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1. **Nature:** R = Report, P = Prototype, D = Demonstrator, O = Other

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Table of Contents

● **List of acronyms and abbreviations**

Acronym	Description
CRS	Coordinate Reference System
DMP	Data Management Plan
DOM	Digital Outcrop Model
GIS	Geographic Information System
git	Version control system
GSF	Guest Storage Facility
JRA	Joint Research Activity
MER	Mars Exploration Rovers (NASA missions)
MSL	Mars Science Laboratory (NASA mission)
RBF	Radial Basis Functions
RID	Review Item Discrepancy
TA	Transnational Access
VA	Virtual Access

Table 1: List of the acronyms used in the document.

● Executive abstract

The objective of this document is the definition of a set of cartographic and technical standards and directions to be used, adapted or - in minor form - established for GMAP.

Standards proposed and mentioned in the present documents include geologic and cartographic aspects. Some of the proposed directions and standards are initial ones that are planned to be refined and/or updated throughout the EPN2024-RI project, to be used within the VA activities and for future sustainable European planetary mapping efforts beyond the RI.

The state of the art and relevant documents are included, as well as process-specific and body-specific best practice and exemplary published cases. The approaches for two-dimensional mapping and three-dimensional geologic mapping and modelling are introduced, as well as the range of non-standard map types that are envisaged within GMAP activities. Mapping review directions are indicated, as well data sharing, distribution and discovery.

Proposed standards, best practice, and tools are based on existing ones or on additional or new developments and adaptations.

Appendices are included and are pointing to either individual developments or external resources and tools that will be maintained throughout the duration of the research infrastructure, and beyond it, through sustainability.

The present document is going to be a live document permanently accessible on the GMAP wiki[1] and periodically updated in form of a deliverable. The latest update is on February 2023.

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[1] https://wiki.europlanet-gmap.eu/bin/view/Main/Deliverables/

1) Scope of the document

The objective of this document is the definition of a set of cartographic and technical standards to be used, adapted or - in minor form - created for GMAP. T**he focus is to streamline the processes which are involved in the production of geological and geomorphological maps of Planetary Surfaces**. It mainly collects already existing approaches and related documents which handle the standardisation of GIS-based mapping process to enable the European community in creating cartographic products. The aim is to describe, develop, store, combine (!), access, update, revise and, finally, visualise scientific cartographic products. As soon as these steps could be handled in one workaround and distributed among researchers and mappers, the highest possible level of homogenization and thus standardisation, is reached. This is the essential step to finally use these research products for further studies as a basis.

As top level questions for an improved and streamlined mapping process the following items are relevant:

1. What is needed for GIS-based systematic mapping and what are the requirements for establishing such a framework?

2. How should communication and workflows of mappers be organised?

3. How can research and mapping results be communicated in the context of science and map data dissemination?

To answer these questions, this document will clarify *what we have* (current status quo), *what we need* (requested requirements), *what we can adopt* (usable submittals) and finally *what we need to develop* (*advancing evolutions*). In particular within this document the following main issues will be addressed: i) Section 2 will give an overview in the planetary geologic mapping process itself from a scientific point of view; ii) A summary of state of the art in Planetary Mapping projects and related data and frameworks will be given in section 3; iii) How process- and body-specific aspects describe individual characteristics of planetary geology and geomorphology will be introduced in section 4; iv) How the specific aspects in 3D geologic modeling and mapping could be handled is described in section 5; v) The volume and variety in base data, processing and mapping environments are highlighted in section 6; vi) By a more detailed description on cartographic aspects and the map data management in section 7; vii) We then derived a top level requirement for the review process for planetary maps and the GMAP intended approaches in section 8; viii) Chapter 9 will give a first hint on how the final products could be used and distributed by the developments done by the GMAP community, based on the experience and results of the H2020 Planmap project; ix) Finally, section 10 will conclude the timeline for the planned issues/developments done and will formulate the open issues within and beyond GMAP. Appendices contain links to internal and external templates, tools and repositories useful to VA geologic mapping activities.

2) The planetary geologic mapping process

○ Scientific relevance and motivations

Geological mapping is the basic tool to understand any kind of planetary surface. The geological map is the only way to describe and understand the distribution and meaning of the landforms/deposits, both vertically and laterally. As such, it represents the prerequisite for exploration, science development, risk management and resources exploitation.

The interpretation of the genesis of the landforms/deposits represent the aim of the scientific investigations, but the science might provide information also on the different kinds of materials which in turn might become targets for future exploration projects aimed at the exploitation of some elements/minerals/rocks. Parallel to science investigations, in-situ exploration needs to take in account the risks associated with landing, navigation, and eventually with permanent or temporary infrastructures.

Different purposes and different data availability result in different cartographic products, but all of them need to comply with the basic stratigraphic principles and geological laws just like it happens with the geological mapping process on Earth.

○ Methodological overview

Despite the conceptual similarities with the Earth, planetary geological maps have some problems and peculiarities that need to be considered:

1. scales are instrument-dependent;
2. remote sensing with no or very limited ground truth;
3. limited information on rock composition;
4. relatively limited erosional weathering and variable preservation of morphologies;
5. relative and absolute dating.

On Earth there are different scales of geological maps, but the choice of the scale of the final layout depends on the aims of the representation, not on the different dataset. On Earth the type and quality of the observations at outcrop scale is mostly the same. In planetary geological cartography, the possibility to map some specific features depends on the resolution of the available dataset, which leads to obvious limits on the identification of the formation process. Moreover, the use of different datasets with

different resolutions, requires attention to keep the final result consistent, i.e., avoiding different level of details in different parts of the study area due to dataset-based resolution.

The most obvious and important difference with Earth is the absence (or very limited amount) of in-situ data that might serve as ground-truth to calibrate the remote sensing analyses and give information on the lithological content. As a consequence, 'true' geological maps based on the lithological characters of the rocks such as on Earth, cannot be - strictly speaking - performed. On the other hand, in many bodies weathering and erosion are relatively limited, thus leading to the preservation of morphologies and structures. These morphologies, unlike what generally happens on Earth, are preserved into the deep geological time, thus implying the necessity to perform stratigraphic reconstructions (both relative and absolute) even more accurately than on Earth although with less potential to make them really effective at a local scale. As a consequence of these factors, planetary cartography is either morphostratigraphic or geomorphologic rather than lithostratigraphic like the more classical geological maps on Earth. In particular, at the global or (supra-)regional scale, planetary geological cartography is based on a chronostratigraphic approach in which units, recognized according to a photo-interpretative approach (roughness, albedo, texture) are ordered in stratigraphic sequence on the base of , crater frequency and overlapping/cross-cutting relationship. At the local (or basin) scale, the approach is generally based on the morphological elements, mostly interpreted in terms of depositional environments/processes. Such approach is used also for the feature-based mapping (e.g., map of all the craters of a specific planet/part of a planet). Dependless from the type (morphostratigraphic or morphologic) and scale (global-regional-local) of the cartographic product, correlating laterally and vertically the different geological units is the only tool to minimise as much as possible, the intrinsic limits of planetary geological mapping.

Indeed planetary geologic mapping (e.g. Hauber et al., 2019), compared to the terrestrial case, is often characterised by a much larger uncertainty on the surface material and bedrock nature and composition, on the structural measurements and on the geological contacts typology (conformal, non conformal, paraconformal, erosive, intrusive ecc.)..In particular the planetary mapping process, largely tied to the early telescopic and spacecraft-based exploration of the Moon linked to the Apollo era, is affected by these uncertainties, to blur the limit across geologic and geomorphic mapping.

• 3) State of the art

○ Earth case as reference

The representation of geological and geothematic features of any territory is a need that continues to stimulate geologists, especially for the research of new and modern methods of representation. GMap will base its map with the support and expertise of terrestrial earth geological maps given by the Geological Survey of Italy - ISPRA.

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■ Small scale geological maps

The Geological Survey of Italy has produced, both on its own and by participating in international research activities, numerous maps at a synthetic scale: the geological maps of Europe at 1:5,000,000 and 1:1,000,000 scale (OneGeologyEurope), the geological map of Italy at 1:1,000,000 scale, regional geological maps at 1:250,000 scale. In addition, the Geological Survey has developed and produced small scale gravimetric and aeromagnetic geophysical maps that, similarly, cover the entire national territory.

A special series of geological relief maps, i.e. three-dimensional representations of portions of land or 3-dimensional models of particular geological contexts, followed and accompanied the realisation of geological cartography as a tool for educational support and dissemination of geological knowledge of the territory. Recently a 3-dimensional geological model of the entire Italian territory has been realised at the scale of 1:1,250,000.

Alongside the geological and geothematic cartography at a synthetic scale, the Geological Survey has realised, since its foundation in 1873, the cartographic coverage of the entire national territory at the scale of 1:100,000.

■ Geological mapping at 1:100.000 scale

The geological knowledge of a territory has always been among the main objectives of the Earth Sciences scientists who, in addition to interest in purely scientific aspects, believed that through an in-depth geological study they could achieve a profitable use of available natural resources.

Geological cartography, therefore, has always been considered fundamental especially for its use in the mining industry. Today, geological cartography is the fundamental tool for a deep knowledge of the territory and it is preliminary to the planning and management on ground and underground.

In Italy, due to various vicissitudes, the survey of the National Geological Map began in 1877 and it was decided to adopt the scale 1:100,000, since the topographic coverage at the scale 1:50,000 was not yet available. The effort continued with

alternating events, conditioned by the two world wars and the related economic crises, until 1989.

Despite the efforts made by all those who worked hard to realise the geological map, and considering the long time span, the cartography produced, which consists of 277 geological sheets, appears with a poor degree of coordination, which today is being tried to harmonise through digital analysis and processes.

■ Geological mapping at 1:50,000 scale

Since 1971, the Geological Survey of Italy has started the surveying of geological and geothematic sheets at the scale 1:50,000 thanks to the presence of the new Topographic map of Italy at the same scale.

The realisation of the Geological map of Italy at the scale 1:50,000 started with some experimental geological and geothematic sheets. Simultaneously, general rules for the field survey, for the cartographic representation and the guidelines for the realisation of the geological database were realised.

The main objective of the cartographic project is therefore the realisation and informatization of the 652 geological and geothematic sheets at the scale 1:50,000 in which the national territory is divided.

■ Geo-thematic cartography

Geo-thematic cartography represents the development and deepening of basic geological cartography in specific topics (geomorphology, hydrogeology, geophysics, slope stability, gravimetry, mineral resources, etc.) and is carried out with the aim of providing additional information essential for the knowledge of the general conditions of risk and vulnerability of the territory.

Within the project of geological mapping at scale 1:50,000, a substantial step forward is achieved with the introduction in large plan areas (i.e. the Po plain and Veneto-Friuli plain) of subsurface geological maps that can be classified as special themes. These maps, together with the development of modern data processing techniques, have given a further important impetus to the knowledge, description and representation of the subsurface and made possible the reconstruction in depth of increasingly large areas of the territory.

■ Database and guidelines

This vast amount of geological data is stored in a specific database set up at a scale of 1:25,000, organised and structured according to specific logical models, that is made available through coded procedures. For this reason, specific technical-scientific tools have been prepared in order to define the data model and to normalise the relationships between geological information and databases.

In order to guarantee methodological uniformity in data collection, archiving and cartographic restitution, several volumes of guidelines have been developed. Specifically, guidelines for geological and geomorphological survey, for geological and

geomorphological cartographic representation and for database structuring have been drawn up.

During the development process of the cartographic project, based on the new results, both the structure of the database and the geological and geomorphological symbology have undergone updating processes.

The cartographic standards experimented in the terrestrial field can also be applied in the planetary field, both for the realisation of geological and morphological or morphostratigraphic cartography, thus providing a standard reading key to cartographic products realised in the extraterrestrial field.

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○ Planetary geologic mapping

Planetary geologic mapping (e.g. Hauber et al., 2019; Hansen, 2000) practice and standards is rooted within early US planetary exploration and led by the USGS (Skinner et al., 2019). General (e.g. Skinner and Huff, 2018) and body-specific, or mission-driven guidelines (e.g. Tanaka et al., 1994) exist. The NASA planetary geologic mapping program is actively supported (e.g. Williams, 2016; Nass et al., 2018).

GMAP embeds non-systematic and non standard mapping (e.g. Rossi et al, 2018) at a variety of scales (e.g. Pondrelli et al., 2020), not only restricted to systematic or quadrangle-based mapping.

■ USGS

USGS-based planetary mapping guidelines are maintained and periodically updated, covering all Solar System bodies The geologic map planning, definition, selection, assignment, execution, review and publication workflow is very well structured and it produces standard maps, since several decades (Skinner et al., 2018).

Moreover, specific mission planning efforts, such as landing site selection and characterization, are linked to specific geomorphic and geologic mapping activities, both science (e.g. Grant et al., 2018) and engineering/safety-driven, supporting NASA missions (e.g. Fergason et al., 2016).

Similar efforts on the ESA side, e.g. for the ExoMars 2022 rover mission, are carried out with the support of various academic and industry partners (e.g. Sefton-Nash et al., 2020).

■ PLANMAP

The PLANMAP project is built on existing geological mapping standards, while it extends and improves the state of the art in suitable areas and specific mapping topics.

The starting point, after decades of refining, are the USGS geologic mapping standards and guidelines.

Strictly standard (systematic) mapping products follow existing practices in an evolutionary way, but non-standard mapping products try to follow innovative representations and a higher degree of complexity and variability including the production of 3D geological models of the subsurface and the setting up of tools for geological measurements in a virtual environment.

Globally accepted standards of planetary mapping have been developed over several decades (since 1961) by the USGS in consultation with the global community. In order to avoid unnecessary divergence from these, the mapping guidelines of Planmap consortium aimed to conform as closely as possible to USGS standards and practice (Rothery et al, 2018; Van der Bogert et al., 2020).

However, as we progress into an era of online digital and multi-layered products there may be situations in which innovation or change is desirable and situations in which it is unavoidable. For this reason, the PLANMAP products have been subdivided into USGS standard-like maps and thematic maps which can not strictly follow USGS standards (PLANMAP non-standard mapping products).

See also section 7 and 9.

■ Exemplary Mission-specific geologic mapping efforts

Several focused geologic mapping efforts took place in the last few decades. Many were USGS-driven, either linked to a single or limited sets of mission (e.g. Viking-based geologic mapping of the 80s-90s)

■ Terrestrial planets

● The Moon

USGS drove geologic mapping on the Moon for several decades, starting in the 1960s/70s based on earlier missions. The decade-long geologic mapping activities

resulted in the publication of several geologic maps in hardcopy and digital form[2] . Digital-based mapping (e.g. Ivanov et al., 2018; Iqbal et al., 2019) and rejuvenation of existing Apollo- and post-Apollo era maps efforts (Fortezzo and Hare, 2013; Fortezzo et al., 2020) have been recently completed. Besides PLANMAP has dedicated particular efforts on the geological mapping of the South Polar Aitken basin in perspective of dedicated explorations planned for the present decade (Poheler et al. 2020), whereas a specific attempt to integrate colour based spectral mapping and crater chronology has been performed in Tsiolkovskiy crater within the GMAP framework (Tognon et al. 2021) .

- Mercury

Mercury has been the target of several mapping projects. The NASA Mariner 10 mission (1973-1975) led to the production of 1:5M geologic maps of nine of the fifteen quadrangles of Mercury (Spudis and Guest, 1988 and references therein). The Mariner 10 geological mapping team followed a workflow typical of the mapping projects done during the 70's and 80's (see Moon, Venus, and Ganymede). In fact, it was based on the photo-interpretation of the available camera mosaics redrawn as airbrush shaded reliefs to be used as basemaps with consistent lighting conditions by means of television cartography techniques (see Batson et al., 1973). Thirty years later, the NASA MESSENGER (MErcury Surface, Space ENvironment, GEo-chemistry and Ranging; 2004-2015) mission covered 100% of the planet covering the previously unknown regions. Despite the availability of a much higher camera resolution and digital topographic products, this only enabled the preparation of a 1:15M global geological map (Prockter et al., 2016). This circumstance activated European geologic mappers to produce higher resolution geological mapping products by using NASA MESSENGER images in support of the upcoming BepiColombo mission. This coordinated global mapping plan (Galluzzi, 2019) is carried on with the aim of exploiting MESSENGER images at the best resolution available (i.e., a global average resolution of 166 m/pixel) with an average mapping scale of 1:400k and released as a quadrangle-based geological 1:3M map series (e.g., Galluzzi et a., 2016; Mancinelli et al., 2016; Guzzetta et al., 2017; Wright et al., 2019). Besides a non standard map, which, together with the morphostratigraphic approach take into account also spectral information and color variegations, has been recently proposed within the PLANMAP framework (Semenzato et al. 2020)

- Venus

Most geologic mapping efforts on Venus have been enabled by NASA Magellan radar data and earlier Pioneer and russian Venera missions. USGS-leadership with Soviet/Russian support have produced a significant amount of morpho-stratigraphic

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[2] https://planetarymapping.wr.usgs.gov

maps throughout the 1990s (e.g. Ivanov and Head, 2011 and ref. therein) and still are being performed using standard USGS mapping and legacy data (e.g. Hansen and Lopez, 2020) for the interpretation of SAR images (Tanaka et al., 1994). Some attempts to extract the composition of the rock from the radar backscatter of Magellan data have been tried with limited success due to the ambiguities in the interpretation of the nature of the radar return signal. Also, limited information of compositional variation from spectral data of the european mission Venus Express suggests a lithological differentiation (Helbert et al. 2008, Gilmore et al., 2017) but the data scarcity doesn't allow to use the composition for cartography purposes.

● Mars

Systematic planetary mapping on Mars has been the most sustained in terms of duration and intensity, being driven by Mariner (e.g. Carr et al., 1973; Scott, 1991; Tanaka et al., 1992;) and mostly Viking missions, later complemented by newer missions from the 1990s onwards (e.g. Tanaka et al., 2014; Platz et al., 2013). The Mars geological maps include classical standard quadrangles as well non standard maps dedicated to specific goals (e.g. Okubo, 2010). Finally 3D geological models from structural geological maps has been recently attempted by PLANMAP project (Pozzobon et al. 2020)

● Outer Planets Moons

Individual missions to the Giant Planets drove most of the geologic mapping while missions were operational and beyond. NASA/USGS mapping of the moons of Jupiter system was based on Galileo imaging data (e.g. Carr et al., 1995; Greeley et al., 2000a; Figueredo and Greeley, 2000; Greeley et al., 2000b; Lopes et al., 2000). Specific new data could also be used to integrate compositional data onto existing archive mission data, such as Galileo (e.g. Tosi et al., 2020). Most of the mission archive data include global-scale multi-resolution basemaps available in USGS Astrogeology repositories and via WMS (e.g. Mrozevski, 2019). This is mainly due to the fact that most of the higher-resolution data acquired were related to flybys integrated with heritage from Voyager missions. Therefore the units have been defined in most cases, such as the moons of Jupiter or Saturn, either from their different albedos, or density of impact craters, if subdued or highly tectonized, and the relationship between the tectonic structures.

Indeed, most of the existing maps include global-based mapping, whose major geologic units are obtained either by subdividing the terrains into major units with respect to the structural setting and kinematics as on Enceladus (Crow-Willard and Pappalardo, 2015) or to different albedos, different degree of tectonic/resurfacing and density of impact craters as on Ganymede (Patterson et al., 2010). On Europa, thanks to the global mosaic from Galileo mission flybys in the mid '90s a global geologic mapping is being attempted, with the 10 different geologic units subdivided according to albedo and tectonic relations (Leonard et al., 2017). Noteworthy are the maps of Io

carried out on a merged Voyager and Galileo data-set where for the first time were applied solutions to record changing volcanic features on geological maps (Leone et al. 2009; Williams et al. 2011)

The availability of static data archives without on-going missions, like in the case of the post-Viking Mars mapping, facilitates the development of planetary infrastructure giving more time to complete the geologic mapping (e.g. Laura et al., 2019).

● Small Bodies and Dwarf Planets

● Vesta/Ceres, Dawn

Beside others, one aim of the NASA Dawn mission was to generate regional and global geologic maps of the asteroid Vesta and the dwarf planet Ceres (e.g. Russel et al, 2006). The tiling schema used in the mapping project based on established recommendations by Greeley and Batson (1990). Consequently Ceres and Vesta are divided into four overview quadrangles (survey orbit, 250 m/pixel for Vesta; 400 m/pixel for Ceres) and 15 more detailed quadrangles (High Altitude Mapping HAMO, 70 m/pixel for Vesta; 140 m/pixel for Ceres). For more information see Roatsch et al. (2012, 2016a, 2016b).

A first geological image of Vesta is given by Yingst et al, (2014) on survey and HAMO resolution. The first global geologic map for Ceres is based on survey and HAMO images and is created by Mest (2017) (see also Buczkowski et al., 2016). This served as a basis for generating a more detailed view of the geologic history and also for defining the chronostratigraphy and time scale of the planetary bodies. A more detailed view is given within the 15 quadrangles (HAMO tiles) which was completed by the Low Altitude Mapping (LAMO) data (20 m/pixel, Vesta; 35 m/pixel for Ceres) (e.g. Roatsch et al, 2013, 2017). For the interpretative mapping one responsible mapper was assigned for each quadrangle. Once individual tile mapping has been finished, datasets are expected to be "combinable" in a GIS environment.

Representing a thematically consistent global map a common mapping template is needed which enables geometrically and visually homogeneous mapping data as result

Through it´s database-driven character this template supports the mapping tasks for the different mappers within a GIS environment and contains different layers for the object/geometry types. Every layer includes predefined attribute values and cartographic symbol specifications. The predefined object descriptions are the result of pre-discussions during the preparation phase. The entries of the symbol catalogue were created by use of the FGDC standard document (2006) as far as possible and individually designed symbols following the rules of visual classification as far as

needed. Templates like this were also used within the Geological Mapping Program conducted and guided by the USGS Astrogeology Science Center.

In order to accomplish all scientific, cartographic and GIS issues in a consistent, integer and sophisticated final map result an iterative discussion between scientific and technical topics during the whole mapping phase is needed. Furthermore a final scientific review of the global dataset, a following adjustment of the cartographical and topological issues and a description by metadata is essential for a sustainable , usability and accessibility of the products.

The geological map results as a team effort are already completed and published in e.g. Williams et al, 2014, Yingst et al, 2014,Scully et al. 2014 for Vesta and e.g. Williams et al, 2018, Mest et al., 2017 for Ceres.

- Asteroids

Individual missions on specific small bodies allowed the production of local or global structural and geologic maps (e.g. Prockter et al. 2002; Buzkowsky et al. 2008) . Notable examples include Lutetia mapped thanks to Rosetta mission data which allowed even the stratigraphic sequence to be reconstructed (Massironi et al., 2012). Smaller, or less geologically complex (in terms of surface heterogeneity or processes acting on the surface) asteroids would allow for more limited mapping (e.g. Ishiguro, et al., 2010; Robinson et al., 2002).

- Comets

Geologic mapping efforts on comets rely on data from either flybys (e.g. Thomas et al., 2013) and, later, from orbital individual spacecrafts, equipped with extensive experimental suites.
While flyby-based mapping is necessarily limited, the geomorphic (e.g. Birch et al., 2017) mapping carried out on comets via the so far unique Rosetta mission allowed not only a complete surface mapping of 67P (El Maarry et al., 2015 ; Giacomini et al., 2016; Lee et al., 2017), but also 3D geologic modelling and subsurface reconstructions (Massironi et al., 2015; Penasa et al. 2017, 2022; Rutzika et al., 2019; Franceschi et al. 2020) (See section 5).

- Specific landing-site-based mapping (characterisation)

Prior to rover-based exploration and mapping, site characterisation is performed using a variety of mapping approaches, ranging from geologic for the science significance of the proposed landing site and its suitability for science requirements, and geomorphic for safety landing and overall trafficability (e.g. Golombek et al., 2012; Grant et al., 2018; see also Rothery et al., 2018). A variety of specific geospatial maps supporting

site selection exists as well as geomorphic and geological maps for proposed and selected landing sites have been carried out on the Moon (e.g. Krasmer et al. 2013; Ivanov et al. 2015, 2017) Mars (e.g.

Pajola et al. 2016; Ivanov et al., 2020; Nobler et al., 2020) and even minor bodies such as on Comet 67 P (La Forgia et al. 2015). They are essential for constraining the landing ellipse; planning the traverses and defining the best sampling sites. Geological maps of analogue landing sites on Earth are useful for simulating the exploration activities, to assess the on site observational biases and testing the technologies that will be used for performing analytical measurements and sampling (see Balme et al., 2019; Rossi et al., 2019).

● Rover-based mapping (landing site mapping performed via rover)

MER 3D-based geologic and structural mapping of landing sites (either shortly after data collection, or later, using all available archived data) has been performed and is currently done using active missions (such as MSL) (e.g. Crumpler et al., 2015; Barnes et al., 2018;De Toffoli et al, 2020). The approach (See also e.g. Caravaca et al., 2020) requires extensive data pre-processing,the use of non standard 2D GIS tools and systems and eventually tools for geological measurements in virtual environments (e.g. Barnes et al. 2020) (See Section 5).

• 4) General geoscientific aspects

Mapping of surface units can follow generic guidelines (e.g. Skinner and Huff, 2018), although non-standard maps can have a variety of needs (e.g. Pondrelli et al., 2011) that can be translated to a wider range of unit diversity, contact types and relevant symbology. Geologic and geomorphic information could be embedded in distinct maps, or, as often the case on terrestrial geologic maps, the geomorphologic information can be an overlay to the geologic/bedrock/stratigraphic one (see Rothery et al., 2018).

On Earth standard geological maps, the bedrock units, being either lito-stratigraphic, volcanic and tectono-metamorphic, are represented by polygons of different colours indicating their age and genesis. They are delimited by polylines representative of different kind of contacts (e.g. certain, uncertain, inferred). Polygons with pale colours and different overlain patterns indicates are instead used for loose quaternary deposits of different genetic origin (glacial, fluvial, gravitational). Polylines are also specific of geological structures (faults and axial fold planes) and of geomorphic features (terraces, scarps, niches, rills, trenches ecc..). Punctual symbols are finally related to strata/schistosity measurements or to small geological features (e.g. springs or sites of mining or paleontological interest).

Being the planetary geological maps based on photo-interpretation their representative geological units are the morphostratigraphic ones which are distinguished by their geomorphological character, general albedo and texture. They are normally shown with polygons with different colours indicating their genetic attribution and relative age, inferred from photo-interpreted overlapping and crosscutting relationship, and crater density. In this case polylines indicate the different nature of the contacts among units (certain, uncertain, inferred ecc.) and geomorphic features of different nature (impact related, tectonic, fluvial, gravitational, glacial). Finally punctual symbols are often used for features too small to be realistically mapped at a given scale (e.g. pits, hollows, mega-blocks, etc..). Symbols for strata attitudes are rarely used and limited to environments exposing sedimentary sequences on Mars.

Besides the above mentioned general rules, the geologist mapping planetary surfaces should take into consideration aspects which are specifically related to given geological processes which are covered in the following sections.

4.1) Process-specific aspects

Mapping of process-specific aspects implies distinguishing the emplacement elements or depositional environments. Any geological map is an interpretative map and in the case of the geomorphological ones the genetic interpretation of landforms is largely not unequivocal (e.g., see the problem of convergence or equifinality) (Baker, 2014). Hence the choice of an area large enough to have different morphologies genetically associated (basin scale) is crucial in order to constrain the interpretation. Feature-

based maps of some unequivocable morphologies (e.g., dunes, channels) can be performed even at global scale, but complex systems necessitate maps where morphologies are laterally and vertically correlated. This last point emphasises the importance of a correct morpho-stratigraphic reconstruction.

In the following sections, each geological setting is quickly described with the list of the morphological and geological elements that can be found and mapped in each setting and a note on the best-fitting scale for any scenarios.

■ Impact processes

Impact crater morphologic mapping is one of the first extraterrestrial geologic mapping exercises performed with pre-spacecraft data (e.g. Shoemaker, 1960; see Rossi and van Gasselt, 2018).

Impact-related units can be present both within impact basins (crater floor, central peak, peak ring, listric blocks in the inner rim) and outside (proximal ejecta). Distal ejecta are much less likely to be mapped from orbital remote sensing data, but they might be visible from field based mapping and sampling, although not directly attributable to certain impact craters and basins, in the absence of returned sample analyses (e.g. Apollo).

Also, proximal impact ejecta could be modified, masked or removed by crater modification, especially where other geomorphic processes are active (e.g. Mars, aeolian or fluvial erosion, collapses, volcanic resurfacing). Crater and related deposits and morphologies are classically distinguished on the base of their degradation stages. The number of degradation classes depend on the crater diameters and the mapping scale and are remarkably variable even among different planetary bodies, different regions of the same body, and diverse authors and their mapping purpose. For example recognizable crater degradation stages on the Moon are up to 8 (e.g. Wilhelms and McCauley, 1971; Scott et al. 1977; Fortezzo et al. 2020) referred subdivided onto the different lunar stratigraphic periods (e.g.), whereas on Mercury can be either 3 (e.g. Galluzzi et al. 2016; Guzzetta et al. 2017) or 5 (e.g. McCauley et al., 1981; Prockter et al. 2016) being class 1 always the most degraded one. Hence the need to relate the different crater degradation classes applied on different maps of the same body. A notable example of this exercise on Mercury is in Wright et al. 2019.

Besides the recognition and mapping of the general crater morphologies mentioned above crater lithologies (e.g. Dhingra et al., 2017), deposits and boulders (e.g. Pajola et al.2019), spectral units (Semenzato et al. 2020); deposits (e.g. Kruger et al., 2016), and structures (e.g. Kenkmann et al., 2016) can be also mapped.

To be noted that many subsurface structural features related to impact craters on planetary bodies are often masked by ejecta, thick impact melt layers and post-impact deposits. Hence, most of our knowledge about the structural characterisation of impact

craters as well as on the distribution of impact related rocks and metamorphic processes derives from Earth craters. Particular interesting are the studies on impact structures retrieved because exposed by erosion (e.g. Kenkmann et al., 2014), via geophysical imaging, drilling (e.g. Gulick et al., 2013) and through fieldwork (e.g. Koeberl et al., 2005; Kenkmann and Schonian, 2010) .

Impact cratering processes can also indirectly support mapping of older, deeper units not cropping out otherwise, as central uplifts can expose such deep-seated units (e.g. Carter and Poulet, 2013).

■ Volcanic and tectonic processes

Deformational records within the Earth crust have a certain applicability to interpret and map tectonic structures visible on terrestrial planet surfaces (e.g. Mege, 2001; Harris and Bedard, 2014, Ernst et al., 2001; Massironi et al. 2015). Likewise, the mapping of volcanic units on Solar System bodies (Platz et al., 2015), particularly on the Terrestrial Planets, has a strong and direct similarity to mapping volcanic deposits and terrains on the Earth (e.g. Tanaka et al., 2009).

The volcanic processes are at least on a first order, well constrained on the Moon , thanks to the direct ground truth and sample return deriving from Apollo and Luna missions (e.g. Geiss and Rossi, 2013). Mars' samples delivered by meteorites lack direct geologic context, apart from useful but indirect evidence (e.g. Werner et al., 2014). Mapping lunar maria due to extensive remote sensing geomorphologic and geologic studies, sample analyses and modelling (e.g. Head and Wilson, 2016), as well as age determinations (e.g.Hiesinger et al., 2000), reached a quite detailed level, including in the last few decades an increasing use of multi- and hyperspectral data (e.g. Lucey, 2004; Thiessen et al., 2014; see also PLANMAP data over SPA Apollo basin[3]). For example, the use of data from ISRO missions (such as Chandrayan) helped to characterise volcanic bedrock composition supporting geological and lithological mapping (e.g. Bhattarcharya et al., 2011).
A notable investigation on the pyroclastic deposits on the Moon have been carried out by Kramer et al., (2013), who produced an extensive mapping in the SPA region of the Moon with particular attention to the Schrodinger crater, the pyroclastic mantling in its surroundings and the related fissure vents. More recently mapping products of the Humboldt crater and the pyroclastic mantling in its interior have been performed by Gustafson et al., (2020).

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[3] https://data.planmap.eu/pub/moon/PM-MOO-C-SPAApollo/

The guidelines for the mapping of volcanic units on Mars have been defined by Scott and Tanaka (1986) at first for the equatorial regions of Mars, both in terms of morphotypes and symbology. Later on these have been amended and upgraded by Scott et al. (1998) in the geologic mapping of Pavonis Mons where lava fronts, trenches, grabens, calderas, fissure vents and associated structural features have been mapped at 1:500.000 using Viking photomosaics, and where regional stratigraphic relationships between them has been established.

A detailed mapping of the summit of Olympus Mons and all the associated features such as lava flows, ridges, inferred tubes, collapses and the calderas themselves has been carried out by Bleacher et al., (2007) by means of HRSC nadir images. Another relevant mapping product of a large Martian volcano is the Hadriaca Patera quadrant by Crown and Greeley (2007) where all the main volcanic units and associated structures have been mapped at a scale of 1:500.000.

More recently, an extensive regional mapping on the Syria planum region, on the basis of a combination between MOLA topography and HRSC photomosaic, has been carried out by Baptista et al., (2008) with the distinction of the units pertaining to volcanic edifices, lava flows and grabens and fractures systems associated, whereas Tesson et al. (2020) have proposed an innovative way of mapping lava flows on Asia Mons .

Volcanic units have been defined on Mars not only thanks to photogeologic mapping and morphologic appearance, but also from compositional variations. OMEGA spectrometer data have been used together with THEMIS IR images (both day and night) in order to extensively map the lava flows in Daedalia planum region, south of Arsia Mons. This produced one of the first integrated maps where the compositional information is tied with photogeologic mapping (Giacomini et al., 2011).

Indeed, effusive volcanism plays a major role on the Martian surface and Daedalia planum is also one of the places on Mars where the relatively low slope gradient and the low-viscosity of the flows contributed to the creation of lava tube systems (Cushing et al., 2012) . These underground conduits have their surface expression in sinuous alignments of rimless collapse pits elongated in the direction of the underground conduit path. Some of these collapses are very large and extend for the maximum width of the tube (Sauro et al., 2020), whereas skylights are smaller in dimension, circular or sub-circular with overhanging walls, therefore hinting for the presence of a larger underground void below. Skylighs have been described and systematically detected by Cushing et al., (2015) and a comprehensive Mars-wide database is now available and maintained from USGS called Mars Global Cave Candidate Catalog[4] (Cushing and Okubo, 2015). IN this catalogue are present not only the skylights related to lava tubes - here named APCs (Atypical Pit Craters) - but also other isolated depressions with steep walls and likely void underneath, and categorised according to their main morphological characters, along with an attribute table presenting coordinates, diameters and depths.

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[4] https://astrogeology.usgs.gov/search/map/Mars/MarsCaveCatalog/mars_cave_catalog

Monogenic volcanic vents mapping has been carried out in the region of Pavonis Mons (Bleacher et al., 2009) Tharsis region and in Syria planum region (Richardson et al., 2013) . A global catalogue of the monogenic vents in Tharsis region is available at the USGS astrogeology website[5].

Monogenic vents are often associated with pyroclastic eruptions and mantling deposits. One of the best mapped and characterised cases is that of the Ulysses colles and associated Ulysses fossae graben system by Brož and Hauber (2012). Here a geo-structural map has been produced together with morphometric analysis of the cones.

Overall magmatism on planetary bodies is strongly tied to tectonism (Rossi et al., 2018, Schultz et al., 2003; Schultz et al., 2010) and especially on Mars and Venus the tectonic systems are directly related to the volcanic provinces and their scales reflect one of the emplaced volcanic landforms (McGovern et al., 2009). For this reason the mapping of volcanic landforms and products is often carried out together with major tectonic structures associated, often performed at regional or planetary scale, as it is visible in the global-scale mapping of dyke swarms on Mars in the major volcanic provinces (Tharsis, Elysium, Syrtis Major) and valles Marineris (Ernst et al., 2001).

On Mars an extensive structural characterization work of the graben systems related to volcano-tectonic activity has been carried out by Byrne et al., 2009. Here, the effects of lithospheric flexure, and the mapping of imbricate *fish-scale pattern* terraces, related to low angle reverse faults extended has been also carried out, expanded in higher detail on the volcano-tectonic analysis Ascraeus Mons (Byrne et al., 2012) and then extended to all the main volcanic edifices on the planet (Byrne et al., 2015).

One of the highest-detailed structural characterizations (not related to magmatism) on Mars has been performed in Okubo, (2010) in south-western Candor Chasma with FGDC standard symbology and mapping scale of 1:18.000[6][7]. In this mapping product, geologic units have been subdivided from wall materials to layered materials, the latter subdivided according to the knobby vs stair stepped morphology and the structures have undergone an extensive and detailed characterization ranging from brittle deformation (normal, thrust faults, fractures) and ductile with presence of a variety of small-scale folds (divided into anticlines, synclines and plunging/double-plunging synclines and anticlines). Exclusively related to faults geometry and kinematics in compressional/strike-slip context is worth to mention the work of Aguita et al. (2006) and in extensional contexts the (Mege et al. 2003) paper about Martian grabens, which, however provide structural sketches but not geological maps.

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[5] https://astrogeology.usgs.gov/search/map/Mars/Research/Volcanic/TharsisVents
[6] https://pubs.usgs.gov/sim/3309/downloads/sim3309_sheet.pdf
[7] https://pubs.usgs.gov/sim/3309/

Collapse chains have also been linked to volcano-tectonism and dilatant behaviour of faults, enabling dykes intrusion in the crust. Several works on such structures have been carried out with a mapping on Ascraeus Mons by Pozzobon et al., (2015).

Similarly, on the surface of Mercury volcanic features such as flows, depressions, channels, flooded impact structures and alike have been characterised via photogeologic mapping by Byrne et al., (2013) using a combination of MESSENGER MDIS WAC global image mosaic and NAC in target areas. Later Byrne et al 2014 provided the complete mapping of structural landforms on Mercury identifying various wrinkle ridges and fold and thrust belt systems, whereas Giacomini et al., (2015, 2020) and Massironi et al. (2015) mapped, dated and characterised in kinematic terms regional fault patterns such as frontal thrusts bordered by lateral ramps, strike slip duplexes and restraining bands. Finally Crane et al, 2019 produced a detailed mapping of shortening features on the northern smooth plains. A good recent example of mapping of Mercury basin tectonism is provided in Semenzato et al. 2020 whereas three dimensional reconstruction of fault structure using Move software (Crane 2020). Explosive volcanism on Mercury is well documented by vents and deposits lying on floors, rims, central peaks or peak rings of impact structures as well as along or close to fault systems (Kerber et al. 2011; Thomas et al. 2014; Kliczack et al. 2018). In particular, the most common evidence of pyroclastic volcanism on Mercury are bright and relatively red deposits called flaculae encompassing volcanic vents. These terrains are regularly represented in standard quadrangle maps such as in Wright et al., 2019. In addition red pitted grounds of possible volcanic origin were also documented by Tomas et al. 2014.

On Venus extensive work has been performed in terms of volcano-tectonic characterization of Coronae in Mnemosyne region (Stofan and Head, 1990) where the distinction and relationship between the corona annulus, lava flows and the ridged-grooved terrain surrounding the volcano has been established. A global structural analysis related to tesserae terrains (defined as terrains with intersecting structural elements, constituting 8-10% of the planetary surface) have been carried out by Hansen and Willis (1996), Hansen et al., 1999, Hansen et al., 2000 with Magellan SAR images. Here the terrains have been subdivided thanks to the intersection relationship and type of deformation into folded, lava flow-bearing, s-c terrains, dome and basin terrains, star-terrains and volcanic flooding materials. Giant fracture systems and dyke swarms associated with coronae on Venus were also globally mapped by Ernst et al., (2001) with Magellan radar images. Later these observations were combined, improved and discretized into geologic units (e.g. groove belts, densely lineated plains, ridged plains, shield plains, shield clusters, rift zones and lobate plains including lava flows) in the global geologic map of Venus at 1:10M scale by Ivanov and Head (2011).

■ Sedimentary processes

Mapping of sedimentary deposits is particularly necessary when the genetic interpretation of these deposits is either impossible or controversial, limited by data or the lack of ground truth. This is specifically the case of the sulfate-bearing light toned deposits on Mars, but the rationale and the concepts are the same for any comparable situation even in different planetary bodies.

These deposits were introduced and mapped by Lucchitta (2010, cum ref.) while their association with a sulfate content was found by Gendrin et al. (2005). Geological maps representing them have been produced by several authors, including Le Deit et al. (2013), Pondrelli et al. (2015), Hynek and Di Achille (2017), and Quinn and Ehlmann (2019).

Compositional studies are also instrumental to characterise lithologies and sedimentary environments (e.g. e.g. Elhmann et al., 2009), although not always mineralogical composition can be traced to individual primary or secondary processes (e.g. Poulet et al., 2005; Loizeau et al., 2007).

In this case the development of a map based on as objective as possible features is envisaged. In particular, since genetically interpreting the morphologies is difficult, the use of descriptive non-genetic terms is important to support the reconstruction of a constrained stratigraphic framework which might serve as a basis for genetic reconstructions.

The necessity to identify the stratigraphic boundaries of the sedimentary unit implies that the scale of the mapping should include at least the basin where these deposits were emplaced, while the passage to a regionale scale can be envisaged in the case a lateral transition to different unit(s) can be recognized.

The sedimentary succession can be mapped as a whole unit or divided depending on changing characters such as albedo or texture. The morphological elements associated with this succession (e.g., mounds, knobs) should be, if possible, mapped as separate and overlaying point, linear or polygonal features.

● Alluvial/Deltaic/Lacustrine processes

This suite of sedimentary depositional environments has been always particularly investigated because it proves the presence of processes similar to the ones present on Earth, with implications both in the understanding of the processes and controlling factors and in the potential habitability. These environments are of major importance in the understanding of surface processes of Mars (e.g., Jerolmack et al., 2004; Moore and Howard, 2005; Wood, 2006; Kraal et al., 2008; Armitage et al., 2011; Schon et al., 2012; Grant et al., 2011, 2014; Goudge et al, 2018) and Titan (e.g.,Birch et al., 2009, 2016; Radebaugh et al., 2018).

The alluvial/deltaic and lacustrine deposits can be mapped at the global scale such as feature-based maps (e.g., Liu et al., 2016; Lopes et al., 2010), regionally, distinguishing the basic depositional sub-environments (e.g., Williams et al., 2011; Malaska et al., 2016), and at the local scale (e.g.,Pondrelli et al., 2008; Di Pietro et al., 2018; Jodhpurkar et al., 2019; Tsibulskaya et al., 2020), where further details in the depositional systems can be represented.

As an example, at the regional scale, the following distinction might be considered:

- Alluvial fan
- Channels
- Alluvial plain
- Delta/Fan Delta
- Terraces
- Lake bottom

At the local scale, further detail might be possibly distinguishable such as: Channel types, crevasse splays, levee, delta plain / delta front / prodelta, beach deposits.

The detail of the recognizable depositional elements is a function of the available dataset, so the map distinctions will change accordingly.

- Catastrophic outflow channels (Mars)

Outflow channels have been the first morphology related to water-related processes to be observed on Mars. They have been described extensively in many papers (e.g., Baker et al., 1983, 1992; Carr, 1996; Wilson et al., 2004). They represent very large structures that can be up to thousands of kilometers long and tens of kilometers large. Examples of detailed geomorphological maps can be found in Pacifici (2008), Chapman et al. (2010), Glamoclija et al., 2011, Erkeling et al. (2014), and Kukkonen and Kostama (2018).

The units and the linear features related to outflow-related processes defined in these maps are:
- Chaotic Terrains/Remnant Terrains - polygonal mounds and knobs
- Smooth Plains - smooth-textured surface
- Terraces - sometimes showing grooved surfaces
- Grooved floor - valleys or portions of valleys sculpted by grooves
- Cataract channel - material deposited downstream of a cataract
- Streamlined features - tapered and/or drop-shaped mounds or plateaus
- Giant bars - features paralleling the flow direction
- Pendant bars - streamlined, tapered mounds or hills, which parallel the flow direction downstream to a bedrock projection
- Channel floor - flat surfaces occurring at the base of the channels
- Small channels

Other units can be present in the specific area depending on the interaction with other geological settings and/or processes (e.g., glacial, volcanic).

It is important to stress that the units mentioned here can be all present or not in the specific study area and many of them can be mapped either as areas (polygonal shapefile) or line (linear shapefile). In some cases, some units can be further distinguished or merged depending on the specific characters of the area.

● Eolian processes

○ Active / present eolian processes and deposits

Active or geologically recent eolian depositional processes are essential to infer the atmospheric conditions and how they changed in the recent geological past. Studies have been especially developed on Mars and Titan surface but the effectivity of eolian processes to shape the planetary surface have been hypothesised or shown in different planetary bodies (e.g., Greeley et al., 1992; Radebaugh et al., 2008; Diniega et al., 2017; Fenton, 2020; Silvestro et al., 2020).

Geological maps can be developed with different aims and accordingly different details and scale. Active or geologically recent dune fields distribution can be mapped at a global scale, while at a regional and even more at the local scale the different dune types (including megaripple/TARs) or different eolian depositional as well as erosional landforms can be mapped. At the local scale, the inferred wind direction and generations should also be indicated in the map.

When data acquired in different times allows recognizing movement of dunes/megaripple, an approach of multi-temporal geologic mapping is envisaged.

○ Fossil aeolian processes and deposits

The presence of fossil eolian deposits can be confidently detected only if high-resolution (or in-situ) data are available. So far, Mars, thanks to in-situ data and the CTX/HiRISE datasets, provides the best opportunity to study such topics (e.g., Ojha et al., 2018; Day et al., 2019).

A local or regional scale is envisaged for mapping purposes, even if the known distribution of some features can also be reported at the global scale. If wind directions can be recognized (e.g., in the case of cross-bedding or recognizable dune geometry), they should be reported in the map.

■ Glacial and periglacial processes

As on the Earth, planetary mapping of glacial and periglacial features includes both erosional and depositional landforms. This is specifically the case of rocky planets, especially of Mars, having a geological history similar to the terrestrial one, characterized by alternating glacial and interglacial periods. Their definition in terms of related geological and geomorphological processes is of primary importance in order

to understand the climate changes on a planet. In this respect, on Mars several steps have been done until now.

As instance, a variety of geomorphological landforms at medium-low latitudes (i.e., eskers, grooved terrains, streamlined hills, moraines deposits, glacial carved valleys, cirques, etc.) related to past glaciers have been described and mapped (e.g., Kargel and Strom, 1992; Kolb and Tanaka, 2001; Head and Pratt, 2001; Lucchitta, 2001; Milkovich et al., 2002; Pacifici et al., 2009; Diot et al., 2015) giving us an idea of the maximum extension and variations of the ice during the past.

At present, mapping structures such as knobby mounds (i.e., pingos), polygonal crack patterns and thermokarst depressions (e.g., Mangold et al., 2004) can help us to define regions interested by permafrost, also found in the top meters of the high-latitude regolith (e.g., Boynton et al., 2002). In this regards, permafrost has been hypothesized also from viscous flow features (Milliken et al., 2003), lobate debris aprons (Pierce and Crown, 2003), dissected mantle deposits (Mustard et al., 2001) and gullies formation (Malin and Edgett, 2001; Milliken et al., 2003) and rampart craters (Baloga et al., 2005; Carr et al., 1977; Mouginis-Mark, 1987; Mouginis-Mark 1978).

However, remnant water ice is presently confined mostly in the polar ice-domes (northern and southern) characterized by seasonal (SIC) and residual caps (RIC) burying the ancient Polar Layered Deposits units (PLD). Both SIC and RIC ice-caps are interested by several surficial textures, forming peculiar landforms such as "swiss-cheese" terrains, pits, "spider" cracks and knobs (e.g., Thomas et al., 2005), all evidencing seasonal sublimation processes of dry ice.
At the same time, PLD ice-domes are dissected by spiral troughs, scarps and topographic reentrants and depressions, such as chasmata and valleys, highlighting exposed sections of stratigraphic sequences, erosional contacts (i.e., angular unconformities) and broad deformations of layers (e.g., Kolb and Tanaka, 2001; Byrne and Ivanov, 2004; Milkovich and Plaut, 2008; Grima et al., 2011; Guallini et al., 2012; 2018).

Starting from all existing works further mapping of glacial and periglacial environment (in particular of the poles and surrounding regions) is an essential instrument to better understand the geologic history of Mars and to focus our attention to the existence of water and maybe of life.

■ Mass wasting processes

Mass-wasting processes are ubiquitous in the Solar System, on bodies with a wide range of gravity, from small bodies (i.e. comets and asteroids) to the Moon (e.g. Xiao et al., 2013) and the terrestrial planets (e.g. Brunetti et al, 2015). They can be triggered by impacts, or endogenic seismic activity, as well as possibly other factors, such as thermal stress or sublimational activity (e.g. Pajola et al. 2017; Tesson, et al., 2020).

Page 30

Mars, with a combination of strong relief energy, well-visible impact cratering record, robust past internal activity, both subaerial and subaqueous condition in the late past, as well as role of volatiles in the upper crust to facilitate mass wasting is the most suitable planet for mapping mass wasting processes, with an approach similar to that on Earth), as well as larger scale tectono-gravitative collapses (Brunetti et al., 2014, Mege et al., 2011; Mazzanti et al. 2016; Crosta et al. 2018).

Mass-wasting at large scale is also present on Mars (e.g. Sharp, 1973; Meresse et al., 2008), and collapse and mass-wasting features are strongly linked with tectono-magmatic processes, and often volcanic, tectonic and hydrologic processes are strongly interconnected (e.g. Carr et al., 1979; Rodriguez et al, 2005; De Blasio et al. 2018). Certain short-lived mass wasting processes can be imaged during their activity or soon after, such as cliff collapse and avalanches on Mars' polar caps (e.g. Russel et al., 2008), possibly linked to surface-atmosphere interaction and dynamics.

Small, low-gravity bodies, such as asteroids also experience mass wasting (e.g. Jawin et al., 2020; Massironi et al., 2012; Williams et al. 2014), either triggered by impact or, in the case of the small moons of Mars (Shi et al., 2016) or the Giant Planet systems, by tidal effects. Additionally, on active comets collapses and mass wasting can be triggered and sustained by loss of volatiles and degassing (e.g.; Vincent et al., 2016; Pajola et al. 2017). All gravitational processes on small bodies can be carefully mapped such as for example in Massironi et al. 2012 for Lutetia, Krohn et al. 2014 for Vesta; Giacomini et al. 2017 and Lucchetti et al., 2019 for comet 67P.

Depending on the spatial and timescale of involved processes, the size and state of activity of the body, mass wasting processes can occur at timescales that range for geologically instantaneous (e.g. avalanches on Mars polar caps, jets and pit formation on comets) to longer-term, such as ice-assisted creep and slope modification (see subsection on glacial and periglacial processes, as well section on dynamic multi-temporal geologic mapping).

■ Metamorphic and Metasomatic processes

Metamorphic units, aside from the obviously impact-metamorphosed rocks (e.g. Stoffler et al., 2018; Ferriere and Osinski, 2012), is not customary on planetary surfaces and, up to date, their cartography is not a main topic in planetary geologic mapping. Since no plate tectonics has been found on other planetary bodies other than the Earth, regional metamorphism seems to be unlikely, but most likely contact metamorphism is developed extensively on once volcanically active planets and Moons. Mappable areas associated with such processes might exist and should be considered (e.g. Bramble et al., 2017), provided that coverage, spatial and spectral

resolution of available datasets is suitable for observing and detecting them. In addition hydrothermal metasomatism has been already documented and mapped using spectral and compositional information on Mars (Thomas et al. 2017; Carozzo et al. 2017; Michalski et al. 2017). Mapping this phenomena on Mars is indeed of particular interest for astrobiological purposes and ISRU research.

Finally, on planetary bodies with abundant tectonic contacts such as Venus (e.g. Basilevsky and Head, 1998) and some icy satellites, as Europa, Miranda and Ganymede (e.g. Pappalardo et al., 1997), the emplacement and juxtaposition of units might have some resemblance in geometrically treating the mapping of metamorphic units and accreted terranes on the Earth (e.g. Carosi et al., 2018).

■ Cryo-volcanic and cryo-tectonic processes

The phenomenon of cryovolcanism has been defined as originating from the melting and eruption of water and other liquid- or vapor-phase volatiles onto the frigid surfaces of the icy satellites of the giant planets (Wood and Radebaugh, 2020, Geissler, 2015). Cryovolcanism is a rather peculiar phenomenon which presents several examples on the outer solar system and in the asteroid belt as well. Indeed, it is mostly common on icy or ocean worlds but evidences were also found on rocky planets such as Mars, Titan, Pluto and Charon (e.g. Lopes et al., 2013; Cruikshank et al., 2020; Ahrens and Chevrier, 2020). In addition, the thermal evolution of trans-Neptunian (Lepoutre et al., 2020) and Kuiper belt objects foresee the possibility, for bodies the size of Charon (~600 km in diameter), to retain subsurface liquids that can be brought to the surface via self-propagating cracks in the icy shell (Desch et al., 2009).
Cryo-tectonism interests the vast majority of the icy satellites' crusts, it is often pervasive and associated with cryovolcanic processes.

The first close-ups of icy surfaces and the discovery of extensive tectonic structures and cryovolcanic products began in 1995 with the images from SSI instrument on Galileo mission around the Jupiter moons. Concerning the mapping of cryovolcanic-tectonic features, the jovian satellites are a primary example of such processes.
More specifically, on the Jovian satellite Europa, the eruptive materials are rather variable with different rheology involving brines and/or slurry-like (as a mixture of water + ice portions and salts). These can be therefore mapped and distinguished thanks to their different albedo, roughness, topographic expression (although with very low resolution DTMs, see Bland et al., 2017). The cryovolcanic edifices can strongly resemble those related to classic volcanism across the rocky planets, and include calderas, vents, spatter cones, fissures surrounded with fine deposits, and the so called *"maculae"* (Fagents, 2003 and references therein).
More recently the surface roughness and its relation with geologic units and intersection with structures was reassessed for targeted areas covered by Galileo stereo images by Steinbrügge et al. (2020).

Page 32

On Europa a correlation between tidal stresses, their implications in creation of cracks and double-ridged bands, possible linked to water resurgence and freezing has been analyzed by Greenberg et al., (1998)

As a heritage of Galileo flybys in the mid '90s, Greeley et al., (2000) provided guidelines to identify and map cryovolcanic features on Europa, which has the largest variety of cryovolcanic/cryotectonic morphologies. The identified primary units include *plains, chaos, band, ridge and crater material.*

In an extensive mapping work of the high-resolution longitudinal mosaics of Galileo SSI images of the leading and trailing hemispheres of Europa, Figueredo and Greeley (2000) created a first regional geologic map of the northern leading hemisphere at 230m/pixel identifying first 12 geologic units and focusing with particular attention to structural features, Later, this mapping was extended and improved by Figueredo and Greeley (2004): it was performed a pole-to-pole geological mapping by distinguishing terrain-type units (plains, bands, ridges, chaos, and crater materials) interpreted from the presence and interaction between tectonic fracturing and lineaments, cryovolcanic reworking of surface units, and impact cratering.

On Ganymede, in particular, most of the resurfacing is thought to be due to cryotectonc extension rather than cryomagma outputs. Broad topographic undulations probably resulted from ductile necking of the crust, while finely spaced fractures were produced by brittle failure (Geissler, 2015). It has been proposed that, since no fluid flow features can be seen issuing from the fractures, most of the resurfacing was achieved by tectonism rather than cryovolcanism (Head et al., 2002). However, embayment of ridged depressions by light smooth material has been interpreted as the product of emplacement of low-viscosity cryo-lavas.

Cryomagma products, however, are also present on the surface, although dominated by pervasive tectonism. In the Sippar Sulcus region embayment of ridges and viscous flows from an irregular caldera-like depression were observed (Schenk et al., 2001). These observations are coherent with the interpretation that the smooth brighter terrains are indeed the product of embayment by low-viscosity cryomagmas.

Later on Pizzi et al., 2017 carried out a new analysis of necking instability vs rifting for Ganymede suggesting that spreading centers involved in the global expansion and icy crustal accretion within these structures is underestimated.

Concerning the mapping of structural features, a first global geologic mapping of the satellite was carried out by Patterson et al., (2010) by means of the best available data from the six close encounters of Galileo mission with the satellite and Voyager data compiling a global mosaic (Becker et al., 2001) resampled at 1km/pixel. On this dataset the output scale was set to 1:15M, and the mapping approach was similar to that from Greeley et al., (2000) on Europa, and therefore only major structural features were represented whereas smaller structures such as *grooves* that are widespread, would obscure the underlying geologic units and therefore only representative lineaments

Page 33

were mapped. This map was later refined by Collins et al., (2014) and publicly available[8].

Cameron et al., 2018 carried out an extensive mapping of strike-slip tectonic structures in both light terrains, grooved terrains and transitional terrains from dark to light terrains. This approach was then improved by Rossi et al., 2018 where a detailed structural mapping was performed in the Uruk Sulcus region. Eventually, Rossi et al., 2020 released a satellite-wide structural map form 60°S to 60°N.

The global mapping of the Saturn's satellite Enceladus, based on Cassini ISS image mosaic, was performed by Crow-Willard and Pappalardo (2015) which identified major domains on the highly fractured surface. This global geologic mapping is being improved by Patterson et al., (2017) with a multi-resolution bundle-adjusted mosaic of Cassini ISS images aiming a mapping output scale of 1:2M.
Cryovolcanism on Enceladus has one of the most impressive expressions as water plumes rising from the south-polar terrain (Porco et al., 2006), from a region with an elliptical thermal anomaly called Tiger Stripes Fractures (TSF). This is a region where large fractures leading to crustal extension (Gioia et al., 2007) have been mapped in detail along with a detailed structural characterization was carried out by (Yin et al., 2015).
Due to the variety of structural features on the surface, a unified nomenclature for the structural features on Enceladus has been recently proposed by Nahm and Kattenhorn (2015) with five classes of identified tectonic structures.

On Pluto most of the mapping is centered in Sputnik planitia where the NASA's New Horizon mission has returned the highest quality images at 386 m/pixel thanks to the LORRI instrument (Cheng et al., 2009). Here the mapping by White et al., (2017) defined the main geologic units and identified major hundreds of km-long longitudinal grabens in the terrains surrounding Sputnik Planitia followed by fault scarps tens of km-long. The majority of the region is covered by the unit identified as bright and dark cellular plains made up by N_2 ice, that present both a smooth or pitted surface, with each cell bordered by troughs with almost absent impact craters. Here the N_2 ice is hypothesized to be low-viscosity in a solid solution with a minor quantity of CO ice and the cells and troughs are the product of a solid state convection, with compression localized at the cell boundaries. The pits are most likely the product of the sublimation of the ice due to the higher heat flow at the center of the cells.
More recently Cruiskshank et al., (2019) and Martin and Binzel (2020) recognized new evidence of cryovolcanism in the geologic map of the crustal-scale extensional features of Virgil Fossae between Picard and Wright Montes. At this location could be a source of erupted cryolava, whose composition was better constrained to be a

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[8] https://pubs.usgs.gov/sim/3237/

mixture of H_2O, ammonia, and NH_3 with a coloured component that is hypothesized to be organic matter.

On Charon a large quasi-equatorial graben system called Mandjet chasma and Serenity Chasma subdivides the two hemispheres with the northern Oz Terra and southern Vulcan Planum, crosscuts the entire satellite and has been mapped via image mosaic and stereo DTMs realised during the New Horizons flyby. The first DEMs by LORRI camera were used by Beyer et al., (2017) to compile a tectonic analysis and mapping. Either way, tectonic extension strongly dominates the entire surface of Charon, experiencing several kilometers of global expansion of the crust leading to the tectonic features observed and possibly to cryovolcanism that resurfaced the southern part of Vulcan Planum (Moore et al., 2016).

Although not presenting an icy crust and located in the asteroid belt, the dwarf planet Ceres is another body of the Solar System where cryovolcanism has been hypothesized at several locations. A cryovolcanic dome in the ~17-km-wide and 4-km-high Ahuna Mons Ruesch et al., (2016), that presents signs of extrusions of highly-viscous melt-bearing material. Krohn et al., (2016) identified in several craters on Ceres post-impact modification in the shape of lobate flows, that from morphometric analyses showed a low coefficient of friction resulting overall similar to low-viscosity cryovolcanic flows. The global mapping performed by Williams et al., (2017) better constrained such features, as well as the structural features such as faults, grabens, ridges, furrows, fractures, lineaments and lobate scarps. Later Krohn et al., (2018) , performed a geologic map and a structural characterization of the Haulani crater and surroundings at a scale of 1:250.000 mapping cryovolcanic features and highly fractured material on top of the subsurface ice-rich layer which probably is the source of the cryovolcanism.

■ Faulting and fracturing on small bodies

Faulting and fracturing on small bodies generally develop from external triggers such as tidal torques, thermal stresses and impacts. Example of structural analysis and maps of such features are in Buczkowski et al 2008 for Eros; in Massironi et al. 2012 and Besse et al. 2014 for Lutetia; in Simioni et al. 2015 for the Phobos grooves, in several geological maps of Vesta (e.g. Scully et al. 2014) and in Auger et al. 2018 and Matonti et al 2019 for the comet 67P.

■ Sublimation Processes

Geological features related to sublimation processes have been documented and several planetary and small bodies' surfaces and it is dominant on cometary nuclei.

Cometary nuclei are the realm of sublimation processes and, as such, their surface displays the widest range of sublimation feature typology in the Solar System. Among the others we recall active pits, sublimating niches, sinkhole collapses, honey combs, pinnacles, blue-bright spots, transient scarps, transient circular bulges and depressions, ripple-like and wind-tail like morphologies (e.g.El-Maarry et al., 2019). The OSIRIS camera data-set allow them to be reported in some geological maps even with a good detail (e.g. La Forgia et al 2015, Giacomini et al. 2017 and Lee et al. 2017).

Sublimation of water ice and the related landforms on Mars at high and mid-latitudes were identified and characterised in great detail by Mangold et al. (2011). Ice pits, bright spots and dark spots on the polar caps on Mars have been observed by Malin and Edgett (2001) as well as sublimation of carbonic ice in the southern residual polar cap in the form of the so-called "swiss-cheese terrains" (Thomas et al., 2000), where circular or sub-circular hundreds-metres-wide depressions with flat floors and steep walls with few metres of height are visible. It is notably that these features can change size and shape seasonally across the Martian years. Another less common landform in the south polar terrain is the "fingerprint terrain" characterised by narrow troughs. Dark spots have also been observed on dune fields subject to seasonal defrosting (Mangold, 2011). The so-called "spiders" are another sublimation landform that are characterised by a central depression with irregular cracks and troughs radially departing from its centre (Piqueux et al., 2003) and typically occur in groups, that were mapped in Angustus Labyrinthus to then perform statistical spatial analyses (Hao et al., 2019).

Sulphides sublimation has been invoked for Hollows features on Mercury which are irregular flat-floored depressions ranging from tens of metres each to tens of kilometers for fields and clusters (e.g. Blewett et al, 2011, 2013; Thomas et al., 2014). Normally found on crater walls, rims, floors, peak-rings and central peaks, they are constantly reported as overlaid polygons in quadrangles and regional scale geological maps (Galluzzi et al. 2016; Guzzetta et al. 2017; Wright et al. 2019; Semenzato et al. 2020) and locally mapped in detail using MESSANGER MDIS NAC images (Lucchetti et al. 2018).

In the asteroid belt, large sublimation processes in correspondence of bright spots has been reported and characterised on Ceres especially in correspondence of the Occator crater region (Nathues et al., 2015) , whereas putative volatile related pitted terrains has been described on Vesta (Denevi et al., 2012).

■ Space weathering

Space weathering can affect surface regolith and mappable units of airless bodies. Morphostratigraphic mapping should not be particularly affected, but compositions can

be considerably affected by such a process which can be particularly important for small bodies (e.g. Gaffrey, 2010; Ishiguro et al.,2007) and on Mercury, due to its close proximity to the Sun (e.g. Braden and Robinson 2013). The interaction of Solar Wind and magnetic fields have implications, albeit relatively small, on geologic mapping (e.g. Blewett et al., 2010).

GMAP and SPIDER are going to interact in order to identify potential plasma/surface geology mapping connections and practical implications and use.

■ Multi-temporal geologic mapping, for dynamic resurfacing

Certain Solar System bodies have internal and surface dynamics so intense that the actual surface changes at much shorter timescales than those typically employed by the geologic mapping process. This is the case for moons such as Io dominated by an intense volcanic resurfacing (e.g. Leone et al. 2009; Williams et al. 2011) or for small bodies, such as comets which at the perihelium are affected by an enhanced surface erosion via sublimation coupled with dust fall back (e.g. El-Maarry, et al., 2019).

Specific areas where strong atmosphere-surface dynamics exists, such as mars, experience noticeable surface changes at the yearly and sub-yearly scale (e.g. Hansen et al., 2013).

The link with terrestrial geologic mapping experience could be tied with geomorphic mapping of areas with very active dynamics, such as slope instability, floodplains, coastal areas.

Therefore multitemporal mapping of units being produced or modified at short timescale on Solar System bodies can refer to the relevant type of process-specific mapping, such as evolution of sublimation related morphologie, mass wasting and fall deposits (e.g. Small bodies), or volcanic (e.g. Io) or cryo-volcanic (e.g. small bodies, icy/water worlds).

■ Mapping of analogue (TA) sites and relevant planetary analogues

Mapping planetary analogues (e.g. Garry and Bleacher, 2011; Baker, 2014) can have science or engineering motivations (e.g. Rossi et al, 2018).

The mapping of analogue terrains can also have methodologic value (e.g. Tanaka et al., 2009), both to explore the uncertainty of remote sensing mapping and for direct analogue site applications.

Certain areas with low vegetation, arid conditions and good remote sensing coverage allow for excellent mapping of both lithologies and morphologies of planetary analogue

features. Impact structures (see subsection on Impact processes) are particularly suited (e.g. Tornabene et al., 2005).

Field / ground truth-blind mapping (e.g. Tanaka et al., 2009) can be performed for TA sites (e.g. Cavalazzi et al., 2019), can be performed, in order to support the contextual analysis of TA sites for both field and lab analyses on samples collected in such sites.

GMAP is going to use the same tools/standards used for Solar System bodies (particularly Moon, Mars) for mapping relevant TA analogues. This includes potential TA sites in South America, as well as the North-West China analogue sites within the GMAP/MOST cooperation. In addition for analogue sites, standards of the Geological Service of Italy set up for different geological contexts on Earth will be also taken as reference.

The analogue site mapping, and the map availability on the upcoming GMAP data portal (as well as discoverability through VESPA, see Section 9) can provide contextual information to other TA data to be released.

○ **4.2) Body-specific aspects**

Certain Solar System bodies are characterised by a subset of geologic processes, e.g. only impact and volcanic, or mainly impact ecc. The extent of processes acting on bodies visited by several spacecrafts is well-known. New spacecraft data on previously unknown bodies, such as Pluto or certain Small bodies, have even shown unexpected geologic features and processes, e.g. sedimentary/eolian-like behaviour on comets where outflow and jets mimic sediment distribution on Earth (e.g. Basilevsky et al., 2017), or spring-like deposits on minor bodies (e.g. Ruesch et al., 2019).

Body-specific mapping aspects are thus mostly dataset-limited.

Processes	Moon	Mercury	Venus	Mars	Icy Satellites	Small bodies/dwarf planets and moons
Impact cratering	X	X	X	X	X	X
Volcanic	X	X	X	X		X
Tectonic/structural	X	X	X	X	X	X
Sedimentary				X		X
Glacial				X		
Mass wasting	X	X	(?)	X		X
Metamorphic/Metasomatic		(?)	(?)	X	X	X
Cryo-volcanic					X	X
Multi-temporal		(?)		X	X	X
Sublimation		X		X	X	X

Table 2: Main geologic processes as highlighted in the previous section and applicability to Solar System bodies discussed here.

Moreover, the larger and more complex a Solar System body is, the more tend to be the range of geologic processes that took place through its geologic history. Some processes are relatively clear to be distinguished, others less, either due to the "exotic"

nature or context on a certain Solar System body, or due to the equifinality, which, without ground truth or independent evidence, is an long-standing problem affecting planetary geologic mapping (e.g. Baker, 2014; Pondrelli et al, 2018).

Dataset-limited body-specific aspects include also the recognition (and its uncertainty) of certain geologic features, such as layering, folding and internal architecture and structure of deposits visible on the surface via remote sensing. An example are the proposed layering or folding on Venus (Byrne et al, 2020), based on data (Magellan) which are at the limit of suitable resolution. Such predictions are useful to set requirements for future missions and experiments, as well as to plan for targeted geologic mapping efforts.

Further details on mapping on Icy Worlds (Ganymede, Europa, Enceladus, etc...) and on Small Bodies are reported in Appendix 8.

● 5) 3D geologic modeling / mapping

○ General aspects

Three-dimensional geological subsurface models are a numerical representation of geological features of interest in a particular area. The three-dimensional representation is obtained by means of meshed surfaces of geological structures as faults/fractures surfaces, bedding planes, stratigraphic horizons and any type of contacts. The meshed surfaces are the result of a modelling process that takes into account all the available geological constraints. 3D geological models in this sense constitute the sum of all geological investigation, summarising the available knowledge into a numerical representation that can be updated with new constraints whenever they become available. The choice of the modelling approach is driven by the availability of geometric constraints for the body of interest.

The creation of 3D geomodels requires the identification of numerical constraints that can be used for geometric reconstruction. Cartography is often the primary source of modelling constraints due to the scarcity of subsurface data in planetary geology, although data from ground penetrating radars are also sparsely available and might be useful in some restricted contexts (e.g. MRO SHARAD/MARSIS, Chang'e III Yutu's GPR). Color variegation and/or spectral variability in correspondence of impact craters excavating superposed units can also be used as borehole-like constraints for subsurface inferences (Semenzato et al., 2020).

Cartographic data need to be merged with additional three-dimensional products (e.g. DEMs for topography) prior to their usage as geological modelling constraints, hence

the availability of high-quality terrain models is desired and mandatory in general terms.

The generation of three-dimensional models requires the use of dedicated software packages. High-level software, used in the mining and oil industries provide easy to use modelling strategies for most of the cases. Some open source software is also available and can be useful in some contexts but is in general still difficult to use and more limited in some aspects. On the other hand, in planetary sciences the severe scarcity of data and subsurface constraints, which also makes more critical the precise control over the chosen modelling strategy, makes it possible (and sometimes preferable) to obtain valuable results with completely open source solutions. A list of open source resources is available at the end of this section.

A good introduction to three-dimensional geological modelling can be found in (Calcagno et al., 2008; Wellmann and Caumon, 2018), while (Hillier et al., 2014) provides technical insights on a commonly-used interpolation method for geologic applications based on Radial Basis Functions (RBF). A more exhaustive mathematical treatise can be found in (Mallet, 2002).

○ Body-specific aspects and applications

Different planetary bodies are characterised by different levels of inherited knowledge that must be taken into account: the variability of the specific missions targets and goals (different instruments, observational constraints etc.), and geological aspects (the family of geological structures that could be modelled) makes the applicability of modelling methods highly variable depending on the overall context.

Planetary surfaces with high variability of geological environments, well visible stratified sequences and structures (i.e. Mars) are the most appealing for three-dimensional geological modelling. Many of those structures (e.g. faults, folds etc) are well known and mostly understood from Earth-based studies, although the overall sparsity of subsurface data makes surface observations the only source of modelling constraints in most of the cases. An example of this modelling strategy can be found in PLANMAP deliverable 6.1 (Pozzobon and Penasa, 2020).

True subsurface data are available for the North and South poles of Mars, provided by SHARAD (MRO) and MARSIS (MEX) instruments, which provide high-quality underground imaging especially suited for the study of martian polar caps (Seu et al., 2004; Jordan et al., 2009). The amount and preprocessing needs of these data poses additional technical challenges but they do provide invaluable three-dimensional information. A radar sounder was also onboard the Kaguya (SELENE) orbiter spacecraft for the study of Moon subsurface (Ono et al., 2010).

Subsurface imaging by means of radar probing have also been employed onboard some lunar rovers (Chang'e 3 and 4, see for example Xiao et al. (2015) and RIMFAX is onboard Mars2020 rover (Hamran et al., 2015) and will provide data up to 500 m deep. An example of such a modeling is in the PLANMAP's deliverable 6.2 (Penasa and Pozzobon 2020)

In the context of small bodies, subsurface information is even scarcer: a notable effort was the CONSERT experiment onboard Rosetta (Kofman et al., 2007), which unfortunately provided very limited data due to the premature loss of the lander. Nevertheless, clues about the inner layered structure were provided by surface-based observation (Massironi et al., 2015), which were then used to create three-dimensional models of the inner structure (Penasa et al., 2017, 2022; Franceschi et al., 2020).

Furthermore, craters might provide important insights for the recognition of stratigraphic horizons in the subsurface of any cratered body. By identifying the intersection of geological surfaces with the crater's flank it is indeed possible to obtain valuable information on the local stratigraphy (Semenzato et al., 2020 and references therein).

To summarize, limiting aspects of the application of three dimensional modelling in planetary geology are a) the scarcity of underground good-quality data or their absence, b) lack of exhaustive conceptual models for some planetary geological structures that could be used to better constrain the overall geometries.

○ DOM-based mapping and 3D cartography visualisation

Recent advances in photogrammetry make it possible to create detailed three dimensional meshed surfaces of outcrops from imagery from rover's cameras. These methods normally produce triangulated meshes with textures which can be employed within advanced virtual-reality systems to allow the study and visualisation of outcrops of interest (Barnes et al., 2018; Caravaca et al., 2020). Thanks to the three-dimensional nature of the data it is possible to take accurate measurements, mimicking the operations that would have been made in the field by a human operator. Applications range from structural studies to sedimentology depending on the context, and they leverage the 3D data to obtain accurate measures of thicknesses, distances and orientations (attitudes) (e.g. Traxler et al. 2022).

Notice that, although the immersive experience being a plus, similar results can be obtained by using visualisation platforms suitable for 3D data exploitation that do not necessarily require complex virtual-reality setups.

Geometries interpreted directly on the 3D model of an outcrop have the obvious advantage of being intrinsically three-dimensional, and do not suffer from distortions introduced by projected imagery, which cannot represent true distances in the whole

field of view. In this sense, greater advantages are obtained when outcrops of variable geometry are studied. Furthermore, this approach can help in retrieving geo-structural measurements otherwise not possible on standard GIS and DEMs (e.g De Toffoli et al., 2020).

○ 3D standards and formats

A variety of file formats do exist for exchanging three-dimensional data. Well-established formats, such as the Wavefront's OBJ format or the Stanford Triangle Format (.ply format) can be read and written by most 3D manipulation programs but they don't carry additional information related to the geological meaning of the represented objects. Although some tentative open-source standardisation does exist for geological modelling, their use and maturity is still to be fully developed.

Mesh representation is achieved by listing the vertices composing the mesh and defying their connectivity to form the faces (triangular, quads, etc). Texture imagery, which is important for geologic interpretation, is most often supported as external texture images (as a standalone png or jpg file for example). The link between the texture and the three-dimensional mesh is achieved by storing UV coordinates for each vertex of the mesh. These coordinates describe the position of the corresponding pixel in the texture as a normalised coordinate on the image plane.

Additional scalar fields (e.g. representing elevation or other space-dependent measure) can be associated to the vertices or to the faces of the mesh, but not all formats do support this kind of additional data to be carried within the file.

Volumetric meshes are often used in geology, where subsurface volumes are discretized in a series of cells of variable shape, together with additional measured or modelled fields (e.g. permeability, density, etc). One of the most complete open-source formats that can handle both standard 3D meshes (triangular meshes) and volumetric meshes is the family of the VTK-based file-formats (Schroeder et al., 2006). The VTK library, being targeted to the scientific community, can read and write 3D data on many different software platforms, but derived files are often not supported by generic rendering software packages (e.g. blender).

● 6) Base data/maps, (pre)processing, and mapping environments

Maps are graphical visualisations of quantitative or qualitative attributes over an area, region, or a whole (planetary) body. Maps emphasise the relationships between different elements, such as geological units, geomorphological features and structural observations. To place these observations into a geographic context, a basemap is often used as a background layer, which provides an easily-readable reference frame (e.g. a true color image of the planetary surface).

On top of the base-map, the features of interest are added in subsequent layers, e.g. to define geological units or depict structural elements. A map, then, is composed by a multi-layer structure of (heterogeneous) data sets, corresponding to several data products and one or more map layouts (See Section 9).

Each layer representing the map may be thought of being provided by a different data source. Data sources may be of different formats, for instance, basemaps are typically raster images (*e.g.*, GeoTIFF), while surface features are in some vector data format (*e.g.*, ESRI Shapefiles, Geopackages, and alike).

Maps are often restricted to a specific region of interest (e.g., a particular quadrangle of Mercury), but can also represent the whole planet. As such, the term map has multiple, slightly different, meanings. Whether we are talking about a morphological description of a crater or a global view of Mars landing sites, an interactive web-app interface or a printed, static representation should be clear from the context.

Primarily, though, in the context of GMAP a *map* means a detailed description (*i.e.*, a multi-layered representation) of a specific region of a planet or moon (Rothery et al, 2018; Rossi et al, 2020).

Basemaps may be *global* or *local*. Global basemaps are typically used as a general background frame providing context over the whole planet. Local basemaps would typically suit a restricted view over a specific region. Depending on the area covered by the map, the basemap might be generated as a mosaic of images. Many different global mosaics are provided by USGS[9] for planetary bodies.

Individual, region-specific maps may need their own custom basemap mosaic, using individual data products/granules and open source software packages (See Mapping tools and Software subsection).

Basemaps of continuous or near-continuous nature, depending on the coverage of relevant imagery, are used as prime dataset for geomorphic and geologic mapping. Their geometric accuracy can vary depending on the data accuracy from which they were created (e.g. SPICE, imagery resolution etc.).

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[9] https://www.usgs.gov/centers/astrogeology-science-center/maps

Additional data-types that are often handled during and as a result of the map-making process are listed in Table X. This list is not exhaustive, but it gives a brief overview of most common data that will be used during the production of GMAP cartography.

Data type	Description
Metadata	The aim of including metadata is to allow reproducibility by providing information about the processing steps used
Raw data	Planetary archives, PDS3, PDS4 imagery and cubes derived from external sources. The type is variable depending on the mission and sensors.
Base mapping data	OGC-compliant data already available from external entities (e.g. USGS) or base mapping data produced ad-hoc in the context of the project. The data is used as context or mapping layer on which maps are created.
(Integrated) Mapping products	Integrated mapping products with individual layers are being produced in OGC-compliant formats, both raster and vector, as well as with suitable 3D formats
Topography	DTMs or derived products which are used to represent elevations
Multi and Hyper-spectral data	Spectral cubes derived from multi and hyper-spectral sensors in OGC-compliant multi-band formats (e.g. geotiff)
Geophysical data	Data derived from remote sensing of geophysical properties. They might be of variable nature depending on the mission and includes radar sounding data and potential field measures (magnetic, gravity, etc..).

	Although not directly used for performing mapping, they might be instrumental to produce large-scale mapping.

Table 3: the most common data-types that are often used as supporting data for the creation of geological maps.

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○ Pre-processing workflows

Basemaps and imagery for GMAP maps will follow best practices and available tools, most of which have been developed and are being maintained by external NASA/USGS or other parties, such as USGS ISIS (e.g. Anderson et al, 2004; Sides et al., 2017; Kirk et al., 2017) and ASP Stereo (e.g. Beyer et al., 2018; Beyer et al., 2020), in local or cloud implementations.

Data expected to undergo pre-processing, and for which dedicated workflows will be developed are mainly images (in the form of raster or data-cubes). Imagery provided by the source archives may require additional processing to e.g. reduce noise or perform additional corrections (to obtain radiometrically, photometrically or geospatially corrected images). Pre-processing workflows will take care of transforming such images into a state ready for scientific activity.

Additional data which might require preprocessing might be provided by instruments which data is used in the context of specific investigations, for example radar sounding data for subsurface investigation, which might require dedicated pipelines.

■ Spatial reference and CRS

GMAP maps will adopt spatial reference, map projections, Coordinate Reference Systems (CRS), depending on the location and extent of the geologic maps. CRS information will be documented within the map-wide metadata (See Section 9 and Appendix 2, 7) or for each dataset when appropriate (e.g. raster imagery or a vector layer which might have a different CRS in respect to the overall map).

■ Accuracies

GMAP products deriving from community inputs on the VA activities will have a range of geometric accuracies, depending on the input data (e.g. the employed SPICE kernels) and the specifics of the processing (e.g. USGS ISIS). Products requiring improved accuracies will make additional use of control networks (e.g. mosaics related to landing sites).

Within the map-wide metadata, the basemap processing history and base data product details should be included for reproducibility as well as for an assessment of the geometric accuracy of the maps, for 3rd party users, such as individual researchers, academic and industrial/agency users (see Appendix 2).

■ Mapping tools

GMAP VA will promote to Europlanet scientists/users the use of Open Source tools and software for performing mapping, such as Qgis[10]. Existing long-term supported data processing and analysis systems exist (ISIS) and when the tools are not entirely available (e.g. DLR VICAR), higher-level datasets are (e.g. Putri et al., 2019). See also Appendices 3-5 on several open source tools available for geological and generic mapping purposes.

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[10] https://qgis.org/

• 7) Map data management and Cartographic aspects

If not referenced differently, this chapter is based on previous work from Nass et al (2010a, 2010b), van Gasselt and Nass (2010), van Gasselt and Nass (2011), Nass and van Gasselt (2013), and van Gasselt and Nass (2015). Additional inputs derive from the H2020 PLANMAP project, where cited.

○ The Geological Mapping Workflow

The geological mapping process in Planetary Sciences is based on the subjective process of identifying, interpreting and delineating mixed-type surface units and structures as spatial entities (see previous chapter). The main difference between the planetary and the terrestrial mapping process is in general the lack of ground truth data. However, some aspects of the overall mapping process are still comparable to the terrestrial ones, with the important difference that field surveys cannot be performed and the geological mapping is done by means of remotely-sensed data only. The process itself can be subdivided into four steps: (1) data acquisition, (2) filtering and pre-processing, (3) mapping and (4) rendering (Haber, 1990; Wood, 1996; Carpendale 2003). These four steps are summarized in Table 4.

Process step	Basis	Requirement	Task	Environment
Acquisition	Data archives of mission data	Access and authorization for the data portal	Selection of base data via spatial and thematic filtering	Web-based interfaces or command line
Filtering	Transformation to preprocessed data	Description of data structure and topology	Reference and structure of the mapping data basis. → resulting in	Processing software or/and GIS

			an object model	
Mapping	Preprocessed data in object model	Geometrically primitive elements (point, line, area) described by graph. variables	Object definition by graph. Variables (like position, colour, size [Bertin, 1974]), textual and attributive description. → resulted in a graphic model	GIS or graphic Software (with limitations in attributive description on object level through decoupled attribute table)
Rendering	Transformation in graph. Model	Frame information and software systems for layout of map sheet	Final presentation of analyses and interpretation results within a media usable image/map	GIS and graphic software

Table 4: Processing steps for the planetary geological mapping process. The process is mostly the same of the approach used on geological mapping through remote sensing on Earth.

○ Approach of Action Aspects

The production of maps thus regards the creation of graphical visualizations of terrestrial or planetary geographical data. However, to create readable, combinable and comparable map products, which should also be searchable, findable and accessible in sustainable way, a software-based mapping framework must cover three further major aspects:

- Map data must be stored in a well-structured way within any map data model. Properties of mapped entities are assigned during the mapping and interpretation process (cf. van Gasselt & Nass, 2010, 2011).
  → **Data model of Geological Objects**

- Map data must be visualised through a homogenous and unambiguous object-symbol-reference. To achieve this, an adapted GIS-integrated symbol library is required which allows mappers to assign standardized sets of symbols for a homogenous appearance of map entities. This object-symbol reference must also be linked to the core data model in order to provide sustained functionality (cf. Nass et al., 2010a, 2013).
  → **Cartographic Representation**

- Map data must be described in order to trace back and review interpretation results. Such a description consists of entries comparable to a classic map legend that allows characterising map layers. Another set of metadata descriptors is composed of information about the primary data basis (sensor data and auxiliary information) as well as the map product itself, including title, scale, mapping period, keywords, context (cf. Nass et al., 2010b).
  → **Description by Metadata** (**divided in data and map entries**)

The results in table 1 as well as the aspects listed before resulted into three main issues: entity structure, visualisation, and attribute description. These issues need to be coupled into the mapping process itself as shown in figure 1).
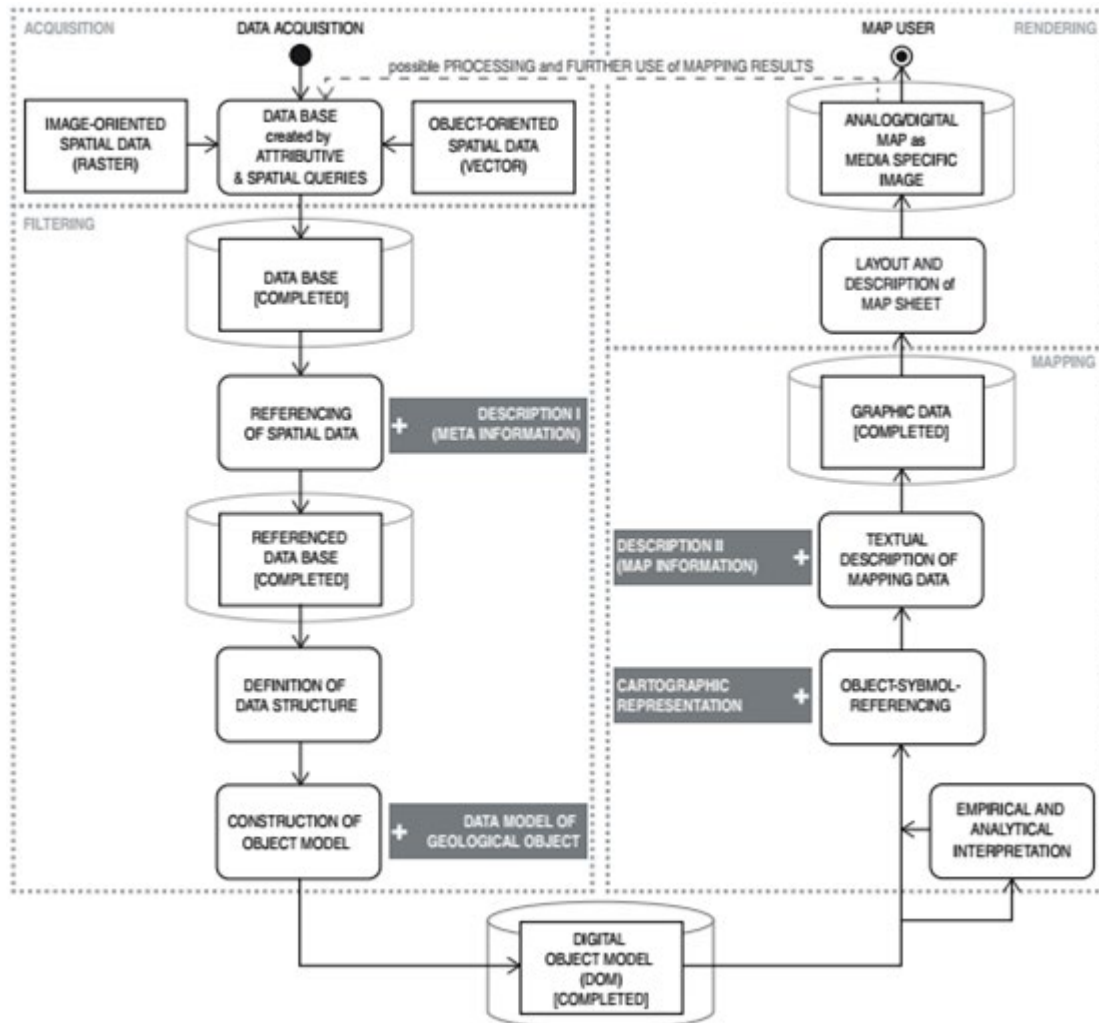
Figure 1: Planetary Mapping process visualised on a technical level. The grey boxes describe where it is possible to interact. (cf. Nass and van Gasselt, 2013)

In order to combine these three basic requirements within a common mapping framework the basic model design should be independent of GIS architecture and implementation specification. As most COTS- and FOS-GIS rely on relational database management systems (RDBMS) a relational database model (DBM) is used to model data flow. For database exchange in terms of DB structure as well as contents the XML interchange format (XMI) is used (OMG, 2007). Signatures and symbols can be transferred to SVG (W3C, 2011) and stored as accessible strings. For metadata description, XML (W3C, 2008) provides a platform-independent description. The hierarchical structure of these formats can conveniently be decomposed into relations by means of XML-shredding (e.g., Freire, 2003).

○ List of Requirements

As a starting point for handling these main issues a list of requirements is needed. This list is modular and could be adapted in the future.

■ I) Data model of Geological Objects

1. Information on and link to base data

2. Query/Request for existing mapping data

3. Combination between object geometry and

4. Link to thematically appropriate analyses data

5. Rules and regularities of the bedrock and surficial units

6. Absolute and relative age determination

Regarding the system requirements the metadata description needs to handle

7. Compactness

8. Modularity

9. Granularity

10. Relational- or object relational character

11. Systematic object naming

■ II) Cartographic Representation

Cartographic representation in Planetary Geology and Geomorphology describes all spatial bedrock and surficial units and linear features which are identifiable depending on the resolution. For a comprehensive and unified cartographic visualization a catalogue for usable representation is needed. This catalogue should handle:

1. Combination of symbols

2. Colour coding and schema

3. Orientation of symbols

4. Scale-depending symbols

5. New symbols for new features

6. Visual hierarchies

Regarding the system requirements the metadata description needs to handle

7. Independence of environment and software

8. Flexibility

9. Rules of visualisation (scale- and overlay dependent)

10. Fix link between object description and representation

11. Textual description of individual symbol

■ III)   Templating

The development of a digital template for a geologic mapping is critical for including the above mentioned information.

A mapping template should address the following issues:
- The geospatial part should be accessible with any mapping/GIS software
- The graphical/written part should be in an open format
- It should be versatile enough to be used for any planetary body and by any agency

The template should evolve with time, so versioning is important as the generated map will report that version of the template in order to maintain long term usability.

See Appendix 1-7.

Existing templates:

USGS:
- https://planetarymapping.wr.usgs.gov/Page/view/Resources

Planmap:
- https://wiki.planmap.eu/display/public/D2.1-public
- https://wiki.planmap.eu/display/public/D7.5-public

■   IV)   Description by Metadata (divided in data and map entries)

The metadata description concerns both, the conducted mapping results as well as the underlying data basis. Therefore, as mentioned above, we subdivide the descriptive metadata entries in two levels, the vector-based map level and the raster-based dataset level.

Map entries (focus on vector data): This level is composed of descriptions for the entire digital object model, each spatial object and object classes interpreted and analysed by the mapper and visualised in a map. Within this map-level the main focus is on vector-based datasets. Thus, metadata descriptions deal with the interpretive background which is visualised by the cartographic map design and which uses graphical variables such as allocations of colour, shapes, sizes etc. The information we need for understanding and further utilising a digital cartographic model in planetary geology are:

1. Which data serves as a database for the mapping?

2. Mapping scale and level of detail?

3. What is the purpose of the mapping conduct?

4. When, under which guidance and by whom was the mapping conducted?

5. Do additional statistics and/or empirical data exist?

6. What is the minimum scale of mapped features?

7. What are the boundary coordinates of the map?

8. Which reference system and projection were used?

9. Where, and in which coordinate system is the position of an individual spatial object defined?

Data entries (focus on raster data): The base-data level dealing with the description of utilised image data, is technically implemented by standardised metadata for planetary raster data (cf. PDS, section 2.3). However, in order to decide (a) which selection of metadata entries should be linked to the database model for planetary mapping, and (b) whether there is a need for modification or extension of the metadata set, the exact definition of descriptions has to be substantiated. Regarding formats for this base-data level the current focus is on raster data. The required descriptions in the field of planetary geology that help understanding the characteristics of base data and subsequently the quality of the elaborated mapping results are:

10. Which quality wrt resolution has a particular image dataset?

11. Which boundary coordinates does the particular orbital image have?

12. At which time/date was the image recorded?

13. Which characteristic information is related to a particular image?

Regarding the system requirements the metadata description needs to handle

14. Assignment of keywords

15. Standardized syntax

16. Fix link between data and description

17. Traceability and Reusability

18. Portability

19. Validation

Further details regarding these requirements are shown in van Gasselt and Nass (2010, 2011, 2015) Nass et al (2010a, 2010b). See also Planmap map-wide metadata[11], similar to product-wide metadata in e.g. USGS Astropedia[12].

○ Envisaged map types

The range of map types in GMAP, given the heterogeneity of the community, is expected to be broad.

A core initial set of map types (See Rothery et al., 2018, and subsequent modifications) includes those non-standard ones developed with the H2020 PLANMAP project. The types of geological maps might be more than those below, but, based on PLANMAP experience, most geologic mapping use cases should be included in the following subsections. Additional information for each map type can be found in Rothery et al. (2018).

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[11] E,g, https://data.planmap.eu/pub/mars/PM-MAR-MS-Crommelin/
[12] E.g. https://astrogeology.usgs.gov/search/map/Moon/LMMP/LOLA-derived/Lunar_LRO_LOLA_ClrShade_Global_128ppd_v04

■ Morphological maps

Morphologic maps deal only with the morphology without any considerations on the stratigraphic relationships among deposits. Particularly well suited to map periglacial and glacial deposits, gravitational processes, and terrains of different roughness on minor bodies.

■ Morpho-stratigraphic maps (i.e. USGS Standard-like maps)

The great majority of the geological cartography on planetary surfaces follow the standard maps principles where mapping is carried out taking into account morphologies and the stratigraphic relationships among the associated deposits.

■ Stratigraphic maps (i.e. compositional integrated maps)

A compositionally integrated map is created by taking into account stratigraphic, lithological and spectral information to define the units subdivision in a planetary geological map or to devise specific symbologies to represent the occurring relationships among these properties of the units. There are very few suggestions from USGS standards for integrating compositional information into planetary mapping, but Semenzato et al. 2020 produced a map showing how to integrate color variegation and morpho-stratigraphic units in a single map.

■ Structural maps

A geo-structural map is a geological map in which all the features able to explain any deformational event that affected the mapped area are properly highlighted (Rothery et al., 2018). Although not always required in USGS standardized geological maps (see Skinner et al, 2018), geological cross-sections are mandatory for any geo-structural map and must be almost perpendicular to the major mapped structures in order to enable their subsurface representation. See also section 5.

■ Landing site maps

Landing site maps will follow the standard defined here above for regional maps. However, they will also include information relevant to the higher resolution of data used for mapping, such as data acquired by in-situ probes when existing. In particular, these differences will include information relevant to landing site selection such as landing ellipses, slope gradients, mapping of boulders, outcropping and cover materials.

■ In-situ maps

In-situ maps are developed at the scale of rover traverse or lander surroundings; i.e. at scales below 1:50,000. These maps are created from the merging of orbital, aerial (when existing) and in-situ data, thus responding to a different logic than maps composed of pure orbital data in which facies cannot be defined as they can in the field.

■ Resource maps

Resource-focused aimed at evaluation of possible resources for in-situ resource utilisation (ISRU), either volatile or mineral-related, could follow best practice examples aimed at supporting robotic and, mostly, human exploration (the Moon, Mars). See also D8.9 (Tesson et al. 2022).

■ 3D geologic models and geo-modelling maps

The production of three-dimensional subsurface models might require the creation of specific structural and stratigraphic mapping products with the aim of providing constraints that can be directly used within geological modelling software packages. The geo-modelling maps, which can often be derived from already-existing maps, must emphasize the structural relationships between geological bodies that are expected to be reconstructed through geological modelling. This can be done by providing two dimensional geometries that will be coupled with a DEM surface to produce true three-dimensional representations. See also section 5 on 3D geological modelling.

○ Map naming

The following map naming (Table 5) follows the H2020 Planmap project conventions, in order to identify with a simple and relatively short alphanumeric code geologic maps on any Solar System body.

GMAP prefix	Target body	Type (multiple allowed in attached substrings)	String or substring	Specific substring

GMAP	MER = Mercury	S = Stratigraphic	<Toponym>	e.g.
	MOO = Moon	C = Compositional	e.g.	3cc = 3 classes
	MAR = Mars	M = Morphologic	Hokusai	5cc =5 classes
	…	G = Geo-structural		
	…	I = Integrated		
	Abbreviations or full name of planetary bodies migth be used.	D = Digital Outcrop / Geologic Model-derived		

Table 5: summary of PLANMAP-like map types. Specific additional thematic geologic or process-specific (e.g. sedimentologic) map types can be added, and they will be documented on the GMAP wiki, repositories and web site.

Versioning of partial and complete maps will be used (See Sections 8 and 9).

● 8) Mapping review process

GMAP intended approach on mapping review will be as agile as possible, and the envisaged review process sees support from the GMAP partners and possible external advisers. Periodic iteration and discussion with USGS and other parties to obtain feedback and seek common benefits will be explored.

The mapping review process is essential, both on a scientific and technical level (e.g. Skinner et al., 2018; 2019). The most important elements that need to be reviewed are the overall approach taken by the operator and, especially how the units and contacts have been traced and attributed. Furthermore, the map needs to be reviewed technically and not only scientifically. This process constitutes the last operation in the mapping process, and grants scientific validity and technical correctness of the resulting dataset.

This review process must thus be handled at two different levels. The methodical and scientific review (more details in the next section) takes care of assessing the adequateness of the scientific interpretations and also the clarity of the visualization, the significance of the described observations and also some technical issues like the

selection of projection. This operation requires a permanent exchange of ideas and fruitful discussion between mapper/author and review board to guarantee the quality of the scientific result.

The technical review verifies the quality of the data composing the resulting digital map. This covers topics like the consistency of topology, the adequate use of fields for the descriptions of the geometries, the correctness of the CRS definitions and their embedding in the data products, etc... On a map level, the technical review will also take care of the whole rendering of the map, e.g. correct usage of standardized symbols, the overall map sheet layout, integrity of legend.

The review process itself can be particularly difficult to track, depending on the scale and extent of review (partial, total, intermediate steps, for thematic maps, etc.). It is therefore difficult to define an unique workflow that can handle all the specific cases, but some approximated guidelines for the most common cases are presented next:

- **Review of a complete map (longer timescales)**
  - Author suggests a map to GMAP board via EPN GMAP calls
  - Board selects the mapping proposals
  - Author performs mapping and completes a map
  - Author provides/uploads map (basemap + GIS + layout)
  - Reviewers can raise issues that need to be solved prior to publication
  - The author responses and improves the map (GIS, basemap, layout, or as needed)
  - Board validates the adequateness of the final map
  - The map is published (supported by templates for map sheet layout or technical guidance for proofed map data upload).

- **Review of a in-progress or partial map (shorter timescales)**
  - Author suggests a map to GMAP board via EPN GMAP calls
  - Board selects the mapping proposals
  - Author performs some mapping, and geologic or cartographic questions arise
  - Author raises an issue that requires the reviewers attention
  - Reviewers provide advices/guidelines to solve the issue
  - Author will proceed with the mapping

The first use case (complete map) might rely on existing best practice (e.g. Skinner et al., 2018) and it does require substantial time (possibly multiple years). The second use case might have a shorter loop and timescale (weeks, months).

The use of spatially-enabled (see section below) version control could enhance the review process in a visual way. GMAP envisages the development of a simple workflow and will support the employment of such systems.

○ Peer-review for geologic mapping

Different initiatives and authorities provide national and international geological mapping campaigns. In order to create valuable and comparable maps these maps are created under consideration of different guidelines and review instructions. One successful and valuable example for the technical guidance for multi-mapper and international mapping projects on European level is the *European Marine Observation and Network (EMODnet[13])*. Guidelines, technical guidance and vocabulary related to this project are given by Asch and Mueller (2020) and Asch et al. (2020).

The *Servizio Geologico Italiano,* now part of ISPRA, developed a review process which included in-agency specialized personnel and also a national-wide board of 10 experienced academic researchers. The guidelines and relative updates are divided into notes and published by ISPRA[14].

The British Geologic Survey review process passes through an internal board including the BGS's director and 6-10 senior representatives of industry, governmental agencies and academia.

Additional best practice from other European geologic surveys is going to be considered and included (e.g. Robida, 2019).

Within planetary mapping the USGS produced public domain Open File Reports guides on peer-review process for both terrestrial and planetary maps (e.g. Skinner et al., 2019). A list of resources that can be of interest can be found on the NGMDB-USGS website[15].

Outside of the USA, Acting as a trans-european and cross-agency project, GMAP aims to contribute to the planetary geologic mapping effort with an agile review concept, using and possibly improving simple state-of-the-art tools

○ Review tools and software

Existing review processes work by visualising and commenting digital files produced by the mappers. The files are submitted following a pre-defined schema by the mapper and reviewed by each reviewer on its own. The reviewer then sends back comments to the author.
Beside traditional text-based reviews, we want to explore existing collaborative systems which track single problems, encouraging a more agile review process. Many issues related to geologic maps are related to geospatial entities, so discussing a

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[13] http://www.emodnet-geology.eu/
[14] Quaderni https://www.isprambiente.gov.it/it/pubblicazioni/quaderni
[15] https://ngmdb.usgs.gov/Info/standards/

problem on the very specific geometry greatly facilitates communications between reviewer and the mapper.

A web-based approach can simplify the process, as all the reviewers' comments would combine on the same data. At the moment of writing this document, no web-based system for reviewing interpretative maps is readily available, but its development will be supported and encouraged by GMAP.

■ Geospatial Version Control System

Tracking edits on geospatial files enables issue-based reviewing. Tracking should allow to make a log of who edited data and when they did it. Once tracking is enabled, each time an edit is made, information about editors is automatically recorded.

Current implementations of Geospatial Version Control are:

Open Source:
- GeoGig: http://geogig.org/
- SNO: https://sno.earth/

Proprietary
- ArcMap version > 10.1

● 9) Final products, usage and distribution

This section inherits some of the work performed by the Planmap H2020 Space project, and it lays out directions from Earth geologic mapping and geospatial/thematic mapping projects and initiatives. Moreover, the overall Europlanet GMAP data will obey to the general Europlanet DMP (Europlanet H2024, 2020) and GMAP data will adhere to FAIR principles (following PLANMAP, See Rossi et al., 2020):

The current long-term archiving and availability of GMAP data is as follows:

- All Raster, vector and layout (pdf) mapping data
  - Short-term: on the upcoming GMAP data portal
  - Long-term: on Zenodo, or the ESA PSA DOI-granting guest storage facility on https://www.cosmos.esa.int/web/psa/psa_gsf
- Additional ancillary geologic models and specific 3D products
  - Short-term: on the upcoming GMAP data portal
  - Long-term: on Zenodo, the ESA PSA DOI-granting guest storage facility on https://www.cosmos.esa.int/web/psa/psa_gsf
- Additional ancillary specific compositional products
  - Short-term: on the upcoming GMAP data portal
  - Long-term on the INAF DOI-granting data repository

Findable data:
- Longer-term discoverability will be guaranteed via connected Institutional repositories (ESA, UNIPD, INAF), VESPA sharing and inclusion in planetary data archives that are accessible and commonly used by the community, ESA PSA, via the ESA Guest Storage Facility[16] (GSF), as performed by earlier H2020 PRojects (e.g. Putri et al., 2019; ESA, 2019) Shorter-term discoverability will be supported by the GMAP data portal (See Appendix 7).

Accessible data:
- Geological mapping products will have multiple level of accessibility, with variable scale and complexity, from individual units to finished products and thematic maps

Interoperable data:
- OGC standards for CRS and formats will be adopted (See Appendix 7)
- Data discovery interoperability will be granted via the use of state-of-the-art VESPA EPN-TAP (Virtual European Solar and Planetary Access EuroPlanet Table Access Protocol) for data search and query.

Re-usable data:
- Raw data will be used and processed/reduced, with embedded re-usability upstream with respect to GMAP, processing logs will be included in the metadata
- Custom base-map data (e.g. mosaics) and partial mapping products and processed/derived datasets underlying geological mapping products (standard, non-standard, integrated, etc.) will be usable by others, also in the future, regardless of the final geological mapping products.
- Integrated and/or final mapping products will be re-usable directly or indirectly, with access to combined information content or individual layers (See Rothery et al., 2018) with relevant topologies (units, contacts, etc.).

Geological Maps (See Rothery et al, 2018) are the project's flagship product. In the previous sections we went through the structure -- theoretical and material -- of a geological map content,

Geological maps released can be further specified into (See Section 7):
- Standard USGS-like geological maps
- Integrated geo-spectral and geo-stratigraphic maps
- Geo-morphological maps
- Geo-structural maps

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[16] https://www.cosmos.esa.int/web/psa/psa_gsf

- Geo-modelling maps
- Landing site and traverse maps
- Digital outcrop models
- Subsurface models

Nevertheless each geologic (or thematic) map is physically composed by raster and vector data, map-sheets, documents and metadata in general.

GMAP geological maps are realized as a package of different data products that integrate each other to address a particular geological view of a body. It is of our interest to publish the whole data package as well the individual data products to maximize the value of the work done (by optimizing the access to the data sets).

○ Mapping products vs. datasets

Data granularity in GMAP has implications for its access and discoverability. For example while individual units can be queried within an individual vector geologic/geomorphic map, a map layout, which comprise multiple layers at once (basemaps, polygon units, linear contacts, linear feature, morphologic overlays, point features, nomenclature, etc.) do not allow to easily perform this operation. Hence, although they convey almost the same information, the two datasets correspond to a different level of accessibility. These differences must be taken into account when the data is served and managed, to grant easy access and discoverability of the data.

For attribution, citation and access reason, an individual geologic map product, e.g. one of those from PLANMAPas reference[17](e.g. Wright et al., 2019) is referred to as a dataset, e.g. in the ESA GSF sense (see Data Citation), containing different products: a map layout document, one or more vector files for geology units, contacts, linear features, basemap(s), additional data layers, models, if applicable. The search granularity, depending on the context, could identify individual products, or just the entire map database/dataset.

○ Data Packages

The (map) data package is an arrangement of files and directories used to consolidate different data products into a single and meaningful data structure. For instance, the structure that was adopted by the PLANMAP project[18], and envisaged for GMAP VA upcoming products can summarized as follows:

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[17] E.g. https://data.planmap.eu/pub/mercury/PM-MER-MS-H05_5cc/
[18] https://data.planmap.eu/

```
.
|-- 3dmodel
|-- README.md
|-- documents
|-- raster
`-- vector
```

`README.md` is a document containing metadata concerning the package as a whole (e.g. description, CRS and references).

On GMAP, in addition to regular text metadata in the README.md there might be also at least the lower level metadata (eg, CRS, bounding-box) in a structured file format (eg, JSON) suitable for machine/software reading that we can use to verification and quality assurance of the package and its products.

The directory 'documents' is used to store high-level products such as map-sheets, articles, or similar. Files within this directory use common file formats (PDF, JPG) so people can easily access them from any platform, allowing easy inspection of the package content.

Directories 'raster', 'vector' and '3dmodel' contain scientific, format specific products providing the data which are presented in the *documents*.

Each data product (eg, a morphostratigraphic map-sheet) can be accessed and used individually, or the full package can be employed, allowing access to a complete dat-set. The way it can be done is discussed in section 'Data Access' below. How to cite the data product and package is discussed below, in section 'Data Citation'.

○ Data access

Planetary data access has a variety of forms, ranging from archives (e.g. FTP servers) to web-based data services (e.g. WMS services), they provide access to a variety of products: raw data, higher level data and derived mapping products might all be accessed by the final users. An exemplary data access service, beyond the processing and analytical facilities, is the USGS Astrogeology Science Center[19].

The basic and necessary service to make a map publication accessible makes it possible to access data packages for direct download through a file-server. As has been done during the PLANMAP project, the contents of a map can be downloaded as a *zip* package (with all data components encapsulated in it) or directly as files from a tree of directories, allowing the user to selectively pick the contents of interest. This is the simplest approach from the software infrastructure point-of-view and also the most

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[19] https://www.usgs.gov/centers/astrogeology-science-center/maps

common one. It does not demand special knowledge or tools on the user end. The issues with this approach are the lack of (1) interactivity, (2) discoverability. Files inside the data package (i.e., the data products composing a map, produced by the map authors) are not suitable to be accessed across the internet through a web browser; they are ideal formats for local access but perform poorly and their visualisation and navigation is very limited in a web environment. On the other hand, the software typically serves files for direct download (e.g. FTP) do not provide communication protocols suitable for making the data easily discoverable (i.e. only file names are served). This limits the interoperability of such a simple strategy for other, third-party services to discover the content being published.

For granular access, discoverability, and possibly remote, real-time interactivity, other services and interfaces must be used, on top of the file-serving strategy. These services should be able to generate additional subsets of the products and serve them on-demand, requiring the ability to perform computations on the server side, comprising:

- Raster cropping: when the user request a subset of the original raster, allowing to reduce download sizes
- Vector intersection: when only a subset of the vector dataset is needed
- Vector query by attribute: to restrict the access/visualisation to specific elements depending on their attributes
- Metadata (raster, vector, model) search: indexing all available metadata allows to search through the dataset in the optimal way, allowing optimal discoverability
- Graphical and interactive data exploration/viewer: using modern web-gis solutions to visualise and interact with the above mentioned operations.

In particular, using a data publication interface, people have more control and an overall better experience on accessing the data. The general downside is the necessary technical skills to access the data and also to publish them as the software services and interfaces involved are substantially more complex and metadata-demanding. This also requires that the data package itself comprises a standardised, well-structured and informative set of metadata.

The data portal being used provides capabilities for free-text search and an intuitive interface for data packages publication. The GMAP data portal is an instance of Invenio-RDM[20], a general-purpose data management system like Zenodo[21]. Having a similar system to the well-known Zenodo improves the experience of GMAP users to the data portal, at the same time we experience organising planetary metadata and data products into such systems.

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[20] https://inveniosoftware.org/products/rdm/
[21] https://zenodo.org

Whereas in PLANMAP we used a custom data repository, and so we had more freedom to define data packages metadata model, in GMAP, in order to improve data accessibility, we have chosen a mature, standard system currently in use (Invenio-RDM). The metadata attributes and data products content stay always the same, complete. We do adapt the structure through the publication interface to make them (1) fit in the system's predefined fields, (2) improve their readability and accessibility.

On this topic see also Appendix 2 and Appendix 7.

■ Data citation

Data citation without a permanent identifier (typically a DOI) relies usually on associated published scholarly literature, e.g. typically for quoting the use of CTX or HiRISE imagery the relevant experiment description papers are quoted (e.g. McEwen et al., 2007; Malin et al., 2007).

Citing datasets is increasingly practised, with system such as OpenAire Zenodo[22], Figshare[23] and institutional repositories.

Geologic maps could in principle use any of those, as final products. The way PLANMAP and earlier projects such as i-Mars, that initiated with ESA the activity, is to use ESA GSF[24] as DOI-granting backend. DOI guidelines for VESPA, to which GMAP is going to contributed (See data discovery sections) exist (Cecconi et al., 2020)[25].

■ Data discovery

Data discovery for GMAP will be primarily performed via VESPA / Planetary VO (e.g. Erard et al., 2020; Erard et al., 2018). Additional data discovery options and systems are considered, e.g. OGC CSW (e.g. Hare et al., 2018; Laura et al. 2017), see also Appendix 7.

■ Data versioning

PLANMAP (e.g. Rossi et al., 2020) data versioning for entire geological maps originally was embedded in the so called PM_ID (PlanMap ID, i.e. a productID for geologic maps produced within the PLANMAPH2020 project), later embedded in the map-wide metadata for each map dataset.

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[22] https://zenodo.org
[23] https://figshare.com
[24] https://www.cosmos.esa.int/web/psa/psa_gsf
[25] https://voparis-wiki.obspm.fr/display/VES/Digital+Object+Identifiers+for+VESPA

As an example, originally a 1st version of a map, before a revision was something like (See also Section 6 on envisaged map types):

PM-MER-MS-H05_5cc_V01 with the suffix "V01" indicating the 1st version, "V_02" the second and so on.

This was later simplified to a permanent ID for a map such as **PM-MER-MS-H05** (without versioning in the name of the product), while previous versions were made available on the PILANMAP archive as subdirectories.

Versioning in PLANMAP had the resolution of the entire map, with its revision. GMAP plans to use a similar approach at first order, although partial map versioning (See Section 7, too), i.e. at the level of sub-map dataset products (basemap updates, vector map evolution, e.g. expanding mapping within a planned extent/quadrangle) will be considered.

(Published) data versioning is also relevant to the review process, on this topic see section 8).

● 10) Outlook

The GMAP VA will use tools and templates from existing sources or developed/adapted from the JRA activities. Once the GMAP data portal for public access is ready, there will already be an initial set of documentation and templates, including geologic mapping vector fields, tools and aids for mapping, as well as links to further documentation, curated lists of resources.

VA geologic mappers will be made available, also from other related H2020 projects, tools and datasets, in addition to existing raw and calibrated data from NASA, ESA archives and GSF, and USGS or 3rd party sources.

Initial templates will follow PLANMAP H2020 project customs and templating, while through the development of JRA activities, a planetary mapping data model (See Section 7) covering the various standard and non-standard mapping use cases. Symbology resources will also be provided and updated throughout the JRA. Own-developed tools (See Appendix 1) will be maintained and integrated with the templates, also through the use of QGIS plugins. External ones (e.g. see Appendix 3.2).

Curated lists of internally developed and externally supported tools and libraries will be developed and maintained, as well as relevant documentation.

The development of tools beyond the DoA will be made on a best-effort basis, as well as cooperating with external community members and projects, e.g. making use of cloud-based basemap processing services from the H2020 Neanias project[26], with some similarities with the USGS POW[27] system (Hare et al., 2014).

Links with other VA activities will include data discovery (VESPA), surface mapping plasma interaction (SPIDER) and data analysis supporting geological mapping (ML).

This document is going to be updated for the duration of the GMAP, as well as based on inputs form VA/community. It will be accessible from the GMAP wiki[28] and Web[29] endpoints.

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[26] https://www.neanias.eu
[27] https://astrocloud.wr.usgs.gov/signup/
[28] https://wiki.europlanet-gmap.eu/bin/view/Main/Deliverables/
[29] http://europlanet-gmap.eu/documentation

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● Appendices

Those appendices, like the overall document, are going to be live and maintained, as well as expanded, pointing to one or more repositories.

Please refer to the entry points below for further links and documentation as it grows and access to tools, as they evolve. Each appendix refers to one or more public web pages, git repositories of GMAP[30] . Future formal and informal iterations of the present document might include additionally or alternatively GitHub repositories, too, within the Europlanet GMAP organisation[31].

○ Appendix 1 - Sample vector fields / tentative vector templates

Templates will be available (field types, actual vector geopackage/shapefile files, attribute and accessory tables) by the time the GMAP portal is up, and preliminary templates will be made available earlier for community feedback.

Initial useful links and references include:

- http://geosciml.org/
- https://inspire.ec.europa.eu/Themes/128/2892
- http://www.onegeology.org/home.html

Initial iterations will be based on the above and templates as well as PLANMAP will be provided to VA within the last months of 2020 and first months of 2021. By the time of the VA GMAP portal (Q1/Q2 2021) the templates will be downloadable.

■ Sample polygon fields (morphostratigraphic mapping)

e.g. code AM39s label "Amazonian lava flow" NAme "X Basin Amazonian lava flow"

Needed Field	Mandatory vs. optional	Data Type	Notes

---

[30] https://git.europlanet-gmap.eu/gmap
[31] https://github.com/europlanet-gmap

Name	Mandatory	STRING	
Shortname	Optional	STRING (limited alphanumeric, short, number of characters, no spaces)	
Code	Mandatory	STRING (less than X characters)	COULD BE KILLED IF NEEDED?
geo_group	Optional	STRING	example: "basin", example: "chaotic terrain"
Type	Optional	STRING	example for "volcanic": "pyroclastic", "lava flows". example for "chaotic terrain": "mesa"
Description	Mandatory	STRING	

Age	Optional	STRING	to have a helper table to match names with absolute model age → see van Gasselt and Nass (2014).
RGB	Mandatory	STRING (containing tuple of 3 short INT)	
Composition	Optional	STRING	
Geometry	Mandatory	POLYGON	

Table 6: Sample polygon fields used for morpho-stratigraphic maps.

■

■ Sample morphologic overlay (e.g. colluvium)

Needed Field	Mandatory vs. optional	Data Type	Description (and relevant example records)
Geometry	Mandatory	POLYGON	
Type	Mandatory	STRING	

Description	Mandatory	STRING	
Name	Optional	STRING	
SHAPE_length	Optional	Number	
SHAPE_area	Optional	Number	
Style	Optional	TBD	Maybe FGDC or QGis' styleQML or styleSLD

Table 7: Sample morphologic overlay

■ Sample linear feature fields

Needed Field	Mandatory vs. optional	Data Type	Description (and relevant example records)	Notes
Sub-type	Optional			e.g. normal fault, thrust fault
Type	Mandatory			e.g. fault, crater rims
Style	Optional	TBD		
Geometry	Mandatory	LINESTRING		

Table 8: Sample linear features fields

■ Sample contact fields

Needed Field	Mandatory vs. optional	Data Type	Description (and relevant example records)	Notes
Type	Mandatory		certain, approximate (must exist, not sure where), uncertain (not sure whether it exists at all), inferred	
Style	Optional	STRING	FGDC code	
Geometry	Mandatory	LINESTRING		

Table 9: Sample contact fields

■ Sample crater size-frequency distribution table

Column	Mandatory .vs. Optional	Data type	Description	Notes
Name	Optional	String		
Geometry	Mandatory	Polygon		
Area	Mandatory	Number		
N(1)	Optional	String	associated Production and chronology function	
Absolute model age	Optional	String	associated Production and chronology function	

Table 10: Sample crater size-frequency distribution table

The inclusion of spectral/compositional mapping (e.g. Zambon et al., 2020), in addition to specific underlying raster/vector data, will include one or more additional vector fields per unit, describing qualitatively or quantitatively the spectral properties or eventually the mineral phases identified. Map-wide metadata (See Appendix 2) should contain information on datasets and processing/analyses used, for reproducibility, as well as access to datasets (See Section 9).

The workflow, deriving from spectral unit definition is roughly outlined below:

- **Input** = 1 or more raster layers of spectral indices, low to no gaps, completely full coverage of spectral, single mosaic files of derived products (one for each product/index) + an existing vector geologic map
- **Task:** consider information from single mosaics at a defined unit with specific values
    - Step 1: Spectral Units Definition = threshold / pre-classification of products, masking/thresholding
    - Step 2: Morphostatigraphic Units that have information (vector fields) for each of the mosaics, e.g. stats, onto a unit derived from 4 base mosaics of indices, i.e .4 additional fields?
    - Step 3: Interpretation (manual, algorithm-assisted, algorithm-based, ML, etc.)
    - Step 4: vector geologic map with additional field(s)
- **Result** = updated vector map

Reference web entry point: https://europlanet-gmap.eu/templates

○ Appendix 2 - Map-wide metadata

The issue here is to collect the individual meta information for the whole mapping products. Therefore it is needed to

(1) first list and evaluate these descriptive information,

(2) to review existing standards for metadata description,

(3) to use as much standardized metadata entries as possible but also

(4) create new and discipline specific entries as needed.

Useful links and references:

- https://inspire.ec.europa.eu/id/document/tg/metadata-iso19139

Reference web entry point: https://europlanet-gmap.eu/documentation

1. Starting point of metadata (first list) from PLANMAP[32]

Field	Field description (and example entries)	Notes
Original Coordinate Reference System	CRS	Mandatory
Heritage used	e..g. Tanaka 201X Map	Optional
Polygon number	E.g. 300 000 (to differentiate optimized low-poly meshes from heavy high-poly working meshes)	Mandatory
Acknowledgements beyond GMAP	E.g. ASI Project XXX, DFG Project YYY	Optional
Modelling method	E.g. DEM extrusion, Photogrammetry, sub-surface modelling	Mandatory
Aims (one sentence)	E.g. Morphologic analysis, astronaut training	Mandatory
Version	e.g., 1	Mandatory
Target body	e.g., Moon	Mandatory

---

[32] https://data.planmap.eu/ and https://wiki.planmap.eu/display/public/Data+and+code and links therein

Map name (PM_ID)	e.g., PM_Mercury_M_4_classes_01	Mandatory
Type	Preliminary, Released	Mandatory
Output scale	Publication scale	Mandatory
Units Definition	Units names, Codes, RGB colors	Mandatory
Title of map		Mandatory
Bounding box - Min Lat		Mandatory
Bounding box - Max Lat		Mandatory
Bounding box - Min Lon (0-360)		Mandatory
Bounding box - Max Lon (0-360)		Mandatory
Author(s)		Mandatory
Data used		Mandatory
Standards adhered to		Mandatory
DOI		Optional
Short description		Mandatory
Related products (*cross link to other Planmap products)*		Optional

Stratigraphic info (*e.g. production function used*)		Optional
Other comments (*reviewer comments, notes on post-processing*)		Optional
Link to other repositories		Optional
Number of attached textures		Mandatory
Basemap processing log	E.g. text or link to document with relevant processing steps, tools, parameter file(s)	Mandatory

Table 11: exemplary map-wide metadata table, as initial iteration for GMAP, deriving from PLANMAP practice. Many fields are similar to e.g. USGS data products shared on Astropedia[33].

We adapted the initial metadata set, based on the experience from PLANMAP, further interaction with USGS/Astropedia data products, and the recent deployment and use of GMAP data portal. The attributes stay the same in the following table, the column "RDM Field" implies a necessary mapping between GMAP metadata model ("Field") and the corresponding field in the data portal.

Field	RDM Field	Notes
Title of map	Title	Mandatory
Author(s)	Creators	Mandatory

---

[33] E.g. https://astrogeology.usgs.gov/search/map/Mars/mars_mro_ctx_spoledtmmosaic_mayer_2020/ctx_abs_align_iau_deltaradius_mosaic

Short description	Description	Mandatory
Map name (GM_ID)	Additional titles	Mandatory
Target body	Additional descriptions	Mandatory
Original Coordinate Reference System		Mandatory
Output scale		Optional
Units Definition		Optional
Bounding box - Min Lat	Location	Mandatory
Bounding box - Max Lat		
Bounding box - West Lon (0-360)		
Bounding box - East Lon (0-360)		
DOI	Alternate identifiers	Optional
Acknowledgements	Funding references	Optional
Modelling method	Additional descriptions	Optional
Polygon number		Optional

Number of attached textures		Optional
Aims	Subjects	Optional
Standards adhered to	References	Mandatory
Heritage used		Optional
Data used	Related identifiers	Mandatory
Link to other repositories		Optional
Related products (*cross link to other GMAP products)*		Optional
Stratigraphic info (*e.g. production function used*)	Additional descriptions	Optional
Other comments (*reviewer comments, notes on post-processing*)		Optional
Type	Version	(auto)
Version		
Basemap processing log	(files)	Optional

The following figure presents an example of the current layout of a data package in the GMAP data portal.

GMAP
Geological Mapping

Search records...

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Published January 30, 2023 | Version v1

Dataset   🔒 Open

Geological map of the Hokusai Quadrangle (H05), Mercury

Wright, Jack;   Rothery, David A.;   Balme, Matt R.;   Conway, Susan J.

Citation

Style   APA ▾

Wright, J., Rothery, D. A., Balme, M. R., & Conway, S. J. (2023). Geological map of the Hokusai Quadrangle (H05), Mercury [Data set]. Planmap.

Description

The Hokusai (H05) quadrangle is in Mercury's mid-northern latitudes (0–90°E, 22.5–65°N) and covers almost 5 million km2, or 6.5%, of the planet's surface. We have used data from the MESSENGER spacecraft to make the first geological map of H05. Linework was digitized at the 1:400,000 scale for final presentation at the 1:3,000,000 scale, mainly using a ~166 m/pixel monochrome basemap. Three major photogeologic units of regional extent were mapped: intercrater, intermediate, and smooth plains. Materials of craters ≥ 20 km in diameter were classified according to their degradation state. Two classification schemes were employed in parallel, one with three classes and the other with five classes, for compatibility with existing MESSENGER-era quadrangle maps and the first global geologic map. This map will provide science context and targets for the ESA-JAXA BepiColombo mission to Mercury.

Spatial information:

- Bounding-Box: minlat = 22.5, maxlat = 65.0, westlon = 0.0, eastlon = 90.0
- Target body: Mercury

Ancillary information:

- Type: Submitted (in review)
- Output scale: 1:3M
- Original Coordinate Reference System: Lambert conformal conicCenter longitude: 45°EStandard parallel 1: 30°NStandard parallel 2: 58°NDatum: 2440 km (non-IAU, MESSENGER team datum)
- Data used: MESSENGER MDIS BDR v0 uncontrolled basemap (166 m/pixel)MESSENGER MDIS HIW v0 uncontrolled basemap (166 m/pixel)MESSENGER MDIS HIE v0 uncontrolled basemap (166 m/pixel)MESSENGER MDIS LOI v2 uncontrolled basemap (166 m/pixel)MESSENGER MDIS 2013 complete uncontrolled basemap (250 m/pixel)Mariner 10 + MESSENGER flyby uncontrolled basemap (USGS) (500 m/pixel)MESSENGER MDIS enhanced color mosaic (665 m/pixel)MESSENGER MDIS MD3 colour basemap (333 m/pixel)MESSENGER MLA DTM (665 m/pixel)MESSENGER global MDIS stereo-DTM (665 m/pixel)MESSENGER H05 DLR MDIS stereo-DTM (222 m/pixel)
- Standards: Planmap mapping standards document
- Aims: Morpho-stratigraphic analysis of Mercury's units and BepiColombo target selection.
- Related products: Geologic Map of the Victoria Quadrangle (H02), Mercury
- Units Definition: Smooth Plains, sp, 255-190-190Intermediate Plains, imp, 245-122-122Intercrater Plains, icp, 137-90-68Crater material-pristine, c5, 255-170-0Crater material-well-preserved, c4, 223-115-255Crater material- somewhat degraded, c3, 92-137-68Crater material-quite degraded, c2, 115-178-255Crater material-heavily degraded, c1, 190-210-255Degraded catenae, dc, 0-153-0Crater floor material-smooth, cfs, 255-175-175Crater floor material-hummocky, cfh, 205-170-102
- Other comments:
- Heritage used: PM-MER-MS-H05_3cc_01
- Link to other repositories:
- Acknowledgements beyond Planmap: This research was initially funded by the UK Science and Technology Facilities Council (STFC). Wright was funded by an STFC PhD studentship (ST/N50421X/1) and is also grateful to the British Society for Geomorphology, UK Remote Sensing and Photogrammetry Society, and Royal Astronomical Society for providing additional funding during the completion of this study.
- Map version: 2.0

Files

PM-MER-MS-H05_5cc.browse.png ▾

Files (18.9 MB) ▾

Name	Size		
PM-MER-MS-H05_5cc_basemap.browse.png md5:57a0b752ed67fc074eb014a25b425d4a	8.8 MB	👁 Preview	⬇ Download
PM-MER-MS-H05_5cc.browse.png md5:ac436614056fa9d9886b44c2a4b1077e	10.1 MB	👁 Preview	⬇ Download

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Identifiers

DOI
10.1080/17445647.2019.1625821

Created: January 30, 2023   Modified: January 30, 2023

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Version v1   Jan 30, 2023

Details

Resource type
Dataset

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Planmap

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○ Appendix 3 - Mapping practices and aid tools

Certain geologic mapping aid tools are existing for Open Source systems (e.g QGIS), some for proprietary software environments (e.g. ESRI ArcGis). GMAP makes use of existing open source implementations and tools, primarily QGIS-based, as well as porting those tools and add-ons currently available on ESRI products (e.g. CraterTools, FGDC planetary symbology), within the GMAP contributors and beyond.

The reference entry point (to GMAP Gitlab, ext
ernal repositories and web sites) is
https://europlanet-gmap.eu/tools

Jupyter-based base mapping aids running on the GMAP Jupyter Hub[34] or anywhere locally are documented on the GMAP Github organisation, specifically in the 2023 winter school repository:

https://github.com/europlanet-gmap/winter-school-2023/tree/main/gmap-tools

■ A3.1 - Generating polygonal layers

A common approach for mapping is to directly draw polygons representing the different units on the map: although this approach appears the simplest one, it poses several issues in terms of topological consistency of resulting maps, especially when it comes to updating existing cartography.

Editing polygonal layers is inherently problematic because vertex and edge correspondence between polygons in contact must be enforced by the operator. Although most GIS software implements appropriate tools (for editing and for topology validation) which can help in achieving error-free polygonal layers, the burden of using them is left to the operator and it is not enforced by the data format itself.

A better solution for generating topologically-consistent geological maps consists in tracing the contacts separating the units, and then transforming them into polygonal layers (by using what is often known as a "polygonize" operation) for map finalization (see Figure 1).

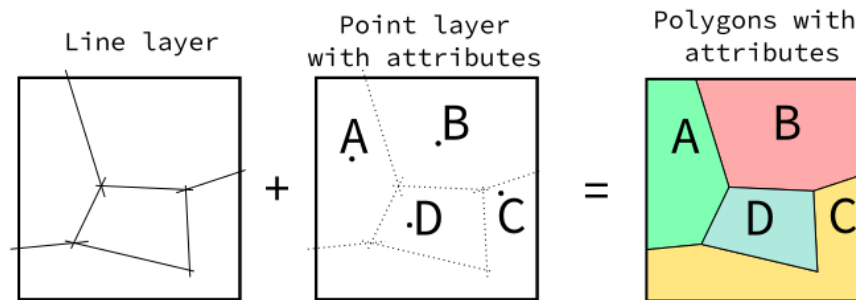[34] https://jupyter.europlanet-gmap.eu

Figure 2: Generation of a consistent polygonal layer by polygonize operation, this can be performed by any GIS and is suggested as a good practice in geological map generation. A line layer is used for tracing the contacts between the different units and a point layer is also needed to define attributes for the polygons.

This approach is also more similar to the geological reasoning that is performed when mapping, especially when remotely sensed imagery is used (as in planetary mapping): the operator tries to identify the boundaries between different terrains rather than directly defining the area covered by the units themselves.

Any GIS software provides polygonization (e.g. polygonize in QGIS) methods that can be easily employed to create polygonal layers from lines, while the points attributes can be joined with a *spatial join* operation.

The described approach has been also implemented in a QGIS plugin "mappy" enabling easy transformation of boundaries layers and points with attributes to consistent polygonal layers and vice-versa (Penasa et al., 2020). The plugin and its source code are freely available on GitHub[35], as well as from the official QGIS Plugin Repository[36].

■ A3.1 - CSFD Tools & CraterStats

Existing tools of use include crater mapping and measurements for proprietary software, such as cratertools (Kneissl, et al., 2011; Kneissl and Michael, 2013), , or craterstats (e.g. Michael and Neukum, 2010; Michael, et al., 2012; Michael, 2013), as well as open-source CSFD tool (e.g. Riedel et al., 2018).

GMAP plans to use those based on availability of the proprietary software to the VA community. Preference to Open Source options (e.g. see Appendix A3.2), when available, will be given.

---

[35] http://github.com/planmap-eu/mappy
[36] https://plugins.qgis.org/plugins/mappy/

■ A3.2. - Circle Craters

Circlecraters[37] (Braden, 2015) was initially developed for Qgis2, and forked later on[38] . It has been lately, within GMAP, initially ported to more modern Qgis3[39]

Within GMAP we plan to use/adapt CSFD tools as well to use CraterStats in its current (IDL VM-based, closed-source) implementation, while planning to use any upcoming derived Open Source version.

■ A3.3 - 3D Geologic modeling tools

Here is a not-exhaustive list of open source resources (Table 12 and 13) that can be used for performing three dimensional geological modelling (See section 5 for introductory material on this topic).

Software/package	Application	Reference
OpendTect	open source seismic interpretation system	http://opendtect.org/
Gempy	implicit 3D structural geological modeling in Python for uncertainty analysis	https://www.gempy.org/
LoopStructural	3D geomodelling library	https://github.com/Loop3D/LoopStructural https://loop3d.org/
surfe	Implementation of Hillier et al. (2014) RBF interpolator for geological modelling	https://github.com/MichaelHillier/surfe

Table 12: List of the tools specifically targeted for geologic modeling

Software/package	Application	Reference
geopandas	Vector GIS data	https://geopandas.org/

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[37] https://github.com/sbraden/circle-craters
[38] E.g. https://github.com/afrigeri/circle-craters
[39] https://github.com/luca-penasa/circle-craters

	management	
VTK	3D visualization and processing	https://vtk.org/
pyvista	Easier front end to VTK	https://www.pyvista.org/
CloudCompare	Point cloud processing	https://www.danielgm.net/cc
ParaView	Scientific 3D visualization	https://paraview.org
Blender	Generic modelling and rendering platform	https://blender.org

Table 13: Useful software for custom modelling.

■ A3.4 - Additional software useful for mapping

The Table 14 lists some open-source software and tools relevant to various aspects of map creation, visualization and layout. Proprietary software is excluded from this table, which is meant to provide some web entry points for the reader interested in adopting open-source solutions as alternatives to commercial ones.

Application	Open source software	Reference
GIS data management and editing	QGIS, gvSIG, GRASS GIS, SAGA GIS	https://qgis.org , https://gvsig.com , https://grass.osgeo.org , https://saga-gis.org
Graphic Editing and Layout	Inkscape, Gimp	https://inkscape.org , https://gimp.org
Web-based map toolkits	OpenLayers, Leaflet, mapbox	https://openlayers.org , https://leafletjs.com , https://mapbox.com
Python toolkits	RSGISLib, Rasterio, Fiona, Geopandas, Shapely	https://rsgislib.org , https://rasterio.readthedocs.io , https://pypi.org/project/Fiona , https://geopandas.org , https://pypi.org/project/Shapely
Web-servers for geographic data	Geoserver, Mapserver	https://geoserver.org , https://mapserver.org

| Lidar Data processing | LAStools, PDAL | https://rapidlasso.com/lastools , https://pdal.io |

Table 14: Additional software useful for mapping

● Plugins and addons

There are many extensions to both open source and commercial software which were designed to make some specific tasks easier. The Table 15 reports some that are relevant to the planetary/mapping community.

Plugin/addon	Host software	Application	Reference
Crater tool	ESRI ArcGIS	Crater size-frequency measurements	https://geo.fu-berlin.de/en/geol/fachrichtungen/planet/software/_content/software/cratertools.html
Qgsurf	QGIS	processing of geological planes and surfaces	https://github.com/mauroalberti/qgSurf
qgis2threejs	QGIS	3D visualization of geographical data	https://plugins.qgis.org/plugins/Qgis2threejs
qProf	QGIS	generation of topographic and geological profiles	https://plugins.qgis.org/plugins/qProf
qCompass	CloudCompare	Structural Measurements on DOMs with semi-automated tracking	https://cloudcompare.org/doc/wiki/index.php?title=Compass_(plugin)
GeoTrace	QGIS	Tools for extracting and analysing the orientations of geological structures	https://github.com/lachlangrose/GeoTrace

Table 15: list of plugins and addons useful for mapping.

Additional tools of use include JMARS (e.g Christensen et al., 2009; Dickenschied et al., 2010) for map creation, as well as tools and services for map publishing and discovery, e.g. NASA Trek (e.g. Law et al., 2019).

A curated list of tools will be available on the GMAP Git repositories and from the entry point: https://europlanet-gmap.eu/tools

○ Appendix 4 - Symbology

Extensive symbology following FGDC guidelines exist, mostly targeting the ESRI software ecosystem. Some of the FGDC planetary symbology has been ported to the QGIS Open Source system. Symbology[40] (Frigeri, 2020).

Reference web entry point: https://europlanet-gmap.eu/templates

The current version of Mappy does integrate the above symbology within the QGIS plugin.

○ Appendix 5 - Review Workflow

The current review workflow (see Section 9) is being outlined. Development of tools and documentation will follow internal JRA practice and tests, and will be progressively rolled out for VA / external users. Prototypal (simple) review workflow, system and documentation/tutorials are going to be available from GMAP web, wiki and git.

Reference web entry point: https://europlanet-gmap.eu/review

○ Appendix 6 - Map sheet templates

Map sheet templates for GMAP, supporting QGIS-based systems are going to be available in one or more version-controlled repositories available on the GMAP website.

Reference web entry point: https://europlanet-gmap.eu/templates

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[40] https://github.com/afrigeri/geologic-symbols-qgis

○ Appendix 7 - Platforms and environments to disseminate mapping results

Access to the data by the users is almost entirely performed via web interfaces, which might be either interactive (for example a web-interface or a command-line interface) or static. *Static* interfaces are usually associated with the actual data itself, which is either streamed or served as single data chunks (i.e., single files).

Interactive interfaces provide tools suitable for the exploration and the discovery of the datasets. Thanks to the interactive access to the data details it is possible to freely navigate the database of available datasets, which can then be visualized, searched and filtered thanks to the available metadata.

For instance, in the PLANMAP project we implemented three different services for data access:

- Maps-app (https://maps.planmap.eu), graphical interface for data exploration;
- Files-server (https://data.planmap.eu), static interface for data access as single data products download; directly exposes the internal data archive;
- GeoServer (https://geoserver.planmap.eu), static interface for data access as data streaming (OGC W*S) and data discovery (OGC GetCapabilities/WFS queries).

In GMAP the same overall approach will be used, with a series of improvements. Interfaces will be engineered to automatically update the content whenever data stored in the archive is changed or added, for example when new data is introduced after the final stage of the data publication workflow. It is worth here noticing that the automation of the data publication workflow will be a goal of the GMAP project.

According to users use-cases performing data access, there are separate steps that are expected to be performed by using GMAP provided interfaces, namely data discovery, exploration and download, which are detailed next.

■ Data discovery

A data discovery interface is intended to allow the use of several keywords to search and find data providers. Potential users start from a scientific (for instance) use-case or question related to a specific topic of interest. So for example the user may have interest in the lithology of Mars, might employ keywords like "mars" and "lithology" for filtering datasets related to lithologic mapping of martian surfaces.

Provided the search keywords, the data discovery mechanism is expected to answer with clear information about the location of related data. The *Location* may be another service(s) for further, refined search or the precise address (e.g., URL) of matching data. Currently, the data portal web-interface provide the text search functionality, but still lacks the geographical search.

In Planetary Geosciences within Europlanet the main data discovery system is the IVOA-based VESPA-EPN/TAP protocol and, secondarily, OGC Web Services, such as GetCapabilities and Catalogue service (CSW).

EPN/TAP suffices very well the data discovery situation presented above: a single, public, standard interface is used for placing the queries, and it provides a simple and well-defined answer pointing to the location (URL) of related data products. This framework is based on a network of world-wide data providers (see IVOA (Hare et al., 2018), which means the discovery is performed on many different services at a global level.

OGC' GetCapabilites and Catalogue features provide data discovery to a more local set of data: GetCapabilites provides general information about data published through OGC W*S services by a given provider, while Catalogue services may relate resources from other data store providers, also providing OGC W*S services.

Overall, GMAP data will be made discoverable within VESPA as a prime discovery platform, and with additional OGC CSW services, as needed. Combining both VESPA and OGC standards is sufficient to cover the whole process of data discovery (Minin et al., 2019).

VESPA results are in the form of simple text tables. On the other hand, OGC discovery services are usually interfaced (e.g., GeoServer) by REST APIs, with clear and well-known attributes, but the answer maybe cumbersome with lots of (unnecessary) metadata (eg, all supported CRSs) in XML/JSON.

■ Data exploration

The availability of OGC interfaces to the data, e.g. after data discovery via VESPA (Minin et al., 2019) will allow for exploration without downloading data. This is already possible on several basemap data from USGS and at the scale of a limited number of geologic maps, also by PLANMAP[41].

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[41] https://maps.planmap.eu

■ Data download

Data download, where desired by GMAP users, e.g. for individual basemaps or similar raster layers will be possible using standard formats (such as GeoTiff), or, for vector layers, using OGC Geopackages. The data access and download infrastructure of GMAP is inheriting that of the H2020 PLANMAP project[42].

■ Derived data exploitation

Discovery, access/exploration and download services ranging from VO, file-based, or OGC web-based access target scientific users. Outreach, training or education can be targeted with specific actions, beyond the scope of this document. An option, based on the record of the H2020 PLANMAP project includes story maps[43], using as backend the very same OGC services and data, with slight to no conversion or adaptation, in order to add narrative and/or training function to the map exploration, using open standards (Brandt and Rossi, 2019). Another option is to use maps in drawing for kids or comics as shown in PLANMAP project (De Toffoli et al 2020)

○ Appendix 8 - Body-specific aspects (Small Bodies and Icy Worlds)

■ Icy and rock-icy satellites

Icy bodies are a subset of natural moons with the surface made up either by ice, a mixture of ice and dust or rock and ice. Their inner structure often include the presence of a subsurface global ocean, kept in liquid state by tidal effects caused by the influence of the planet they belong to, or by the thermal state of the core, which is most of the times silicatic or metallic.

- Callisto
- Ganymede
- Europa
- Enceladus
- Pluto
- Charon
- Mimas

Ceres is a peculiar case since it is located in the asteroid belt and cannot be classified as a satellite and formally falls into the "small bodies" class, although it shares most of the characters with the previously mentioned objects.

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[42] https://data.planmap.eu/
[43] https://stories.planmap.eu/

Indeed, Ceres is also one of these few bodies that was globally surveyed with high resolution by Dawn mission in the past decade. Here a global HAMO mosaic of 60m resolution and a global DTM of 63m resolution are indeed present and publicly available.

Instead, each of the aforementioned icy bodies share specific aspects and issues related to the amount of datasets available for mapping and their retrieval. The most common are related to data heterogeneity in terms of spatial resolution and coverage:

- Global datasets alleady mosaicked are available on USGS Astrogeology repository[44]
- Color composite images with multiple filters are available and generally not difficult to process from raw
- High-resolution image data and/or stereo coverage are often limited to the flyby regions
- Global mosaics, if available, are multi-resolution enabling small-scale mapping only on a small number of targeted areas at high resolution, whereas the general low resolution or poor illumination conditions at places enable generally only large-scale mapping
- In most cases topography is somewhat absent or limited to the internal tools available to instrument/mission team members.
- Some tools for extracting topography from photoclinometry are freely available but rather old and poorly documented (pc2d on ISIS2 VM is an example, see Kirk, 2003)

■ Small bodies

A Small Solar System body (SSSB) is an object in the Solar System that is neither a planet, a dwarf planet, nor a natural satellite. The term was first defined in 2006 by the International Astronomical Union (IAU) as follows: "All other objects, except satellites, orbiting the Sun shall be referred to collectively as 'Small Solar System Bodies' ". SSSBs are: the comets; the classical asteroids, with the exception of the dwarf planet Ceres; the trojans; and the centaurs and trans-Neptunian objects.

- Non projectable imagery

Due to the size of comets/asteroids and observational constraints, standard mapping reference systems often cannot be consistently employed. Imagery often covers large percentages of the whole body area making it difficult or impossible to orthorectify the imagery in a sensible way even when detailed shape models are available. This issue

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[44] https://www.usgs.gov/centers/astrogeology-science-center/maps

poses strong limits on the injection of small bodies datasets into generic GIS data processing/visualization tools (i.e. standard GIS/WEBGIS).

Furthermore, bodies that have concave shapes (i.e. bilobate objects) do not allow to define a consistent latitude/longitude reference system for the body (due to duplication of the same coordinates) making it very difficult to generate globally valid projected representations of the body. For these reasons standard cartographic tools and CRS can be difficult to employ on bodies with convex shapes or with small size in respect of the available imagery used for mapping.

- Mapping on small bodies without cartographic projections

Due to the strong distortion and sometimes the impossibility to use standard CRS-based projections, several guidelines can be delineated:

  - Use the imagery as it is, possibly higher-level, optically undistorted imagery for any mapping effort. The state of the imagery in terms of optical distortion should be always reported in the metadata.
  - The imagery can be imported in any GIS software without any CRS and mapped in image (pixels) coordinates. We suggest to not apply pixel scaling to the imagery if not necessary because such information is only valid for a small portion of the image, furthermore subsequent processing will require additional care to take into consideration the applied scale.
  - Depending on the GIS used for mapping the (0,0) pixel coordinate can be automatically placed either in the center of the top left corner or on the edges of that pixel.
  - Whenever a position on the body should be communicated avoid the usage of purely latitude/longitude references. Prefer latitude, longitude and radius or x,y,z, coordinates. The reference frame should also be always esplictated.

- Gravity

Gravity on small bodies can be derived using the shape model and assuming fixed density (Werner, 1994). Some morphological terms are related to the local gravity: e.g. terraces/mass wasting deposits etc. For this reason gravity might provide useful information for mapping purposes and should be considered if an approximation of the 3D shape is available.

- Terminology

Small bodies are often very poorly known in terms of formational and morphological processes, hence all terminology for mapping should try to avoid definitions that imply

specific formational processes whenever they are not certain. Purely morphological terminology is preferable for uncertain features.

- Small Moons

Small moons will be approached similarly to small bodies, as they share similar geometric and morphologic aspects. They will be treated as closed surfaces with non-projectable images and ad-hoc CRS (Simioni et al., 2015).

○ References quoted in Appendices

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