski et al., 2011). Unit cfe can reveal the spectral characteristics of the continuous layer of fresh proximal ejecta. Unit 5 R is located in the zone of transition between proximal and distal ejecta, hence it can provide a spectral characterization of this transition zone. Unit 10 R can instead provide a full spectral characterization of distal ejecta.

We used the same external reference area (era unit) already defined by D’Incecco et al. (2015) for the local scale analysis over Waters crater and Kuiper crater (Figs. 1 and 5). This area, centered at 2.4°N, 83.3°W and 100 km × 70 km in size, is situated within a region previously mapped by King and Scott (1990) as intercrater plains. Because era unit encloses a portion of intercrater plains, this area can be used as a term of comparison when analyzing the spectral characteristics of all the other defined units.

3.3. MASCS observations selection procedure

Since a complete photometric correction was not performed on MASCS data, we normalized the MASCS spectra in order to reduce phase angle effects (i.e., D’Amore et al., 2012, 2013a, 2013b; D’Incecco et al. 2015), which might affect reflectances. To do this, we normalized the values of reflectance of each spectrum to its mean value of reflectance in the 700–750 nm range. This means that the normalized reflectance of all spectra is \( \sim 1 \) in the 700–750 nm range. We used the 700–750 nm range for the normalization as we noticed it is less affected by instrumental effects and we have chosen a relatively wide wavelength interval in order to increase the signal to noise ratio (SNR).

Due to the great quantity of data, for this analysis, we used normalized spectra with only six values per spectrum, where each value represents the mean normalized reflectance of a 10-nm wide interval (Fig. 6). The six windows are 345–355 nm, 445–455 nm, 495–505 nm, 545–555 nm, 595–605 nm and 645–655 nm (Fig. 6). We selected these six intervals because they cover parts of the MASCS spectrum with good SNR. We have also extracted the mean values of absolute reflectance in the 700–750 nm range. Since multiple observations were available for each defined unit, we calculated the mean of all the values for each of the six intervals to get a single mean normalized spectrum, and we also got a single mean value of absolute reflectance in the 700–750 nm range for each defined unit. After obtaining a single mean spectrum for each defined unit, we calculated a value of spectral slope for the 350–450 nm and 450–650 nm ranges using the linear regression function. In the case of the 350–450 nm range, we calculated the spectral slope from the 345–355 nm and 445–455 nm intervals. In the case of the 450–650 nm range, we calculated the spectral slope from the 445–455 nm, 495–505 nm, 545–555 nm, 595–605 nm and 645–655 nm intervals.

Fig. 10. The figure displays the location of 34 out of the 121 initially selected craters which are characterized by a complete dataset. For this selection, MASCS observations of areas shared by multiple craters were excluded as in Figs. 2b,c and 3b,c. The 34 craters are plotted over an MDIS monochrome global mosaic at 250 m/pixel resolution.
Fig. 11. MASCS absolute mean reflectance in the 700–750 nm interval and slope from spectra (normalized at 700 nm) in the 350–450 nm and 450–650 nm intervals, respectively, of all units defined for each of the 34 craters represented in Fig. 10, are plotted above. (a) absolute reflectance vs 350–450 nm slope, (b) absolute reflectance vs 450–650 nm slope, (c) 350–450 nm slope vs 450–650 nm slope.
### Table 1

Location, name and size of the 34 impact craters with complete dataset resulting from the more conservative approach which excludes MASCS observations contained within areas shared by multiple craters. The list displays also the craters with slope constantly increasing from $cpm$ to $10 \, R$ unit in the 350–450 nm interval (light green), in the 450–650 nm interval (dark green) and in both intervals (highlighted in green), as well as those with constantly decreasing slope in the 350–450 nm interval (light red) and in the 450–650 nm interval (dark red).

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Fig. 12. The spectral slope (normalized to that of era unit) of all units defined for the 34 craters in Fig. 10 – calculated in the 350–450 nm and 450–650 nm intervals, respectively – is plotted against Latitude and Longitude. Trend lines are also indicated.

Fig. 13. Location of the 45 craters out of the 121 initially selected, which are characterized by a complete dataset. For this selection, we used the approach which includes MASCS observations of areas shared by multiple craters as in Fig. 7a and b. The 45 craters are plotted over an MDIS monochrome global mosaic at 250 m/pixel resolution.
Fig. 14. MASCS absolute mean reflectance in the 700–750 nm interval and slope from spectra (normalized at 700 nm) in the 350–450 nm and 450–650 nm intervals, respectively, of all units defined for each of the 45 craters represented in Fig. 13, are plotted above. (a) absolute reflectance vs 350–450 nm slope, (b) absolute reflectance vs 450–650 nm slope, (c) 350–450 nm slope vs 450–650 nm slope.
Table 2

Location, name and size of the 45 impact craters with complete dataset resulting from the less conservative approach which counts also MASCS observations contained within areas shared by multiple craters. The list displays also the craters with slope constantly increasing from cpm to 10 R unit in the 350–450 nm interval (light green), in the 450–650 nm interval (dark green) and in both intervals (highlighted in green), as well as those with constantly decreasing slope in the 350–450 nm interval (light red), in the 450–650 nm interval (dark red) and in both intervals (highlighted in red).

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Before starting the spatial join procedure, we applied a number of preliminary filters to the MASCS dataset. In order to use the absolute reflectance from data with no preliminary photometric correction, we selected only observations with incidence angles < 72°. When comparing Waters and Kuiper craters, we initially selected only observations with incidence angles between 25° and 35° (D’Incecco et al., 2015). However, applying such a narrow filter in the current study would have resulted in too few observations (and craters) to perform a global study of crustal heterogeneities. We already tested the influence of incorporating incidence angles up to 72° by comparing the results with those of a narrower filter, which includes only incidence angles between 25° and 35° for Waters and Kuiper craters. This test showed that – at least in the case of Waters and Kuiper craters – the final results were not affected by using a broader filter to include all incidence angles < 72° (D’Incecco et al., 2015).

As a secondary filter for reducing the influence of phase angle effects, we have selected only impact craters between 60°N and 60°S. Hence, we excluded the polar regions where incidence angles are usually higher than in the equatorial region and may potentially lead to a greater influence of phase angle effects when analyzing the absolute 700–750 nm mean reflectance.

We filtered our data also basing on the MASCS instrument operating temperature. During the calibration process, the MASCS instrument operating temperature range was set between −30°C and +30°C (i.e., McClintock et al., 2004; McClintock and Lankton, 2007). Sensitivity calculations on the VIRS instrument showed that SNR greater than 200 can be reached at 20°C (McClintock et al., 2004). Subsequently, during the MESSENGER mission, the MASCS instrument operating temperature range was slightly changed, varying from −10°C to > 50°C (i.e., Izenberg et al., 2014). In order to be more conservative and optimize the SNR, we included only MASCS observations with instrument temperature between 10°C and 30°C.

We applied an additional filter that we already mentioned in the previous section. All MASCS observations are represented by diamond-shaped multipolygons with four external vertices, plus a fifth central vertex (i.e., Fig. 4a–c). To be more conservative, we decided to select only the MASCS observations whose five vertices were all completely contained within the multipolygons representing the defined morphologic units (i.e., Fig. 4b–c).

When performing the spatial join between all the defined classes of morphologic units and the preliminarily filtered MASCS observations, we used two different approaches.

In the first and more conservative approach (Figs. 2b,c and 3b, c), before running the spatial query, we excluded all areas shared by multiple craters. So, after deleting all intersecting areas from the morphologic units defined for the 121 selected impact craters (Figs. 2b and 3b), we joined all MASCS observations completely contained within the non-intersecting areas (Figs. 2c and 3c).

In the second and less conservative approach, we also included MASCS observations completely contained within the areas shared by multiple craters (Figs. 2a, 3a and 7a,b). In the case one observation is shared by more craters, we applied the relation “one to many”. Following the “one to many” relation, as many copies of one observation are created as many craters (and morphologic units) that observation is shared by. For example, given two impact craters “Cx” and “Cy”, if a MASCS observation “Z” is found which belongs to

![Fig. 15. The spectral slope (normalized to that of era unit) of all units defined for the 45 craters in Fig. 13 – calculated in the 350-450 nm and 450-650 nm intervals, respectively – is plotted against Latitude and Longitude. Trend lines are also indicated.](image-url)
both Cx’s 5 R unit and Cy’s 10 R unit, our query will create two copies of the MASCS observation Z, ‘Zx’ and ‘Zy’. Zx will be included into Cx’s 5 R unit, and Zy will be included to Cy’s 10 R unit. This means that the total number of MASCS observations retrieved with this less conservative approach is actually higher than the real number of MASCS observations effectively contained within all the defined morphologic units, as the observations shared by multiple craters are counted more times. Intersecting areas with related shared observations can be seen in detail in Fig. 7b.

We plotted the spectral slope from normalized spectra in the 350–450 nm and 450–650 nm intervals, respectively, against the MASCS absolute mean reflectance in the 700–750 nm interval, and the spectral slope from normalized spectra in the 350–450 nm interval against that in the 450–650 nm interval. We did this for both the used approaches. We initially considered all units containing at least one MASCS observation (Figs. 8a-c and 9a-c). Subsequently, we considered only craters with complete data set, that is only the craters which had at least one available MASCS observation for each of its related morphologic units, from cmap to 10 R units. In the case of the first approach (without shared areas), 34 craters out of the 121 initially selected have a complete dataset (Figs. 10 and 11a–c; Table 1). In the case of the second approach (with shared areas), 45 craters out of the 121 initially selected have a complete dataset (Figs. 13 and 14a–c; Table 2). We also analyzed longitudinal and latitudinal trends of the spectral slope (normalized to that of era unit) in the 350–450 nm and 450–650 nm ranges, respectively. We did this for the 34 craters with complete dataset resulting from the first approach (Fig. 12a–d) as well as for the 45 craters with complete dataset resulting from the second approach (Fig. 15a–d).

Table 3 displays the values of areal extent and number of observations for both approaches described above, with the relative differences between them. All quantities are indicated both in terms of absolute values and percentage.

We analyzed the trend of the spectral slope of all craters with complete dataset retrieved using the two different approaches of data selection (Tables 1 and 2), both in the 350–450 nm and 450–650 nm ranges. On the basis of their spectral characteristics (spectral slope and absolute reflectance), we have selected the following three impact craters for a detailed analysis: (a) the 54.9 km diameter C007 (Degas) crater, centered at 37.1°N 127.2°W (Figs. 10, 13 and 16a; Tables 1 and 2), (b) the 66 km diameter C078 (unnamed) crater, centered at 13.2°S, 89.7°W (Figs. 10, 13 and 16b; Tables 1 and 2), and (c) the 71.5 km diameter C064 (unnamed) crater, centered at 0.7°E, 108.3°W (Figs. 10, 13 and 16c; Tables 1 and 2). The values of normalized slope and absolute reflectance of the three craters (Fig. 17a–c) are those calculated following the first approach.

We display the range of mean values of normalized reflectance in the 345–355 nm, 445–455 nm, 495–505 nm, 545–555 nm, 595–605 nm, 645–655 nm intervals and the range of mean values of absolute 700–750 nm reflectance, with the relative range of standard deviations from the mean values, for each of the five classes of units (Table 4), and for the era unit (Table 5). Table 5 also displays the total number of MASCS observations contained within the era unit.

### Table 3

<table>
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<tr>
<th>Classes of units</th>
<th>Approach without shared areas</th>
<th>Area (km²)</th>
<th>n. of MASCS observations within each class of unit</th>
<th>Craters with complete dataset</th>
<th>Percentage of area (%)</th>
<th>Complete dataset</th>
<th>Area (km²)</th>
<th>n. of MASCS observations within each class of unit</th>
<th>Craters with complete dataset</th>
<th>Percentage of area (%)</th>
<th>Complete dataset</th>
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<td>28</td>
<td>42</td>
<td></td>
<td>8,978,238</td>
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### Table 4

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<th>Classes of units</th>
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<th>Area (km²)</th>
<th>n. of MASCS observations with complete dataset</th>
<th>Craters with complete dataset</th>
<th>Percentage of area (%)</th>
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4. Results and discussion

The main goal of this work is that of identifying the presence of compositional heterogeneities in the shallow crust of Mercury by analyzing the spectral differences between central peaks, external impact deposits and the surrounding intercrater plains. Following the first and the second approach, respectively, we plotted the spectral slope calculated in the two windows 350–450 nm and 450–650 nm ranges against the absolute 700–750 nm mean reflectance, and the 350–450 nm against the 450–650 nm spectral slopes for:
(a) all units with available MASCS observations (Figs. 8a–c and 9a–c); (b) the 34 craters with complete dataset resulting from the first approach (Figs. 10 and 11a–c); (c) the 45 craters with complete dataset resulting from the second approach (Figs. 13 and 14a–c). As we can see on the plots of Figs. 8a–c, 9a–c, 11a–c and 14a–c, there is no evident dependency of the results from the two different approaches we have used. For this reason, the results we are going to discuss are valid for both approaches.

The class of cpm units exhibits a relatively wide spectral heterogeneity both compared to the more external classes of units and within the class of cpm units themselves (Figs. 8a–c, 9a–c, 11a–c and 14a–c). In general, the larger the distance from the center of the

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**Fig. 16.** (a) The 54.9 km diameter Degas crater on Mercury, centered at 37.1° N, 127.2° W. MDIS monochrome global mosaic at 250 m/pix. (b) A 66 km diameter unnamed crater on Mercury, centered at 13.2° S, 89.7° W, identified as C078. MDIS monochrome global mosaic at 250 m/pix. (c) A 71.5 km diameter unnamed crater on Mercury, centered at 0.7° S, 108.3° W, identified as C064. MDIS monochrome global mosaic at 250 m/pixel.
crater, the more the spectral signatures of the external units tend to be clustered. The class of units 10 R is the most clustered, and its spectral characteristics are similar to those of the era unit (Figs. 7a–c, 8a–c, 10a–c and 13a–c). Although the values of absolute 700–750 nm mean reflectance may be partially affected by phase angle effects, the results indicate a strong spectral diversity between central peaks (cpm unit) and intercrater plains (era unit). Moreover, moving outward from cpm to 10 R unit, the spectral characteristics of the defined morphologic classes tend to get increasingly similar to the spectral characteristics of the intercrater plains (era unit). Previous studies on Lunar deposits (i.e., Fischer and Pieters, 1994) have demonstrated that space weathering acts reddening the spectral slope of more mature deposits, if iron is abundant. However, recent studies on the elemental composition of Mercury (i.e., Riner and Lucey, 2012;
Table 4
The table displays the range (minimum and maximum) of mean values of normalized and absolute reflectances observed within each of the five defined classes of units and the related range (minimum and maximum) of standard deviations from the mean values.

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<td>Range of mean values of reflectance observed within each class of units (min-max)</td>
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<td>495–505 nm</td>
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<td>545–555 nm</td>
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<td>595–605 nm</td>
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<td>&quot;Absolute&quot; reflectance</td>
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</tbody>
</table>
Izenberg et al., 2014; Weider et al., 2015) showed that the abundance of iron on Mercurian surface is relatively low. While on the Moon space weathering effects strongly characterize albedo variations between deposits of different age (i.e., Fischer and Pieters, 1994), Riner and Lucey (2012) found evidences for what albedo variations between different surface materials on Mercury can be explained by a combination of compositional variations and differential accumulation of submicronscopic Fe (SMFe) between the terrains. For this reason, the wide range of spectral variety found within the class of cpm units, and between the class of cpm units and the more external classes, might reflect the occurrence of compositional heterogeneities in the shallow crust of Mercury. This result is fully consistent with the indications we get from the models of formation of impact craters with complex morphology on Terrestrial planets, which demonstrate that central peaks expose materials from greater depths (i.e., Melosh, 1989; Ochinski et al., 2011), with composition eventually different from that of surrounding surface deposits.

We looked for eventual dependencies of the spectral slope from latitude and longitude. For each class of units, we plotted the spectral slope (normalized to that of era unit) in the 350–450 nm and 450–650 nm ranges against latitude and longitude, respectively. We used both the 34 craters with complete dataset resulting from the first approach (Fig. 12a–d) and the 45 craters with complete dataset resulting from the second approach (Fig. 15a–d). We found no dependency of the spectral slope (in the 350–450 nm and 450–650 nm ranges) from the longitude (Figs. 12a,c and 15a,c). On the other hand, we observed a certain dependence of the spectral slope from the latitude (Figs. 12b,d and 15b,d). In the 350–450 nm range (Figs. 12b and 15b) the trend lines of the spectral slope constantly increase in steepness moving from the class of cpm units to the most external class of 10 R units. In the 450–650 nm range (Figs. 12d and 15d) we observe a similar scenario, with the only difference that the trend line of the class of 5 R units is steeper than that of the class of 10 R units. The general trend – for all defined units – is that slope is slightly decreasing with increasing latitudes from S to N (Figs. 12b,d and 15b,d). This result indicates the presence of a global N–S dichotomy in the composition of the shallow crust of Mercury. This compositional dichotomy is better displayed by the cpm units, as space weathering effects might eventually mitigate the differences in spectral slope between the more external units (in particular 5 R and 10 R units) and the unit era (Figs. 12b,d and 15b,d).

As we mentioned above - analyzing the two lists of craters with complete dataset resulting from the two approaches we have used (Tables 1 and 2, respectively) – we notice a general similarity in the results we get by including or excluding MASCS observation contained within the areas shared by multiple units, with some small differences. In order to better highlight similarities and differences between the two approaches, we looked for craters with constantly increasing as well as decreasing spectral slope from cpm unit to 10 R units, in both the 350–450 nm and 450–650 nm ranges.

The main differences concern the C010 (unnamed), the C057 (Tansen), the C047 (Yeats), the C079 (Moody), the C084 (unnamed) and the C093 (unnamed) craters.

In the first approach, the C057 (Tansen) crater displays a constantly decreasing spectral slope in the 350–450 nm range (Table 1). In the second approach, we do not observe the same thing (Table 2). In the second approach, the C010 and C047 (unnamed) craters display a constantly decreasing spectral slope in the 450–650 nm range (Table 2), while we do not observe it in the first approach (Table 1). Other three craters, the C079 (Moody), the C084 (unnamed) and the C093 (unnamed) craters only have a complete dataset in the second approach, so they are not included in Table 1. In the second approach, those three craters show the following spectral characteristics. The C079 (Moody) crater displays a constantly decreasing slope in the 450–650 nm range. The C084 (unnamed) crater displays constantly decreasing slope in both the 350–450 nm and 450–650 nm ranges. The C093 (unnamed) crater displays constantly increasing slope in both 350–450 nm and 450–650 nm ranges.

The most evident similarities in the results between the two approaches are shown by the C004 (unnamed), C105 (unnamed), the C024 (unnamed), the C078 (unnamed) and the C007 (Degas) craters.

The C004 (unnamed) crater displays a constantly increasing spectral slope in the 350–450 nm range in both approaches (Tables 1 and 2). Similarly, the C105 (unnamed) crater displays constantly increasing slope in the 450–650 nm range in both approaches (Tables 1 and 2). The C024 (unnamed) crater displays constantly decreasing slope in the 350–450 nm range in both approaches (Tables 1 and 2). The C078 (unnamed) craters displays constantly decreasing slope in the 450–650 nm range (Tables 1 and 2). The most interesting is the C007 (Degas) crater, which displays a constantly increasing spectral slope in both (350–450 nm and 450–650 nm) wavelength ranges, in both approaches (Tables 1 and 2).

From the two lists in Tables 1 and 2, we display and discuss with more detail the spectral characteristics of three sample craters with three different spectral configurations: the C007 (Degas) crater, the C078 (unnamed) crater and the C064 (unnamed) crater. The values of normalized slope and absolute reflectance in Figs. 17a–c and 18a–c are those calculated following the first and more conservative approach.

The 54.9 km diameter (Degas) crater is centered at 37.1°N 127.2°W (Figs. 10, 13, 16a; Tables 1 and 2). As we mentioned above, this is the only craters whose units display – on both the 350–450 nm and 450–650 nm ranges and using both approaches – a constantly increasing spectral slope moving outward from cpm unit to 10 R unit (Figs. 17a and 18a–c, Tables ). Moreover, all the defined units of this crater display a shallower spectral slope than that of unit era (Figs. 17a and 18a–c). We can observe a gradual
Fig. 18. MASCS absolute mean reflectance in the 700–750 nm interval and slope from spectra (normalized at 700 nm) in the 350–450 nm and 450–650 nm intervals, respectively, of all units defined for each of the 3 selected craters shown in Fig. 16a, b and c, respectively, are plotted above. (a) absolute reflectance vs 350–450 nm slope, (b) absolute reflectance vs 450–650 nm slope, (c) 350–450 nm slope vs 450–650 nm slope. Units are color coded as in Fig. 7a and b.
transition from the relatively shallow spectral slope of cpm unit to the steepest slope of unit era (Figs. 17a and 18a–c). The values of absolute 700–750 nm mean reflectance for the units of this crater are generally much lower than those of unit era (Fig. 18a–c). In terms of absolute 700–750 nm mean reflectance and spectral slope, units cpm and cfm of C007 (Degas) crater are the most different from unit era (Fig. 18a–c). This likely indicates that cpm and cfm units, on C007 (Degas) crater, are compositionally different from the surrounding deposits and from unit era. Given their relatively low values of absolute 700–750 nm mean reflectance, all deposits of C007 (Degas) crater, and in particular cpm and cfm units, might be compared to the Low Reflectance Material (LRM) as defined on the basis of the studies performed on the MDIS dataset (i.e., Robinson et al., 2008; Denevi et al., 2009) and with the dark blue VIRS spectral unit as defined by Izenberg et al. (2014) on the basis of the MASCS dataset.

The 66 km diameter C078 (unnamed) crater is centered at 13.2°S, 89.7°W (Figs. 10, 13 and 16b). All its units display spectral slopes and absolute 700–750 nm mean reflectances similar to those of unit era (Figs. 17b and 18a–c). Given their spectral output, all units of C078 (unnamed) crater are compositionally similar to unit era. In this case, we might compare the units of C078 crater with the intermediate plains as defined by Denevi et al. (2009) on the basis of the MDIS dataset or with the average unit defined by Izenberg et al. (2014).

The 71.5 km diameter C064 (unnamed) crater is centered at 0.7°S, 108.3°W (Figs. 10, 13 and 16c). The units of this crater are all characterized by steeper spectral slopes and higher absolute 700–750 nm reflectances than unit era (Figs. 17c and 18a–c). Given their spectral characteristics, materials of units cpm, cfm and cfe (1 R) of C064 crater most likely have different composition from era unit material. The relatively high absolute 700–750 nm mean reflectance and the relatively steep spectral slope characterizing the cpm, cfm and cfe units of C064 crater make these units a possible term of comparison with the High Reflectance Plains (HRP) materials as defined on the basis of the studies on the MDIS dataset (i.e. Robinson et al., 2008; Denevi et al., 2009) or eventually with the bright MASCS VIRS spectral unit defined by Izenberg et al. (2014).

The three selected craters are located relatively close to each other, all being enclosed in an area of 41° in longitude x 54° in latitude (155°S–39°N; 120–88°W) (Figs. 10 and 13). Since the three craters are also comparable in size, their maximum excavation depth must be also similar (i.e., Ernst et al., 2010; D’Incecco et al., 2015). This means that the materials of the cpm units of the three craters originated from similar depths. If the presence of spectral differences between central peaks and surrounding deposits generally indicates the occurrence of vertical heterogeneities in the composition of the shallow crust of Mercury, the differences in spectral characteristics observed between the cpm and cfm units of the three sample craters reflect as well the presence of short-range horizontal heterogeneities.

Previous studies provide some important indications on the elemental composition of surface materials on Mercury. The results obtained from the analysis of MASCS reflectance spectra (Izenberg et al., 2014) and from the X-Ray measurements (Weider et al., 2015) are consistent with relatively low iron content (2–3 wt% FeO or less) in surface silicates. The relatively darker albedo of Mercury compared to the Moon might be explained assuming the presence of small amounts metallic Fe particles, or other opaque minerals, in the surface deposits. Nanophase Fe particles darken and reddened surface materials (Noble et al., 2007), while submicroscopic Fe particles darken without reddening (Lucey and Noble, 2008; Lucey and Riner, 2011). Hence, the spectral heterogeneities observed within and between the defined classes of units can partially reflect the different amounts and size of metallic Fe particles in the surface deposits on Mercury.

5. Conclusions

This work is a direct continuation of the study by D’Incecco et al. (2015). In that work, for the first time, we tested the use of Datasets Fusion Techniques (DFTs) as tool for identifying the presence of compositional heterogeneities in the shallow crust of Mercury through a local scale analysis of two impact craters, Kuiper and Waters craters, which combines morphologic mapping on MDIS data with the MASCS dataset. Here, we extended the study by D’Incecco et al. (2015), testing the use of DFTs on a global scale.

On the basis of morphologic criteria, we selected 121 fresh impact craters with complex morphology, globally distributed on the surface of Mercury. Using high resolution MDIS images, we defined five different classes of units, moving outward from the central peak to the external impact deposits until a distance of ten radii from the crater rim. As a term of comparison, we also used an external reference area to represent intercrater plains. We defined six classes of units representing central peaks, floor deposits, impact craters’ proximal ejecta and distal ejecta and intercrater plains. The goal was that of identifying the presence and distribution of spectral and compositional heterogeneities within each defined class of units and between them. Starting from the list of 121 selected impact craters, we simultaneously retrieved all available MASCS observations from each of the five classes of units, using two different approaches. In the first and more conservative approach we did not include the areas shared by multiple units, while in the second we included also the shared areas. The two approaches provided very similar results. For all units, we analyzed the spectral slope in the 350–450 nm range and in the 450–650 nm range, and the reflectance in the 700–750 nm range.

This analysis indicated that the class of central peaks is spectrally heterogeneous, as it is characterized by a wide range of reflectances and spectral slopes. The spectral variety of each defined class of units tends to constantly drop as we move from the central peak to the more external impact deposits. The results display that the most external class of units we defined in this study (ten radii distance from the crater rim) is, in terms of reflectances and spectral slopes, the most homogenous class and the most spectrally and compositionally similar to intercrater plains. This means central peaks are characterized by a wide range of compositions which differ from that of more external deposits and, in particular, intercrater plains. The spectral differences observed between central peaks and more external deposits indicate the presence of vertical heterogeneities in the composition of the shallow crust of Mercury.

We have analyzed the dependency of the spectral slope of the five classes of units from latitude and longitude. While we observed no longitudinal dependency, the results show a certain dependency of the spectral slope from the latitude. The general trend shows that the spectral slope of all units tends to decrease at increasing latitudes. This might reflect a global N-S dichotomy in the composition of the shallow crust of Mercury.

After analyzing and comparing the spectral characteristics of the two lists of craters with complete dataset resulting from the two different approaches, we selected three craters with comparable dimensions and different spectral configurations for a more detailed comparison. The central peaks of the three craters have very different spectral characteristics. The three craters have a similar maximum depth of excavation and are enclosed in a relatively small area of 41° in longitude x 54° in latitude. Hence, the spectral variety observed between the central peaks of the three craters indicates also the presence of short-range horizontal (as well as vertical) heterogeneities in the shallow crust of Mercury.

6. Implications for future studies

The results of this work have important implications when
looking at the future ESA Bepi Colombo mission to Mercury. The MERcury Thermal Infrared Spectrometer (MERTIS), the Spectrometers and Imagers for MPO BepiColombo Integrated Observatory System (SIMBIO-SYS) and the Mercury Imaging X-ray Spectrometer (MIXS) mounted on the Bepi Colombo spacecraft, are particularly relevant for this study as they will map morphology, spectral characteristics and elemental composition of the surface of Mercury with higher level of detail compared to MESSENGER MDIS, MASCs and XRS instruments. MERTIS will cover a wavelength interval between 7 μm and 14 μm, globally mapping the mineralogical composition of the surface of Mercury with a spatial resolution of 500 m (i.e., Hiesinger and Helbert, 2010). SIMBIO-SYS will study geology, stratigraphy and global tectonics of Mercury (i.e., Flamini et al., 2010, 2016). This instrument will perform a global mapping in stereo and color imaging as well as in high spatial resolution imaging. The Stereo Channel of SIMBIO-SYS (STC) will provide global color coverage of Mercury at a resolution <110 m. The High spatial Resolution Imaging Channel (HRIC) will reach a spatial resolution of 5 m/pixel for specific targets of interest. SIMBIO-SYS will also perform imaging spectroscopy in the 400–2000 nm interval. The MIXS instrument will produce global elemental abundance maps of key-rock-forming elements to an accuracy of 5–50% (i.e., Fraser et al., 2010). The data retrieved from MERTIS, SIMBIO-SYS and MIXS will allow a likely complete de-


Paper III

Idunn Mons on Venus: location and extent of recently active lava flows.

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Idunn Mons on Venus: Location and extent of recently active lava flows

Piero D'Incecco*, Nils Müller, Jörn Helbert, Mario D'Amore

Institute of Planetary Research, German Aerospace Center, Rutherfordstrasse 2, D-12489, Berlin, Germany

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A B S T R A C T

From 2006 until 2014 the ESA Venus Express probe observed the atmosphere and surface of the Earth's twin planet. The Visible and Infrared Thermal Imaging Spectrometer (VIRTIS) has provided data that indicate the occurrence of recent volcanic activity on Venus. We selected the eastern flank of Idunn Mons - Imdr Regio's single large volcano – as the study area, since it was identified in VIRTIS data as one of the regions with relatively high values of thermal emissivity at 1 μm wavelength. Using the capabilities of specific techniques developed in the Planetary Emissivity Laboratory group at DLR in Berlin, our study intends to identify location and extent of the sources of such anomalies, thus the lava flows responsible for the relatively high emission observed by VIRTIS over the eastern flank of Idunn Mons. We map the lava flow units on the top and eastern flank of Idunn Mons, varying the values of simulated 1 μm emissivity assigned to the mapped units. For each configuration we calculate the total RMS error in comparison with the VIRTIS observations. In the best-fit configuration, the flank lava flows are characterized by high values of 1 μm simulated emissivity. Hence, the lava flow units on the eastern flank on Idunn Mons are likely responsible for the relatively high 1 μm emissivity anomalies observed by VIRTIS. This result is supported by the reconstructed post-eruption stratigraphy, displaying the relative dating of the mapped lava flows, that is independent of the 1 μm emissivity modeling. Values of average microwave emissivity extracted from the lava flow units range around the global mean, which is consistent with dry basalts.

1. Introduction

The Visible and Infrared Thermal Imaging Spectrometer (VIRTIS), mounted on the ESA Venus Express probe monitored the surface of Venus and mapped its surface 1 μm emissivity to get more accurate scientific information about volcanic activity and surface composition on the planet (Drossart et al., 2007; Smrekar et al., 2010). The map of thermal emission provided by VIRTIS imaged most of the southern hemisphere of Venus. We focus on the analysis of the summit and eastern flank of Idunn Mons (46°S; 146°W) - a 200 km diameter volcanic structure (Fig. 1a, b) – where the VIRTIS data show positive variations in the 1 μm emissivity (Mueller et al., 2008; Stofan et al., 2009; Smrekar et al., 2010; Fig. 2). Building on the capabilities of the Datasets Fusion Techniques (DFTs) - that we successfully developed and tested on Mercury in the Planetary Emissivity Laboratory (PEL) group at DLR in Berlin (D’Incecco et al., 2015, 2016) - we overlay VIRTIS emissivity data with the Magellan Satellite Aperture Radar (SAR) images to assess location and extent of the lava flows possibly responsible for the unusually high 1 μm emissivity observed over the eastern flank of Idunn Mons.

2. Large volcanic rises on Venus

Large volcanic rises on Venus are characterized by a broadly uplifted topography (i.e., Stofan et al., 1995; Stofan and Smrekar, 2005). Those regions, generally over 1000 km in diameter, have been associated as the surface expression of Earth-like hotspots and mantle upwelling (i.e., Stofan et al., 1995; Stofan and Smrekar, 2005). Nine major Regiones have been surely identified and described as large volcanic rises on Venus: Atla Regio (Phillips and Malin, 1984; Senske et al., 1992), Beta Regio (McGill et al., 1981; Campbell et al., 1984), Bell Regio (Basilevsky and Janle, 1987; Janle et al., 1987; Campbell and Rogers, 1994), Dione Regio (Keddie and Head, 1995), eastern, center and western Eistla Regio (Campbell and Campbell, 1992; Grimm and Phillips, 1992; Senske et al., 1992; McGill, 1994), Imdr Regio (Stofan et al., 1995; Stofan and Smrekar, 2005). On the basis of the dominant structures characterizing each Regionem, Stofan et al. (1995) divided the volcanic rises into three different morphologic classes: rift-dominated, volcano-dominated and corona-dominated.

Atla and Beta are rift-dominated rises. Both Regiones are cut by 50–100 km wide and up to 2 km deep rift valley, extending for thousand kilometers (i.e., Solomon et al., 1992; Smrekar et al., 1997). The rift-dominated are the topographically highest topographic rises and are
characterized by large apparent depth of compensation. A minor
distribution of large shield volcanoes and coronae has been observed
on Atla and Beta Regiones (i.e., Smrekar et al., 1997).

Themis, central Eistla and eastern Eistla Regiones have been
classified as corona-dominated topographic rises. Those Regiones
contain coronae 200 km to approximately 500 km diameter with
associated widespread volcanism (i.e., Stofan et al., 1995; Smrekar
et al., 1997).

Western Eistla, Bell, Dione and Imdr Regiones have been classi-
fied as volcano-dominated rises. Volcano-dominated rises are charac-
terized by the presence of one or large shield volcanoes as defined by Head
et al. (1992).

Schaber (1982) observed that the rift-dominated rises (Atla and Beta
Regiones) are located on the junction of regional chasmata systems
which have been interpreted by Stofan et al. (1995) to be the surface
expression of extensional stress state. Corona-dominated rises are
interpreted as resulting breakup of a plume or secondary convection
(i.e., Stofan et al., 1995, Smrekar et al., 1997). The volcano-dominated
rises have been instead associated with mantle plumes comparable with
Terrestrial hotspots (McGill et al., 1981; Phillips and Malin, 1984;
Smrekar, 1994; Stofan et al., 1995; Smrekar and Parmentier, 1996;
Stofan and Smrekar, 2005).

3. Geologic overview of the study area

According to the previous observations by Stofan et al. (1995), Imdr
Regio is regionally crossed by wrinkle ridge patterns which indicate a
minimum uplift of 200 m. Imdr Regio has been described by Stofan
et al. (1995) as being characterized by the least complex morphology
of all volcanic rises, with no associated coronae and a relatively small
volume of volcanics (48 x 10^6 km^3). On the other hand, Stofan et al.
(1995) observed that Imdr Regio is characterized by the highest
apparent depth of compensation of all volcanic rises, with its 260 km.

Idunn Mons (46 S, 146 W, Fig. 1a, b) - approximately 200 km
diameter - is the major volcanic edifice of Imdr Regio and is defined as a
large volcano on the basis of the classification provided by Head et al.
(1992). Using the brightness variations in the SAR left-look image, we
realized a map of fractures for better studying the structural character-
istics of the local study area (Fig. 3). Idunn Mons lays along the axis of
Olapa Chasma, a long and steep-sided depression whose morphology is

Fig. 1. The figures shows Idunn Mons (46 S; 146 W), a 200 km across volcanic edifice located at Imdr Regio on Venus. a) Magellan left-look SAR image. b) Magellan right-look SAR image.

Fig. 2. Magellan SAR image overlain on VIRTIS emissivity anomaly (see color bar) observed by the VIRTIS instrument over the summit area and eastern flank of Idunn Mons (46 S; 146 W). From Smrekar et al. (2010).

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Fig. 3. Structural map of Idunn Mons (46 S; 146 W), showing the most visible fractures
crossing the study area. (Magellan left-look SAR image).
Idunn Mons (Fig. 5) shows a slightly truncated summit area, with gently sloping sides. Building on the morphometric classification of Crumpler et al. (1997), we might describe the profile of Idunn Mons at the transition between a simple straight-sloped cone and a straight-sloped cone with truncated summit. On the other hand, we can observe a number of lava flows originating from the flanks of the large volcano, whose contacts and source vents are instead better visible. The lowermost lava flows are located ~1500 m above the planetary datum. These lava flows are radially distributed around the volcano within an approximate distance of 200 km from the peak of Idunn Mons, with the only exception being represented by the south-eastern lava flow which is located ~900 m above the planetary datum and reaches a distance of ~300 km from the Idunn Mons summit area (Fig. 1 a, b).

Because of the intense flank eruption activity characterizing its style of volcanism, we might compare Idunn Mons to Gula, Sif and Kunapipi Montes (Stofan et al., 2001). However, the lava flows with digitate morphology characterizing in particular the eastern flank of Idunn Mons and the summit calderas on its top make our study area more suitably comparable to Gula Mons. In any case, the truncated profile of Idunn Mons differs from that of all three volcanic structures analyzed by Stofan et al. (2001).

4. VIRTIS data processing and modeling

The Venus surface temperature and thus the thermal emission at constant emissivity is constrained by models (Stone, 1975) and descent probes (for a summary see Seiff et al. (1985), Seiff (1987)) to be primarily a function of surface elevation (Lecacheux et al., 1993). Mueller et al. (2008) rely on this constraint to predict the observed thermal emission based on the Magellan Global Topography Data Record (GTDR) (Ford and Pettengill, 1992). Local deviations between observed and predicted thermal emission can indicate deviation in local 1 μm emissivity from the global average, or of course errors in either the VIRTIS or in the GTDR datasets (Mueller et al., 2008) or inconsistencies in coordinate referencing between the two datasets (Mueller et al., 2012).

Here we use the improved version of the GTDR dataset by Rappaport et al. (1999), and assume an average Venus rotation period of 243.023 days in the 16 years between the Magellan and the Venus Express Missions (Mueller et al., 2012) to align the two datasets. A further change relative to the data reduction of Mueller et al. (2008) is the exclusion of tessera terrain based on mapping by Tanaka et al. (1997) from the statistics used to predict average thermal emission. Tessera terrain occurs more frequently at higher elevations (Ivanov and Head, 1996) and in the areas covered by VIRTIS either results in biased altimetry errors or has significantly lower than average 1 μm emissivity (Mueller et al., 2008).

The VIRTIS data reduction here consists of photometric correction, cloud correction and topography correction and image mosaicking as in the work of Mueller et al. (2008). The result is a map of the brightness of 1 μm emission relative to the average brightness adjusted for topography. This relative brightness is correlated with any emissivity variations on the surface but not linearly proportional to emissivity, due to multiple reflections between clouds and surface (Hashimoto et al., 2003).

This relative brightness map has been used to study 1 μm emissivity of geological features (Helbert et al., 2008; Mueller et al., 2008) and scaled to an absolute 1 μm emissivity map assuming an average surface emissivity (Smrekar et al., 2010). It is however limited in spatial resolution to about 100 km due to atmospheric blurring (Hashimoto and Imamura, 2001). In order to better understand this low resolution information on 1 μm emissivity, we model the brightness distribution observed by VIRTIS using information based on mapping of the

![Fig. 4. Detailed look of Idunn Mons (46°S; 146°W), displaying the summit caldera and the inferred flat top (Magellan left-look SAR image).](image)

![Fig. 5. Altimetric profile of Idunn Mons, showing an intermediate morphology between a simple straight-sloped cone and a straight-sloped cone with truncated summit area (Crumpler et al., 1997).](image)
Magellan Synthetic Aperture Radar (SAR) images at much higher resolution.

4.1. Top of atmosphere relative brightness modeling

VIRTIS observes the thermal emission of the surface as it emerges from the optically thick atmosphere of Venus, with each photon on average scattered on the order of $10^3$ times by molecules and cloud particles (Hashimoto and Imamura, 2001). This effectively results in a blurred image of the surface emission projected on the upper cloud layer. The blurring has been modeled by Monte-Carlo simulations (Hashimoto and Imamura, 2001; Basilevsky et al., 2012) to resemble the effect of a Gaussian blur, i.e., a moving average weighted with a Gaussian function with a full width at half maximum (FWHM) of approximately 90–100 km (Hashimoto and Imamura, 2001; Basilevsky et al., 2012, respectively).

In order to fit the relative brightness observed by VIRTIS we assume a map of surface 1 μm emissivity, multiply this with the surface blackbody radiation assuming a surface temperature of 735–8.06 K/km Z, where Z is topography. This is the assumed surface thermal emission at the surface level. To simulate passage of this radiation through the scattering atmosphere it is convolved with a 2 dimensional Gaussian function with a FWHM of 90 km (Hashimoto and Imamura, 2001).

The two stream approximation describing the multiple reflections between surface and atmosphere is then applied to reduce the contrast of the top of atmosphere brightness (Hashimoto et al., 2003). Surface 1 μm emissivity and reflectivity in this step is derived from the blurred surface thermal emission divided by the equivalently blurred surface blackbody radiation and Kirchhoff’s law for reflectivity. The assumed atmospheric reflectivity is 0.82 (Hashimoto and Imamura, 2001). The resulting emerging flux at the top of atmosphere is then divided by the emerging flux of an emissivity map at constant background 1 μm emissivity of 0.58, chosen to match that derived by previous works (Smrekar et al., 2010; Kappel et al., 2015). This scales the modeled top of atmosphere brightness to the same average as the processed VIRTIS observations.

5. Methods and procedure

In the present study we combine information from two different datasets: thermal emissivity data from the ESA Venus Express VIRTIS (Piccioni et al., 2007) in the atmospheric window at 1 μm (Helbert et al., 2008; Mueller et al., 2008) and Magellan SAR images at the highest available resolution (75 m/pixel) (Saunders et al., 1992). The procedure we used can be divided into three main steps: a) background SAR image selection, b) geologic mapping of the lava flows on the eastern flank of Idunn Mons c) search for the configuration with the smallest root-mean-square (RMS) error between the simulated 1 μm emissivity assigned to the mapped lava flows and the VIRTIS observations.

5.1. Background SAR image selection

We analyzed both left-look and right-look SAR images in order to achieve as much information as possible from the observable differences in radar backscattering. Variations in radar backscattering can be caused by three main processes: 1) topographic effects, 2) surface roughness, and 3) electrical properties. Topographic effects cause terrains that slope toward the sensor to appear radar brighter and spatially compressed and terrains that slope away from the sensor appear radar darker and spatially extended. Surface roughness has also an effect on radar backscattering. Relatively rough surfaces are characterized by more enhanced radar backscattering than smoother surfaces. Topographic effects are usually the dominant in radar backscattering when Magellan SAR incidence angles are < 20°, while for incidence angles between 20° and 60° surface-roughness effects are the main factors influencing such variations (i.e., Ford et al., 1993). In addition to topographic and surface roughness effects, the intrinsic electrical properties can also affect the radar brightness of a certain terrain. High dielectric constants (depending on composition and/or bulk density) enhance radar backscatter (i.e., Ford et al., 1993).

When choosing between left-look and right-look SAR images we have initially paid attention to the Magellan SAR incidence angles as a function of the latitude. The aim was that of trying to avoid as much as possible the influence of local topography, selecting the radar image with higher incidence angle. However at 46°S, the latitude of Idunn Mons, both left-look and right-look SAR images have been taken with equal incidence angles of approximately 24°. There is not a noticeable difference in backscattering over the eastern side of Idunn Mons between left and right looking images (Fig. 1a, b). Nevertheless, the left-look image (Fig. 1a) is less affected than the right-look image (Fig. 1b) by diffuse scattering in the summit area of Idunn Mons, and it allows a slightly better differentiation of the contacts between the mapped lava flows. Moreover, on the left-look image (Fig. 1a) we could easily distinguish and map (Fig. 4) the caldera collapses on the top of Idunn Mons. For these reasons, we favored the left-look over the right-look image for our geologic mapping.

5.2. Geologic mapping of the lava flows on the eastern flank of Idunn Mons

Using common GIS software, we created a map from the Magellan SAR images (Fig. 3) to highlight the lava flow units characterizing Idunn Mons’ summit area and its eastern flank, where the 1 μm emissivity anomalies are higher. We mapped the flow units observing variations in radar brightness, visible source vents and slope.

Using GIS polygonal shapefiles, we defined five lava flow units (Lfu) classified with letters from a to e. Lfu-a covers the summit area of Idunn Mons, while Lfu-b, Lfu-c, Lfu-d and Lfu-e cover its eastern flank (Fig. 6). Lfu-a and Lfu-e are characterized by a relatively higher radar backscattering than Lfu-b, Lfu-c and Lfu-d. To improve the geologic analysis, for all five mapped lava flows we have also calculated: 1) uppermost elevation, 2) lowermost elevation, 3) average slope, 4) visible extent, 5) average distance from the Idunn Mons’ summit peak (Table 1).
5.3. Search of the configuration best approaching VIRTIS observations

We inserted the polygonal shapefiles representing the mapped lava flows as parameters into the model of top of atmosphere brightness, assigning each polygon a simulated value of 1 μm emissivity. At the end of every iteration, the software used for the 1 μm emissivity modeling creates the following output products: a) the 1 μm emissivity map used as input (Fig. 7I–VIII); b) the overlay of Magellan left-look image, unit outlines, and separate isolines of the 1 μm top of atmosphere relative brightness as observed by VIRTIS and the modeled relative brightness (Fig. 8I–VIII); c) a value of RMS error between the observed and modeled brightness for each configuration we try (Table 2).

Building on the results from Smrekar et al. (2010), for the simulation of the 1 μm thermal emissivity we use values varying between 0.58 (background) and 0.95. We tested eight different scenarios, calculating the value of RMS error for each of them (Table 2). In the configurations I–V we alternatively assign a high value of simulated emissivity to one single lava flow unit, respectively from a to e (Table 2). In configuration VI we assigned the same value of moderately high simulated 1 μm emissivity to all mapped lava flows. In configuration VIII we assigned instead high values of 1 μm simulated emissivity to lfu-a and lfu-e. In the next section we are going to discuss

<table>
<thead>
<tr>
<th>Units</th>
<th>Uppermost elevation (m)</th>
<th>Lowermost elevation (m)</th>
<th>Slope (%)</th>
<th>Extent (km²)</th>
<th>Avg. distance from peak (m)</th>
<th>Avg. Microwave Emissivity ($\varepsilon = 1 – R$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>lfu-a</td>
<td>4300</td>
<td>2900</td>
<td>1.1</td>
<td>14458</td>
<td>0</td>
<td>0.80</td>
</tr>
<tr>
<td>lfu-b</td>
<td>3200</td>
<td>2000</td>
<td>2.5</td>
<td>1280</td>
<td>43.8</td>
<td>0.85</td>
</tr>
<tr>
<td>lfu-c</td>
<td>4000</td>
<td>3100</td>
<td>3.5</td>
<td>1274</td>
<td>66.7</td>
<td>0.80</td>
</tr>
<tr>
<td>lfu-d</td>
<td>3000</td>
<td>1900</td>
<td>1.7</td>
<td>2119</td>
<td>79.9</td>
<td>0.86</td>
</tr>
<tr>
<td>lfu-e</td>
<td>3400</td>
<td>1600</td>
<td>1.4</td>
<td>4464</td>
<td>98</td>
<td>0.86</td>
</tr>
</tbody>
</table>

Fig. 7. Grayscale image showing the emissivity assigned to the mapped lava flow units in eight different configurations (I–VIII). The images are scaled linearly from white indicating 1 μm emissivity 0 to black indicating 1 μm emissivity 1.
results and implications related to data showed in Table 2.

6. Results

6.1. 1 µm VIRTIS emissivity modeling

The scenario with the lowest RMS error, which best approximates the VIRTIS observations, is the number VII in Table 2. This configuration was obtained assigning extremely high values of simulated emissivity to lfu-b, lfu-c, lfu-d, while assigning very low values of simulated emissivity (close to the background value) to lfu-a, lfu-e.

We also tried to find a good fit with the VIRTIS observations by assigning higher values of simulated emissivity to lfu-a and lfu-e which, especially in the SAR left-look image (Fig. 1a), appear brighter than the other mapped units (scenario VIII in Table 2). After a number of attempts, the lowest RMS error we could obtain in this case is anyway higher than the RMS error obtained for configuration VII (Table 2).

Configuration VI - where we assigned the same moderately high
value of simulated emissivity to all the mapped lava flows - is characterized by a relatively low RMS error, slightly higher than that of configuration VII but lower than that of configuration VIII (Table 2).

Configurations I to V instead all display RMS errors higher than the RMS errors of configurations VI to VIII.

6.2. Radar properties and relations of the mapped flow units

VIRTIS data show a relatively high 1 μm emissivity over the eastern flank of Idunn Mons (Smrekar et al., 2010), and the main target of our study is that of understanding which units might be responsible for this relatively high 1 μm emissivity. We identified five lava flow units, where \( \text{lfu-a} \) is the summit composite unit of Idunn Mons and \( \text{lfu-b, lfu-c, lfu-d} \) and \( \text{lfu-e} \) are flank flows which likely originate from the several fissures situated on the eastern flank of the volcanic edifice (Fig. 9).

The average microwave emissivity of the mapped lava flows ranges between 0.80 and 0.86 (Table 1). Hence, the values of microwave emissivity of the units mapped across Idunn Mons are close to the global average value of 0.845 indicated by Pettengill et al. (1992). Those values are consistent with a dielectric permittivity of ~4.0, which is typical of dry basaltic minerals (i.e., Pettengill et al., 1992).

\( \text{lfu-a} \) is the summit unit (Fig. 10) with the largest visible extent of all mapped units with its 14458 km\(^2\), it is characterized by relatively high backscattering, an average slope of 1.1% and a value of average microwave emissivity of 0.80. (Table 1). This unit contains the summit area of Idunn Mons that appears to be disrupted by a number of caldera collapses (Fig. 4). However, due to very uniform radar backscattering characterizing the Idunn Mons’ summit area, \( \text{lfu-a} \) is most likely a composite unit.

On the north-eastern boundary, separating the summit composite \( \text{lfu-a} \) from the flank unit \( \text{lfu-c} \), a number of fractures with length variable between ~10 km and ~50 km were identified and mapped (Figs. 6 and 9). With a total extent of 1274 km\(^2\), \( \text{lfu-c} \) likely originated from this set fractures (Fig. 9). This unit is characterized by an average slope of 2.4%, it ranges between 4000 m and 3100 m in elevation and it is 66.7 km distant from the summit peak of Idunn Mons (Fig. 10, Table 1). This unit is also characterized by an average microwave emissivity of 0.80 (Table 1).

\( \text{lfu-b} \) extends for 1280 km\(^2\) from the north-eastern boundaries of \( \text{lfu-c} \). We identified two fractures located on the northernmost boundary of this unit, respectively 7 km and 17 km long. \( \text{lfu-b} \) slopes down from the flank of Idunn Mons with SW-NE direction, with an average slope of 2.5% and an average microwave emissivity of 0.85 (Table 1). This unit ranges 3200 m and 2000 m above the planetary datum (Fig. 10), and it has a 43.8 km average distance from the summit peak of Idunn Mons. The two fractures are therefore located near the lowest point of \( \text{lfu-b} \), so they can’t be the source of this lava flow (Fig. 9). Given that \( \text{lfu-c} \) and \( \text{lfu-b} \) are characterized by uniform radar backscatter, it is likely that \( \text{lfu-b} \) originates from the same fractures as \( \text{lfu-c} \), but from a previous eruption. Alternatively, the source fractures of \( \text{lfu-b} \) may have been buried by the following eruption that originated \( \text{lfu-c} \). In both cases \( \text{lfu-b} \) eruption event predate the formation of \( \text{lfu-c} \). Moreover, if \( \text{lfu-b} \) originated from the same fissures as \( \text{lfu-c} \), then the \( \text{lfu-b} \) eruption event is likely to postdate the eruption which formed the summit composite unit \( \text{lfu-a} \). Following this interpretation, the set of fractures that originated \( \text{lfu-c} \) - and in this case also \( \text{lfu-b} \) disrupts \( \text{lfu-a} \) (Figs. 6 and 9).

\( \text{lfu-d} \) extends for 2119 km\(^2\) and it constantly slopes down from the flank of Idunn Mons with a W-E direction. \( \text{lfu-d} \) is characterized by a slope of 1.7% (Table 1), it ranges in elevation between 3000 m and 1900 m above the planetary datum (Fig. 10), and its distance from the summit peak is 79.2 km. Along with \( \text{lfu-c, lfu-b, lfu-d} \) is characterized by the highest average microwave emissivity of all mapped units, with a value of 0.86 (Table 1). There is a ~15 km long fracture extending just on the boundary between \( \text{lfu-a} \) and \( \text{lfu-d} \) (Fig. 9). Given its position, it is possible to identify this fracture as the potential source of eruption for the \( \text{lfu-d} \). There are other two additional fractures of ~8 km located on the lowest part of the unit (Fig. 9). Following the same considerations we made above for the \( \text{lfu-b} \), these fractures can’t be the eruption source of this lava flow. While it is plausible that \( \text{lfu-b} \) postdates the formation of the summit composite \( \text{lfu-a} \), the stratigraphic relation between \( \text{lfu-c} \) and \( \text{lfu-d} \) is not clear due to the absence of direct contacts.

With its 4464 km\(^2\), \( \text{lfu-e} \) is the most extensive of the flank flows mapped on the eastern side of Idunn Mons (Table 1). \( \text{lfu-e} \) is also the most distant and the lowermost of the mapped units from the peak of Idunn Mons (Fig. 10 and Table 1). This unit is characterized by a very low slope of 1.4% and its lowermost point reaches a distance of 98 km from the peak of Idunn Mons (Table 1). \( \text{lfu-e} \) is crossed by a number of fractures of variable length between 5 km and 36 km (Fig. 9). This set of fractures is concentrated in the central part of the flow, and most likely they postdate the emplacement of \( \text{lfu-e} \) (Fig. 9). We do not observe any source fissures on the uppermost boundary of \( \text{lfu-e} \), being likely buried by \( \text{lfu-b, lfu-c and lfu-d} \). This implies that \( \text{lfu-e} \) is partially overlain by and thus predates the emplacement of \( \text{lfu-b, lfu-c and lfu-d} \). Following this whole discussion, it was possible to reconstruct a post-eruption local scale stratigraphy beneath the eastern flank of Idunn Mons, relative to the five mapped lava flow units (Fig. 9). According to the
Post-eruption stratigraphy of the eastern flank of Idunn Mons

<table>
<thead>
<tr>
<th>Ifu-c</th>
<th>Ifu-d</th>
</tr>
</thead>
<tbody>
<tr>
<td>recent eruptions, possibly active volcanism</td>
<td></td>
</tr>
<tr>
<td>Ifu-b</td>
<td>Ifu-e</td>
</tr>
<tr>
<td>older eruptions</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 11. Post-eruption stratigraphy of the eastern flank of Idunn Mons. The stratigraphic columns display the relative position of the five lava flow units (Ifu) mapped on the eastern flank of Idunn Mons.

stratigraphic interpretation we have provided, it is plausible that the flank units Ifu-b, Ifu-c and Ifu-d are stratigraphically younger than Ifu-a and Ifu-e (Fig. 11).

Idunn Mons was imaged by both left-looking and right-looking geometries at incidence angles of 24°. At this incidence angle, surface roughness is the dominant parameter which affects the resulting radar backscatter.

Previous studies (i.e., Pettengill et al., 1992; Wilt, 1992) highlighted how the microwave emissivity of the lava flows of a number of volcanoes on Venus suddenly drops above a certain "critical radius," for then increasing again at higher altitudes. The critical radius varies from feature to feature, but on average it lies at a planetary radius of about 6054 km (Wilt, 1992). Among the lava flow units we mapped on Idunn Mons, only two Ifu-a and Ifu-c lie above 6054 km. In fact, Ifu-a and Ifu-c are the units with the lowest observed values of microwave emissivity than all other lava flows mapped on Idunn Mons (Table 1). However, the microwave emissivity of the lava flow units mapped over the eastern flank of Idunn Mons varies between 0.80 and 0.86 (Table 1). Hence, all values are close to the global mean value of 0.845 seen using horizontal polarization (the same we use in this work), as found by Pettengill et al. (1992). For comparison, Pettengill et al. (1992) observed a much bigger gap between the minimum and the maximum microwave emissivity of Ozza Mons, 0.34 and 0.92, and Sapas Mons, 0.46 and 0.70, respectively.

Following those arguments, the relatively high radar backscatter and low microwave emissivity decrease Ifu-a and Ifu-c might be partially with the correlated with microwave emissivity above the critical radius observed over several Montes across Venus (i.e., Pettengill et al., 1992; Wilt, 1992; Campbell et al., 1997). Chemical weathering on highlands and Montes should act ubiquitously and on a short time scale, causing a general increase in the dielectric constant (i.e., Campbell et al., 1997 and references therein). Basing on this assumption, we can imagine chemical weathering to have partially affected Ifu-a and Ifu-c increasing their dielectric constant and radar backscatter, and decreasing their microwave emissivity. However, the drop in microwave emissivity which characterized Ifu-a and Ifu-c is limited if compared to that observed on other volcanic structures such as Ozza Mons and Sapas Mons (Pettengill et al., 1992). For this reason, we can consider Ifu-a and Ifu-c just beneath the critical radius, and only limitedly or not at all affected by chemical weathering.

7. Conclusions and discussion

We have created hypothetic 1 μm emissivity maps by assigning 1 μm VIRTIS emissivity values to lava flow units mapped based on Magellan radar brightness. These maps are convolved with a Gaussian to simulate scattering in the atmosphere for comparison with the top of atmosphere brightness observed by VIRTIS.

The increased thermal emission brightness at the western flank of Idunn Mons is most consistent with an increased 1 μm VIRTIS emissivity in the area of several flank lava flow units emanating from a set of NW-SE fractures to the NE of the summit (Table 2).

Relatively high 1 μm VIRTIS emissivity is thought to be an indicator of recent volcanism, because fresh basalt has a higher 1 μm emissivity (at room temperature) than the likely weathered crust of basalts exposed to the Venus atmosphere for significant time (Smrekar et al., 2010). The stratigraphic interpretation we have provided suggests that the flank flows Ifu-b, Ifu-c and Ifu-d are the most recent units. The somewhat increased 1 μm VIRTIS emissivity of the summit unit might possibly indicate an intermediary weathering stage or a mix of weathering states of various flows composing this unit.

A further improvement in the efficiency of DFTs to fit the specific requirements of the higher resolution of future dataset of the NASA Venus Emissivity, Radiative Science, InSAR, Topography, and Spectroscopy (VIRTIS) mission might help answering the important questions related to age and composition of surface deposits on Venus.

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