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50 Years of Sensor-Based Planetary Cartography: Review and Perspectives

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Abstract: This contribution provides a concise review of the current developments and challenges in the domain of planetary cartography. Considered to be one of the more exotic branches of cartography, it currently re-positions itself due to (1) an increasing community-centric research interest, but also due to (2) the current development in the field of space exploration led by industry as well as ambitious international countries. Imaging, mapping and cartographic compilation have always been the primary tools for exploring terrain, and while the terrestrial planets have been mapped in some relative detail, planetary cartography is still largely stuck at medium map scales. While planetary cartography shares some similarities with developments in the field of terrestrial cartography, it developed largely differently and thus requires in-depth discussion about how these new challenges can be addressed and eventually solved. Advice and support from the terrestrial cartographic community is highly needed in order to develop sustainable long-term strategies.

Keywords: Planetary Maps, Planetary Cartography, Planetary GIS

1. Introduction

Maps have been accompanying planetary research since the beginning of telescopic observation and have since then been constantly refined and improved to serve as a basis for follow-up work. As such, maps have always been the highest level of spatial and thematic abstraction of information derived from raw data returned by observations from the ground or by telescopes from orbit. Today, types of planetary maps range from classical (photo-) image maps to topographic reference maps based on terrain model data, to interpreted geologic and geomorphologic maps to landing-site maps, and despite the wealth of available data, the variety of planetary maps is naturally limited due to the lack of anthropogenic overprint and variations of land cover. Despite this lack of variety, the planetary sciences have seen a number of maps being published over the last decades through various publishers and channels of procedures. While some maps have been serving as reference work for many years, other maps have nearly been forgotten or remained unknown in the scientific literature. Digital technology allowed to flexibly apply new techniques for analysis, organization and visualization of planetary map contents, and thus helped to develop and create map products in a more efficient way. The way maps are being re-used as research products and inserted into a research cycle, however, has not experienced the same amount of attention, due to a lack of standards, query tools, and accessible platforms.

The aim here is to review, discuss and characterize different elements which influence planetary mapping and extract open issues in that field in order to be able to address long-term strategies. This can be achieved through experiences and established working procedures in the various fields of terrestrial cartography.

In order to meet this aim we summarize the background of planetary cartography and mapping, after which we will review sensor-based planetary map production (section 2). Within this context we define the meaning and aims of planetary mapping, and describe the characteristics and types of planetary maps. We furthermore explore the current status of planetary mapping and its refinement, leading to the process of abstraction during the transformation from data to knowledge (section 3. Based on these discussions, we highlight a number of open issues that are currently observed in the field planetary mapping (section 4).

2. Concept and Character of Maps

Cartography is often described as the science, art, and technology of making and using maps, with a map being an abstract visual representation of the spatial environment. Based upon this general-purpose definition one could understand maps as knowledge base in which various topics are tied to at least one concrete instance in time and location in an abstract graphical way. There is no confinement regarding spatial location as long as it can be cartographically well described. This opens cartography to all known objects in our Solar System and beyond.

The area of extraterrestrial mapping and planetary cartography has a history that predates the age of space exploration originating back in 1959 with the emergence of first orbital platforms. The beginning of a long-lasting period was earlier marked by the development of the telescope the early 17th century and the continuing improvement of not only observations in terms of magnification and quality, but also with respect to the development of a geodetic framework along with a coordinate grid, and a cartographically consistent nomenclature (see also (Hargitai and Naß,

2019) and (Greeley and Batson, 1990)). With the advent of photography in the 19th century came the ability to store photos and to finally produce photographic maps based on telescopic observations. These three phases mark significant changes in planetary cartography regarding to mapping techniques, consistency of map quality and detail. For an up-to-date summary of *Planetary Cartography and GIS* see (Hargitai, 2019).

2.1 The Mapping Process

Planetary mapping is understood as wider concept in general and it is not well defined. It encompasses a number of activities related to the collection of data from planetary bodies, some of which are highlighted in, e.g., (Greeley and Batson, 1990). Mapping can be understood as (1) systematic data acquisition using mainly imaging sensors, and it could also be the (2) systematic development of thematic cartographic products in a more classical cartographic sense. Maps are commonly interpreted and integrated products that require human experience, knowledge and abstraction to develop, in order to generalize information and to compile according to an intended message. Despite the increase of artificial intelligence techniques in recent years, human experience is still required to accomplish this kind of abstraction (Mustière et al., 1999, Mustière et al., 2010). Planetary mapping in the second, and more conventional sense of designing and developing cartographic products, has seen significant changes due to the digital revolution at the end of the last century. With this event, a fast transition from analog to digital map production has been initiated which is ongoing at this time. Even more, classical large-format map products are less frequently seen as their production requires considerable resources and the need has been pushed back in favor of digital map-projected datasets. One could therefore argue that the use of conventional map products are limited, as they lack any option to be searched and do not allow to be harvested digitally.

The major difference between both meanings are within their respective relevance in the light of primary research-data values and both concepts depend on each other. Map compilation – in contrast to systematic mapping – refers to a higher-level process that builds upon distillation of original map data, and thus both concepts need to be distinguished.

2.2 Planetary Maps as Research Products

In the planetary sciences, the majority of cartographic products are made for research purposes related to supporting scientific understanding and exploration aims. In extension, the intention of creating such maps is aimed at generating new research products and establishing a reference basis for further map development. To a minor degree, published maps may serve as reference for engineering purposes, such as landing-site studies or illumination and terrain analyses for rover navigation or for the purpose of future resource extraction.

As interpreted products of research data, *planetary maps* belong to the research-data domain and represent a human-interpreted higher-level derivation of measurement data obtained by remote-sensing or by in-situ sensors. To qualify as a research product, maps usually have to be published through either agencies or research platforms and have to undergo quality-control such as a scientific and/or technical review process.

In (Skinner et al., 2019) an applicable short definition of different map products in the domain of planetary science has been given. Within that contribution *base maps* are described as *derived data products upon which units or terrains may be identified (for example, controlled mosaics, digital terrain models, elemental composition). Maps that discretely delineate and describe units or terrains using base maps* are hence termed *geoscience maps*. Specific types depend on the exact map content and can be geologic, structural, geomorphological, stratigraphic maps. Another distinction of geoscience maps are *standardized maps*, which indicate maps published by the USGS under adherence to cartographic standards, conventions, and principles, and *non-standardized maps*, which are published by other venues, for example, by journal publishers, or academic organizations by means of theses, or book chapters. The latter of these two groups are likely not required to, but might, adhere to cartographic standards, conventions, and principles.

We here refer to *maps* as conventional cartographic visualization products which contain a classical map layout composed of the main map contents (the topics), map frame, map grid information related to at least one cartographic reference system, map scale information, map title and map legend, as well as other map-related meta-information (Robinson et al., 2010, Hake et al., 2001). These maps can be provided as

1. print-only large-format maps on physical map sheets,
2. digital map products in PDF or comparable formats,
3. maps published as small figures in publications,
4. any combination of the above listed map types.

Interactive web-based maps and downloadable map-projected raster data lacking a map layout are therefore not further considered here as they do not constitute a cartographic map product in its conventional sense. Thus, a GIS-ready referenced and map-projected data product might become an integral part of a map but in itself it does not serve as a map. Maps can furthermore be classified according to a variety of schemes, among which topical contents, scales and degree of development are relatively common approaches (Hake et al., 2001, Robinson et al., 2010). The majority of planetary maps usually resides within a constrained scale range of 1:500,000 to 1:5,000,000 representing small-scale, large-area quadrangles or hemispheric to global views, and the degree of development is – given the natural limitation of complexity – comparably small. Thus, the topical content seems the most accessible way to look at different planetary maps as outlined hereafter.

2.3 Types of Planetary Maps

Classical (ortho-) photo- and image maps and derived products such as albedo and airbrush maps are developed from photos and data obtained by imaging instruments, and are eventually assembled to image mosaics of varying degree of internal control. Image maps and map atlases have been published systematically for a small selection of missions. In recent years, such maps have been created for the Cassini and DAWN missions and are based on systematic imaging campaigns (Roatsch et al., 2016b, Roatsch et al., 2016a, Roatsch et al., 2017, Roatsch et al., 2018). Map data for these missions (Roatsch et al., 2015) are accessible via the central planetary archives, the Planetary Data System (PDS) and the Planetary Science Archive (PSA). More historical examples are maps developed and published in the *Surveyor Lunar Photomap and Map Series* or the Voyager 1 and 2 Atlas (Batson, 1984). Maps with uncontrolled but map-projected data form the lowest level of derivation as these constitute visualization of spatially referenced basic measurement data. More common are semi-controlled and controlled image (or photo) mosaics that may be used as raster images in subsequent studies as basemaps. Despite being mono-thematic in nature, image maps are best described as stand-alone reference base maps and are unsuitable for further development due to inherent limitations associated with the particular format.

A second class of maps constitute topographic maps as well as derived hillshade and contour maps based on terrain data obtained from (1) laser ranging (Kaula et al., 1974, Smith et al., n.d., Zuber et al., 2010, Steinbrügge et al., 2018), (2) radar measurements (Johnson, 1991, Ford et al., 1993, Wall et al., 1995), or (3) photogrammetric derivation (Gwinner et al., 2010, Gwinner et al., 2016, Liu and Wu, 2017, Hu and Wu, 2018). A large number of topographic maps have been published in the earlier days of planetary exploration in the context of the Apollo program. Systematic approaches such as the planned topographic atlas based on HRSC data (Albertz et al., 2004) have been shown to provide visually pleasing results, their specific long-term research value however seemed limited due to the lack of purpose in environments focusing on GIS analysis. Today, most of these data are made available using readily map-projected raster images for GIS integration. Exemptions are the global topographic maps of a selection of planetary surfaces, such as the Moon or Mars (USGS, 2002, USGS, 2003, Hare et al., 2015).

A third class of maps comprises geologic and geomorphologic thematic maps depicting lithologies, processes, ages, (chronostratigraphy), structural features as well as major landforms. Planetary geologic maps are usually monothematic, i.e. analytical maps in a classical cartographic sense. This interpretation of geologic information differs considerably from terrestrial geologic maps that are usually complex-analytic, multi-thematic maps synthesizing lithologic and stratigraphic information, topography as well as building and landscape information for orientation purposes. Planetary geologic maps assemble the visual interpretation of landforms, and to a limited degree that of hyperspectral investigations, in order to reconstruct the volcanic and depositional as well as structural history of an area of interest. As such they may form a synthesis of knowledge acquired over different areas at a given scale or scale range. Their use therefore is primarily concentrated on the investigations related to the geologic and structural history. On a secondary level, and to a far lesser degree, they might provide base maps for superimposing additional information related to engineering purposes for example. While conceivable, however, such maps have not been seen published thus far. It would therefore be safe to say, that in particular small-scale large-area geologic and geomorphologic maps have the sole purpose to synthesize knowledge published over various areas (either as investigation

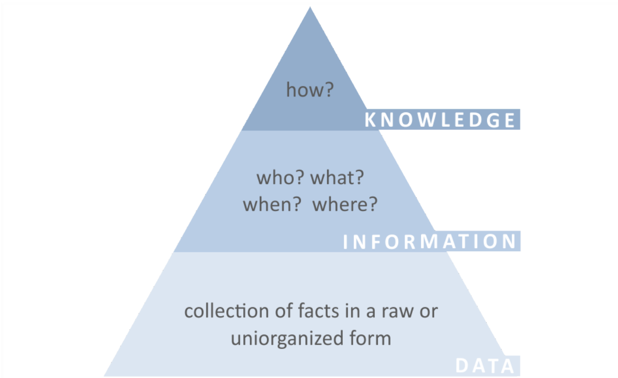

Figure 1. Data-Information-Knowledge-pyramid (after (Rowley, 2007))

series map or as stand-alone publication) at various times using different kinds of sensors. They are commonly reused as reference map in journal publications to establish the stratigraphic context of an investigation area or to introduce larger-scale mapping.

Representative map examples include the:
Unified Geologic Map of the Moon published at a scale of 1:5,000,000 which builds on a series of geologic maps originally created in the 1970s that have now been updated to common boundaries and control-point information (Fortezzo et al., 2020);
Geologic Map of Mars published in 2014 at a scale of 1:20,000,000, both digitally as well as in print (Tanaka et al., 2014).
Global Geologic Map of Ganymede (SIM 3237) published in 2013 at a scale of 1:15,000,000 (Collins et al., 2013).
Global Map of Io (SIM 3168) published in digital format as map and GIS database in 2011 at a scale of 1:15,000,000 (Williams et al., 2011).
Geologic Map of the Northern Plains of Mars (SIM 2888) published in 2005 at a scale of 1:15,000,000 and at a scale of 1:7,500,000 which updates previous mapping using recently released image and spectrometer data (Tanaka et al., 2005).
Geologic Atlas of the Moon as a collection of various mappings at scales between 1:5,000 to 1:250,000 for detailed investigations, at a map scale 1,000,000 for 44 lunar quadrangles published between 1963 and 1974, and at a scale of 1:5,000,000 for geologic maps of the lunar hemispheres published between 1971 and 1979. All maps are hosted online on the *Lunar and Planetary Institute* website[1].

More than 300 regional geologic investigations have thus far been published as part of the as geologic map investigation series through the USGS, or are currently being mapped at the time of writing. These investigations include maps of, e.g., Mercury, Venus, Europa, and Enceladus[2].

3. Status of Mapping in the Planetary Sciences

The process for planetary mapping can be represented by the classical concepts of the *data-information-knowledge-pyramid (DIK)* in combination with that of the *visualization pipeline* (Haber and McNabb, 1990, dos Santos and Brodlie, 2004). Both concepts are complementary as they

[1] `https://www.lpi.usra.edu/resources/mapcatalog/usgs/`
[2] `https://planetarymapping.wr.usgs.gov/Review`

describe knowledge extraction by data abstraction in visualization processes. The steps within the hierarchical DIK-pyramid or within the sequential visualization pipeline model help answering questions about initial data and products as well as the value that is added through defined working steps.

3.1 The Process-Oriented Refinement Process

It is said that *the more we enrich our data with meaning and context, the more knowledge and insights we get out of it so we can take better, informed and data-based decisions.*[3]. The development process from raw data towards information and knowledge data starts with the acquisition of base data (see figure 2), usually collected by an orbiter- or rover-based instrument. In order to enable the use of raw data for analysis and interpretation, data need to be processed and calibrated (see Figure 2). This step will be mainly accomplished by data providers within their individual mission teams, and it could thus represent the first step within the scientific refinement process in planetary cartography. The data provider finally enriches data with essential descriptions regarding technical, geometrical and cartographic parameters. After application of valid metadata adhering to a standard, mapping products may be uploaded to international archiving systems or kept accessible locally. Starting from this point, base data have become *information* which can be queried and downloaded by the community to start compiling individual interpretation and analyses. This first part of the process (see bottom left, light blue part in figure 2) could be understood as transition from data to information.

Within each step of data refinement, available information is classified, generalized and analyzed, where results then represent an abstracted view on the data. This step is carried out by individual researchers within a specific discipline or within in a larger team. When the interpreter finalizes analyses, results may be submitted to a central coordination node such as a topical research portal, a mission-team node or a survey for further use. Alternatively, a researcher may submit research results to a publisher in form of a scientific paper opting for peer review (see Figure 2). Independent of the exact way, data or a subset thereof will be eventually published and made available to a larger community. At this stage further research and developments can build on the published results. This could be currently understood as final step in the knowledge generation process (see top right, dark blue part in figure 2).

The way this process influences a user-oriented view of scientific mapping and how responsibilities in this process are distributed is further outlined in (Nass et al., 2021 (in revision)).

3.2 The Object-Centric Abstraction and Visualization Process

In this view, individual cartographic objects are placed at the center of investigation in order to identify the products that are generated through a mapping process (object-centric view). This representation corresponds to the four main stations in the visualization pipeline: *acquisition*, *filtering*, *mapping* and *rendering* (Haber and McNabb, 1990, dos Santos and Brodlie, 2004). It describes the abstraction from data to image, i.e. a form of knowledge representation (Figure 3). In contrast to the refinement process (see Figure 2), scientific abstraction begins with querying of base data from, e.g. established archives.

The *acquisition* process comprises querying raw data using various tools and levels of sophistication depending on the provided interfaces. see Figure 3). Such queries commonly involve spatial coverage, geometric resolution and temporal coverage.

In the second *filtering* step (see Figure 3) meaningful information is extracted from data by means of transformation of, e.g., pixel values and geometries using georeferencing and map projecting. This step also includes basic data-management aspects so that only one consistent data product is available for the next steps. For this product, first selections, such as attribute-based data abstraction and generalizations can be performed. In the case of geologic mapping, digital geometric objects can be derived. The resulting products then represent a digital object model (DOM) (cf. (Hake et al., 2001)) in which individual geo-objects are geometrically captured and put into context with each other. In the optimum case, the DOM is stored and managed within a database structure.

During the third step, *mapping*, the scientific interpretation is associated with information derived during the previous step by means of an empirical and analytical approach (see Figure 3). Geometrical objects are enriched with contents and descriptions by, e.g., attributes. Based on this foundation, a cartographic visualization can finally be realized by referencing attribute values to visualization parameters. This then leads to another product within the scientific visualization domain: the digital cartographic model (cf. (Hake et al., 2001)).

This directly leads to the transition towards the final step, *rendering*, during which a map layout is realized. Here, the separation and distribution of graphical and textual map sheet elements is organized under consideration of the medium and target audience. Along with a meaningful metadata description and a distribution concept the scientific visualization process is considered to be finished

4. Open Issues in Planetary Mapping

When referring to open issues in the domain of planetary mapping we likely need to put some emphasis on the focus of the refinement process during extraction of information as well as during the publication process (see Figure 2). With regard to the concept of the visualization pipeline, these aspects are covered by the processes of *filtering*, *mapping* and *rendering* (figure 3).

Under this premise, this section therefore covers open issues not only from a process-oriented, overarching viewpoint but also from an object-oriented case-centric point of view, which are both required to promote generation of geoscience maps in an efficient and more research-sustainable way. However, the focus here is put on the cartographic framework and technical GIS-related aspects in the context of research data reuse and availability. The user-centric requirements are here covered by establishing a connection to a recent investigation which has been

[3] `https://www.ontotext.com/knowledgehub/fundamentals/dikw-pyramid/`

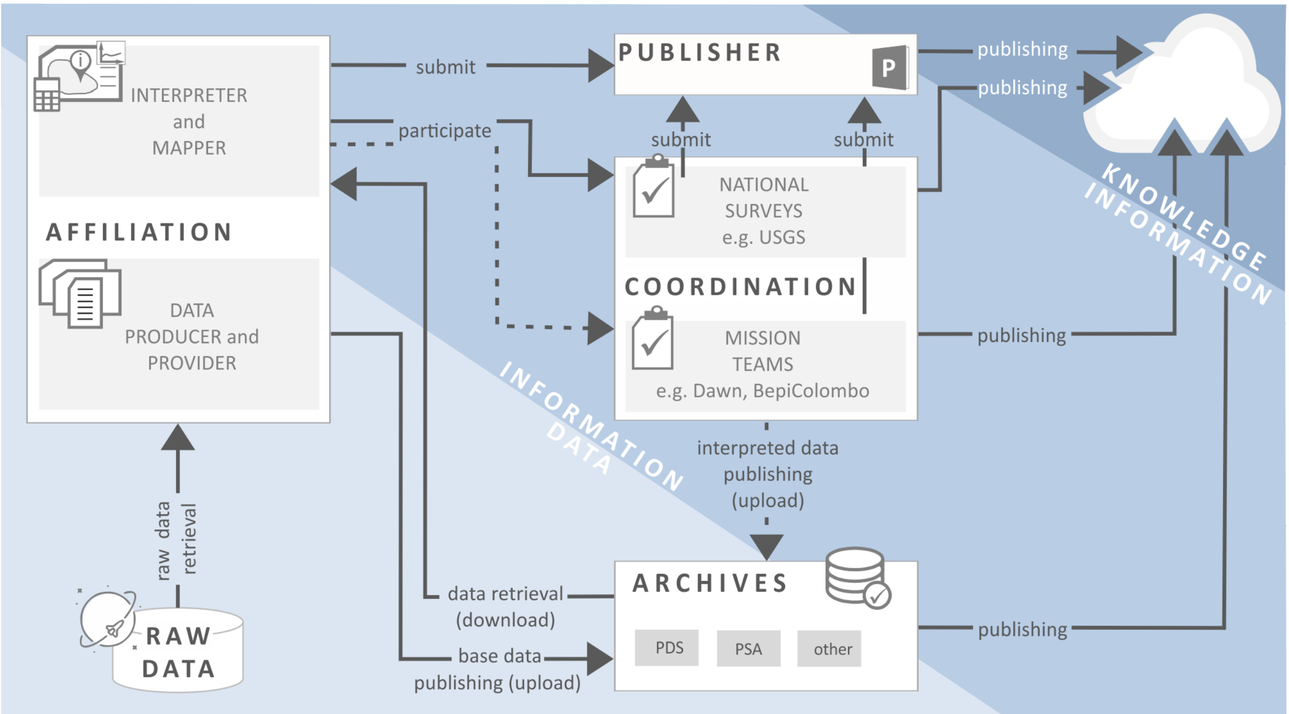

Figure 2. Visualization of the data refinement process in the planetary sciences.

conducted in the context of the USGS Planetary Geologic Mapping Program in 2018/19 (Skinner et al., 2019).

The topics hereafter are considered to qualify as open issues covered by aforementioned criteria:

Review. Above all open aspects, geoscience maps require a dedicated review process, which could be separated into a scientific review and a more technically oriented cartographic review. This is accounted for by the high level of individual interpretation processes which strongly depend on mappers' experiences. Such a review processes could be directly connected to journal publishing services or it could be related to organization which take over a more centralized role. Other scenarios are equally conceivable and require an in-depth discussion within the community.

4.1 Cartography and GIS

Reference Systems and Map Projections. Given the increasing needs and developments regarding exploration of small bodies in the solar system, there will be an increasing need for possibilities to define irregular-shaped bodies using targeted small-area cartographic projections and definitions of reference systems using a non body-centric definition.

Symbology. Symbology plays an integral role in the production and communication of, for example, geologic maps as the complexity of historic evolution is communicated through colors and hence, a consistent color scheme across different map sheets and perhaps also bodies could become a crucial map design element. The first challenge therefore includes identifying similar and representative objects for visual description. A first aid to support this point is provided by standards, such as the (**?**). In general the visual description of spatial data, either raster or vector data, strongly depends on individual software specification. However, a recommendation or instruction for system-dependent implementation would benefit the whole mapping community. A second challenge influences cartographic realization indirectly by agreeing on an approach to unify the description of mapped units but leaving room for some flexibility in expression. This point has also been mentioned in (Skinner et al., 2019, *finding 5*).

Generalization and Scale of Objects. The topic of generalization in dependence of map and object scale is a major field in cartography in general and while many tools exist, there is no single approach or solution to solve all kinds of different needs and mapping scenarios. Information density is not only an important characteristic for each map layer, but also across different layers that are stacked to form a vertical hierarchy. It is important for good map communication to understand dependencies between layers and develop approaches that respect various geometries and their aggregation and clustering.

Contour Lines and Hillshading. When compared to planetary cartography, hillshading on terrestrial maps seems to be a more optional technique to communicate relief, while it certainly has advanced to one of the most important assets in planetary cartography due to the general lack of other thematic information. And yet, on the other hand, the repertoire of hillshading for planetary cartography has usually not been developed beyond the standard techniques thus far. In order to add topographic information as a meaningful piece of information to a thematic map, the creation of a well-designed and balanced hillshade layer as well as geometrically correct and well generalized contour lines are essential. Global data sets are particularly demanding here, as the global relief trends as well as important local relief nuances have to be balanced well. Here, connections to terrestrial developments would likely turn out to be very helpful (see, e.g., (Horn, 1981, Jenny et al., 2021, Jenny and Patterson, 2021)).

Map Layout and Elements. "Geologic maps are perceived as the most relevant planetary geoscience map type" according to a survey carried out by the USGS (Skinner et al., 2019, *finding 3*). In order to be able to create a meaningful

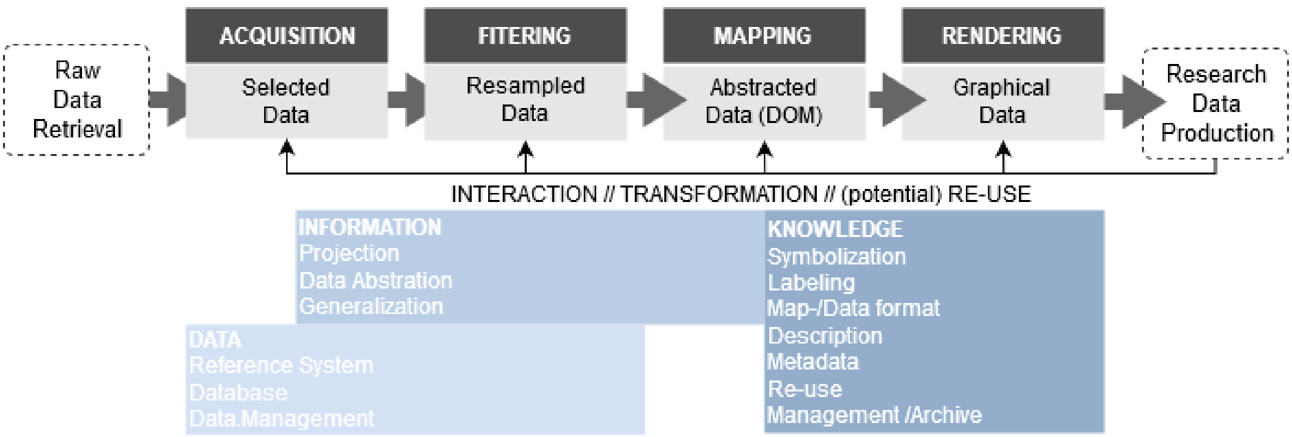

Figure 3. Transformation process of scientific abstraction and visualization based on the DIK pyramide ranging from spatial base data to high-level map products (cf. concept of the visualization pipeline).

geological map, a large number of additional elements are required on the map sheet, which both in their representation and in their positioning influence the understanding of the entire map sheet. This fact is the reason why the map sheet design is also assigned as an open issue. This topic is relevant also when it comes to formats and media that are used to present geoscience maps, e.g. digital and analog planetary atlases, story maps or maps in research papers.

Optimization of Mapping and GIS-Tools. Most tools in the world of planetary mapping are either general purpose tools or they are developed to answer needs for terrestrial mapping. In order to be fit for purpose, they need to be adopted for planetary use cases. In order to facilitate better access for the mapping community it would be beneficial to provide tools, templates and learning material (Skinner et al., 2019, *finding 14*).

4.2 Provision, Visibility and Reusability

Metadata Description. Metadata are understood as a description that complements data and that is equally important as the data products itself. While this holds on a organizational level, for individuals dealing with this matter might be more of an optional task. It is important to increase an understanding of the importance of metadata and develop, adopt and use international standards for spatial data description, such as the 19115:2003, ISO19115:2014, FDGC, INSPIRE, Dublin Core, and to connect to existing community efforts, such as PLANMAP and GMAP (Massironi et al., 2018, Rossi et al., 2018), in order to develop a meaningful set of metadata descriptions for a map. For cartographic products, such metadata information is very much comparable to entries at map sheet margins which contain mandatory and optional information to help understanding the map's origin and its larger context.

Identification of Map Products: In order to allow tracing and referencing map products, a stable procedure for registering digital object identifiers (DOI) might be needed in the future. This might also be an option for supplying identifiers for analog maps (**?**) for establishing a complete archive.

Repositories. The establishment of an international map catalogue for longtime archiving of map products would improve the accessibility and re-useability of geoscience maps (Skinner et al., 2019, *finding 8, 10*). Such an archive could potentially be linked to international agencies and other archives (e.g., PDS, PSA) working in the planetary sciences domain. By establishing web-based maps using common open geospatial technology (Open Geospatial Consortium (OGC) Web Map (WMS), Web Feature (WFS) and Web Coverage Services (WCS)) map access will be facilitated and enlarge the visability in order to use the maps as knowledge base for further future investigations (cf. (Skinner et al., 2019, *finding 11*)).

Licensing. Research work is not necessarily part of the public domain, and thus map products and distributed GIS data needs to show information about its re-use and licensing. For that, a number of license schemes are available, e.g., Creative Commons license.

The collection of open issues here is by no means complete. In particular when talking about future developments it becomes quite conceivable that rights management will play a major issue as soon as industry is getting more involved in exploration and resource extraction, and security issues become more relevant.

5. Conclusion

The developments in the domain of planetary cartography parallels that of terrestrial cartography only in the way techniques have been adopted. On the Earth, ground-based neighborhood cartography was supplemented by large-area remote sensing-based cartography in the early 20th century. For planetary cartography, remote sensing as a tool came first starting in the 17th century, evolving significantly in the 20th, and it is only starting to be complemented by in-situ investigations and through remote measurements. Beyond that, in particular the topical limitation, observation and data sources and scale restrictions are some of major differences that planetary cartography is experiencing.

In order to address the open issues that planetary cartography is currently facing and which it will be facing in the near future, it might be feasible to look into solution proposed and practically implemented for terrestrial cartography by agencies that have developed man years of experience, such as the USGS, the BGR, BGS, ISPA and many others. Also organizations such as International Society of Photogrammetry and Remote Sensing (ISPRS) and the International Cartographic Association (ICA) with experienced members from academia and industry might provide valuable insights. In particular when it comes to specialized commission, e.g., commission on *Map Projection*, *Map Toponymy*, *SDI and Standards*, *Open Source Geospecial Technologies*, *Mountain Cartography*, *Cartographic Heritage into the Digital* might provide much needed insights and advice for developing long-term strategies.

At the end, developments towards long-term strategies can only be fruitful, when continuous funding sources are made available that allow to build infrastructures and well-maintained archives. In how far these needs can be answered relies on discussions within the community and established funding organizations, also in order to identify potentially new sources.

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