Planetary Mapping: A Historical Overview

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2 authors:

Henrik Hargitai
Eötvös Loránd University

Andrea Nass
German Aerospace Center (DLR)

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Henrik Hargitai and Andrea Naß

Abstract The development of the methods of visualization, control, and content of planetary maps goes in parallel with terrestrial ones. Both reflect technological, scientific, sociopolitical, and graphic design changes. However, while terrestrial maps are ubiquitous and show abstract or iconic representations of the Earth features, planetary surfaces are much more frequently represented with uninterpreted images, despite the wealth of planetary spatial data. In this paper, we highlight the key maps and map series made before the space age and the new cartographic methods introduced in the early 1960s when rectified, geologic and airbrush maps, and space-borne planetary photography, revolutionized the way we can look at planetary surfaces. This chapter also highlights the most recent novel approaches in planetary cartography.

Keywords Planetary cartography · History of cartography · Mapping · Geologic maps · Nomenclature

1 Introduction

We can distinguish the following major time periods in planetary cartography: the era of Earth-based visual observations, that of the photographic observations, and the era of digital spectral and topographic observations from space.

The *visual era* started with naked eye observations (with only one example in 1600), followed by astronomers' observations using their own telescopes (selenographers and areographers, 1610–ca. 1960), and astronomers using a large observatory (ca. 1900s–1960s). In *the photographic era*, astronomers used

H. Hargitai (✉)
Eötvös Loránd University, Múzeum Krt 6-8, Budapest 1088, Hungary
e-mail: hargitaih@caesar.elte.hu

A. Naß
Institute of Planetary Research, Planetary Geology, German Aerospace Center (DLR), Rutherfordstr. 2, 12489, Berlin, Germany

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photographic plates collected from different sources for mapping that were typically supplemented by *visual observations*. The era of "armchair astronomers" started by the International Astronomical Union (IAU) and their lunar reference map that was produced without the personal visual observations of the mappers in 1935. In the late 1950s, all major observatories' best available photographs were combined for creating planetary atlases to support both IAU's lunar mapping agenda and America's entry into the space age. However, it also became evident that even the best photographic plates by itself are unable to show the geology behind the landscape.

Planetary maps at the end of the 1950s with the new approaches were created using Earth-based images but knowing that this will change soon: Future maps would be created using space-based cameras, and it would soon become possible to start studying the geology of the Moon in situ, ending the era of speculations. The introduction of the new mapping methods signaled a preparation for the space age (Almar I., personal communication 2018).

Understanding the lunar geology was essential for choosing the appropriate landing sites for the Apollo and automatic missions. Planetary mapping moved into adulthood with the application of *geologic mapping* methods to planetary surfaces. This, advanced, form of manual mapping is based on the same types of images that were used in previous mappings, and it also included morphologic–structural details as before. The new element on these maps was the lines for material unit contacts, combined with the analysis of these units' stratigraphic, and consequently, age relations. Instead of studying a heterogenous image, a geologic map reduces the complexity into comprehensible units (Williams 2016). Planetary mapping was decoupled from astronomy, and now it supported the newly born discipline of *astro*geology.

In the space age, sensors onboard orbiting or flyby platforms provide source material for mapping with additional data from landed missions. The survey of the relief of planetary surfaces, without theodolites, was made possible by applying the new cartographic technologies, such as stereophotogrammetry, laser and radar altimetry, which have become the source for topographic data since the 1960s.

Regarding the end product, paper maps began to be replaced by GIS databases in 2011, since when all new planetary maps at USGS are produced in GIS format while the most significant previous (historic) maps and atlases are also being digitized ("renovated").

When speaking of the history of planetary mapping, it is important to distinguish maps from other graphical depictions of a landscape. Many astronomers created drawings of planets that were not maps. We may distinguish *drawings*–(popular or scientific)–from *maps* using various criteria. We list some of these in the followings, noting that maps may utilize any or several of these criteria. Most importantly, (1) *maps* offer a uniform view across the planetary body both in geometry and theme. Uniformity is expressed in that the image has a map projection (including orthographic view, e.g., for the Moon), and features are shown under similar conditions, e.g., illumination. Furthermore, (2) maps show the surface in a synthetic way compiled from multiple observations, showing *inherent* characteristics and not the actual expression of these qualities at a particular moment, as much as available data make it possible; (3) maps display designations of the represented features, preferably a systematic, standardized nomenclature with a hierarchical system of local and regional names, taken from a well-defined pool of specific elements and descriptor terms; and this is displayed in a systematic typographic way; (4) maps use a coordinate system, and positions of the surface features and markings may be linked to the coordinate frame by controlled measurements; (5) the map (or atlas) of an entire body may be split into sheets or quads, and may have multiple, thematic views of the same regions; (6) maps represent the surface in consistent ways, including stylized (iconic) or symbolic (abstract) visual representations (symbology); and (7) maps include metadata (data about the data, e.g., title, legend, information on the scale, projection, production, error, source of data, etc.); some of this information may appear as marginalia on paper or static maps in the form of graticules, north arrow, scale bar, etc.; or as a supplementary file in digital maps.

Maps provide higher fidelity view of planetary surfaces than photographs in many ways. During image-based mapping, we turn individual observations (single views or photographs) into a representation of the surface that accurately shows real spatial relations. These maps may use either a photographic or photorealistic (synthetic) representation of the surface, or a more abstract, symbolic, generalized cartographic representation. This cartographic representation communicates "deeper" (analyzed, distilled) information than an image map where this *information* may be included but in hidden, "raw" *data* form (Naß et al. 2019). Maps could be regarded as a type of "augmented reality" in that they combine multiresolution, multitemporal data, their analysis, and annotation, into a single, often customizable, view.

2 Milestones in the History of Planetary Cartography

2.1 Before the Space Age

The history of the planetary cartography (also called *extraterrestrial mapping*) dates back to shortly after the invention of the telescope at the beginning of the seventeenth century. This event marked a milestone in planetary exploration, because observational evidence could have started replacing reasoning-based natural philosophy. Additionally, the telescopic view of the Moon was not only scientifically exciting but it was also appealing for the general public. Numerous map manuscripts were created in the next centuries that were reproduced in popular books and encyclopedias in the forms of better or worse quality engravings. Claude Mellan's engravings of the Moon, made in 1635, were remarkably realistic. Besides detailed maps, these early drawings of the disk of the Moon served the same purpose as photographs today, so they are not real maps. However, they *are* maps because the illustrator had to use the mapping principle of generalization and made decisions of classifying the surface features and using iconic representations as part of the drawing, for repeated features such as craters.

The first detailed *maps of the Moon* showed different visual and toponymic approaches to represent the lunar landscape. *M. van Langern* (also known as *Langrenus* (Krogt and Ormeling n.d.)) in 1645 used an iconic, simplified representation of the surface; introduced the mare/terra distinction, as well as the concept of assigning personal names to craters, abstract concepts to terrae, and terrestrial descriptor terms (Montes, Lacus, etc.).

J. Hevelius in 1647 created two Moon displays: a realistic full Moon engraving and a symbolic, highly interpretive map showing the Moon almost as a region on Earth, in both visuals and labels. In this map, he used the "termite hill"-style, then standard, representation of mountain ranges for crater rims (that were called "ring mountains" in the eighteenth century), and clearly marked the coastlines of maria that he thought to be water bodies with islands. Accordingly, he assigned geographic names from the Mediterranean to these features with similar arrangement to that on Earth.

G. B. Riccioli and F. M. Grimaldi in 1651 created a third nomenclature and an objective visual representation, reflecting the telescopic view even if the features seen could not be explained. Riccioli produced the nomenclature, taking van Langern's descriptors, but changed specifics of crater names from dignitaries to ancient and modern astronomers. He also changed the names of mare to weather-related terms. The Riccioli nomenclature became the basis of today's planetary nomenclature scheme. For centuries, however, Hevelius' and Grimaldi's maps (both the visuals and nomenclature) were used in parallel, with some Moon maps showing both versions (e.g., Dopplemayr 1742).

Many improvements were introduced during the upcoming centuries, and extraterrestrial mapping became a scientific discipline. Map design was determined by the artistic talent of the observing astronomer or his financial status to hire good engravers, while the level of details was determined by the used telescope.

A milestone in planetary mapping is the map of "the *first* selenographer," T. J. Mayer (1748), who first used control points, measured at the telescope, which became a standard procedure afterward. He established the lunar coordinate system with equator and prime meridian.

The title of the "*last* visual selenographer" goes either to P. J. H. Fauth or H. P. Wilkins. Fauth used his own observatory, and his 342-cm-diameter map was completed by his son, H. Fauth, in 1964. The addition of details in drawing-based selenographic maps culminated in the 300-in. (7.62 m diameter) map of Wilkins (1946). This map was divided into 25 regular sheets. Additional special sheets showed the libration zones on farside-centered stereographic projection, and two polar stereographic views completed this work with actual data for the nearside portion only. These latter map views became common only after the space age. Wilkings also attempted something unprecedented: to draw the "probable appearance" of the farside. Data for the marginal regions were taken from libration observations. He traced nearside crater rays back to the farside and added speculative maria (Wilkins 1953).

Early maps showed the Moon north-up, as seen by the naked eye but standard lunar maps later became oriented south-up until the 1960s. The projection, understandably, remained sub-Earth-centered orthographic throughout the telescopic era: Maps were produced for users of telescopes, showing the view as seen through a telescope. One of the last projects using this style was the map supplement of the System of Lunar Craters catalog (Arthur et al. 1963).

Mapping the Moon and Mars required entirely different approaches until the space age, where available data types became more uniform. *Mars,* unlike the Moon, could be mapped globally as it rotated. Surprisingly, the earliest maps of Mars (Herschel 1784; Beer and Mädler 1841) used polar projections. The first map, by *Herschel* (1784, his Fig. 25; Stooke 2012) is also the first map made by image *mosaicking* technique. Herschel combined the drawings of his successive observations of the Martian disk in a south pole-centered petal-like mosaic. This process resulted in a single figure, allowed Herschel to correct single-observation distortions, and showed a view of Mars that can never be seen from Earth: a triumph for cartography. Mercator projection for Mars was first used by a geologist, *Philips* (1865). Mercator and polar stereographic projections together first appeared in *Green's* map (1879) and were also used by Schiaparelli, whereas popular reproductions of the map manuscripts of Schiaparelli and Flammarion were reprojected to two-hemisphere Mollweide projection.

The Venus map of Bianchini (1728) shows Venus in equirectangular projection. The next example is Kaiser's Mars map (1864). Equirectangular projection is commonly used today for computer-generated maps (Hargitai et al. 2019).

Telescopes provided details for 1:10 M lunar maps in the 17th century and for 1:3.5 M lunar maps in the 19th century (e.g., Wilhelm Lohrmann's 1824 maps). As telescopes became more powerful, it began to be possible to map the albedo features of Mars (*Beer and Mädler* 1841), during the oppositions every two years. Mars, unlike the Moon, displayed no shadows, and only albedo markings could be mapped that, showing another difference, significantly changed in time. The mapping of the low-contrast albedo features seen on the small diameter Martian disk (Fig. 1) through variable seeing conditions soon resulted in surprisingly detailed and highly controversial maps that showed a network of linear features called canals, starting with *G. Schiaparelli*'s maps that accompanied his very detailed descriptions of the surface features he named. On these maps, canal features first appeared as sharp, wide, curved bands (1877 opposition), then lines (1879), and parallel-running ("twin") straight lines (1881) (Tucci 1998).

The canal controversy had major implications on Mars science and cartography. During the visual observer era, maps were drawn after the observers' dynamic, ever-changing personal visual experiences. In addition, what the maps showed were filtered through the cognition process of the observer, i.e., they were subjective. At the turn of the nineteenth–twentieth century, two observer schools existed, one that had seen and drawn canals and another that had not.

The most detailed canal maps were those made by *Lowell* (1906) at his personal observatory in Flagstaff. Lowell based his theory of intelligent life on Mars on the "cognitively observed" canal properties. This theory survived until the space age despite canalists failed in its first test of objectivity. It was demonstrated that canals were likely mere optical illusions (Evans and Manunder 1903). However, for the public, with the effective help of journalists, canal maps served as a true and

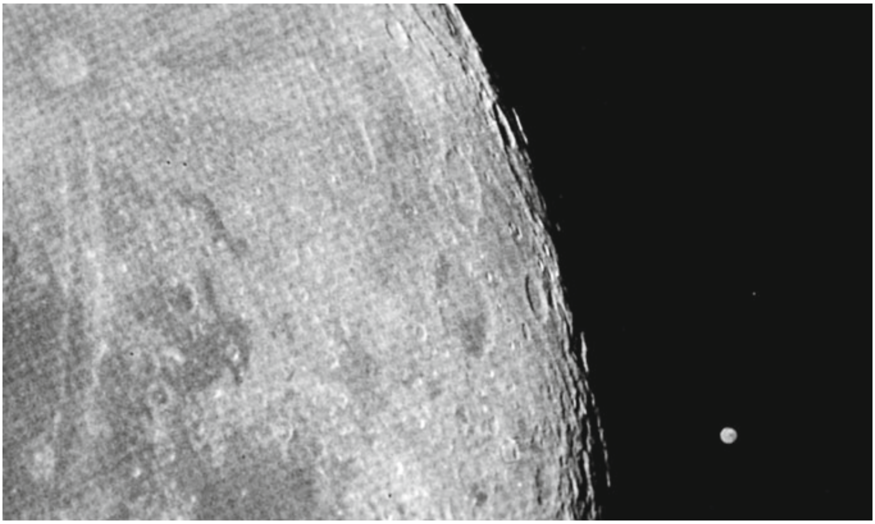

Fig. 1. Telescopic view of the Moon (left) with Mars (right) The picture was taken when Mars appears larger than usual, around opposition. *Photograph*, 12.04.1911. (Plate III in Slipher 1962a)

exciting representation of Mars that was generally believed to be inhabited. The debate triggered new, photographic techniques (Markley 2005), and canal maps remained authoritative sources of the Martian geography for the interested public.

However, the difference is not just the content and level of details but also the type of representation. Mars mapping at this time was about seeing and recording the surface details during the sometimes seconds-long favorable seeing conditions. Sharp lines could result from extremely good conditions or eyesight—or wishful seeing. The brain's visual data reduction system automatically connects random spots to more meaningful shapes, as the author of this chapter could have experienced during geomorphologic field mapping. Linear objects are the most prominent and best remembered elements on any map (Ooms et al. 2014; Albert et al. 2017). Lines on a map usually represent an abstract concept, artificial object or are *symbolic/iconic* representations. In contrast, these Mars maps claimed to be true representations of Mars: hand-drawn maps with "photorealistic" details but sharper than what photographic techniques could have achieved (Fig. 2). For the canalists, a realistic, pictorial representation may have been unconsciously confused with the urge to create a better, that is, map-like (cartographic) representation of Mars. They appeared to be cartographic maps, but in fact, they were (imagined) image maps (Fig. 3) (the problem of the clear distinction between the representation and the represented also appeared in the arts: Magritte's famous *Ceci n'est pas une pipe* image was painted around this time, in 1928–29). As Lane (2011) notes, these early maps of Mars lent the planet a fundamentally geographic identity, while previously Mars was an astronomical object. Maps competed for the visual authority of depicting the real Mars. This "representation war" began at the 1876–77 opposition.

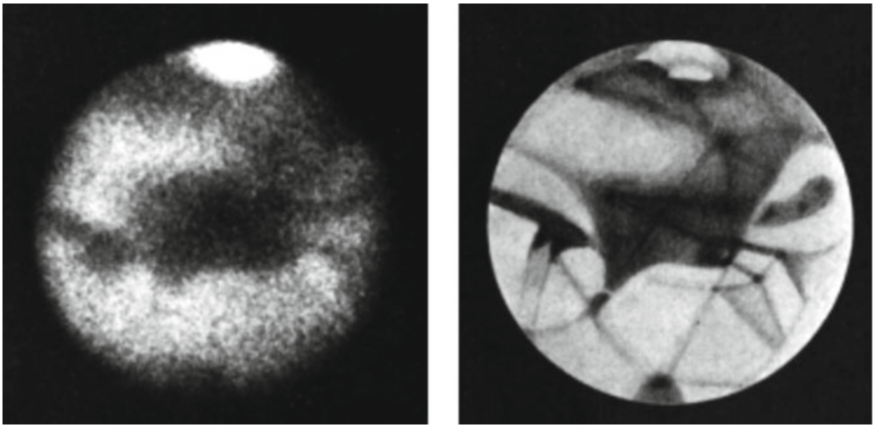

Fig. 2. Two views of Mars on the same night (Sept. 2. 1924) by R. Trumpler. A photograph and a drawing that are intended to faithfully represent what was seen through the telescope. Even if we consider occasionally excellent seeing conditions, the resulting map goes beyond the available contrast and spatial resolution and somewhat overinterprets the low-quality data (Trumpler 1924: Plate XX)

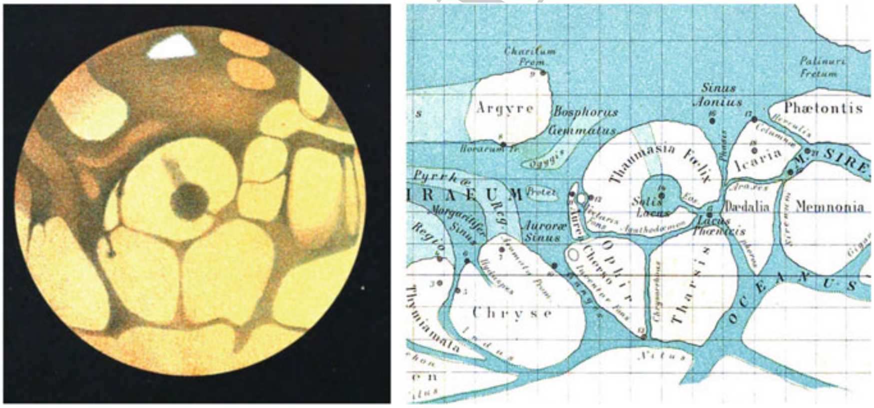

Fig. 3. A drawing that represents what the observer saw through the telescope, and a map representing features on that drawing. Argyre, corresponding to Argyre Basin, is the roughly circular white feature on the upper left of the map (Schiaparelli 1878)

The seemingly more accurate maps were those that showed prominent, sharp outlines (e.g., Schiaparelli 1878, Fig. 4 and also by Flammarion, from 1876), providing a familiar, "cartographic" visualization that the readers could recall from their school atlases. In contrast, less accurate-looking, definitely *less map-like*, maps displayed blurred spots and subtle colors (Green's map of 1879, Fig. 4, and the maps of Antoniadi), much closer to the actual telescopic view. We would today call it an image map. Photographic maps are rarely used for Earth and are difficult to

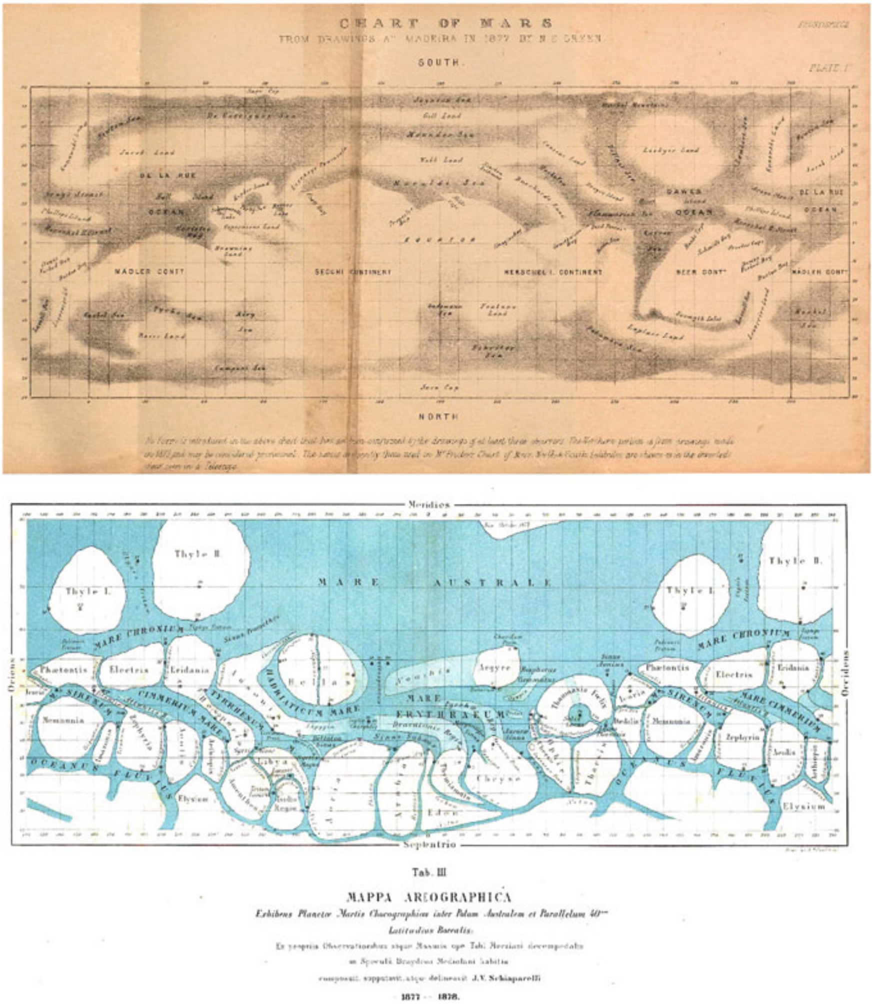

Fig. 4. Two different visual representations of the same planet, Mars, both drawn in 1877. Top: map by N.E. Green, who was a painter and painted Mars in pale yellow-brown colors in the original version (Ledger 1882) Bottom: map by Schiaparelli (1878). Note that central longitudes are different and the upper map duplicates the marginal zones. South is up

understand because of their uninterpreted, raw content. The maps with subtle, blurred spots communicated to the general public that these maps are *less transparent* and *less detailed* than the familiar cartographic ones with strong outlines, and razor sharp straight lines. Both map types were updated almost at each apparition, adding new details every second year. The sharp lines eventually evolved into a system of double canals and oases, tied to the fast-developing implications for life on Mars.

After decades of uncertainty, canals and their names were eventually removed on IAU's official nomenclature reference map, made by de Mottoni at Pic du Midi (IAU 1960, plate I–II, Dollfus 1961) despite Lowell meticulously named all his canals and oases. Interestingly, mission planning maps of the first NASA Mars project did show the canal features (Slipher 1962b; JPL 1967) until the Mariner 6, 7, and 9 missions sent back the first close-up photographs and straight canals were permanently removed from subsequent planning charts (Roth and de Vaucouleurs 1971) and Mars' geology (Sagan and Fox 1975; Moore 1977). While Lowell triggered a decades-long public debate about extraterrestrial geology and biology, many scientists today regard Lowell's contribution to planetary mapping as damaging that created distrust in Mars science. An ironic twist in this story is that most of the dark markings are geologically relatively insignificant ephemeral aeolian features.

2.2 The Photographic Era

Since the beginning of the telescopic era, individual astronomers mapped the Moon and later Mars, as parts of "personal space missions" (MacDonald 2017). In the first half of the twentieth century, planetary exploration moved to the largest observatories.

For lunar mapping, atlases with large-sized photographic plates provided a new way to show and study the surface, using Earth-based telescopic views. The first major project of this kind was that of the *Paris Observatory* (Loewy and Puiseux 1896) and simultaneously another at *Lick Observatory* (Holden 1896). However, these and the subsequent photographic atlases were systematic collections of reference photographs, not cartographic *maps*. In 1910, the British *W. Goodacre* combined photographs from two major observatories with his visual observations in making his line art Moon map. At around the same time, M. A. Blagg and W. H. Wesley entirely abandoned visual observations for their line-drawing Moon map made in 1911 and 1922 for IAU (Blagg and Müller 1935). As for Mars, the new, canal-free IAU map of Mars, presented in 1958 (IAU 1960), was based on both visual and photographic observations (Dollfus 1961) at the Pic du Midi Observatory.

2.3 Transition to Modern Planetary Mapping

Transitional periods are the most exciting in history. These nodes in time define future practices. The technology, organization, and the place of mapping all have changed fundamentally by the beginning of the 1960s when the world entered the space age, marking the transition from traditional to modern planetary mapping. Changes in mapping practices were accompanied by a significantly advanced understanding of the geologic processes that shaped the mapped surface.

At this time, static, but still Earth-based *photographs* provided a solid base for mapping instead of the ever-changing and personal telescopic view. For a short period in the 1960s, decades after the first photographic lunar atlases were published, lunar cartographic products (atlases, image mosaics, contour maps) were based on carefully selected photographs that had been taken at the largest observatories. These projects used the best available data, which could be compared to the invention of writing that decouples the text from limitations in time and space: Observations from different times and places were combined for the first time.

At the end of the 1950s, IAU, an *international organization*, began new mapping projects that were based on the photographs of the largest telescopes, and supplementary visual observations, for both Mars and the Moon. Finally, the focal point of planetary mapping activities moved from Europe to the *USA* (and also the *Soviet Union*) where, now entering the Space Race, *systematic* planetary mapping was organized by the military and civilian *government-sponsored agencies.* This was the scene when the first spacecraft were launched.

This change of technology coincided with a change in the organization of map production. Teams of cartographers, planetary scientists, and graphic artists, and later mission team members, produced maps instead of individual observing astronomers, and typically by government-sponsored agencies that operated space missions.

The *Photographic Lunar Atlas* (PLA) (1960) project was led by G. Kuiper at Yerkes Observatory of the University of Chicago. Plans for this Atlas were first discussed by IAU in 1955. The Atlas was revolutionary in that it contained the best available photographs of not one, but five large observatories. It showed the nearside of the Moon, in several different illuminations, as seen from Earth. Photographs were selected in 1959 (Kuiper 1959). The photographs in the Atlas were oriented south-up, for use at the telescope. Its No. 2 supplement, the *Rectified Lunar Atlas* (1963) (Fig. 5), used a novel projection method: Earth-based photographs were projected onto a physical globe (Whitaker et al. 1963;

Fig. 5. "Discovery image" of the Orientale impact basin. Parts of Mare Orientale were previously known as individual marginal mountains. Photograph of the Rectified Lunar Atlas, Table 16-a (Whitaker et al. 1963)

Spradley 1962). The physical globe with the projected images was then photographed by directly looking “down” to the globe from the vantage point of an imagined spacecraft orbiting around the globe. This process generated photographs in orthographic projection, as seen from above the center of the photograph. This project produced the first rectified images of the limb regions; however, the analog photorectification method was originally developed around this time for the production of the LAC series at ACIC. Photographs there were rectified with an instrument called “Variable Perspective Projector.” The resulting image was rephotographed and used as a mapping base (Carder 1962). Rectification technique abandoned Earth-bound viewing angles and provided an early preview of the space age orbital views of planetary surfaces. Just as digital mosaics today, this atlas was used for studying the Moon, including crater counting (Baldwin 1964).

By the time these atlases were published, the United States government also have had become interested in lunar mapping, as part of its Space Race politics. During these years, planetary mapping was taken over by mapping teams of professional (civilian and military) cartographers utilizing cutting-edge cartographic and instrumental techniques, to prepare for human lunar missions.

At this time, three options were considered in the USA and probably in the Soviet Union also (Myler 1957), for the use of the Moon as a resource in the Space Race: dropping a nuclear bomb on the Moon as a globally visible demonstration, establishing a permanent military base, and sending men to the Moon for a short trip. Each of these projects were fundamentally political missions. The US Air Force involved Kuiper who led lunar mapping at Yerkes (e.g., Ulivi 2004:44; US Army 1959). However, the United Nations forbid testing nuclear and other weapons and establishing military bases on the Moon in 1967 (UN 1967). Although lunar military plans were already dropped by that time, these early military mapping procedures defined the framework for subsequent planetary mapping. Nuclear bombs also played a role in the birth of modern astrogeology, also during this time, when nuclear explosion craters, observed by E. M. Shoemaker in 1959, provided evidence for the impact (explosion) origin of lunar craters and experimental data for the development of the method of crater counting (Shoemaker et al. 1963). Shoemaker created the prototype of lunar geologic maps in the following year, in 1960, of the Copernicus crater region.

Two independent lunar mapping programs started at the military: one at the *Air Force Aeronautical Chart and Information Center* (ACIC, St. Louis, MO) and another at the *US Army Map Service* (AMS, Washington, D.C.) in 1957 and 1958, respectively (Weir 2009).

AMS investigated the requirements for establishing a subsurface military outpost on the Moon. This project was called *Horizon* (US Army 1959). AMS focused on topographic mapping: It began works on a 1:5,000,000 topographic map of the nearside of the Moon in 1961, using stereo-photogrammetric technique on photographs from the large observatories. It is the first lunar topographic map that used photogrammetry, and also the first in stereographic projection (1-AMS 1963) (Fig. 6). Another, 1:1,000,000-scale series was planned to be completed between 1959 and 1962, based on future “earth-orbiting telescope camera systems,” and

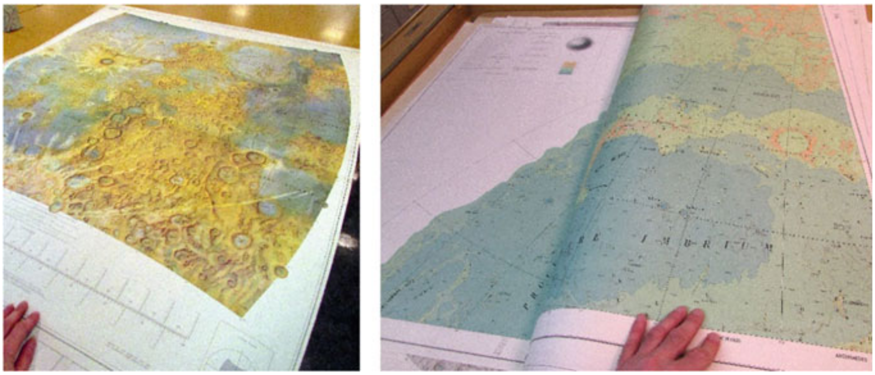

Fig. 6. Two sheets from the AMS topographic lunar maps (1962). Left: shaded relief version, right: gradient tint version (*Photograph* by H.H.)

"lunar circumnavigating and satellite vehicles." According to the plans, by 1964, 1:10,000 maps would have supported the landing site selection (US Army 1959).

ACIC also began mapping the Moon and planned to obtain far side images for creating topographic maps in cooperation with the newly (1958) established NASA. This mapping project was to support a planned human mission to the Moon within its proposed *Lunex* program (USAF 1961). This project continued as the Lunex and Horizon projects were dropped and the Apollo program was born. ACIC published the 1:5,000,000 Lunar Reference Mosaic (LEM-1) map in 1960 and was available by the time J.F. Kennedy announced the Apollo program. ACIC focused on the novel *airbrush hillshading* technique in its *Lunar Astronautical Chart* (LAC) (Carder 1962) for which ACIC used its existing terrestrial World Aeronautical Chart series used for navigation by pilots as a model (Weir 2009; Kopal and Carder 1974:115). LAC was the first lunar mission planning airbrush map series supporting the US Space Program, utilizing photographs from several observatories (similar to PLA) with supplementary visual observations first at Yerkes Observatory (with the help of Kuiper, Arthur, and Whitaker) (Carder 1962) and at the newly established Air Force Observation Unit at Lowell Observatory in Flagstaff (1:500,000 Apollo Intermediate Chart (AIC) series, 1:1,000,000 LAC series). ACIC put in enormous efforts into determining elevations, and while AMS experimented with stereogrammetry, ACIC chose the traditional shadow measurement technique. Photographs were taken every 20 seconds of the Moon at Pic du Midi with the direction of Zdenek Kopal, amassing 12 thousand images over 2 years and measured shadow lengths using a microdensitometer (Carder 1962).

Following this short period dominated by the US military, planetary mapping became coordinated by a civilian US government agency, the *United States Geological Survey* (USGS), where now astrogeologists took over planetary mapping. Mapping had a well-defined aim: to support future NASA missions and analyze the returned space-borne images. In Flagstaff, home of the Lowell Observatory, USGS began an institution-based systematic planetary survey program using NASA mission data (USGS Planetary Geologic Mapping Program, Tanaka et al. 2011). Another positive consequence of this move from private to government-funded mapping is that USGS maps and NASA's planetary image data are in the public domain, freely accessible to everyone.

Over the next decades, photographic atlases became common platforms for publishing planetary maps in easily accessible form. These books reproduced photomosaic or shaded relief NASA maps or newly produced photomosaics with nomenclature overlay with a collection of spectacular images (Batson et al. 1984; Davies et al. 1978; Greeley 1994; Greeley and Batson 1997; Bussey and Spudis 2004; Schenk 2010; for the new Indian Mars Orbiter Mission images: ISRO 2015). However, in addition to image mosaics and topographic maps, a third kind of planetary map was born: geologic maps.

2.4 The Beginnings of Astrogeologic Mapping

Until the 1960s, lunar cartography was developed by adding more and more minuscule details in the maps, as telescopes became more powerful, in accordance with a descriptive geographic approach (referred to as "selenography" for the Moon and "areography" for Mars). It became evident, though, that a new approach is needed to unravel the processes that shaped the landscape. This new conceptual approach was introduced with the foundation of the USGS *Brach of Astrogeology*. Instead of showing the surface morphology (or "physiography") in ever higher detail, and artistic realism, new planetary maps showed surface units classified by their geologic properties. Two novel photogeology-based approaches were proposed in 1960, which both required laborious manual investigation: one by Robert J. Hackman and Arnold C. Mason at AMS, and another led by Eugene Shoemaker at ACIC/USGS.

Mason and Hackman (1962, first print 1960) created a nearside map trio (Wilhelms 1993:37-40), still in traditional Earth-based orthographic projection, but North-up. Hackman's *photogeologic map* of the Moon defined rock formations based on their inferred age derived from *stratigraphic* relationships (pre-maria, maria, post-maria). This mapping required the delineation of the major stratigraphic units (enclosed by contact lines) across the entire surface. Hackman used stereopairs of photographs from different observatories enlarged to approx. 1:5,000,000 scale for the mapping, obtained with the help of G. Kuiper (Wilhelms 1993:38) (AMS used stereogrammetry to produce a contour line lunar map at that time). Another map, showing *physiographic divisions,* delineated and classified surface regions by *morphology* into lowlands, highlands, and crater provinces, and named them following geographic traditions (e.g., "Northern Lowlands"). This map followed a broader, landscape-scale categorization of the relief, where terrains (landscapes) were assumed to have resulted from a long and complex surface evolution (divisions based on "degree of similarity or difference in type of surface features, extent of preservation, type of modification, type of surface material,

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elevations, slopes, and structural disturbances”). Morphology, materials, features, and, perhaps most importantly, evaluation of landing, surface movement and in situ material excavation (“construction”) possibilities, were described for each region. Additionally, a thematic feature map of the lunar rays completed this series of the “Engineer Special Study of the Surface of the Moon.” Mason and Hackman’s newly proposed nomenclature, physiographic (terrain) and chronologic division, was not accepted by the community. Physiographic analysis was replaced by a geologic approach.

A concurrent and independent photogeologic project in 1960 utilized the established method of terrestrial *geologic mapping* delineating *material units* based on stratigraphic analysis, for just a relatively small region around Copernicus crater (Shoemaker and Hackman 1962), at ACIC (drawing, printing, airbrush base chart) and USGS (where Shoemaker established the Branch of Astrogeology at this time), for NASA. This map departed from the telescopic-view-defined orthographic projection and used Lambert Conformal Conic projection. Geologic units were grouped according to their relative age (derived from superposition) and assumed material. Surface materials were inferred from morphology, which suggested a particular formation mechanism. The test map included a description of the observed morphology of each unit, their assumed material and formation process. The map also included a geologic cross-sectional view. This work also established the lunar timescale. This mapping approach immediately became the prototype, as intended (Shoemaker and Hackman 1961), and standard procedure for systematic planetary geologic mapping (Shoemaker and Hackman 1961, LPC 58 Chart, 1:1,000,000) (Portree 2013). Hackman also participated in the series, mapping the Kepler crater region (the first map in the ACIC series, Carder 1962), also signifying the end of the telescopic era in that he used his own “visual telescopic observations at the Leander McCormick Observatory” in 1960–‘61 (USGS map I-355), perhaps the only planetary geologic map based (partially) on visual observations. This project also produced the first research paper on planetary stratigraphic analysis (Shoemaker and Hackman 1962). It was established that major periods in the geologic time scale can be defined by a type locality, or an age-indicator feature (e.g., crater rays).

Shoemaker and Hackman (1962) recognized first that “the geological law of superposition is as valid for the Moon as it is for Earth.” With the introduction of geologic mapping in planetary science, it became possible to understand and reconstruct the evolution (chronology) of planetary surfaces. Interestingly, most methods and techniques used in planetary geologic mapping were laid down (Steno 1669) much before *planetary* geologic mapping was “invented.” Terrestrial geologic mapping standards were already implemented at the USGS after its 1879 foundation (US Geological Survey 2006). The construction of a relative surface chronology is based on both stratigraphy and crater counting. Unlike morphology, crater counting can be used for *quantitative* age determination of geologic units. Crater counting was a new element in planetary geologic mapping, developed during the 1960s. The first attempts to connect relative ages to absolute ones used terrestrial analog regions to estimate the impactor flux over time (Öpik 1960; Shoemaker et al. 1963; Baldwin 1964; Hartman 1965). Just a few years later, Apollo astronauts collected and returned lunar samples that could be used for accurate radiometric dating that in turn could be linked to crater density.

The discovery that craters are also common on Mars (Hartman 1972), and that they are the most common planetary landforms, enabled the usage of this technique across almost all solid surface solar system bodies, as proposed by Shoemaker et al. (1963).

Mars's surface morphology was first globally mapped by Mariner 9 (1971). The first geologic map of Mars used the same technique and conventions as for the Moon earlier, and *geologic* interpretation was based on *topographic* features that were "highly diagnostic of their origin" (Carr et al. 1973). Mariner 9-based stratigraphic mapping was formalized in the 1:25,000,000 geologic map (Scott and Carr 1978), which was later updated using Viking Orbiter (1976–80) imagery and crater density values were also assigned to units (Tanaka 1986). These maps were drawn over manually airbrushed shaded relief maps, while the most recent global geologic map of Mars is drafted over MOLA and THEMIS mosaics, similarly using photogeologic methods (Tanaka et al. 2014). Radar provided new geologic information as Earth-based and orbiting imaging radar data showed cm-scale surface roughness and radar reflectance properties, especially for mapping Venus.

The delineation of geologic material units is based on a standard procedure. On Earth, material properties are objective, descriptive parts of geologic maps. However, planetary material units are commonly delineated and properties *inferred* using macroscopic *morphologic or spectral* properties and not direct geochemical/elemental or microscopic analysis, or core sampling. Relative unit ages can be confidently determined through stratigraphy. Crater counting of homogenous map units and the application of crater chronology systems can provide cratering model ages that can be utilized to globally correlate spatially distant units, providing an "absolute" reference age (Williams 2016). New, higher resolution, or different wavelength image data, together with new impact flux models and statistical methods, may result in a different delineation of the units in updated geological maps (Fig. 7).

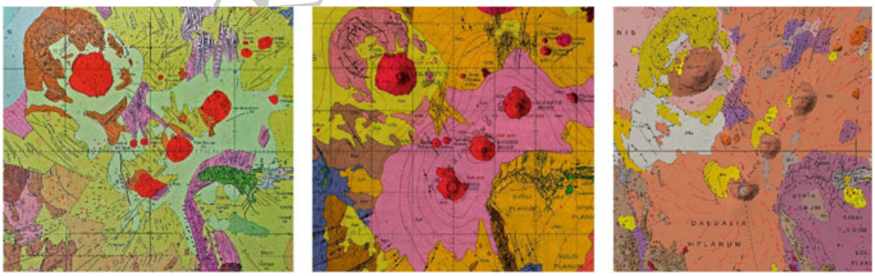

Fig. 7. Map cutouts of the Tharsis Montes region, Mars. Left: geomorphologic map, Makarova et al. (1978). 1:20 M; middle: geologic map, Scott and Carr (1978). 1:25 M; right: geologic map, Tanaka et al. (2014) (paper version), 1:20 M

2.5 New Mapping Techniques During the Space Age

Despite successful Earth-based telescopic and radar observations of Venus, Mars, and the accessible lunar nearside, topographic features of the planets and their satellites could only be mapped in detail from observation platforms onboard spacecraft.

The era of *space-borne mapping* started with the first set of pictures received from the far side of the Moon (Luna 3; Babarashov et al. 1960) and Mars (Mariner 6; Davies et al. 1970). Ranger VII–VIII photography was transformed into a series of different scale (1:1 M-1:10 k) airbrush maps (*Ranger Lunar Charts*) in 1964–66. Just a few years later, *Lunar Orbiter* images were used directly in the photomosaic maps of the equatorial zone of the Moon (LEMC), compiled manually (US Army 1968); and a global photographic reference atlas was also published (Bowker and Hughes 1971).

The first image-mosaic-based globes were produced, manually, from Mariner 9 Mars photographs glued to a very large globe (Staff 1973). Large-scale (1:10–1:50 k) "topophotomaps" during the mid-1970s were produced from Apollo 15 and 17 high-resolution panoramic photography with red 10- to 20-m-interval contour line overlay.

In *topographic mapping*, shadow length measurements (Schröter 1791) mainly provided local elevation data: peak elevations and crater rim profiles. The first attempt to create a topographic contour map of the Moon is that of Franz (1899). These techniques were superseded by stereophotogrammetry (AMS 1963), laser altimetry (Wollenhaupt and Siogren 1972), Earth-based and space-based radar altimetry (Pettengill et al. 1969, 1980), and radar interferometry (Zisk 1972). The photogrammetric control point technique developed by M. Davies at RAND Corporation was introduced to provide a basic reference framework for controlled planetary maps (Davies and Berg 1971) and served as a basis for stereophotogrammetry and bundle adjustment techniques (Wu 1978). Digital Elevation Models in 2018 are available for Mercury, Venus, the Moon, Mars, Ceres, Vesta, and the encounter hemispheres of Pluto and Charon. Regional topographic maps are generated from stereo- and photoclinometry for several other bodies.

New photometric technologies made it possible to objectively measure *radiance* data per pixel, first only indirectly, on photographic plates, and later with direct photoelectric telescopic observations (Pohn et al. 1970). Data from space-borne platforms all were digital that needs calibration.

While Mars was initially mapped visually as a disk with blurred dark markings, new, Earth-based techniques allowed *indirect mapping* of planetary surface markings before spacecraft could have visited and resolved them into multipixel images. Crude maps of surface albedo can be derived using the light curve inversion technique that analyzes the change in the photometric record of a body's light curve due to planetary rotation, occultation, or transits. Using light curve data collected over many decades, Iapetus was revealed to have two contrasting albedo hemispheres (Morrison et al. 1975) (Fig. 8b). Occultation light curves provided data for the first

(a) (b) (c)

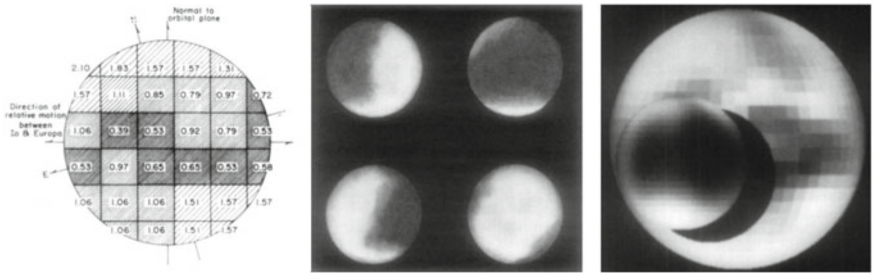

Fig. 8. Albedo maps derived from light curve analysis. Left: map of Europa, centered on 324°W longitude, showing relative reflectivity values on a scale normalized to 1.00 for the whole disk, visualizing reflectivity bins with cross-hatching in a 6 × 6-grid resolution (Vermilion et al. 1974); center: "artistic representation" of Iapetus based on a computed albedo distribution model centered on 0, 90, 180, 270° longitudes (Morrisson et al. 1975); right: Modeled albedo image of the transit of Charon across Pluto determined from right curve inversion (Buie et al. 1992)

map of Europa (Vermilion et al. 1974) (Fig. 8a). Pluto's surface map before the New Horizons' visit was calculated from mutual event light curve data, using a "disco ball" visualization (Buie et al. 1992, 1997; Young et al. 2001) (Fig. 8c).

2.6 *Planetary Mapping and Maps in the Digital Era*

Parallel to terrestrial developments, since the mid-1990s, digital cartographic techniques using vector- and raster-based graphic software arose. In the map *production* process, a major step was the introduction of the requirement that USGS geologic maps be produced in a *Geographic Information System* (GIS) *platform*. Astrogeologic maps are produced and published in GIS format at USGS since 1996, exclusively since 2011 (Tanaka et al. 2011).

NASA-produced digital web mapping tools, such as the *Mars Global Surveyor Interactive Data Maps,* were already available in 1999 and became quickly popular (Gulick and Deardorff 2003), almost a decade before Google released its planetary products. Today the production and display of planetary maps are available in diverse GIS and WebGIS/Web Mapping Service (WMS) platforms that support multilayer, multiple projection, multiple style, and multiscale viewing (Dobinson et al. 2005). GIS technologies dominate in planetary mapping and cartographic representation (e.g., Hare and Tanaka 2001; Hare et al. 2009; van Gasselt and Nass 2011; Nass et al. 2011; Frigeri 2011; Hare et al. 2015b).

Digital technologies have not only changed the mapping interface for both map creators and readers, but it is changing how map data are collected. New, supervised and unsupervised classification and machine learning techniques are emerging and are capable of automatically mapping surface features. After appropriate training, the user interface is not a map, but a content-based image search (e.g., “show images with > 30% coverage of dunes *and* fresh craters”). Neural networks capable of “mapping” millions of images (Wagstaff et al. 2018) and research papers (Wagstaff et al. 2016) could revolutionize planetary mapping the production and use of planetary maps.

2.7 Planetary Cartography in the Soviet Union and East Asia

During the Space Race time period, both the USA and the Soviet Union produced their lunar map series using manual hillshading and albedo, initially both involving military mapping facilities. However, in time, USGS maps became more and more detailed (from 1:5 M to 1:5 k) while Soviet mapping moved toward large-sized representative, thick-framed 1:10 M global maps of the Moon printed in 10,000 copies (Rodionova et al. 1985). USGS produced 173 geologic planetary maps between 1961 and 1990, during which time the Soviet Union produced 15, and other nations none (Hargitai and Pitura 2018).

The seven-sheet 1:1 M central nearside lunar map series (Lipsky 1968) and the nine-sheet 1:5 M “Complete map of the Moon” produced at the Sternberg Astronomical Institute with updated editions between 1967 and 1989 using the results of Soviet and American missions use similar visualization principles (but different colors) to the American airbrush maps (Shevchenko et al. 2016). Only few sheets of 1:5 M Mars maps were published, using images of the Soviet Mars 5 probe and covering small regions (Tefinim and Krestnikova 1977). In 1987–88, Venus radar maps of the Venera 15–16 Synthetic Aperture Radar images were published in both separate sheets and atlas format in the Soviet Union. Exceptionally, a “US/USSR Joint Working Group on the Solar System Exploration” produced a three-sheet (topographic, shaded relief, radar image) map from these Soviet radar data to support the American Magellan mission planning (USGS 1989, Basilevsky et al. 1990). Instead of geologic material unit mapping, Soviet scientists produced the “Tectonic map of the Moon” (Kozlov et al. 1969) and geomorphologic, structural geomorphologic (Makarova et al. 1978), and geologo-morphologic maps of Mars (Bugaevsky et al. 1992), and the USGS-published geomorphic/geologic map of Venus (Sukhanov et al. 1989) that latter show what Basilevsky et al. (1989) calls the “Soviet interpretation of the geology”. A unique product of Soviet-era planetary cartography was the first comprehensive cartographic planetary atlas. It was produced in over a decade of cartographic work at MIIGAiK, Moscow, and contained global thematic maps compiled using conventional map drawing techniques, and pencil-drawn shaded relief representations of the terrestrial planets and their moons along with a large number diagrams, photographs and thumbnail reproductions of historic and modern planetary maps (Bugaevsky et al. 1992[1]). Lunar maps from this

[1] http://planetmaps.ru/atlas.html.

Atlas were also published as a school atlas (Shingareva and Krasnopevtseva 2011). The 1970–1980s in the Soviet Union marked the peak in shaded relief map production of Mars, Phobos, the Moon, and radar maps and atlases of Venus (GUGK 1988). Today Russian planetary cartographic centers produce a variety of outreach-type global topographic maps and globes of terrestrial planets and the Moon (e.g., Grishakina et al. 2014; Lazarev et al. 2012) with a signature two-hemisphere layout. MIIGAiK's MExLab developed its own Web mapping service called Planetary Geoportal (Garov et al. 2015). Following their traditions in atlas cartography, the comprehensive atlas of Phobos offers a detailed view of this irregular body (Karachevtseva et al. 2012, 2019).

China recently joined the countries with a complete planetary mapping infrastructure from data acquisition to publication. Results from the *Chang'E* lunar probe series were published in photomosaic and topographic map, atlas and globe formats (e.g., Compiling Committee 2013, Mu et al. 2019), and also in an interactive WMS for Chinese audience. In *Japan,* the perspective views of lunar landscapes from the Japanese Kaguya mission's HDTV camera were published in a pictorial atlas format (Shiao and Wood 2011).

3 The Short History of Specific Cartographic Tools

3.1 Generating Synthetic Views: Concepts

Lunar telescopic observations reveal two "faces" of the Moon: one during high-sun (noon) and another representation reflecting the visual experience during low-sun (sunset/sunrise). The high-sun Moon shows albedo features: subtle tone variations, bright rays around craters, and dark and bright spots of different sizes and shapes. The low-sun Moon shows sharp shadows, which are cast to the east or west, depending on the actual local Moon time. While the high-sun (albedo) view of the Moon had not directly implied any geologic explanation before geologic mapping began (the water vs. land hypothesis was not considered very seriously in the last centuries), low-sun shadows and shading reflected topography, a key to geology. Later, Mars showed only the high-sun albedo view, while Venus revealed none of its surface optically.

For the lunar mapper, the basic problems in visualizing the lunar surface are how to synthesize the two characters of the lunar disk (brightness or albedo, and topography) and how to derive a single picture of the relief from the shading and shadows that change length, shape, and direction with the movement of the terminator line. The first mappers either produced one map view that combined albedo and sharp shadows, or separated the two themes. A combined-theme map assumes two different illumination conditions at the same time. Albedo is derived from a realistic full Moon view, showing the lunar disk during sub-Earth noon (or local noon views). The topographic view applies shading for the entire lunar disk with a single illumination angle, as if local times would be similar (near sunset or sunrise) on the entire disk. Maps may combine these two views: the uniform-illumination shading and albedo. The reader who is used to seeing planar surfaces with uniform illumination does not find anything unusual in a map view where all craters cast similar-oriented shadows. It is not realized consciously that here a sphere is projected on a plane and this synthetic view of normalized shadows never occurs in nature. Seller (1700), for good reason, called these views "Phasis Lunae Naturalis" and "Phasis Lunae Artificialis." Moreover, shadows and shading do not exist as materials do. Shading itself is not an inherent characteristic of the surface materials. Hillshading as a separate map theme is only used to create the mental image of the 3D relief in the map reader's mind, using a 2D technique, without perspective view.

The problem of showing relief was approached with different visual methods and techniques, from line drawing to hachure to airbrush hillshading, but the problem always remained how to create a synthetic, uniform reflectance and relief view of the surface as it never appears in real life. Generating composite maps usually needs some compromise. A topographic shading overlay on an albedo map makes albedo information ambiguous because both are expressed in a change of tone. Adding a low-resolution color overlay on a high-resolution panchromatic photomosaic is a common method of enhancing the map; however, if the image mosaic is in color, colors cannot be used to express elevation.

Modern technologies allow the creation of uniform-illumination maps by mosaicking multiple photographic observations, or synthetically by the generation of hillshading effect from elevation data. Albedo (reflectance) maps can be produced directly by combining noontime visual observations: DEMs have no albedo information. On the other hand, new computational techniques allow the reconstruction of surface albedo from low-sun images, by removing all effects of shading from the scene using DEM (Nefian et al. 2013).

Today, generic maps can be produced from the combination of several base raster layers: for example, DEM (coloration), reflectance (monochromatic tone that shows visual or infrared albedo), and shaded relief (Table 1).

3.2 Topographic, Brightness (Albedo), and Physiographic Maps: Examples

As for general (reference) visualization of a planetary surface, the images seen over a telescope were replicated by hand drawing and line engravings for printing. Albedo, relief, and nomenclature can be separated or combined in many ways.

In 1647, *Hevelius* produced three views: a realistic full Moon engraving (equivalent of a photograph), a symbolic line drawing with termite hills and names (the cartographic map), and a simple sketch map. *Grimaldi and Riccioli* made an engraved picture without names and a similar view with octant grid and carefully typographed names.

Table 1. A list of map themes and their source data

Map theme	Origin	Type
Albedo, visual	High-sun photographic or visual observation	Observed
Color, true or false	Multispectral observation	Observed
Relief: shadows	Low-sun photographic or visual observation or DEM	Observed or reconstructed (calculated)
Relief: shading	Low-sun photography or DEM	Observed, manually created or reconstructed (calculated)
Chronology: position (relative age)	Contact lines (manual determination units)	Derived from superposition (stratigraphic relations)
Chronology: absolute age	Crater counting, impact flux functions, radiometric ages of lunar samples	Derived from crater size frequency curves
Material	Morphology or spectral data (albedo, hyperspectral)	Inferred
Formative process	Morphology (shape, relief, pattern), albedo, or material	Inferred
Nomenclature	May be proposed by mission team. Assigned by IAU. Descriptor term is based on morphology.	Descriptor element is derived; specific element is not geology related
Surface roughness	cm-dm scale: radar echo, km-scale: from DEM	Observed or derived
Thermal inertia	IR observations (day and night)	Calculated from observation
Relief: elevation raster/contours	Radar or laser altimetry, stereogrammetry, radar interferometry, shape from shading	Calculated from observation
Morphology/structural feature type	Shadows, shading, DTM	Visual inspection or automated machine learning

Cassini's Moon map, engraved by *J. Patigny* (1679) (Whitaker 1999:140), shows albedo combined with a fine hillshading with a superior 3D effect.

The map of *J. Russell* (1805) combined pictures from his 40 years of observations separating albedo and topography and published two drawings of the Moon: a contrast-enhanced full moon (with "the rays of the sun falling oblique upon [the surface]") and one showing topographic details only (with "rays falling perpendicular to it") (Whitaker 1999:99–100). This separation of albedo and relief reappears regularly, both on Mars and Moon maps.

In finding ways to depict the lunar surface realistically, J. Nasmyth produced 3D plaster terrain models and photographed it in grazing light, instead of using actual photographs (Koeberl 2001). These pictures determined how the cratered lunar surface was seen for many decades. In their book, *Nasmyth and Carpenter* (1874) showed two representations of the lunar nearside: a *picture map* and a *sketch map* (Fig. 9).

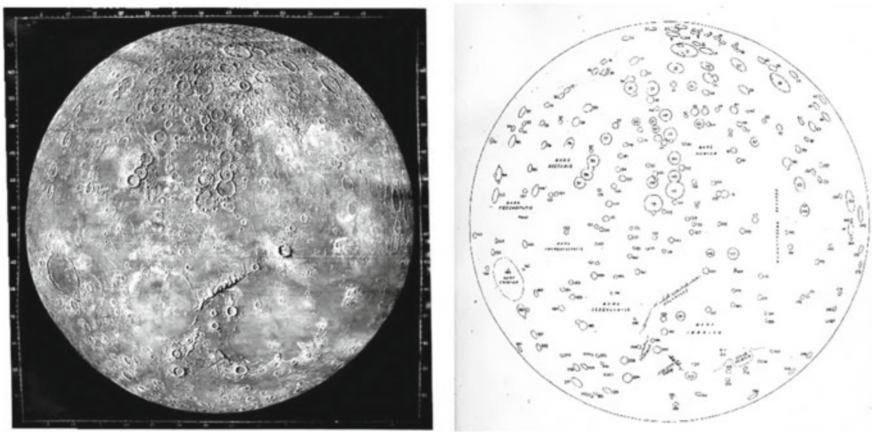

Fig. 9. Pictorial (left) and sketch map (right) of the Moon (Nasmyth and Carpenter 1874)

The picture map was copied from *Beer and Mädler's* detailed map (1841), and background tones and shadows were *manually added*. The hillshading in this map has uniform northwesterly illumination to convey a "fair impression" of the lunar landforms. USGS shaded relief maps continued this tradition by applying uniformly westerly (Batson 1991) and later northwesterly (USGS 2017) illumination.

The simple "*skeleton map*" was created using a micrometer, and showed the outlines of craters and mountains, with additional labels. This map showed the need for an interpreted, generalized (more abstract, less realistic) but accurate, *cartographic* representation of surface landforms.

This technique developed into a double-layer representation where the sketch map with nomenclature was printed on a transparent paper that was placed over a realistic drawing (e.g., Flammarion 1900).

In the early space age, similar, but more detailed, *line-drawing* outline maps served as reference to identify the crater inventory of the nearside of the Moon (44 sheets, Arthur et al. 1963, also used as nomenclature reference maps, Fig. 10), the far side of the Moon (32 sheets, Lipskiy 1967), and Mars (30 sheets, Mutch et al. 1976, this being also one of the first line-drawing maps drawn by computer). These maps using a technical drawing style were now the authoritative cartographic products.

With a similar approach, 1:50 M line-drawing "*blank maps*" were produced initially as preparation for the production of more complex maps in the Atlas of Terrestrial Planets and Their Moons (Bugaevsky et al. 1992), but they were eventually included in the atlas.

Cartographic line-drawing techniques moved to a next level in geologic maps that now showed contact lines in addition to structural feature outlines.

Image maps of airless bodies where low-sun shadows are sharp and dark frequently show the same region in multiple illumination angles. The *Rectified Lunar Atlas* displayed the same regions in five complementary views from near-terminator

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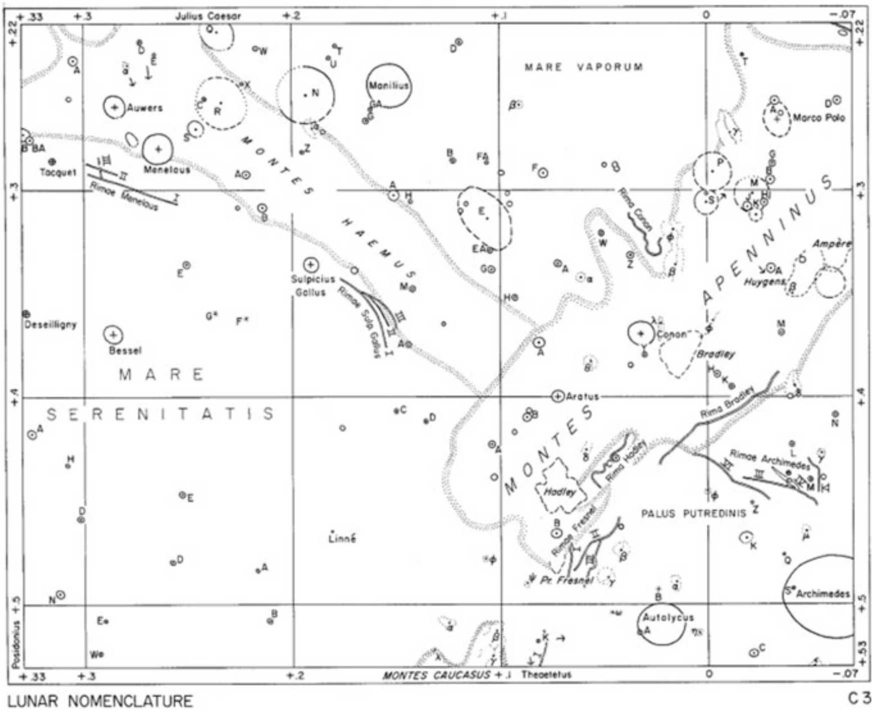

Fig. 10. Technical-drawing-style map of the Montes Apenninus region, Moon (Arthur et al. 1963, Sheet C3). South is up. Cf Fig. 11 that shows the same area

morning and evening images that accentuate low relief morphology, to high-sun mosaics that accentuate albedo variations; and a view with a nomenclature and grid overlay. *MESSENGER Mercury* images were acquired for building four different mosaics: a grazing light eastern and western mosaic, a moderate incidence angle mosaic, and a high-sun mosaic. These image mosaics are also synthetic as the mosaics combine individual images showing these regions at similar local times (Murchie et al. 2017).

W. G. Lohrman, a selenographer and professional cartographer, introduced *hachures* in 1824 (Fig. 11) to indicate length and steepness of slopes, a new technique in terrestrial cartography at that time (Whitaker 1999:116). His maps showed albedo variations using several shades of grey.

A new style of *hillshading* was developed in the 1970s where some maps were drawn by pencil and charcoal in the USA by the British cartographer C. Cross (Morton 2002:50) and in the Soviet Union at MIIGAiK. However, airbrush superseded this technique.

The realistic *airbrush hillshading* technique was introduced into planetary cartography by *P. M. Bridges* in the US Air Force ACIC lunar LAC maps in 1959 (1:1 M, 44 sheets out of the planned 144, 1959–1967; Carder 1962), which

Fig. 11. Montes Apenninus region, Moon (Lohrman 1878, Sheet IV). South is up. Cf. Fig. 10

revolutionized the representation of planetary surfaces (Inge and Bridges 1976; Batson 1991; Schaber 2005). Air Force mappers moved to the Lowell Observatory to draw maps of the Moon and Mars from telescopic views (IPPP 1971), where *J. L. Inge* augmented the airbrush technique. Bridges and Inge were hired by the USGS Astrogeology Branch also in Flagstaff (Morton 2002:51) to perform "topographic interpretation," i.e., shaded relief map production from images and visual observations.

These manually produced shaded relief maps incorporate details that never appear in a *single* photograph and *exclude* inherent albedo information ("surface markings") (Batson 1973). However, if needed, a synthetic albedo drawing can be added to hillshading (e.g., USGS Moon map i-2276, plates 1 and 2 showing manual hillshading with and without albedo markings).

Airbrush was utilized in more than a hundred sheets of lunar maps, mostly based on Lunar Orbiter and Apollo photographs. This 1960s technique reappeared with the computer-processed Mariner 9 Mars images that contained numerous artifacts and were taken by a variety of atmospheric, illumination, and surface conditions at different resolutions and therefore had to be synthesized manually (USGS 1973; Inge and Bridges 1976). Airbrush technique was also used throughout the Voyager mission.

The Mariner 9 orbiter mission, along with Earth-based radar observations, presented new challenges in data integration. It generated a diverse set of data that were used to produce the first topographic map of Mars (Wu 1978). The final map showed the relief using shaded relief airbrush drawing combined with 1-km contour line, or albedo ("surface marking") overlays (Batson 1973).

Manual airbrush technique could not be easily employed for interpreting radar mosaics which lead to the development of *computer-based* hillshade production (Kirk 1993), although radar-derived airbrush maps were also produced by Bridges (USGS 1989). Airbrush maps were gradually replaced by shaded relief maps produced from gridded digital elevation data (DEMs) (Batson et al. 1975; USGS 1984).

Another element in visualization is the use of signature *color schemes*. The application of saturated, vivid colors in the "*Geologic Atlas of the Moon*" series, also published in nearside and farside thematic views (Wilhelms 1987), became a signature of post-Apollo era lunar geologic mapping (e.g., Wilhelms and El-Baz 1977) and were coincided with and perhaps subconsciously influenced by the color schemes of the contemporary pop culture originating from the San Francisco-based Psychedelic Movement. Most other lunar reference/planning maps were published in bluish to yellowish colors (for maria and highlands, respectively), for example, in the multisheet LAC series, and Chinese maps (AMS 1963; Carder 1962 Compiling Committee 2013) modified to blueish to brownish in the LOC and LMP series (Schimeran 1973) and deep blue to gray to yellow tints in the most recent one-sheet topographic map (Hare et al. 2015a). In contrast, Soviet lunar maps had a brown-orange to white color scheme (Lipsky 1968) (Fig. 12). Modern *topographic* mapping is symbolized with the rainbow colors of the MOLA Mars topographic map (Smith et al. 1999).

3.3 Map Sections and Schemata

It was Grimaldi who first divided a planetary map into segments. His one-sheet Moon map consisted of eight circle sections or *"octants"* instead of a coordinate grid. Multisheet maps were introduced by Lohrman who constructed a lunar map in 25 square sheets, published between 1822 and 1878. The most time-consuming part of the map production was to engrave the drawings into copper plates (Whitaker 1999). Beer (a banker who provided his rooftop observatory) and Mädler produced their lunar map (1834) in four large sheets, combined from 104 manuscript sections.

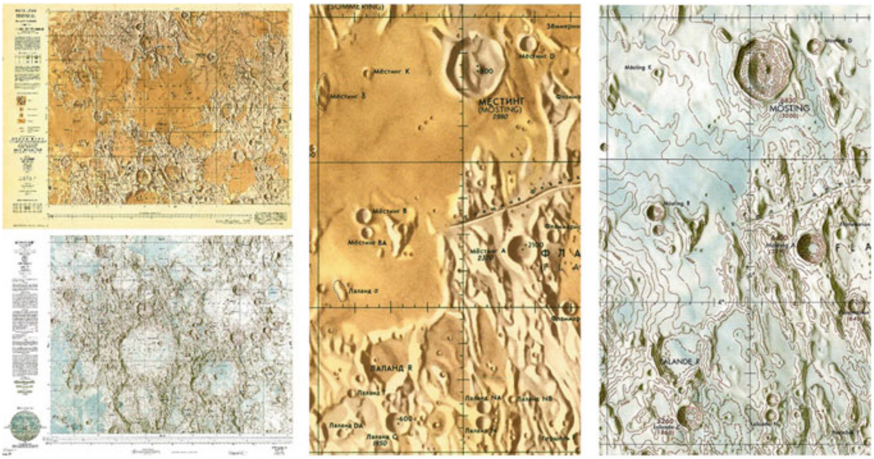

Fig. 12. Soviet (orange) and American (blue) 1:1 M general (planning) map sheets of an overlapping central nearside region of the Moon. Detail images show the same region. (A) Karta Luny, List 4, Zaliv Tsentralniy. Shaded relief with height points. Sternberg State Astronomical Institute, Nauka, Moscow, 1968. (B) Lunar Chart LAC-77 Ptolemaeus. Aeronautical Chart Information Center, United States Air Force, 1963. Shaded relief with contour lines

For systematic, long-term geologic mapping, USGS divided the surfaces of planets to schemes of named and numbered mapping *quadrangles*. These include the 44-quadrangle scheme for the Moon at 1:1,000,000 scale (Wilhelms 1972) and 30 quadrangles (Mars Charts – MCs) for mapping Mars at 1:5,000,000 scale (Batson 1973). The 62-quadrangle scheme for Venus at 1:5,000,000 scale was first used in the Soviet Venera mapping (GUGK 1988), where 27 northern quadrangles were mapped. Projections of quadrangles are also standardized, first defined for the LAC series (Carder 1962): Mercator is used for the equatorial quadrangles, Lambert Conformal Conic for intermediate latitudes, and polar stereographic for the two polar quadrangles. All these projections are conformal. Quadrangle schemes for different-sized bodies at different scales are presented in Batson (1990). Nomenclature reference maps also use the quadrangle schemata (Hunter et al., this volume).

Since the systematic mapping guided by the USGS is conducted over the timescale of decades, and quadrangle maps are updated from time to time, the ongoing standardization of the mapping and visualization methodology (Naß et al. 2017) is a basic requirement as much as possible to make adjacent quadrangles and quads in a series comparable and compatible (Galluzzi 2019).

The Dawn Mission used a 15-quadrangle scheme, based on the recommendations of Greeley and Batson (1990). Individual quadrangles were produced by different groups within the mission team during the systematic mapping of Vesta (Roatsch et al. 2012; Yingst et al. 2014; Williams et al. 2014) and Ceres (Williams et al. 2017; Roatsch et al. 2016).

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3.4 The Development of Planetary Nomenclature

The core concepts and names in the planetary nomenclature are based on the personal choices of early planetary mappers. Since the language of science, and cartography, was Latin at that time, they uniformly used Latin for naming features. With the birth of national sentiments over Europe, German (1821, Gruithuisen), French (1860, Lecouturier and Chapuis), and English (1869 M. Ward), equivalents of all or some of the lunar names were introduced, and place-names of Mars were also given in the native tongue of the observing astronomers until Schiaparelli (1878) reintroduced Latin—not very different from his native Italian. Planetary place-names were uniformly (re-)latinized by IAU in 1961 (Sadler 1962), this time to ensure international political neutrality.

For the early mappers, it was apparently tempting to name surface features after members of royal families: The very first map of the Moon (Langrenus 1645) and the first map of Venus (Bianchini 1728) equally include such names for the most prominent features. None of these names survived (the Venus features were in fact the telescope's artifacts).

Specifics of place-names show a transition from ancient European names (nineteenth century) to American/Soviet names (1950s) to a "worldwide representation" (IAU 1974) and multiethnic naming system initially suggested by Carl Sagan for Martian valleys (de Vaucouleurs et al. 1975).

The neutrality of the nomenclature was a goal from the beginnings, when Hevelius discussed that he has chosen classical geographic names over personal names for naming lunar features in order to be as impartial as possible (Whitaker 1999:55). Although Hevelius's system did not survive, this theme of archaic geographies reappeared when Schiaparelli's new Martian nomenclature conflicted the existing one. Before Schiaparelli, features of Mars bore the names of contemporary astronomers (Lane 2005), similar to the lunar map of van Langern that preceded that of Hevelius.

Albedo features of Mars were given ancient "Old World" names (Schiaparelli 1878; Burba 1981). Spacecraft observations of topographic features that were uncorrelated with albedo features made that scheme obsolete for geologic use. The former names were "saved," however, and many albedo names were transferred to topographic features (de Vaucouleurs et al. 1975). For some time, Earth-based visual albedo mapping activities were continued at Lowell Observatory (Inge et al. 1976) and are still being conducted by amateur astronomers who actively use the "old," or parallel, albedo-based nomenclature.

Almost all selenographers added a few names for their newly discovered features here and there, even though the basis of all works was Riccioli's toponym corpus. Blagg and Müller (1935) correlated the existing maps of Mädler, Schmidth, Neison, and others, creating the "collated list," the first edition of the standardized IAU "selenographic" nomenclature. Standardization of the nomenclature also meant that IAU became the name authority where names were approved by a commission instead of individuals (Blagg and Müller 1935). The *IAU Working Group for*

Planetary System Nomenclature (WGPSN, e.g., IAU 1977) is responsible for approving name themes, descriptor terms, quad names, and astronaut-given names. The new lists of standardized planetary place-names (gazetteers) were published informally in Arthur et al. (1963), and Masursky et al. (1986), formally since Batson et al. (1995), and now online.[2]

Today IAU WGPSN, based at USGS in Flagstaff, supervises planetary nomenclature. The Gazetteer of Planetary Nomenclature is maintained by USGS, and names are approved by IAU WGPSN (USGS 2016, Hunter et al., this volume). G. A. Burba published the Russian localization of the Gazetteer in the 1980s (Gazetteer 2016), and lunar names now also have Chinese standardized equivalents (Hargitai et al. 2014).

4 The Current Practice of Geologic Mapping

Geologic maps are essential to any planetary missions. Spacecraft-based geologic mapping has served as reconnaissance for landing site selection, where maps produced from one mission justify the need and choice for landing the next mission. At USGS, planetary geologic maps are published within its *Scientific Investigations Map* (SIM) series that includes terrestrial geologic maps. In this section, we document the current practice (Williams 2016, J. Ziegler, email communication, 11/24/2017, Skinner et al. 2018) to demonstrate the need for a strictly enforced review and production procedure that follows scientific analysis.

Tasks during the production of a planetary geologic map include delineating structural units and contact lines, crater counting, GIS database management, and geologic and geomorphic analysis to answer science questions. The maps then go through technical peer review by two mappers. This could take up to 40 hours of work per reviewer, and review and revision can spread over several years. After this stage, map production continues at USGS. Following technical review, a geologic map editor edits for clarity and consistency of scientific data, as well as for grammar, spelling, and USGS style, in the printed publication. This editor inspects that the information in different parts of the printed product and the database is consistent. In addition to symbols and colors, descriptions and discussions in the pamphlet must match the information shown on the map and in the *Description of Map Units* and *Correlation of Map Units*.

After the edit is complete, the author contact reconciles the edits in collaboration with the editor. When all issues are resolved, the materials are submitted to three individuals for approval for publication. The approving officials check that the scientific content is thorough, complete, and focused on the main subject; they also make sure the content is unbiased.

[2]http://planetarynames.wr.usgs.gov.

After the publication is approved, the materials are submitted to a cartographer for production—to be formatted and laid out according to USGS policy and style. When the publication production is complete, the author contact and the editor both review the final materials for accuracy, clarity, and consistency. Part of the editor's tasks is to make sure data are not changed during the production process.

Today, USGS planetary maps are published on the Web with database, metadata, and readme files, but USGS produces a printed publication too. Generally, USGS releases publications on the Web as soon as they are final and the printed copies become available soon after. PDFs (soon XMLs) of the printed product (interpretive pamphlet and the map sheets) are also available on the publication Web page. *The database is the main product,* but it is also important to provide the compiled map, explanations, and interpretations in printable and plottable formats. Printed materials represent the content of the database in a form that can be displayed for visual comprehension, study, discussion, comparison, and understanding of the author's interpretations. Without an accompanying visual compilation of the map, a database user may not be able to quickly and easily reproduce the map that the authors are discussing and interpreting.

Statuses of ongoing works are reported at the annual Planetary Geologic Mappers Meetings and other conferences.

Calculating with two work-years over a four-year project period and an average annual salary of $125,000, the total cost of the production of a planetary geologic map is about $250,000, before editing. The total duration of a project from start to printing is typically 5–7 years.

In Europe, universities and research organizations may produce their own planetary maps, typically but not always as part of a mission where their instruments fly. In the USA, upcoming mapping projects are selected via a proposal process open for all US-based scientists. In Europe, however, mission teams or research institutions decide on the mapping projects in an internal process. Map products are typically available online through various journals and mission Web sites, but some are not published formally and only exist in printed manuscript form, or as figures in conference proceedings, research papers, or theses. Mapping is also carried out in international collaborative projects such as the cartographic mapping of Vesta. China's planetary map-editing procedures are described in this volume (Mu et al. 2019).

5 Conclusion

We distinguish three stages of planetary mapping regarding its goals. Between 1610 and ca.1960, planetary mapping was driven by the scientific interests of professional and amateur astronomers, selenographers, and areographers who predominantly worked in Europe (Germany, Italy, France, and Great Britain) and were financed from private resources. Planetary maps also were produced for outreach: Reproductions of planetary maps were engraved for encyclopedias, popular science books since the eighteenth century. Many lunar maps were produced for amateur observer astronomers when this hobby became widespread.

From 1960, as a result of Space Race, planetary mapping moved from Western Europe to the USA and Moscow. Lunar mapping became one of the top national priorities in both the USA and the Soviet Union. The Soviet Union had no planetary mapping activities previously. In 1960, both countries started planetary mapping that supported their space programs. The USA, preparing for human landing, produced more than 300 lunar maps until 1969, while the Soviet Union did about half a dozen. During the next ca. 50 years, the USA produced approx. 1400 planetary maps, while the Soviet Union and Russia produced about 50 (Hargitai and Pitura 2018). These mapping activities were financed from government funds and involved astrogeologists and professional cartographers. The turn of 1950s/1960s is perhaps the most significant turning point in the history of planetary cartography. There emerged new concepts (geologic planetary mapping, crater counting), new technologies (photogrammetry, radar), new visualization methods (airbrush hill-shading), new projections (rectified images), new motivations (landing site selection), new financing plans (public money), and planetary mapping moved almost exclusively to the USA.

This era of modern planetary cartography is ending now. Analog technology is replaced by digital, with machine learning based systems emerging. Mapping became international, now including not only Europe but Asia too. Europe restarted planetary mapping in the 2000s with German maps related to the Mars Express, and later to ExoMars 2020 missions, and an increasing number of planetary maps are also produced in other European countries in the 2010s. China produced its first lunar maps in 2008 from Chang'E data and continues to expand planetary map production. Although financing is still almost solely based on public resources such as NASA, Europlanet, Russian and Chinese central resources, private companies may soon emerge for mapping the geologic resources of asteroids or the potential landing sites of their own missions. In the 2010s, citizen mappers and private companies emerged online and produce outreach-type digital maps. Geologic mapping now does not only support earth and planetary sciences but also astrobiology where geologic data can serve as the basis for the identification of potential past, present—and perhaps, future—habitats on other planets.

6 Further Reading

The most comprehensive review on planetary cartography in general is that of Snyder (1982, 1987), and Greeley and Batson (1990). The history of planetary mapping is discussed in, e.g., Wilhelms (1972), Schimeran (1973), Moore (1984), Martin et al. (1992), Whitaker (1999), Kopal and Carder (1974), and Morton (2002), Markley (2005), Lane (2011), Stooke (2012). Historic lunar maps are available at the LPI Web site (LPI 2015). Radar mapping techniques are discussed in Ford et al. (1993). For detailed summaries on the development and evolution of planetary cartography, the reader is referred to Shevchenko et al. (2016) for the history of Soviet and Russian planetary cartography, and to Jin (2014) for Chinese lunar mapping results. Recent planetary cartographic techniques and tools are reviewed in Beyer (2015) and Hare et al. (2017, in prep). The international catalog of planetary maps is available at the Web site of the International Cartographic Association's Commission on Planetary Cartography (Hargitai and Pitura 2018).

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