NASA Conference Publication 3005

Planetary Geology: Goals, Future Directions, and Recommendations

Proceedings of a workshop held at
Arizona State University
Tempe, Arizona
January 1987

NASA

NASA Conference Publication 3005

Planetary Geology: Goals, Future Directions, and Recommendations

NASA Office of Space Science and Applications
Washington, D.C.

Proceedings of a workshop held at
Arizona State University
Tempe, Arizona
January 1987

National Aeronautics
and Space Administration

**Scientific and Technical
Information Division**

1988

Preface

This report gives results of a workshop on planetary geology held in January, 1987, at Arizona State University at the request of Dr. David Scott, Discipline Scientist, Planetary Geology and Geophysics, NASA. In addition to reviews by the workshop members, it was reviewed by the Planetary Geology and Geophysics Working Group and incorporated comments from Dr. James Underwood, current Discipline Scientist for the program.

R. Greeley, January 1988

TABLE OF CONTENTS

1. EXECUTIVE SUMMARY

The last quarter century has seen two revolutions in the Earth sciences that have radically altered our perception of planets and how they evolve. The theory of *plate tectonics* came from the realization that much of the geologic history of the Earth is not characterized by isolated, unrelated events. Rather, it is a record of the movement and interaction of a few, large "plates" riding a conveyor of recycling crust and upper mantle. The second revolution began with information returned from spacecraft sent throughout the Solar System. Planets and satellites are now recognized as bodies with surfaces amenable to geological analysis and interpretation. As a result, the study of planetary surface features and geologic processes is no longer constrained by knowledge gained from Earth; rather, it now embraces the entire family of planets, of which the Earth is but one member.

Planetary exploration has provided a torrent of discoveries and a recognition that planets are not inert objects but that each has evolved along a distinctively different path. This expanded view has led to the notion of *comparative planetology,* in which the differences and similarities among planetary objects are assessed in terms of the interplay of processes that have been involved in their evolution. Solar System exploration is now undergoing a change from an era of reconnaissance to one of intensive exploration and focused study. Analyses of planetary surfaces are playing a key role in this transition, especially as attention is focused on such exploration goals as returned samples from Mars. In order to assess how the science of planetary geology can best contribute to the goals of Solar System exploration through the 1990s, a workshop was held at Arizona State University in early 1987. This workshop was charged with the objective of assessing the current research directions in the Planetary Geology community and recommending to NASA Headquarters a series of goals to maintain the vigor and scientific value of this research. During an intensive three-day period, participants (Table 1) discussed previous accomplishments of the planetary geology program, assessed the current studies in planetary geology, and considered the requirements to meet near-term and long-term exploration goals.

The conclusions from the workshop and recommendations to NASA administrators focus on three areas:

1. The study of planetary geology is now a well-established discipline. Research in this field is naturally evolving from the descriptive phase to quantitative, process-oriented topics. However, traditional studies, such as geological mapping, will continue to be required. A wide variety of research problems can be identified and should be supported, including those that can be studied by single investigators, by teams of investigators, and those involving study projects, all of which can be pursued with existing data.
2. Digital data and the hardware and software needed for the efficient analysis of these data must be made widely available to the community to capitalize on the vast amount of information contained in the digital data returned from planetary missions. Rapidly-advancing technology

in digital data storage and processing, coupled with reduced hardware costs, make the achievement of this recommendation possible.

3. The NASA Planetary Geology Program must support research on ways to extract the maximum information from new and improved sensors to be flown on forthcoming missions, such as Mars Observer. The full utilization of the data requires background work in laboratory and field studies.

Table 1. PLANETARY GEOLOGY WORKSHOP PARTICIPANTS

Ronald Greeley, Chairman	*Arizona State University*
Joseph Boyce, Ex Officio	*NASA Headquarters*
James Underwood, Ex Officio	*NASA Headquarters*
Raymond Arvidson	*Washington University*
Victor Baker	*University of Arizona*
Michael Carr	*U.S.G.S./Menlo Park*
Philip Christensen	*Arizona State University*
René DeHon	*Northeast Louisiana Univ.*
Michael Malin	*Arizona State University*
Dennis Matson	*Jet Propulsion Laboratory*
George McGill	*University of Massachusetts*
Peter Mouginis-Mark	*University of Hawaii*
David Pieri	*Jet Propulsion Laboratory*
David Scott	*NASA Headquarters*
Larry Soderblom	*U.S.G.S./Flagstaff*
Paul Spudis	*U.S.G.S./Flagstaff*
Steven Squyres	*Cornell University*
Robert Strom	*University of Arizona*
Graduate Assistants	
David Crown	*Arizona State University*
Robert Pappalardo	*Arizona State University*

2. INTRODUCTION

Planetary Geology--the study of the solid bodies of the Solar System--is essential for meeting the goals of Solar System exploration. The Planetary Geology Program and the general approach in assessing the geology of Solar System objects are presented in a series of documents: ***A Strategy for the Geologic Exploration of the Planets*** (Carr, 1970), ***A Geological Basis for the Exploration of the Planets*** (Greeley and Carr, 1976), and ***Planetary Geology in the 1980s*** (Veverka, 1985). As specified by the National Academy of Sciences (NAS, 1978, 1980, 1986) and amplified by the Solar System Exploration Committee (SSEC, 1983, 1986), exploration goals include:

- determining the origin, evolution, and present state of the Solar System;
- understanding the Earth through comparative planetary studies;
- understanding the relationship between the chemical and physical evolution of the Solar System and the appearance and evolution of life; and
- surveying the resources available from near-Earth space.

Planetary geology, especially the study of planetary surfaces, plays a key role in meeting these goals. During the quarter century between the first flyby of Venus by Mariner 2 in 1962 and the Voyager encounter with Uranus in 1986, space exploration has proceeded at an exhilarating pace. Planetary geology has provided fascinating insights into the character and history of the surprisingly diverse solid objects of the Solar System. Many exciting discoveries have been made and many age-old, fundamental questions have been answered. At the same time, many equally fundamental--but more sophisticated--questions have emerged.

Some examples of key insights provided by the study of planetary surfaces are:

- Impact cratering played a major role in the early history of the Solar System, including that of the Earth.
- Most planetary bodies show complex geologic histories that can be reconstructed from the record preserved on their surfaces.
- Planetary bodies have followed widely diverse evolutionary paths depending on their composition, size, position in the Solar System, relation to nearby objects, and other factors.
- Volcanism has been surprisingly pervasive. Almost all bodies have been volcanically active, although the style and extent of volcanism has varied greatly in response to the particular conditions on the planets.
- Many planets and satellites have been tectonically active via styles reflecting the unique lithospheric properties and deformational histories of each body.
- Mars has had drastically different climates in the past; substantial water was present on or near its surface.

These and other results are fundamental contributions in meeting the goals of Solar System exploration. Contributions of equal importance may be expected with application of new analytical techniques to existing data and the acquisition of new data from future planetary missions and Earth-based measurements.

The principal objectives of this report are to provide to NASA management an overview of the evolving challenges and opportunities that are afforded through the study of planetary surfaces and to formulate recommendations that will enable planetary geology to continue to make major contributions to Solar System exploration. A further objective is to provide investigators in the community with a statement of the potential research directions that they may wish to pursue through NASA's Planetary Geology Program. The main conclusions of the workshop are presented in Section 3, and the specific recommendations to NASA that were formulated as actions to respond to these conclusions are given in Section 4.

3. WORKSHOP CONCLUSIONS

Workshop discussions focused on the current studies in planetary geology, the potential areas for scientific development, and the requirements to meet the goals of future planetary missions. Results from these discussions can be summarized in three principal conclusions:

3.1 *The study of planetary geology is in transition from the description of landforms and surface materials to process-oriented, physically-based studies of surface features and their relation to planetary interiors.*

This transition phase is very similar to the changes that occurred in terrestrial geology earlier this century. In its early phase, geology was mostly a descriptive science and the emphasis was on the geological survey of the Earth. This involved mapping features and materials exposed on Earth's surface. In most regions, as reconnaissance mapping neared completion, the emphasis shifted to studies that often required a more quantitative, process-oriented approach. This transition was aided by advances in instrumentation, the ability to obtain radiogenic ages of rocks, and the development of theories such as plate tectonics.

In a similar sequence, the reconnaissance of the solid bodies of the Solar System will be nearly completed by the early 1990s. From this reconnaissance, the basic framework for the characterization of most planet and satellite surfaces will be established, although coverage of some objects, such as Mercury, will remain incomplete. The next phase of planetary exploration will involve obtaining global remote-sensing data to characterize surface chemistry, mineralogy, and physical properties, in addition to topography, gravity, and magnetic fields. The combination of image and non-image global data sets with results from studies of surface processes will allow more ambitious and detailed geologic investigations to be planned and executed, particularly in anticipation of data from the Magellan, Mars Observer, and Galileo missions.

3.2 *Quantitative techniques can be applied to existing digital data to extract new and important scientific information. A major problem within the planetary geology community is the lack of access to digital planetary data and the tools necessary to analyze these data.*

Advances in computer technology permit the application of new analytical techniques to existing digital data, and the results can be used to evaluate new models of planetary processes and surface evolution. For example, topographic data for the martian surface (as well as information on its physical and chemical properties) can now be extracted from calibrated Viking Orbiter imaging data. Topographic data are especially critical in testing models important in planetary surface evolution, such as channel formation. Knowledge of gradients enable assessment of fluid flow rates, erosive power, and potential depositional sites.

Topography can be derived photogrammetrically from stereoscopic images or--under some conditions--by using photoclinometric techniques on monoscopic images that have been calibrated.

Only recently have such calibrations been derived. As more calibrated data become available, the derivation of topography can be applied to a wide range of problems dealing with planetary surface processes, including not only channel formation, but also studies of the emplacement of lava flows and other processes. Moreover, topographic data are required for gravity analysis of spacecraft perturbations that yield information on the interior, such as lithospheric thickness.

However, the primary impediment to the full use of existing digital data and to the transition to process-oriented studies is the lack of ready access to the digital data. This impediment, which has generated a "data-starved" community, must be removed as quickly as possible. In order to capitalize on new opportunities using existing and future data, NASA should proceed as rapidly as possible to ensure that all planetary geology investigators have ready access to the full digital planetary data set, together with the hardware and software necessary to use it.

3.3 *New sensors planned for future missions require laboratory studies and fieldwork for data interpretation.*

Planetary missions planned for the 1990s include Mars Observer, Magellan, and Galileo, and possibly the Comet Rendezvous/Asteroid Flyby (CRAF) and the Lunar Geoscience Observer. Mars Observer will acquire information on the mineralogy, chemistry, and physical properties of the martian surface. The Magellan mission will obtain high-resolution radar images and altimetry data for most of the surface of Venus. Together with other mission objectives, Galileo will acquire images and spectral data for the surfaces of the Jovian satellites. CRAF could return the first detailed information on the morphology and composition of a cometary nucleus and asteroid surface.

Data from these missions will advance the understanding of the origin and evolution of planetary surfaces and interiors. However, NASA must recognize that the complexity and volume of new data will also require planetary scientists to learn how to manipulate large data sets and how to extract information on physical, chemical, and mineralogical characteristics. Some of the sensors to be flown are radically different from instruments previously carried to the planets and will provide data that may be unfamiliar to many planetary geologists.

Several activities must be advanced by NASA in order to help the community become familiar with the technologies and types of data produced. Earth-based spectroscopic and radar data, use of calibrated Viking and Voyager multispectral images, and use of imaging spectrometer and radar data for terrestrial analog sites all should be used to test planetary models. The thrust of analog studies should be to acquire advanced remote sensing data so as to understand how to process the data and how to extract the maximum information, a use that is particularly crucial, in as much as the sites can be checked independently to calibrate how well the information extraction was done.

4. SPECIFIC RECOMMENDATIONS

The conclusions reached by the workshop have led to the formulation of three specific recommendations for NASA management (Table 2).

4.1 *Recommendation: Continuing support must be given to conduct research on existing data; the focus should be on applying new, quantitative techniques.*

The Solar System exploration program has produced an enormous quantity of exciting data for research on planetary surfaces. Much of the first-order descriptive work based on these data has been completed. The next step is to apply more physically-based, quantitative techniques to the data in order to extract information not otherwise available. Laboratory and theoretical work based on fundamental physics and chemistry should be supported in order to provide new information on planetary processes. In addition, topics considered to be "qualitative" remain important for

Table 2. RECOMMENDATIONS OF THE PLANETARY GEOLOGY WORKSHOP

Continuing support must be given to conduct research on existing data; the focus should be on applying new, quantitative techniques.

Research is naturally evolving from the descriptive phase to quantitative, process-oriented topics. However, traditional geological studies, such as mapping, will continue to be required. A wide variety of research problems can be identified, including those that can be studied by single investigators, teams of investigators, and those involving study projects.

Digital data and the hardware and software needed for analysis must be made widely available to the community.

In order to carry out research on planetary surfaces, investigators must have access to digital data-processing capabilities. Rapidly-advancing technology in digital data storage/processing and reduced hardware costs permit this recommendation to be achieved.

Research must be supported to enable extraction of the maximum information from new sensors to be flown on forthcoming missions.

Many new and improved instruments will be placed on future missions such as Mars Observer. The full utilization of the data requires background work through laboratory and field studies.

understanding the evolution of planetary surfaces. For example, we recommend to NASA that geologic mapping should be an ongoing effort within the Planetary Geology Program. Finally, field analog studies should be encouraged in order to provide insight into complex geological processes that cannot be fully simulated in the laboratory nor obtained through computer modelling. These field analog studies must continue to be an important part of the overall research program.

In the following sections, three examples are presented of the types of research that NASA should support that can be conducted using existing planetary data. The examples represent three modes of investigation: (a) research involving one or two investigators, (b) research requiring a team approach, and (c) a study-project approach. All three examples demonstrate research that requires a quantitative approach to the study of planetary surfaces. They should not be construed as the highest priority scientific goals for the program but are given as typical examples.

4.1.1 Evaluation of degradation processes on the terrestrial planets and their relationship to climate (single investigator or small-team topic):

Planets with dynamic atmospheres display landscapes formed by processes that reflect the interaction of the atmosphere and the surface. In some cases, the surface features provide clues to possible changes in the climate. Mars and possibly Venus, like Earth, have experienced prolonged degradational histories under the influence of processes such as wind and water erosion. Detailed topographic information can be used to determine the volumes, rates, and energy gradients associated with planetary degradation. Studies involving laboratory investigations, terrestrial field work, and numerical modelling should also be used to constrain the hypotheses concerning the erosion, transportation, and deposition of surface materials on these planets. For Mars, multispectral images and other remote sensing data such as infrared thermal mapping measurements should be used to identify sources and depositional sites of materials and to establish a more accurate history of the movement of materials.

As an example, Mars displays a wide variety of surface features indicative of running water and mass wasting. Determining the precise style of formation (e.g., fluvial erosion, sapping, glacial), the amounts of water involved in their formation, and the relative timing of formation are all tractable geological problems that could constrain various models of the evolution of the martian atmosphere and climate.

4.1.2 Use of impact craters as probes of planetary crusts (consortium or team topic):

Determining the origin and geologic evolution of planetary crusts is one of the fundamental goals of Planetary Geology. One approach to the problem is through the use of large impact craters and basins as natural "drill holes" into planetary crusts. This technique requires understanding the processes of large crater and basin formation, including the shapes and dimensions of excavation cavities (so that excavated volumes and depths can be assessed), the mechanics of ejecta transport (to determine the provenance of ejecta), and the degree of mixing of primary ejecta with local material (to isolate components derived from depth from those of the local surface). Remote sensing data on the mineralogy and geochemistry for the crater or basin primary ejecta can then provide the compositional details of crustal structure and composition.

Lunar remote sensing data, together with results from studies of Apollo and Luna samples, provide an important means to test this concept. Research is needed to provide a better understanding of the mechanics of large impact events, and to determine the composition of ejecta deposits from existing remote sensing data. If the general concept of using large impacts as probes of the crust is demonstrated for the Moon, it could then be applied to other planets. The approach to this topic requires a team effort involving specialists in impact cratering mechanics, geophysics, lunar sample analyses, and geochemical remote sensing, as well as the study of surface features and geological mapping.

4.1.3 The early history of the terrestrial planets--a possible study-project:

Some research problems are so broad and complex that they are best approached as study projects. Study projects involve a coordinated multi-disciplinary approach that is more likely to lead to breakthroughs than a less-focused program in which individuals are working completely independently. In addition, projects provide the rationale for bringing together scientists working on different problems, thereby providing cross-correlations and stimuli to the whole team. One example of the coordinated approach was the highly successful MECA (Mars: Evolution of its Climate and Atmosphere) program. Under the auspices of this program, workshops were organized on various themes related to the central goal of understanding the climate history of Mars. The workshops included scientists from different disciplines (geology, meteorology, chemistry), each working on a different aspect of the problem. The result was a major revision of the understanding of martian climatic history.

The early history of the terrestrial planets could be approached in a similar manner. The era between 4.5 and 3.8 billion years ago was a critical stage in the evolution of the Moon and perhaps most terrestrial planets. By the end of heavy bombardment, the character of each of the planets appears to have been established. During this early era, global differentiation into crust, mantle, and core apparently occurred; outgassing had largely been accomplished. The climatic regimes on the planets may have been essentially established by about 3.8 by ago, and on at least one planet, life had begun.

Yet, very little is known about this early stage in the evolution of the planets. There are various approaches that a team of investigators could use for achieving a better understanding:

- by forward extrapolation from studies of meteorites and modelling of planet formation;

- by backward extrapolation from the state of a given planet around 3.8 billion years ago, after which the geologic record of a planet is preserved; and
- from theoretical modelling, to include the thermal history of the interior, the effects of large impacts, geochemical evolution, and other processes and events.

As a recommendation from this workshop to NASA, such a study project could include a variety of topics directly relevant to understanding this early era. These include:

- derivation of the cratering history of the inner Solar System;
- stratigraphic studies aimed at understanding the sequence of events on different planets immediately after the period of heavy bombardment;
- geomorphic studies aimed at better understanding of climatic conditions and volatile inventories at this time;
- theoretical investigations on the thermal state of each of the planets at the close of heavy bombardment, including estimations of lithospheric thickness;
- geochemical studies--particularly on the Moon--aimed at reconstructing events during heavy bombardment;
- theoretical analyses on the effects of large impacts on planets with and without atmospheres;
- studies of the role of large impacts in the evolution of planetary surfaces.

A research focus on the early histories of the planets could stimulate interaction among individuals working in these different areas and so lead to breakthroughs in the understanding of the evolution of the terrestrial planets.

4.2 *Recommendation: Digital data and the means to analyze such data must be made widely available to the community.*

The rapid evolution of computers, software, and data-handling techniques has led to sophisticated systems that are small and relatively inexpensive. This evolution has brought impressive data-processing capabilities within the reach of individual researchers. Concurrently with this enabling technology, new planetary data were acquired from spacecraft and Earth-based systems, setting the stage for the opportunities that are now presented to the scientific community.

The use of all available data to address scientific questions is recognized as the most efficient and fruitful approach in research. Large data sets--such as those for images--are presently available, together with cost-effective means for data processing. The workshop recommends to NASA that the following be made widely available to the planetary geology community:

- Digital data for all planetary spacecraft images
- Data from selected Earth-based telescopic observations
- Data from spacecraft remote-sensing (non-photographic) instruments

- Training sessions for software use and new processing methods
- Image-processing hardware and software systems

These data sets and processing equipment, and the training to use them, are crucial in order for the community to make the next logical step in planetary geology research. The potential for stimulating and enabling new research is so great that not only are those who are denied this capability at a disadvantage, but the standards of the profession have advanced to the stage in which it is now required.

4.2.1 Distribution of existing planetary data

For the planetary community to conduct new research with existing data, NASA management must make the following digital data sets available to all investigators as soon as possible:

Mars Data Sets: Mariner 9 and Viking (lander and orbiter) images, the Martian Consortium data sets, and other digital cartographic data.

Lunar Data Sets: Multispectral images, topography (from radar interferometry), radar backscatter data, orbital geochemistry (including gamma-ray and X-ray fluorescence data), gravity, and other lunar consortium data, and data from Earth-based observations. Further manipulation and reduction of existing data (e.g., lunar topography), as well as the application of new technologies (e.g., X- and P-band Earth-based radar systems, imaging spectrometers), will lead to additional data sets.

Venus Data Sets: Measurements from Pioneer-Venus (altimetry, line-of-sight gravity, surface roughness, dielectric constant, SAR, and emissivity measurements), Soviet Venera 15/16 SAR and altimetry data, and Venera Lander images; Earth-based radar data (Arecibo and Goldstone backscatter; Goldstone topography) should be included.

Mercury Data Sets: Mariner 10 images and potentially new data from the topographic experiments (Doppler-frequency tracking) conducted at Goldstone and from the scattering-model experiments (continuous-wave) carried out at Arecibo and Goldstone. These observations should be tailored to specific science goals, such as the measurement of equatorial topography and studies of the physical surface properties.

Selected Terrestrial Data: In addition to the planetary data outlined above, the community should be provided with data obtained for the Earth by NASA's Airborne Imaging Spectrometer (AIS), Advanced Visible Infrared Spectrometer (AVIRIS), and the Thermal Infrared Multispectral Scanner (TIMS) instruments. Data from visible/near-IR and thermal IR imaging spectrometers for aeolian, sedimentary, and volcanic terrains would be particularly valuable for comparative studies of planetary surface features. We strongly recommend that the Planetary Program support the acquisition of new data through NASA aircraft deployments for planetary analog studies using these instruments.

Existing digital radar data for terrains on Earth should also be provided to planetary geologists. The ability to interpret the multi-wavelength Venera (C-band) and Magellan (S-band) data will require familiarity with digital radar images. Two orbital radar systems (Seasat and SIR-B) and the NASA Aircraft Radar Program (CV-990 and DC-8 SAR's) have obtained digital radar data. These terrestrial data sets are relevant to the planetary community for studies of viewing geometry, signal processing (number of looks, calibrations of SAR, radar stereogrammetry), and geologic studies of planetary surfaces. In addition, the planetary geology community should acquire aircraft SAR data for terrestrial areas where planetary analog studies are justified.

4.2.2 Establish analysis capability within the community

Computer systems exist or are under development for the analysis of the digital data described above. However, the dissemination of these systems throughout the planetary community must be accelerated. The data sets, hardware, and software will make possible a wide variety of research programs dealing with planetary surfaces. To establish community-wide systems, NASA should:

- Develop and distribute plans for hardware configurations for a range of capabilities (e.g., PC-based to full-scale image processing facilities).
- Develop and distribute lists of software systems that are (or will be) available and supported.
- Encourage investigators to propose for the acquisition of digital data processing systems.

It is essential that NASA and the developers of planetary software have a long-term commitment to support these systems and to provide the necessary information and consultation to assist the general planetary user community.

4.2.3 Implementation

The need for the planetary community to conduct research using digital data is urgent. Consequently, NASA must have a high-priority for the immediate generation and distribution of digital data and a plan to establish digital processing capabilities. This could be achieved as follows:

Year 1

- Begin the production and distribution of CD-ROMs
- Identify hardware and software systems, and inform the planetary community; include a method for assessing the community needs

- Compile a "responses and costs" estimate for NASA planetary program administrators

Year 2

- Complete production and distribution of CD-ROMs for the existing data outlined above
- Begin funding investigators for the acquisition of hardware and software

Year 3

- Complete the funding for purchase of hardware and software

4.3 *Recommendation: Research must be supported to enable the extraction of the maximum information from the new sensors to be flown on forthcoming missions.*

Planetary science is on the threshold of an enormous increase in the amount and diversity of data to be returned by spacecraft. Magellan, Mars Observer, Galileo, and the Voyager Neptune flyby, together with other possible new missions such as the Comet Rendezvous/Asteroid Flyby (CRAF) and the Lunar Geoscience Observer missions, will carry sophisticated instruments designed to make detailed measurements in a variety of modes and formats. It is crucial that NASA enables the planetary community to establish the means for understanding and exploiting the full potential of these new data.

Some of the instruments to be flown will provide data familiar to planetary scientists; others will provide data currently familiar to only a few specialists. Examples of the first type include data from altimeters, magnetometers, and cameras. Although there may be problems related to calibration or data reduction, the final products will be familiar to most investigators and will be immediately usable. On the other hand, instruments such as synthetic-aperture radar systems, gamma-ray spectrometers, thermal-emission spectrometers, and visible/near-infrared mapping spectrometers will yield data that are not widely familiar to planetary photogeologists. Because future missions will provide the opportunity to use such data routinely in the solution of planetary problems, the community must become familiar with the use and limitations of the sensors. More importantly, the community must understand the characteristics of geological materials as observed over a wide range of wavelengths and under diverse observing conditions. Gaining this understanding will provide the foundation for obtaining maximum scientific return from future planetary missions.

Pre-mission field research must be carried out to test the geological interpretations of the data and to provide "ground-truth" for comparison with data returned from other planets. In addition, theoretical modelling and laboratory studies must be conducted to understand the basic physics responsible for the data obtained. In certain cases, support for these activities will require a change responsible for the data obtained. In certain cases, support for these activities will require a change in funding philosophy within NASA, in that a prime objective of an investigation may well become the testing of a new data set or instrument on a well-known geologic target, rather than the current assumption that the geology is of immediate value as a planetary analog. Specific research requirements differ among the data sets and instruments, as summarized below.

4.3.1 Thermal Emission Spectrometer (TES)

The TES instrument to be flown on the Mars Observer mission will enable the mineralogy and petrology of silicates, carbonates, weathering products, and other geologic materials to be determined. TES will measure the thermal-infrared spectrum from 6.25 to 50 μm in 141 separate wavelength bands. Existing data have demonstrated the rich information content of this spectral region. At present, however, no systematic laboratory investigation of candidate martian materials has been performed for the wavelengths in this spectral region. For example, the detailed characterization of the spectral properties of primary mineral and rock compositions, mineral mixtures, coatings, and shock effects--all for a range of particle sizes and degree of bonding--has not been addressed. These studies are essential to the full extraction of compositional information for the martian surface.

There is the potential through laboratory investigations to address many of the key science tasks to be addressed on Mars using TES data. Through terrestrial-analog investigations NASA should promote these efforts and begin with the support of process-oriented models to predict surface development, together with radiative transfer models necessary to predict the energy distribution emitted from complex, natural surfaces. For example, aeolian processes can lead to both mixing and sorting of surface materials. A combination of theoretical mixing models, weathering and transport models, TIMS observations, and field measurements of relevant properties would provide a means for testing mixing models. The demonstrated success of these models will be particularly critical for the identification of active sand surfaces on Mars and to separate bedrock components in the TES spectra from pervasive mantles of windblown dust.

4.3.2 Visual Infrared Mapping Spectrometer (VIMS)

The VIMS instrument on the Mars and potential Lunar Geoscience Observer missions, and similar instruments on Galileo and CRAF, are designed to yield mineral compositions of surface materials by simultaneously measuring radiance spectral bands between about 0.4 and 5.2 μm. Although the primary interest will be the identification of bedrock compositions, most areas observed will yield spectral signatures of mixtures of bedrock and surficial material, so that "unmixing" will be necessary. Two studies are required: 1) determine the extent of mixing on Mars by using calibrated multispectral Viking Orbiter images and extracting the "end-member" compositions using a mixing model; and 2) test the validity of mixing models by applying them to regions on Earth where the true extent and type of mixing can be determined in the field.

4.3.3 Gamma-ray Spectrometer

Gamma-ray spectrometers may be included on several possible planetary missions including the Mars and Lunar Geoscience Observers, and CRAF. Enormous advances have occurred in gamma-ray detector technology since the gamma-ray experiment was flown on Apollo. With the advent of high-purity germanium detectors, an improvement in spectral resolution approaching two orders of magnitude has occurred. This improvement increases the number of gamma-ray lines that can be identified in a planetary spectrum and, hence, the number of elements that can be identified on a planetary surface and the accuracy with which their abundances can be determined. Detector technology has improved to the point that uncertainty in the understanding of the production of a planetary gamma-ray flux is often the limiting factor in the ability to measure elemental abundances on the planets. Work is necessary in two areas to correct this problem within the planetary community. First, experiments must be conducted to determine cross sections for nuclear reactions of geochemical interest. Accurate knowledge of reaction cross sections is necessary for the conversion of measured gamma-ray photon fluxes to elemental abundances. Second, theoretical calculations of the production of gamma rays and neutrons by planetary surface materials must be performed. Particular emphasis should be placed on the roles of volatiles such as H_2O and CO_2, and on the influence of inhomogeneous mixing or layering of materials.

4.3.4 Synthetic-Aperture Radar

Synthetic Aperture Radar (SAR) images are becoming more common in geological studies of the Earth. However, radar images generally have not been used as the sole data source except in a few regions of Earth that are nearly always cloud covered, precluding the use of aerial photographs for geologic reconnaissance. Typically, even in these scattered applications, ground-truth checking has been done in critical areas.

The science objectives of the Magellan mission are to map Venus using a SAR with a resolution sufficient to perform geologic analyses. The rationale for this mission arises from the fact that Venus, more than any other planet, resembles Earth in size and bulk composition and yet the surface cannot be imaged with conventional cameras because of the thick atmosphere. Thus, Venus may be the most important planet for understanding Earth-like planets in general.

Much experience has been gained in the use of planetary images for deducing the nature and evolution of planetary surfaces. The use of radar images for this purpose has been sufficiently demonstrated so that, in principle, the geologic history of Venus can be determined from Magellan data. However, there is a need for the community to improve these interpretive tools and to develop new techniques that are valid when SAR images are the primary data base. The four main areas of research that NASA should promote in support of radar data analysis are as follow:

Radargrammetry. Radargrammetry involves the derivation of positional, topographic, or morphometric information from radar images. Techniques must be developed and tested for extracting such information from single and multiple SAR images. In additional, techniques must be developed for using altimetry profiles in conjunction with SAR images to enhance the geologic interpretation of both data sets.

Relationships between radar backscatter and aerodynamic roughness. This work is under way, but is far from complete. More support should be given to determine the relationship between the surface roughness that establishes equilibrium air flow over surfaces and the roughness sensed by the radar. Use of quad-polarization radar flown on NASA aircraft should be encouraged for planning radar missions beyond Magellan.

Earth analogs. It will be essential to have a comprehensive interpretation key developed from single- and multiple-angle SAR images for typical surface features and geologic relationships such as the superposition of rock units. It is especially important that techniques be derived to infer large-scale stratigraphic relationships from radar data alone. Investigators will require these techniques in order to determine global distributions and relative ages of geologic units and features on Venus, but currently NASA is not supporting this work with the priority that is required.

Earth-based and spacecraft data for Venus. An accessible and documented data base of Earth-based and spacecraft radar data should be established by NASA for the benefit of the entire planetary science community. This data base should include planetary radar data from the Pioneer Radar Mapper, the Venera 15/16 SAR instruments, and the Haystack, Arecibo, and Goldstone stations.

4.3.5 Terrestrial Field Analog and Laboratory Studies

When confronted with extraterrestrial landforms, the new features are typically compared with familiar features on Earth. To the extent that terrestrial analogs reflect processes similar to those on other planets, they can be useful natural laboratories for testing geologic interpretations.

Contrasting planetary environments and histories complicate analog-based studies. Nevertheless, in those places where landform genesis is dominated by a specific process, analogs can be useful for testing the understanding of geologic processes on planetary surfaces. For example, aeolian transport of sediment can be modelled from a purely physical-process standpoint for a range of environmental parameters (e.g., critical threshold velocity vs. atmospheric density), relatively independent of the history of the particles involved. Similarly, the emplacement processes of lava flows are relatively independent of environmental history because the dominating intrinsic parameters (such as eruption temperature or viscosity) are mostly independent of surface conditions. Thus, terrestrial examples of both kinds of activity can be viewed as excellent planetary analogs because they provide succinct tests for the application of process models. Such models must satisfy the terrestrial case as a boundary condition. Likewise, the application of such models to different planetary environments and scales provides the opportunity to test the general integrity of such hypotheses. Thus, well-posed and focused terrestrial analogs can provide convenient tests of the understanding of basic planetary surface processes and provide much of the "ground-truth" needed in support of future missions.

Laboratory work will be needed to provide the physical basis for interpreting not only the planetary data but also the terrestrial analog environments. Frequently, terrestrial spectral and radar data are used qualitatively to map unit colors or textures, rather than to derive precise physical properties such as particle sizes. Because the planetary community must rely solely on remote sensing data for many of its investigations, the need to understand the physical basis for interpreting the data is greater than for the Earth. As a result, laboratory measurements and the associated theoretical modelling must form an integral part of the planetary program.

5. CONCLUDING REMARKS

The NASA Planetary Program should recognize that the funding base for the community must continue to evolve to take maximum advantage of the increasingly sophisticated use of existing and future data sets. Not only must the general level of capability within the community be raised by the provision of digital analysis methods and equipment, but new expertise must be developed by funding studies devoted to the understanding and interpretation of data derived from the latest generation of spacecraft sensors. Of necessity, this preparatory work for the Magellan, Mars Observer, and Galileo missions requires funding Earth-analog and laboratory studies, as well as providing the necessary data sets and laboratory capabilities to planetary scientists.

6. REFERENCES

Carr, M.H., ed., 1970, *A Strategy for the Geological Exploration of the Planets,* U.S. Geol. Survey Circular 640.

Greeley, R. and M.H. Carr, eds., 1976, *A Geological Basis for the Exploration of the Planets,* NASA SP-417, 109 p.

SSEC, 1983, *Planetary Exploration through Year 2000, A core program,* Solar System Exploration Committee of the NASA Advisory Council, Washington, D.C., 167 p.

SSEC, 1986, *Planetary Exploration through Year 2000, An augmented program,* Solar System Exploration Committee of the NASA Advisory Council, Washington, D.C., 239 p.

Strategy for the Exploration of the Inner Planets: 1977-1987, 1978, National Academy of Sciences, Washington, D.C., 97 p.

Strategy for the Exploration of Primitive Solar-System Bodies--Asteroids, Comets, and Meteoroids: 1980-1990, 1980, National Academy of Sciences, Washington, D.C., 83 p.

A Strategy for the Exploration of the Outer Planets: 1986-1996, 1986, National Academy of Sciences, Washington, D.C., 100 p.

Veverka, J., ed., 1985, *Planetary Geology in the 1980s,* NASA SP-467, 187 p.

NASA
National Aeronautics and Space Administration

Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA CP-3005		

4. Title and Subtitle	5. Report Date
Planetary Geology: Goals, Future Directions, and Recommendations	August 1988
	6. Performing Organization Code EL
7. Author(s)	8. Performing Organization Report No.
	10. Work Unit No.
9. Performing Organization Name and Address NASA Office of Space Science and Applications Solar System Exploration Division	11. Contract or Grant No.
	13. Type of Report and Period Covered Conference Publication
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

Planetary exploration has provided a torrent of discoveries and a recognition that planets are not inert objects. This expanded view has led to the notion of comparative planetology, in which the differences and similarities among planetary objects are assessed. Solar system exploration is undergoing a change from an era of reconnaissance to one of intensive exploration and focused study. Analyses of planetary surfaces are playing a key role in this transition, especially as attention is focused on such exploration goals as returned samples from Mars. To assess how the science of planetary geology can best contribute to the goals of solar system exploration, a workshop was held at Arizona State University in January 1987. The participants discussed previous accomplishments of the planetary geology program, assessed the current studies in planetary geology, and considered the requirements to meet near-term and long-term exploration goals.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
solar system exploration planetary geology digital data storage and processing	Unclassified - Unlimited Subject Category 91

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of pages	22. Price
Unclassified	Unclassified	28	A02

National Aeronautics and
Space Administration
Code NTT-4

Washington, D.C.
20546-0001

Official Business
Penalty for Private Use, $300

SPECIAL FOURTH-CLASS RATE
POSTAGE & FEES PAID
NASA
Permit No. G-27

NASA

POSTMASTER: If Undeliverable (Section 158 Postal Manual) Do Not Return