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COMMENTARY
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Key Points:

- Planetary geologic maps are critical products that link science goals and objectives to space exploration
- Maps are also used to support safe and productive surface navigation and are imperative for crewed and robotic surface missions
- International cooperation is essential to produce maps needed in the coming decade

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Planetary Geologic Maps: Essential Tools for Scientific Inquiry and Space Exploration

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Abstract Planetary geologic maps are crucial tools for understanding the geological features and processes of solid bodies in the Solar System. Over the past six decades, best practices in planetary geologic mapping have emphasized clear and objective observation, geological interpretation, multi-sensor fusion, and iterative revision of maps based on new data. We summarize here four ways in which maps serve as indispensable instruments for scientific investigation, from enhancing observations to interrogating surface processes. With respect to space exploration, we underscore the role of planetary geologic maps as tools to link testable, hypothesis-driven science to exploration goals and provide actionable information for hazard identification, resource evaluation, sample collection, and potential infrastructure development. To further advance the field of planetary geologic mapping, international collaboration is essential. This includes sharing data and maps through FAIR (findable, accessible, interoperable, and reusable) platforms, establishing standardized mapping practices, promoting diverse nomenclature, and fostering continued cooperation in space exploration.

Plain Language Summary We summarize why planetary geologic maps are important for science and space exploration. We review the history of these maps and present four ways in which planetary geologic maps contribute to scientific understanding. We further outline six ways in which maps help humanity plan and execute space missions productively and safely. These endeavors require international participation; thus, we end with a call for collaboration to train the next generation of mappers, develop maps for future missions, and use maps to communicate the significance of space exploration to everyone.

1. Introduction

Planetary geologic maps serve as comprehensive records of the spatial-temporal distribution and characteristics of rock, sediment, and soil across the surfaces of solid bodies in the Solar System (e.g., Maltman, 1990; Spencer, 2000; Wilhelms, 1990). These maps not only capture the diverse landforms, tectonic structures, and erosional patterns present in the material units but also contribute to our understanding of the geological processes that have shaped planets in the past and may continue to influence them in the future (Greeley, 2013; Okubo, 2014; Tanaka et al., 2015). The process of planetary geologic mapping involves both methodical observation, such as defining units and delineating contacts, and geological interpretation, wherein these units are linked to process-based explanations. Established over the last six decades, best practices in planetary geologic mapping emphasize three key principles. First, maps should clearly separate feature observations from geological interpretations to avoid ambiguity and broaden use. Second, maps should objectively apply fundamental stratigraphic principles, including cross-cutting relationships, to aid clear conveyance of relative timing between discrete geologic events (Baker, 2014; El-Baz, 1974; Mutch & Saunders, 1976). Third, planetary geologic maps should be recognized as iterative scientific products that are always open to revision pending the collection of additional data. This adaptability is particularly crucial in planetary geologic mapping, where each new mission contributes fresh and exciting information for integration with existing data sets (Hodges & Schmitt, 2011).

With space exploration objectives connected to planned missions over the next decade, we anticipate a global interest in and demand for contemporary, content diverse planetary geologic maps. In particular, crewed missions to the Moon and Mars and robotic missions throughout the Solar System will necessitate maps throughout the various stages of mission development, across a wide spectrum of spatial scales, and designed for a diverse set of users from astronauts to the general public (LSSW 20, 2024; NASEM, 2022; NASA, 2023; Weber et al., 2020). The significance of these maps extends across two primary objectives: (a) to enable scientific investigations; and (b) to facilitate safe and scientific navigation during exploration. Herein, we review these two interrelated yet distinct goals, illuminating the crucial role that planetary geologic maps play in sustaining and advancing international space exploration endeavors. We also advocate for increased international collaboration to advance humanity's understanding of our neighboring bodies through cartographic investigation and innovation.

2. History of Planetary Geologic Maps

The evolution of planetary geologic mapping closely aligns with over 70 years of progress in remote sensing technology. Modern mapping began in the 1950s and 1960s with telescopic observations of the Moon (Mason & Hackman, 1961; Shoemaker, 1960, 1964). Early flyby and orbital missions throughout the Solar System provided visible wavelength data sets used to identify surface features and characterize geologic units (Arvidson et al., 1980; Binder et al., 1977; Markov et al., 1972; Masursky et al., 1977; Millman, 1973; Mutch & Saunders, 1976; Wilhelms & El-Baz, 1977; Wilhelms & McCauley, 1971), and the Luna, Mariner, Apollo, and Viking missions set the stage for focused, standardized planetary geologic mapping and map campaigns in the following decades (Butler & Morrison, 1977; Carr et al., 1973; El-Baz, 1974; Wilhelms et al., 1979). The Clementine mission further advanced early lunar mapping efforts by providing high-resolution, multispectral data that allowed for detailed characterization of lunar surface features and composition (Sorensen & Spudis, 2005).

The introduction of radar technology, combined with multi- and hyper-spectral data, advanced orbital observation through the end of the twentieth century. Missions like Venera and Magellan provided high-resolution radar data that transformed our understanding of Venusian geology (Barsukov et al., 1984; Ivanov & Head, 2011; Tanaka et al., 1994). The advent of laser altimetry enabled topographic maps of unprecedented accuracy and coverage, revolutionizing not only global geophysical science and geologic unit characterization, but also providing a more precise global geodetic grid for science investigations (Aharonson et al., 1998; Smith et al., 2001; Solomon et al., 2005). The Galileo mission to Jupiter and the Cassini mission to Saturn further expanded planetary geologic mapping by studying moons like Europa and Titan and revealed familiar geological processes blended in unfamiliar proportions and with unfamiliar compositions (Greeley et al., 2000; Lopes et al., 2020; Williams et al., 2011). In the 21st century, missions such as Hayabusa, Rosetta, New Horizons, Dawn, and OSIRIS-Rex collected data used to map small bodies like comets, asteroids, satellites, protoplanets, and dwarf planets (El-Maarry et al., 2019; Giacomini et al., 2016; Jawin et al., 2022; White et al., 2017; Williams et al., 2018; Yingst et al., 2014).

Robotic surface missions brought about opportunities to validate geologic maps with landers and rovers. On Mars, these missions included Sojourner, Spirit, Opportunity, Phoenix, Curiosity, Insight, Zhurong, and Perseverance, which conducted in situ analysis of rocks and soil to link ground observations to orbital data sets (e.g., Bennett et al., 2023; Crumpler et al., 2011; Crumpler et al., 2023; Liu et al., 2022; Squyres et al., 2006; Sun & Stack, 2020).

Finally, the Moon remains the only body other than Earth where planetary geologic mapping has been used in conjunction with astronaut field work at six different locations to better understand geologic processes and in situ resources (e.g., Apollo Field Geology Investigation Team, 1973; Schmitt, 1973; Wilhelms, 1972). For example, candidate landing sites for Apollo 17 were meticulously mapped at multiple scales (e.g., 1:250,000 and 1:50,000) to facilitate targeted scientific investigations and maximize the mission's geological return (Carr, 1966; Scott et al., 1972; Wolfe et al., 1981). Orbiting the Moon since 2009, the Lunar Reconnaissance Orbiter now provides detailed base map data and high-resolution topography for modern surface mapping of Apollo landing sites and candidate sites for future Artemis campaign missions (Bernhardt et al., 2022; Iqbal et al., 2020; Krasilnikov et al., 2023). More than a decade of remote sensing data from Kaguya, Chang'e, and Chandrayaan missions also contributes to lunar mapping efforts and provides critical insights into the Moon's geology, surface features, and potential resource distribution (Chen et al., 2022; Ji et al., 2022; Lu et al., 2022). Image, topography, radar, and multispectral data make up the foundational data products and along with geologic maps play a central role in past and future lunar missions, supporting ongoing exploration (LSSW 20, 2023; NASEM, 2022; NASA, 2023).

3. Creating Maps for Planetary Science Investigation

In the pursuit of scientific investigation, the process of creating a geologic map involves a series of deliberate steps, each contributing to a rich understanding of planetary terrains and processes from which they arise. In this context, we summarize four ways in which planetary geologic maps are critical instruments for science by providing insights into the composition, history, and processes that shape Solar System bodies. We note that while traditional, terrestrial geologic maps distinguish units based on lithology and texture, planetary geologic maps inherently rely on morphologic, topographic, spectral, and other data types in which lithology may be interpreted but is rarely tested through on-the-ground observations.

Enhanced Observation through Mapping: The act of geologic mapping encourages a systematic, objective examination of the terrain and fosters a thorough accounting of geological features present and the processes they individually or collectively implicate (e.g., Baker, 2014). Common elements of a planetary geologic map include: (a) a basemap data set upon which geologic units and features are identified, delineated, and described; (b) supplemental data sets that provide additional information about the area of interest; (c) a description of map units to include unit names, labels, definitions, and geologic interpretations; (d) a correlation of map units to illustrate how geologic units relate to each other in space and time; and (e) an explanation of map symbols (Skinner et al., 2022). Geologic maps provide a baseline to extend observations made at the surface of a body through cross sections and into the shallow underground, resulting in 2-dimensional and 3-dimensional map-based models.

Defining Material Units and Structures at Multiple Scales: Advancements in camera technology have resulted in better spatial resolution and lower signal to noise ratios, enabling detailed geologic mapping and more precise identification and categorization of surface features. For instance, data from the High Resolution Science Experiment (HiRISE) instrument has enabled the creation of geologic maps to reveal details of Martian surficial processes (Okubo, 2014). Delineating distinct units such as rocks (lithology), soil, and other surficial deposits on a map forces researchers to identify both similarities and differences among geological materials. This process not only aids in categorizing surface compositions to be documented in a Description of Map units but also lays the groundwork for understanding the diverse geologic processes that have shaped a planetary body. Moreover, identifying specific secondary (often imparted by tectonic and (or) erosional processes) structures that occur on the surface of morphological units emphasizes the record of surface deformation and modification. Maps ultimately provide context for disparate observations made by scientists working at global to local scales. Viewing these results through the lens of a geospatial system ensures that insights learned from studying in situ or small areas are then integrated with broader conclusions regarding regional planetary geologic processes, and vice versa.

Determining Temporal Relationships: Geologic mappers identify specific features and their spatial relationships to determine the sequence of geologic events within a map area. The concepts of (a) embayment and onlap, where superpositions can be established, and (b) cross-cutting relationships, where one geologic feature intersects another, each serve as fundamental principles in geologic interpretation. Temporal relationships inform scientists about the relative timing of events—for instance, a crater (and its ejecta) cutting across (or overlying) other features implies that the crater formed after the features it intersects, providing decisive chronological insights into the planetary history. Depicting relationships between units in a Correlation of Map Units, geologic mapping helps scientists to build a layered history of an area to create nuanced timelines of geologic events across different locations. Furthermore, superposed impact crater density and absolute model ages calibrated by radiometric data of sampled units help to establish an absolute chronology (e.g., Hiesinger et al., 2023). This type of analysis results in science-driven mission exploration goals, providing the rationale for *why* a location should be explored, *what* data need be collected during exploration, and *how* such study will contribute to answering modern, posited research questions.

Linking Present-Day Terrains to Past Processes: Finally, planetary geologic mapping plays a crucial role in subdividing the present-day landscape into spatial and temporal events, thus revealing the signatures of various geological processes that have operated over time, including those that are ancient and no longer active. This linkage is essential for unraveling the long-term geological history of a planetary body. For example, geologic mapping helps promote exploration of Mars by rover, and the results of such mapping have helped uncover the historical presence of water and the implications of such deposits for interpreting the planet's climate history (Crumpler et al., 2011, 2023; Squyres et al., 2006). Moreover, planetary geologic maps set the stage for terrestrial analog investigations by highlighting units, structures, stratigraphic relationships, and relevant geologic processes that may have Earth-based equivalents (e.g., Garry et al., 2012; Greeley, 1971, 1982).

4. Utilizing Maps for Space Exploration

Planetary geologic maps play a pivotal role across the entire trajectory of mission development, execution, and post-mission analysis proving especially crucial for surface examination via landers, rovers, and crewed endeavors. For example, a 2023 NASA Lunar Surface Science Workshop focused on geologic mapping for surface exploration reviewed the significance of geological mapping to support Artemis strategic decisions. The resultant report outlined key stakeholders in pre-, syn-, and post-mission phases (LSSW 20, 2024). In this context, geologic maps serve a wide-ranging function from science-driven mission development, where specific landing sites such as the lunar south pole for Artemis III are determined, through mission execution, as astronauts embark on surface exploration activities, to post-mission phases where collected samples undergo curation and archival for subsequent scientific investigations (NASA, 2023). The following summary underscores the indispensable role of planetary geologic maps in ensuring the success, instructiveness, and safety of space missions.

Mission Design and Development: Mission proposal teams that design forays into new territories or testing scientific hypotheses, particularly those targeting rocky surfaces, rely on the best available planetary geologic maps. These maps aid in anticipating observations during flybys, from orbit, through landing sequences, or on the ground, providing key insights for mission planning. During the penultimate stage of landing site selection in mission development, planetary geologic maps become indispensable as they provide information on scientific value, potential hazards, terrain stability, and resource availability. Whether using small scale (large area) maps for geologic context or large scale (small area) maps for specific landing locations, the choice of landing site profoundly influences the expected scientific outcomes. Months or even years are dedicated to the discussion and selection process, with maps guiding every phase of decision-making for both robotic and crewed surface missions.

Linking Science Goals to On-the-Ground Observations: Maps are powerful tools in planetary exploration, revealing scientific narratives about a body or landing site through orbital data and guiding the formulation of pertinent questions for surface investigation. Remote sensing data are used to generate geologic maps and derived geologic profiles as well as associated stratigraphic columns, unit descriptions, and time scales, which ultimately reflect the current understanding of the geological sequences of events. Thus, maps play a fundamental role in missions that include crewed or robotic surface exploration, serving as tools to connect testable hypotheses and science investigation goals to anticipated field observations. Science traceability matrices or concepts ensure that surface or orbital operations are aligned with science objectives, and that explorers always have an open mind and open eyes for unanticipated discoveries (Fagan et al., 2023; Skinner et al., 2023). This approach emphasizes efficiency with the goal to maximize scientific return on an investment in space exploration.

Resource Identification and Evaluation: In situ energy, mineral, and water resources are required to support sustained space exploration. As on Earth, mapping these resources and linking them to underlying geologic units enhances recovery and reduces risk associated with extraction. Lunar south pole ice, for example, is both a high-value science target for understanding volatile evolution and a critical resource for human habitation and emerging lunar technologies. Similarly, maps that reveal the presence of mineral deposits such as iron, aluminum, and titanium contribute to the assessment of economic viability of mining operations on asteroids or other planetary bodies. The development of space infrastructure will undoubtedly be linked to resource availability and guided by geospatial analysis of critical reserves.

Hazard Identification and Traverse Planning: Tactical geologic maps, accounting for mission science, engineering constraints, and the mechanical properties of surface deposits (cf. Doan et al., 1960), are essential for hazard identification and efficient, safe traverse planning. The Apollo 17 mission serves as a notable example where geologic maps, created in advance, guided every step of the mission, determining station locations, documentation priorities, “flexicution” options, and sample collection strategies (Hodges & Schmitt, 2011). This application involves astronauts, flight control, mission-supportive science and engineering teams, and the media. It also contextualizes real time observations and crew movements, enhancing scientific return and decreasing risk.

Geologic Context for Sample Collection: Planetary geologic maps define the spatial context for missions involving sample collection. By documenting the setting and significance of sample locations, these maps contribute to the long-term study of collected samples, which may span many years and yield valuable scientific insights, particularly as analytical technologies for acquired samples are developed and refined. For instance, geologic mapping plays a pivotal role in guiding the sampling strategy of the Perseverance rover on Mars, ensuring that samples have been collected from diverse and scientifically significant geologic units, thus maximizing the rover's scientific return on investment (Simon et al., 2023; Sun et al., 2023).

Communication Tool for Public Engagement: Beyond mission logistics, planetary geologic maps serve as effective tools for scientists to communicate the value of space exploration to the general public. Whether illustrating the exploratory path of a Mars rover or detailing in situ resources on the lunar south pole, these maps offer a visual representation of spatial data, which helps foster communication with audiences of all ages. Web-based interactive maps further enhance accessibility, allowing the public to explore planetary surfaces and missions in an engaging and educational manner, promoting a deeper understanding of the Solar System's geological diversity and the importance of scientific exploration.

5. Planetary Geologic Mapping Community Call to Action

Anticipating significant scientific breakthroughs achievable with the help of planetary geologic mapping in the forthcoming decades and recognizing the essential role of such map products in supporting mission objectives, we collectively urge collaboration within the international scientific community toward shared planetary geologic mapping goals. The development of new AI-based techniques for automatic feature extraction and data classification will only amplify the scientific and operational impacts of mapping. We advocate for a global acknowledgment of the dual benefits: planetary geologic mapping not only propels scientific advancement but also mitigates inherent risks associated with space exploration. To foster this collaborative spirit, we encourage participating countries and the scientific community at large to: (a) sustain efforts in providing necessary education, training, professional development, and career opportunities for the next generation of planetary geologic mappers; (b) emphasize the scientific value derived from planetary geologic maps throughout all mission phases; (c) actively pursue and publish robust science traceability matrices that link mission science to planetary geologic maps; and (d) leverage these maps to effectively communicate the profound importance of space exploration to humanity. One ongoing instance of such a collective endeavor, with a particular emphasis on student education, is exemplified by the International Venus Research Group (IVRG). This group is engaged in meticulous mapping of over 40 regions on Venus, utilizing radar data obtained from the Magellan mission (Ernst et al., 2022; Head et al., 2024).

As upcoming missions unfold, we also anticipate that innovative approaches will enable the planetary science community to make greater and more efficient strides in mission-supportive geologic mapping. Firstly, we advocate for the sharing of mission data and resultant maps through findable, accessible, interoperable, and reusable (FAIR) data platforms (e.g., van Gasselt & Naß, 2024). This ensures that map-based scientific insights can be leveraged across numerous countries and scientific agencies, fostering a diverse array of perspectives on geologic problems and planetary phenomena. Secondly, we emphasize the immense value of standardized planetary geologic mapping and encourage international collaboration towards establishing cartographic standards for the full range of terrestrial planets, moons, and small bodies, emphasizing use of those standards across multiple spatial scales. We suggest aligning these standards with terrestrial approaches where practical, while also acknowledging the necessity for more novel methods in cases where no terrestrial equivalent exists. Thirdly, we urge strengthened efforts by the International Astronomical Union (IAU) to promote diverse nomenclature, and by our community when proposing names with IAU rules. These efforts aim to ensure that names on other bodies in the Solar System reflect the diversity of nations, languages, cultures, and people on Earth. Finally, we wholeheartedly support ongoing international collaboration in space exploration and within the planetary mapping community. Through our collective efforts, we aim to utilize maps to advance our understanding of the Solar System and inspire the pursuit of knowledge beyond our planet.

Artificial Intelligence Transparency Statement

To improve the grammar and clarity of this commentary, an early full draft authored by JWL was fed through ChatGPT artificial intelligence for editorial feedback. All subsequent versions were manually edited by the authors.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

No data were used or generated as part of this commentary.

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Erratum

The originally published version of this article contained an error in the affiliation for coauthor Alessandro Frigeri. The affiliation has been corrected as follows: Italian National Institute for Astrophysics (INAF), Rome, Italy. This may be considered the authoritative version of record.