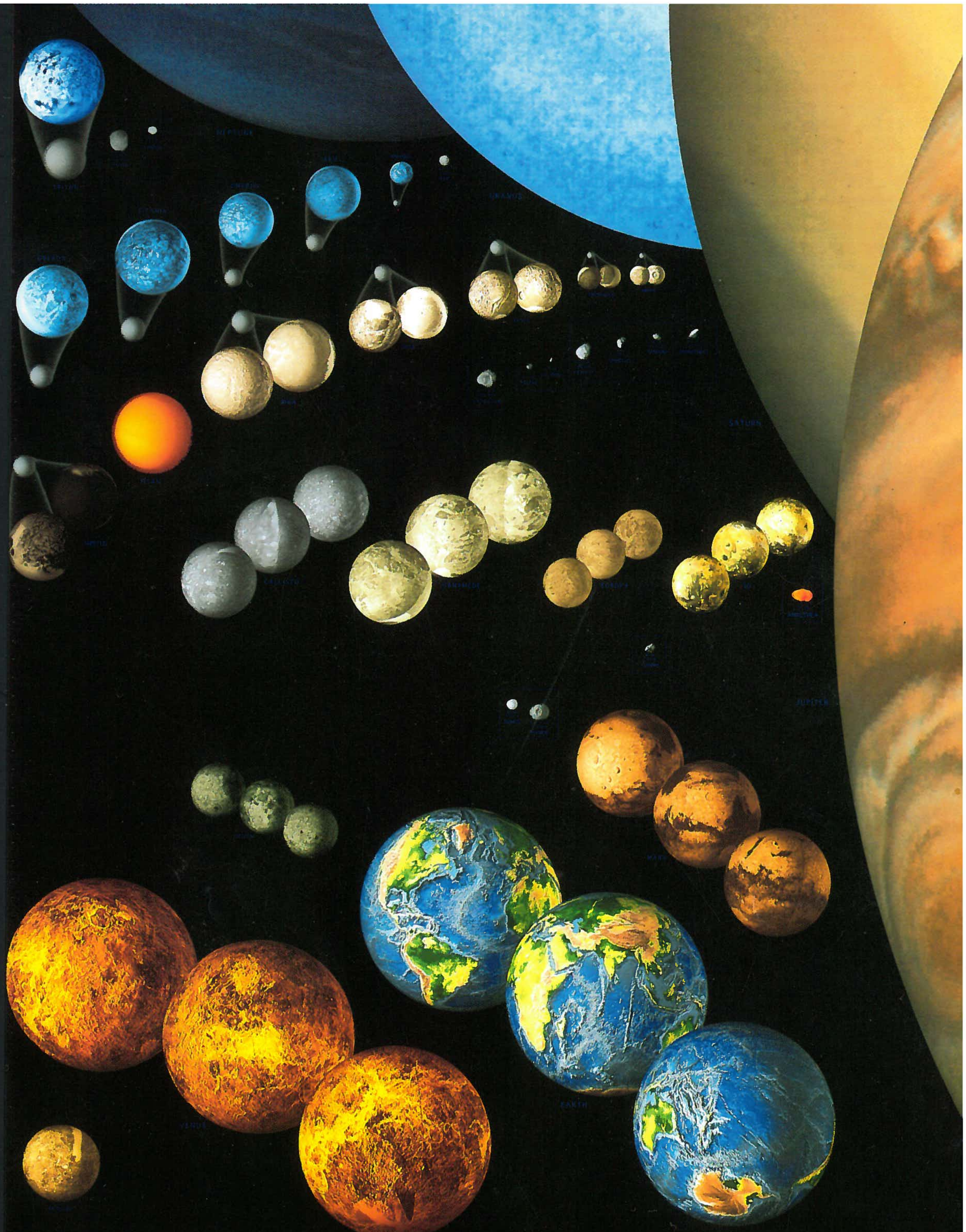


Planetary Cartography 1993–2003

PLANETARY CARTOGRAPHY WORKING GROUP

Planetary Cartography 1993–2003

Planetary Cartography Working Group

Planetary Cartography Working Group
Contributing Authors

James R. Zimbelman, Chair, Smithsonian Institution

Raymond Batson, U.S. Geological Survey

William V. Boynton, University of Arizona

William Cannell, Environment Research Institute of Michigan

Merton E. Davies, RAND Corporation

Frederick J. Doyle, Environmental Research Institute of Michigan

Daniel M. Janes, Cornell University

Baerbel Lucchitta, U.S. Geological Survey

Harold Masursky, U.S. Geological Survey

Peter J. Mouginis-Mark, Hawaii Institute of Geophysics

R. Stephen Saunders, Jet Propulsion Laboratory

Paul Schenk, Lunar and Planetary Institute

Peter C. Thomas, Cornell University

Steven H. Williams, Lunar and Planetary Institute

Sherman Wu, U.S. Geological Survey

Joseph Boyce, NASA Headquarters

Stephen Baloga, NASA Headquarters

TABLE OF CONTENTS

List of Acronyms .... **vii**

Introduction: Planetary Cartography Working Group **1**
Geometrical Basis for Planetary Cartography 2
Digital Cartography 4
New Planetary Mapping 4
Content of this Report 5

Part 1 Executive Summary **7**
General Recommendations 9
Recommended Map Products 9
Planetary Atlases 9
New Missions and Changing Circumstances 9

Part 2 Uses of Planetary Cartography **11**
Science Data Analysis 11
Indexing 12
Mission Planning 13
Education 14
Regional Planetary Image Facilities 15

Part 3 Planetary Cartography Acquisition Systems, Methods, and Products **17**
Introduction 17
Acquisition Systems 17
Magellan 18
Mars '94 18
Mars Observer 19
Galileo 19
Clementine 20
Scout 20
Artemis 20
Mars Environmental Survey (MESUR) 20
Near Earth Asteroid Rendezvous (NEAR) 21
Map Projections 21
Digital Data Systems 22
Cartographic Products 23
Corrected and Rectified Images 23
Uncontrolled Mosaics 24
Controlled Mosaics 25
Topographic Contour Maps 25
Orthoimage Maps 26
Shaded Relief Image Maps 26
Derived Cartographic Products 27
Perspective Views 27

Synthetic Stereoscopic Images ... 27
Planetary Lander Images ... 27
Thematic Maps ... 28

Part 4 Cartographic Database ... 29
Moon ... 29
Mercury ... 30
Venus ... 30
Mars ... 30
Galilean Satellites ... 30
Saturnian Satellites ... 31
Uranian Satellites ... 31
Neptunian Satellites ... 31
Asteroids ... 31

Part 5 Current Status of Planetary Cartography ... 33
Control Networks ... 33
Map Types ... 34
Published Planet and Satellite Maps ... 34
Accuracy and Quality of Maps ... 34
Planetary and Satellite Atlases ... 35
Mercury ... 35
Moon ... 35
Mar ... 35
Saturn ... 36
Uranus ... 36

Part 6 Planetary Cartography Ten-Year Plan ... 41
General Recommendations ... 41
Recommended Map Products ... 42
Scientific Rationales for Cartographic Products from Existing Data ... 42
Venus (Magellan, Arecibo, and Venera 15/16 Data) ... 46
Mars (Earth-based Radar and Viking Data) ... 46
Moon (Galileo, Digitized Lunar Orbiter, and Earth-based Data) ... 47
Galilean Satellites (Voyager 1 and 2 Data) ... 47
Scientific Rationales for Cartographic Products Using Data from Future Missions ... 47
Mars (Mars Observer and Mars '94 Data) ... 47
Galilean Satellites (Galileo) ... 48
Small Bodies (Galileo, NEAR) ... 48
Planet and Satellite Atlases ... 48
Estimated Level of Effort ... 49

LIST OF ACRONYMS

CCD	Charge-coupled device
DIM	Digital image model (or map)
DMA	Defense Mapping Agency
DN	Data number or density number
DTM	Digital terrain model (or map)
HRSC	High-Resolution Stereo Camera
LPACC	Lunar Photography and Cartography Committee
LPI	Lunar and Planetary Institute
MDIM	Mosaicked digital image model
MESUR	Mars Environmental Survey
MOC	Mars Observer Camera
MOLA	Mars Observer Laser Altimeter
NEAR	Near Earth Asteroid Rendezvous
NIMS	Near-Infrared Mapping Spectrometer
PCWG	Planetary Cartography Working Group
SAR	Synthetic aperture radar
SSED	Solar System Exploration Division
SSI	Solid-state imaging
USGS	United States Geological Survey
VLBI	Very-long-baseline interferometry
WAOSS	Wide-Angle Optical Stereo System

INTRODUCTION

Planetary Cartography Working Group

Spacecraft of the U.S. and the U.S.S.R. have acquired enormous amounts of images along with geological, geophysical, geochemical, atmospheric, and other types of data about the planets and their satellites. Scientists in these disciplines usually present the results of their investigations on maps showing the distribution and relative locations of features of interest. Earth scientists naturally expect that topographic map series at suitable scales will be readily available for their use. But planetary scientists have often had to prepare their own base maps, with a consequent confusion of scales, reference systems, and standards, so that one scientist's data cannot be easily compared to another's.

In the summer of 1974, faced with the mass of lunar data acquired by the Apollo program and a great number of investigators in various disciplines, the Lunar Programs Office at NASA Headquarters directed the Lunar Science Institute to establish an ad hoc Lunar Photography and Cartography Committee (LPACC). This committee was charged with coordinating requirements for photography and maps, recommending map series and cartographic standards to satisfy these requirements, establishing priorities for map production, monitoring the archiving and distribution of maps and photographs, recommending guidelines for lunar nomenclature, and encouraging international cooperation in lunar mapping.

In May 1977 the name of the committee was changed to Lunar and Planetary Photography and Cartography Committee (LPPACC) with a corresponding increase in the scope of its responsibilities. In May 1979 a new charter was adopted for the Planetary Cartography Working Group (PCWG), under which title the committee has continued to function.

The PCWG is made up of representatives from the Defense Mapping Agency and the U.S. Geological Survey, which perform the actual mapping, and from universities and scientific organizations that use the map products. Ex officio guidance and funding are provided by NASA Headquarters, and administrative support is provided by the Lunar and Planetary Institute. The PCWG submits recommendations to NASA regarding the sensor characteristics and flight operations for planetary exploration missions and proposes time-phased plans for production of cartographic products.

Only major map series or first-order maps needed to characterize the surface physiography of a planet or satellite are considered. Included in this category are maps needed as bases for plotting geologic, geophysical, geochemical, and atmospheric phenomena, and maps needed for planning future planetary missions. All these products are published and are available to the scientific community and the general public. Interpretative maps, such as geologic maps, and special-purpose maps are not within the scope of the PCWG overview.

In 1984, the PCWG prepared NASA Special Publication SP-475, *Planetary Cartography in the Next Decade (1984–1994)*. That document summarized progress to date, established priorities for continued exploitation of available data, and recommended map products from new missions anticipated in the near future. In 1987, Supplement I to this report considered the opportunities and needs made possible by the rapid development of digital mapping technology.

For this report, the PCWG has assessed the cartographic products required to support planetary science and exploration in the next 10 years. Their approach has included solicitation of help from the general planetary science community in identifying priorities for map products required for research projects in a variety of disciplines, with the objective of keeping the number of map products to the minimum that will support the requirements of the entire user community while still exploiting the content of the original data. This goal must be accomplished within the constraints imposed by available resources.

GEOMETRICAL BASIS FOR PLANETARY CARTOGRAPHY

There are several fundamental sources of information from which planetary cartographic products can be developed. The most important data are individual moderate- and high-resolution images of the planetary body acquired from spacecraft in orbit around the body or on flyby trajectories. In addition to portraying the characteristics of the terrain surface from which information on geologic, geophysical, or atmospheric processes can be inferred, the images show the relative spatial location of terrain features within the area covered by the image. However, this information is subject to a large number of distortions caused by the perspective view, departure of the terrain surface from a plane, and geometric conditions of the optical and electronic components of the imaging system. Individual image frames must be connected together to provide a regional or global context. This connection is accomplished by identifying terrain points that are common to several adjacent images and measuring their coordinates within each image. These image coordinates are expressed in a mathematical model of the imaging system that is derived from preflight (or sometimes inflight) calibration of the geometric characteristics of the instrument. A second principal source of information is the location of the spacecraft at the instant the images are acquired. This positional information is expressed in the inertial coordinate system in which the spacecraft is navigated, and is derived by tracking the radio signals transmitted from the spacecraft. Another valuable source of information is the attitude data, which describe the direction the sensor is pointing when the images are acquired. These data can be obtained by stellar tracking, by horizon

sensing, or by inertial or gyro stabilization systems, each of which operates in its own coordinate system. Still another source of information is altimetry, which measures the distance between the spacecraft and the terrain at precise intervals of time. Gravity information is also valuable because it affects the shape of the spacecraft orbit from which sensor positions are derived.

It is the complex job of the planetary cartographer and photogrammetrist to take all these disparate forms of information in different coordinate systems and to meld them into a consistent and uniform cartographic reference system for the planetary body. Before a single map is made, the cartographer derives such fundamental information as the orientation of the body's spin axis in inertial space, its rotation rate, the dimensions of the spheroidal reference surface, the position of the latitude and longitude graticule with respect to recognizable features, and the positions (and in ideal circumstances, the elevations) of a network of identifiable points uniformly distributed over the body's surface. Only after these fundamental parameters have been derived and their accuracy evaluated can the usual cartographic products—regional and global mosaics, shaded relief maps, and topographic contour maps—be compiled.

Unfortunately, planetary cartographic datasets are rarely complete or uniform. Areal coverage of the planetary body is frequently incomplete and may be acquired from several different missions at different orbital altitudes and inclinations. Sensor systems with radically different geometry may be employed, and sensor calibration data may be deficient or absent. Spacecraft tracking and attitude data are frequently inaccurate or inconsistent. The consequence is that the ideal progression of cartographic knowledge from the basic parameters to small- and large-scale detailed maps with appropriate accuracy is rarely possible for the entire planetary body.

The current condition of lunar global mapping illustrates this problem. Medium- or high-resolution images have been acquired for more than 90% of the lunar surface. But these images come from Ranger; Lunar Orbiter wide- and narrow-angle cameras; Apollo Lunar Topographic, Panoramic, and Metric cameras; Soviet Zond cameras; and the Galileo imaging system. Some of these systems have high geometric integrity, while others have none at all. Thus, while relative positional accuracy is about 30 m within the Apollo Metric Camera coverage, positional uncertainties up to 20 km exist over nearly two-thirds of the globe. This will make it difficult to land a spacecraft at a site selected on the basis of the map coordinates of its image, or to target high-resolution image surveys from orbit for landing sites selected from images on a map.

In many regards, current planetary cartography is more a tribute to the skill and ingenuity of cartographers and photogrammetrists than to the quality of the input data. Careful consideration of this problem will be essential to the mission design, choice of sensors, and data-reduction procedures if future planetary exploration is to reach its full potential.

The most important cartographic data are individual moderate- and high-resolution images. Collectively they constitute a regional or global picture of a planet or satellite surface. Although individual images provide important local information on geologic, geophysical, or atmospheric processes, they do not convey a regional or global context into which these processes can be placed. Surface information must therefore be compiled into regional and global controlled photomosaics, shaded relief maps, and topographic contour maps. Only from these cartographic products—combined with other datasets and examined with various techniques—is it possible to achieve a comprehensive view of a planet or satellite and an understanding of its evolution.

DIGITAL CARTOGRAPHY

Digital storage and display of maps is now commonplace and has greatly expanded the uses of cartographic products. This is a natural outgrowth of the way planetary exploration has been conducted: In all but the Apollo missions, image (and other) datasets are transmitted to Earth as analog or digital electronic signals. Conventionally these have been converted to hard copy for use in well-established procedures. However, recent developments in digital image processing techniques now make it possible to apply geometric and radiometric corrections to individual image frames, to mosaic large numbers of frames, to register these to geodetic control, and to print out the resultant image on any selected map projection at scales compatible with the resolution of the original data. Furthermore, it is possible to digitally scan products such as airbrush-shaded relief maps, topographic contour lines, and various thematic extractions to convert them into digital datasets. Compact and relatively inexpensive digital storage media, such as floppy disks and CD-ROMs, and readily available software make it possible for scientists to analyze these data on machines as small as desktop personal computers. Various datasets can be overlaid, and illumination direction and elevation can be varied, different colors selected, and perspective views prepared. When the scientist is satisfied with the product, the data are transferred to a digital printer to produce a hard-copy output. While general-purpose printed maps will always be required, digital cartographic products will be increasingly in demand.

NEW PLANETARY MAPPING

The total mappable surface area of solid surfaces of planets and satellites in the solar system is approximately 1.6×10^9 km. This area is distributed as shown in Fig. 1. During the past 30 years, an enormous amount of information on these surfaces has been acquired by various space missions. Much of the data has already been transformed into useful map products, and current mapping activities will exploit the remaining records from concluded missions. However, over the next 10 years there will be several new missions, as shown in Table 1 and discussed in the 1991 Strategic Plan of NASA's Solar System Exploration Division. Data from these missions will provide the basis for planetary cartography in the near future.

TABLE 1. Current and planned planetary missions returning mapping data from the present through the year 2003.

Planet/Satellite	Mission	Data Return	Expected Data
Venus	Magellan	1990–1994	High-resolution radar images, altimetry, gravity
Moon	Galileo	1991–1992	Spectral maps, stereo images
Moon	Clementine	1994	Medium-resolution multispectral surveys
Moon	Scout	1996–1998	High-resolution geochemical and photogrammetric surveys
Moon	Artemis	1999–2000	Benchmarks for geodetic control
Mars	Mars Observer	1997?–	High-resolution images, laser altimetry, elemental, mineralogic
Mars	Mars '94/'96	1996–1998	High-resolution photogrammetric images
Mars	MESUR, MESUR Pathfinder	1998–2004	Geochemical, geophysical surveys; benchmarks for geodetic control
Asteroids	Galileo	1991–1993	Images; multispectral data
Asteroids	NEAR	1998–	Imaging, radiometry, geochemical
Jupiter System	Galileo	1995–1997	Images of satellites; multispectral data

CONTENT OF THIS REPORT

This report has six parts. Part 1 is an executive summary of the entire document. Part 2 reviews the requirements to be met by planetary cartography, and Part 3 covers relevant cartographic methods and the planetary missions that will provide the data. The basic data used in planetary mapping are presented in Part 4, and the current status of planetary mapping is given in Part 5. Recommendations are detailed in Part 6; however, because mission plans can change drastically over a decade, the exact recommendations may be updated as the situation warrants.

PART 1

Executive Summary

Spacecraft exploration of the solar system has transformed our view of planets and satellites from distant blurred disks to an amazingly diverse collection of worlds with individual characteristics that impress scientists and laypeople alike. Cartography is the first and most fundamental way of documenting and classifying these worlds. In the last 25 years the techniques of remote cartography have developed alongside the progressively more ambitious spacecraft missions. There are significant mapping data for over 20 planets and satellites.

The ultimate goal of planetary mapping is to provide complete frames of reference for any study or illustration of planetary objects in a manner that is straightforward to use and accurate in its results. While this will never be achieved for all solar system objects, it is important to keep this goal in mind when setting priorities and designing programs. There is little point in generating high-resolution special-use maps for part of a planet if the global data have not been incorporated into useful global maps. There is also little use in going through the exercise of making maps if the products are not available, cannot be found, or are difficult to use. The requirements for a good mapping program are data that are as uniform and accurate as possible, and resources sufficient to produce products to support data analysis projects.

Orbital mapping in the 1960s concentrated on the Moon, and in the 1970s focused on Mars. The 1990s will include intensive orbital mapping of Venus, Mars, outer planet satellites, and possibly the Moon and an asteroid. The Strategic Plan of the Solar System Exploration Division also describes Discovery-class missions for the near future that could also return important cartographic data of diverse objects. Missions such as Magellan and Mars Observer were specifically designed as mapping missions. The amounts of data from these missions, and the applicable techniques and kinds of studies, will be unprecedented. The cartographic and scientific opportunities are far greater than the resources, either financial or human, can handle. For this reason the cartographic efforts need to be organized for the maximum return to the scientific and technical communities as well as the most effective source of public information.

The Planetary Cartography Working Group (PCWG), which is made up of representatives of many different fields and institutions, is charged with advising

NASA of the best cartographic opportunities and methods. Recommendations are made in both long-term general planning reports, such as this one, and reports on specific issues. This report covers the period 1993–2003. The previous report covered 1984–1994; the overlap in periods is the normal consequence of specific programs not being fully predictable for a 10-year period, even though the general opportunities are well defined. This report covers the transition from flyby missions to detailed orbital mapping missions that generate vastly different datasets with significant consequences for mapping and scientific investigations.

The diverse but fundamental uses of planetary cartographic data are discussed in Part 2. Besides being at the heart of any scientific study of a planet's surface (or interior), cartographic data are the key to indexing all kinds of surface data on planets and satellites. This activity is absolutely vital to any study of the planets given the number and complexity of different datasets. Planning future missions likewise has been highly dependent upon cartographic products since precursor missions to the Moon in the 1960s. The safety of unmanned and manned landers depends on advance knowledge of surface topography and absolute coordinates, and this information is developed only by progressive improvements in cartography of the target surfaces. Cartographic products are also vital in education, both for presentations to the general public and in schools and university courses. This wide variety of important uses of cartographic products means that the choices of products to be made are important to many organizations and programs.

Parts 3 and 4 describe the cartographic methods, spacecraft missions, and data that have and will provide information on planetary surfaces. The actual status of what products have been generated is discussed in Part 5. These three parts show the status of planetary mapping and what tools are required to continue the program and to allow it to evolve.

The final part is a set of recommendations for planetary cartography from 1993–2003. These recommendations are the result of considerable discussion of the needs and uses of cartography and the data that will most likely be available. Examples of the scientific needs for the various products are given, and the approximate volume of products is given in Tables 10 and 11.

Two fundamental themes pervade this report: the need for many digital products and the large amount of data that will be generated in the next few years. Analysis of all kinds of planetary data is becoming dependent upon digital storage, display, correlation, and calculation. The need to record coordinates of features from image displays requires that many different map products be in digital form so they can be used with other data and with current analysis techniques. This development is closely related to the volume of planetary data expected; Magellan data alone have a volume exceeding that of all previous planetary digital images combined. As other missions take advantage of mapping opportunities and onboard data compression, the volume of data returned will become very large and will require careful organization to keep the information fully useful to the community.

Before the end of the decade there will probably be a resumption of lunar exploration providing cartographic data before the end of the decade, but the specific mission designs, timetables, and approval are not yet secure. Although these lunar missions are not included in the specific tables of this report, the data acquired will be very important and will require resources to convert it into useful cartographic products.

GENERAL RECOMMENDATIONS

- The following are the general recommendations for the priorities of planetary cartography:
- From 1993 to 1995 the mapping of Venus with Magellan radar data is to be given the highest priority.
- From 1994 to 1996 mapping of inner solar system objects will have highest priority.
- From 1996 to 2000 Galilean satellite mapping and Mars mission data will have the highest priority.
- From approximately 1994 to 2003 significant lunar and small-body mapping will be possible. Cartographic data should be key objectives of forthcoming lunar and asteroidal missions.

RECOMMENDED MAP PRODUCTS

Recommended map products are given in Tables 8 and 9 in Part 6.

All products are recommended for release in both paper and digital form. The working group emphasizes the need for *both* kinds of products in order to assure full utilization of the data for overview, instruction, and scientific research.

As shown in Part 6, many different scales and areas of coverage are ideally desired for the high-priority scientific analysis of planets and satellites. The recommended map products are a subset of the possible products from the expected data, selected to meet the greatest range of requirements without unduly taxing available resources.

PLANETARY ATLASES

Atlases of planetary and satellite maps have been prepared by government and private publications, and constitute a valuable summary of planetary surface data. The PCWG recommends that atlases be prepared of Venus, Mars, and the Galilean satellites at the end of the respective missions to these bodies. The current status of planetary atlases is discussed in Part 4.

NEW MISSIONS AND CHANGING CIRCUMSTANCES

Specific recommendations for products from funded missions will need to be updated as new programs come on line. The most probable are lunar and near-Earth asteroid missions that could return very large quantities of high-quality cartographic data.

The requirements of a Space Exploration Initiative have not been dealt with here because of the uncertain schedules and goals of such a program. However, the PCWG recommends that the cartographic requirements of human lunar and Mars exploration be resolved as early as possible to ensure an efficient approach to such issues as precursor exploration, site selection, and actual mission goals and feasibility.

PART 2

Uses of Planetary Cartography

Maps not only present the general characteristics of a region to provide a qualitative impression but also are the basis for almost any quantitative scientific study of the area. In the centuries of terrestrial exploration, the improvement of maps has been both a requirement for and a primary result of exploration.

In planetary exploration, cartographic products are essential for scientific data analysis, mission planning, and public presentation of both plans and results. They provide a record of knowledge at a given time in our exploration of the planets that may be analyzed in many ways. Planetary maps display surface features within a standard coordinate system that provides precise locations and, in some cases, elevations. Other data that may also be displayed include surficial and bedrock geology, albedo, surface chemistry, geophysical measurements (e.g., gravity, heat flow, magnetic anomalies, dielectric constant), and surface-roughness properties (e.g., radar backscatter).

Three-dimensional displays derived from elevation data allow quantitative descriptions of surface features necessary for interpreting the geologic and geophysical evolution of planetary surfaces and interiors. The ability to project digital terrain maps from different viewing directions permits the visualization of surface processes and geomorphology.

Planetary maps are also essential for planning more detailed exploration of a planet or satellite by orbiters, probes, landers, rovers, return samplers, and human exploration; for indexing photographic records and other scientific data; for the education of future planetary scientists; and for a better public understanding of the solar system and our place within it.

SCIENCE DATA ANALYSIS

The study of the evolution of the planets depends heavily on the analysis of the dimensions and areal distribution of geologic, geochemical, geophysical, and atmospheric phenomena. Maps are required base materials for comprehensive portrayals of landforms on mathematically defined and scaled projections. Almost every type of geologic study uses maps of one type or another. Photomosaics, produced either photographically or digitally, as well as individual images (photographs or multispectral scenes), are commonly used for geologic interpretation of many geologic processes (Fig. 2).

Cartographic products at various scales are the basis for systematic geologic mapping. Shaded relief quadrangle maps and photomosaics have supported geologic mapping programs of the Moon, Venus, Mars, Mercury, the Galilean satellites and the moons of Saturn, Uranus, and Neptune (Fig. 3). Topical studies of landforms such as impact craters, fluvial channels, volcanic flows and vents, erosion surfaces, and eolian deposits all benefit from the presentation of spatial information on special maps or in three-dimensional displays with selected vertical exaggeration (Fig. 4). Topographic maps provide important information on the spatial distribution of heights from which slopes and volumes can be derived (Fig. 5). The combination of Magellan radar backscatter images obtained at different viewing angles to produce stereo pairs (Fig. 6) have also facilitated the analysis of geologic phenomena on Venus. Albedo maps, particularly those of Mars and the Galilean satellites, can be used to interpret the distribution of surficial materials and the rate of surface weathering. The geologic maps developed from the original data and from the above cartographic products (Fig. 7) are often stored digitally (Fig. 8).

Cartographic products are also required for plotting geophysical data, such as seismic epicenters and variations in the gravitational and magnetic fields. It is necessary to correlate these data with topography or geologic features in order to interpret the internal structure of a planet or satellite (Fig. 9). Display of surface radar backscatter, root-mean-square (rms) slope distribution, thermal inertia, and orbital geochemical data also requires cartographic products. Radar backscatter, obtained either from the Earth or an orbiting spacecraft, predawn temperatures or derived thermal inertias, X-ray fluorescence, gamma ray, and multispectral color information must be plotted on comparable maps to determine the relationship between the data and the geology of a planet or satellite (Fig. 10). Such geologic/remote sensing relationships provide essential insight into the genesis and history of any region.

Atmospheric sciences also benefit from cartographic products. Studies of the distribution and direction of martian wind streaks or the distribution of dark plumes on the neptunian moon Triton provide information on the near-surface atmospheric circulation (Fig. 11). Local and regional topographic information is used to explain orographic effects in the atmosphere. Mosaics of the views from the Viking Landers can be used to generate photometric properties and orientations of rocks on the surface of Mars. The comparison of polar frosts on Mars at different times during the martian year can also be used to study the seasonal distribution of volatiles on the planet's surface.

INDEXING

Data returned from spacecraft are intractable until placed in their correct spatial (and in some instances temporal) context. For example, hundreds of images are often used in the compilation of a single map. "Footprint" plots and cutline diagrams (Fig. 12) are compiled as overlays to aid researchers in determining the scale and location of images they may want to study in detail. Stereo pair maps are also available that show where on the planet the appropriate image pairs exist to view the surface in three dimensions. Areas of overlap between images obtained at different wavelengths can be used in the construction of color images of the surface as an aid to compositional mapping (Fig. 13). With the advent of multi-incidence-angle, multipolarization, and multiwavelength radar images of the Moon from Earth-based telescopes, and of Venus from Earth-based telescopes, Pioneer Venus, Venera 15 and 16, and Magellan, similar multiparameter images of the surface (such as Fig. 10) can be produced. Nonimaging data such as radar ground tracks for Mars, or the footprints of spectroscopic sensors, must be plotted on maps if the data are to be applied to the study of surface features and/or processes.

MISSION PLANNING

Data from early reconnaissance missions to planets and satellites are commonly used in the design and planning of future missions. Lunar maps made from Earth-based observations were used extensively in planning the Ranger and Lunar Orbiter missions. Thematic maps, such as terrain analysis, slope distribution, and geologic maps, were compiled from Lunar Orbiter photographs for use in selecting landing sites for Surveyor and Apollo missions. Lunar Orbiter images and Zond 3 photographs were used to plan the Galileo Moon encounter prior to the spacecraft's imaging of Mare Orientale on the lunar farside as it passed by the Earth en route to Jupiter (Fig. 13).

In the case of Mars, Mariner 9 photomosaics and maps were first used to define the capabilities of the Viking Lander spacecraft, and orbital images of varying spatial resolution were used to select the two Viking Lander sites. Earth-based radar roughness profiles were also used to estimate the mean roughness (rms slope) of the candidate landing sites. Essential cartographic requirements for Viking site selection were topographic maps, because only in the topographically lowest regions of Mars was the atmospheric density great enough for the parachute to slow the Viking Landers effectively. In the future, it is likely that the Mars Observer high-resolution camera and the highest-resolution (10–50 m/pixel) Viking Orbiter images will be used to study traverse sites for a Mars rover and sample return mission (Fig. 14). Because of the limited range of planned rover vehicles, absolute map coordinates must be accurate to a few kilometers, absolute elevations to a few hundred meters, and (within a target area) relative map coordinates to a few tens of meters.

Earth-based radar images of Venus from Goldstone and Arecibo Observatories, Pioneer Venus altimetry, and radar maps of surface roughness slopes, reflectivity, and emissivity were used to select the U.S.S.R. Venera 13/14 and Vega 1/2 landing sites. Altimetry and radar backscatter data from the U.S.S.R. Venera 15/16 were also used to determine the optimum radar parameters for the Magellan radar. Numerous radar backscatter photomosaics have also been assembled from Venera 15/16 scenes. Planning the data-gathering sequences for the Magellan spacecraft required detailed analysis of existing Pioneer Venus, Venera 15/16, and Earth-based datasets.

Maps of the Galilean satellites derived from Voyager observations are being used to determine an optimum satellite tour for the Galileo mission. This mission will obtain much-higher-resolution images (10 to 100×) than were obtained by

Voyager, together with infrared and ultraviolet spectral and photopolarimetric data. In addition, temporal coverage may also be obtained of the volcanic activity on Io during the two years that the Galileo spacecraft will orbit Jupiter. Intercomparison of these data, and the detection of changes compared with maps of Io based on Voyager images, will be essential for understanding the rates and characteristics of active volcanic processes.

The Moon will be explored again by both robotic missions and humans. Although many of the necessary cartographic data were obtained for the lunar nearside by the Apollo and Lunar Orbiter missions, additional high-quality maps will be needed for mission planning and data analysis. A unified selenodetic control net and an accurate map of global topography are still much-needed additions to our knowledge base. The polar regions and lunar farside are both inadequately imaged, and new techniques, such as dual-polarization multiwavelength Earth-based radar (Fig. 15) and high-spectral-/high-spatial-resolution visible and near-infrared imaging spectrometers permit additional information to be collected for the lunar nearside. New lunar geophysical and geochemical data will inevitably require conversion to accurate base maps to be easily interpretable.

EDUCATION

Planetary cartographic products are valuable as educational tools. Maps, diagrams, and globes are widely used by researchers, universities, secondary schools, libraries, museums, and planetariums. In addition, the National Geographic Society has used derivatives of planetary maps in its magazine (which has a current circulation of about 10,000,000), in books such as *Our Universe* that are widely used by the general public, and with its "Spacekit" for school children. College textbooks such as Kaufmann's *Exploration of the Solar System*, Glass's *Introduction to Planetary Geology*, and Pasachoff and Kutner's *University Astronomy* also use planetary maps to illustrate surface features on a global or regional scale. A cursory literature search shows that more than 80 books have used planetary maps to illustrate surface physiography. Planetary maps have been made available to secondary school classes only in a limited way. Those maps and globes that have been distributed are used to illustrate the general geography of planetary landscapes.

Many educators and the public in general have shown a strong interest in planetary maps, as attested by the sales of the *Atlas of Mercury* and *Atlas of Mars* (a combined total of more than 10,000 copies sold). Similarly, planetary maps as individual sheets have had a continuing high sales record: More than 300,000 copies have been sold through distribution centers. The public is increasingly shown global maps of the Earth in both print and broadcast media to explain such things as climate, climate change, pollution, ozone, vegetation cover, extent of deserts, etc. Global maps of other planets have been used for comparison to Earth and should continue to be effective at presenting messages to the general public.

At the university level, more courses in planetary science at the undergraduate and graduate levels are being established because of the high level of interest in this subject. The number of such courses is likely to increase as more planetary exploration and data analysis take place. These courses are usually taught in the astronomy and geoscience departments, where planetary cartographic products are used to show regional or global surface features. Although individual high-resolution pictures may show details of geologic or atmospheric processes, only cartographic products can convey to the student how these processes operate on a regional or global scale. Many of these products are now available digitally in forms usable by small computers in universities and secondary schools.

REGIONAL PLANETARY IMAGE FACILITIES

Currently, there are 11 Regional Planetary Image Facilities located throughout the U.S., and there are 6 centers in other countries (Table 2). These facilities contain images of planets and satellites acquired from various space missions and the cartographic products derived from these images. The image facilities are intended for the use of individuals or groups that require photographic and cartographic materials for research, education, or public information, but have only limited or no access to such material.

TABLE 2. Regional Planetary Image Facilities (RPIFs).

Name	Location	Director
Domestic Facilities		
Regional Planetary Image Facility	Brown University *Providence, Rhode Island*	Peter Schultz
Spacecraft Planetary Image Facility	Cornell University *Ithaca, New York*	Joseph Veverka
Regional Planetary Image Facility	Jet Propulsion Laboratory *Pasadena, California*	R. Stephen Saunders
Planetary Image Center	Lunar and Planetary Institute *Houston, Texas*	David C. Black
Regional Planetary Image Facility	Smithsonian Institution *Washington, DC*	James Zimbelman
Planetary Data Facility	U.S. Geological Survey *Flagstaff, Arizona*	Laurence Soderblom
Space Imagery Center	University of Arizona *Tucson, Arizona*	Robert G. Strom
Pacific Regional Planetary Data Center	University of Hawaii *Honolulu, Hawaii*	B. Ray Hawke
Regional Planetary Image Facility	Washington University *St. Louis, Missouri*	Raymond E. Arvidson
Space Photography Laboratory	Arizona State University *Tempe, Arizona*	Ronald Greeley
Eau Claire Planetary Imaging Center (EPIC)	University of Wisconsin *Eau Claire, Wisconsin*	Paul Thomas
Foreign Facilities		
Phototheque Planetaire	Universite Paris-Sud *Orsay, France*	Philippe Masson
Southern Europe RPIF	Istituto Astrofisica Spaziale *Rome, Italy*	Marcello Fulchignoni
Observatory Annexe	University of London Observatory *London, England*	John Guest
Regional Planetary Image Facility	DLR *Wessling, Germany*	Gerhard Neukum
Regional Planetary Image Facility	Institute of Space and Astronautical Science *Kanagawa, Japan*	Hitoshi Mizutani
Regional Planetary Image Facility	University of Oulu *Oulu, Finland*	Jouko Raitala

PART 3

Planetary Cartography Acquisition Systems, Methods, and Products

INTRODUCTION

The challenge of planetary cartography is to produce a graphical or digital description of solid bodies in the solar system. In recent years the traditional techniques of terrestrial map compilation by analog or analytical photogrammetric instruments have been overtaken by digital methods. Linear features are represented by vector methods in which strings of coordinate pairs give the location of points in the map coordinate system. Images of planetary surfaces are represented by raster techniques in which each picture element (or pixel) is assigned a digital row and column number in the map coordinate system, a density number (DN) that represents its photographic gray level, and any number of additional attributes. For planetary maps these attributes can include topographic elevation, thus producing a Digital Topographic Model (DTM). Other attributes can include albedo, geologic structure, rock or soil type, magnetic field strength, or any other parameter having an areal extent. These digital data are fed to computer-controlled vector and raster plotters, which then produce image base maps with any number of thematic line overlays. The maps are then reproduced by standard photographic or lithographic procedures.

This part of the report describes the spacecraft acquisition systems of most relevance to the period of this report, the map projections used in presenting planetary data, and finally the kinds of cartographic materials that are end products of the map-making process.

ACQUISITION SYSTEMS

Photographic, electro-optical, and microwave sensors are all used in planetary data acquisition. Film camera systems can provide high surface resolution but maximum utilization requires the original film be returned from space. The last use of these systems for planetary cartography was on the Apollo lunar missions, and they are not likely to be used again until new manned missions return to the Moon or go to other planets.

Because radar will be used extensively on future planetary missions, it is essential to note that radar images are not the same as those produced by sensors operating in the visible and near-infrared wavelengths. Because these wavelengths are similar to the sensitivity of the human eye, the pictures have a familiar appearance. The gray levels depend primarily upon the reflectivity of the terrain and upon the phase angle between the incident and reflected solar illumination. Radar, on the other hand, operates in wavelengths far removed from human-eye sensitivity, and since it provides its own illumination source the phase angle is always zero. The gray levels depend primarily upon terrain surface roughness, secondarily on the aspect angle between the incident radiation and the terrain surface, and thirdly on the electromagnetic reflectivity of the surface materials. Application of conventional photomapping and photointerpretation techniques to such images may lead to wildly erroneous conclusions about the terrain.

Magellan

The Magellan spacecraft carries a 3.7-m-diameter high-gain antenna that is used as an imaging synthetic aperture radar (SAR) and for communication with Earth. A second, horn-shaped antenna is used as a radar altimeter to measure spacecraft altitude above Venus' surface.

The SAR operates at 12.6 cm wavelength and its resolution is from 120 to 360 m, depending upon latitude because of the elliptical orbit. These reflected data are sampled in 75-m pixels. Each strip image covers 26 km east-west by 17,000 km north-south. These images, commonly known as "noodles," extend from 90°N to 54°S latitude on one pass, and from 76°N to 68°S on the adjacent pass during the first mapping cycle. Nominal sidelap between adjacent noodles is 18 km at 80°N latitude and less than 6 km near the equator. Data are collected at low altitude and transmitted back to Earth during the high-altitude part of each orbit. In 243 Earth days the planet Venus makes a complete revolution below the spacecraft orbit and, in principle, one complete cycle of coverage is obtained. The first cycle mapped 84% of the planet with left-looking images. The second cycle filled several gaps in the cycle 1 coverage, including the south polar region, bringing total coverage of the planet to nearly 97%, and resulted in right-looking/left-looking coverage of about 50%. Cycle 3 was devoted to left-looking images to provide stereoscopic coverage and to obtain gravity measurements. Cycle 4 was dedicated to gravity mapping.

The footprint of the radar altimeter varies between 10 × 12 km and 20 × 29 km, increasing with latitude. The footprints are located at about 8 km spacing north-south along each orbit pass and are consequently about 20 km spacing east-west. The instrumental accuracy is about 5 m, but the actual data may have errors exceeding 1 km, due to orbit tracking uncertainty and horizontal ambiguity in deciding which surface point gave rise to the range measurement.

Mars '94

The Russian Mars '94 spacecraft will carry a high-resolution stereo camera (HRSC) and a wide-angle camera (wide-angle optical stereo system, or WAOSS) to provide both stereoscopic and multispectral images of sites of particular scientific interest. The HRSC is designed and manufactured jointly by the German Space Agency (DLR) and Dornier Deutsche Aerospace corporation and is also proposed for the Scout missions. This camera is a "push-broom" design with 9 rows of 5184 pixels each. In addition to multispectral surveys, it will provide continuous recording of 19° fore, nadir, and 19° aft stereoscopic image strips. It is anticipated that images from the Mars '94 mission will be made available to investigators in the U.S.

Mars Observer

The Mars Observer spacecraft was planned to be in a near-polar Sun-synchronous orbit at a mean altitude of about 380 km, and was expected to operate for at least a full martian year, providing the opportunity to acquire data from any location on the planet. The imaging system consists of one high-resolution narrow-angle camera for detailed observations of limited areas of the martian surface, and two low-resolution wide-angle cameras to provide a daily record of martian weather and surface features and context images for the narrow-angle images.

The narrow-angle camera has a 3.5-m focal length and a 2048-element linear array charge-coupled device (CCD) detector. From the nominal altitude of 380 km the surface resolution will be 1.4 m/pixel, and the nominal scene will be 2.8 km wide × 15.8 km long. However, by using only a portion of the linear array, swath width can be traded for length. The CCD pixels can also be summed in the instrument to allow larger-area but lower-resolution images to be acquired.

The two wide-angle cameras have 11.3-mm focal lengths with 3456-element CCDs in the focal plane, providing a 140° field of view. One camera has a red filter, the other a blue filter. At the nominal altitude, the subnadir pixel is about 250 m, increasing to about 3 km at the limb. As with the narrow-angle camera, the image size can be adjusted in both the cross-track and along-track directions. The pixels can also be summed in both directions, but the summing need not be square, so that, for example, a limb-monitoring observation can be summed in the along-track dimension but not in the cross-track.

The Mars Observer cameras are always pointing at the spacecraft nadir. Since the narrow-angle camera swath is less than 3 km, and adjacent orbit passes are 1684 km apart at the equator, it will generally not be possible to build up multiple swath mosaics with this camera. Because the wide-angle camera coverage extends out to the limb of the planet, it is possible to treat the camera as though it could be pointed by sampling only a portion of the array. Narrow-angle images will usually be accompanied by small wide-angle images, which will serve to locate the narrow-angle images on maps.

The Mars Observer will also carry a laser altimeter, which uses infrared pulses to measure the distance from the spacecraft to the planet's surface with a vertical precision of several meters. Global coverage by the altimeter will provide topographic data of uniform precision for the entire planet; this will be an important improvement for both scientific and cartographic uses.

Galileo

After passing Venus, Earth, the Moon, and two asteroids, the Galileo spacecraft is expected to reach Jupiter in 1995. Imaging of both Jupiter and its satellites is a key part of this mission.

The solid-state imaging system (SSI) incorporates a modified flight spare of the 1500-mm focal length, f/5.8 narrow-angle telescope that was carried on the

Voyager mission. The detector array is an 800 × 800-element CCD. This device will provide a surface resolution of about 0.5 km/pixel at a range of 50,000 km. An eight-position filter wheel will provide spectral response in the range 611–986 nm.

En route to Jupiter, on October 29, 1991, the Galileo spacecraft passed within 1600 km of the asteroid Gaspra. Several imaging sequences were performed, the best of which has a surface resolution of 55 m/pixel. The mean radius of this irregular object has been measured at about 6.1 km, and stereo coverage permits some topographic mapping. An encounter with the asteroid Ida occurred in August 1993 and returned images of 35-m/pixel resolution.

Clementine

Clementine is scheduled to be placed in lunar orbit in early 1994. Global coverage of the Moon in 10 spectral bands at resolutions of 125–200 m/pixel is expected. A high-speed framing camera capable of returning about 500,000 (256 × 256 to 288 × 384 pixels) images in the course of a two-month mission will be used. The photogrammetric potential of this system is lower than that for Scout, but Clementine will provide valuable mineralogical data. A long-focal-length lidar camera will give high-resolution images of selected areas. This mission is scheduled to include a high-speed flyby of the asteroid Geographos after leaving lunar orbit.

Scout

These two small spacecraft are each proposed for one-year operations in 1996 and 1997. The mission has significant potential for making global topographic maps from stereoimages of the Moon with horizontal and vertical resolutions on the order of 15 m and special-area surveys with resolutions of 4 m. It may include a version of the HRSC to be flown on Mars '94.

Artemis

Surface-based surveys from automated roving vehicles will be used to help certify potential sites for eventual piloted landings and/or lunar bases. These roving vehicle missions are planned for 1999–2000. The position in inertial coordinates of any landed spacecraft can be determined very precisely by laser-ranging measurements to passive arrays of retroreflectors. The positions thus derived can be verified and improved by techniques of very-long-baseline interferometry (VLBI). An imaging system on a landed vehicle may be used to identify the position of the vehicle on images taken from orbit. Thus, while the imaging systems on landed vehicles do not contribute materially to global cartographic coverage, they provide essential bench marks that link orbital surveys to each other and to spacecraft landing and navigation systems.

Mars Environmental Survey (MESUR)

Between 1998 and 2004, MESUR, a series of individual geophysical stations, will be landed at well-distributed sites on Mars. Each of these stations will have a Viking-like facsimile imaging system that can be used to locate their positions on existing image maps made from orbit, thus allowing precise geodetic control of

the orbital surveys, as described in the discussion of Artemis. An engineering test version, MESUR Pathfinder, is designated as the first of the Discovery-class missions.

Near Earth Asteroid Rendezvous (NEAR)

The second of the Discovery-class missions, NEAR will be launched in 1996 to orbit Eros, a near-Earth asteroid. It will survey the asteroid from various orbital heights for several months. Images will achieve resolutions of less than a meter. Compositional and elemental information will also be gathered. This is the first mission to obtain large amounts of mappable asteroid data.

MAP PROJECTIONS

Most planetary bodies are essentially spherical in shape, with topography representing departures from the sphere. Positions of features on the sphere are defined by meridians of longitude and by parallels of latitude. Topographic heights are usually measured as elevations above the spherical surface, although in the most refined systems they are measured as departures from an equipotential surface that most closely approximates the spheroidal surface. It is not possible to represent meridians and parallels on a flat map surface without introducing distortions of shape and variations of scale in the features depicted on the map. To solve these problems the science of map projections is invoked. The meridians and parallels are projected by a mathematical transformation onto a surface, such as a cylinder or cone, which can be developed into a plane. Planetary cartographers employ several different map projections, depending on the scale, location on the spheroid, and extent of the surface to be shown on the map. This group of map projections is known as conformal, i.e., the shape of features is preserved, but not their areas. For special-purpose maps, equal area projections can be used. As might be expected, such projections preserve area at the expense of shape.

In the Mercator Projection the reference surface is a cylinder that is either tangent to the body's equator, or is secant at two standard parallels of latitude. The Mercator is most useful for areas near the equator that extend mainly in the east-west direction. Figure 16a illustrates the characteristics of the Mercator Projection.

The Transverse Mercator Projection also uses a cylinder as the reference surface. However, as shown in Fig. 16b, the cylinder is either tangent to a central meridian or intersects the sphere at two small circles east and west of the central meridian. Such a projection is most useful for areas having greater north-south extent and not departing very far east and west of the central meridian. The primary applications of the Transverse Mercator are for larger-scale maps of limited areas and for printed gores to be assembled into globes.

In the Lambert Conformal Conic Projection, illustrated in Fig. 16c, the reference surface is a cone with its vertex on the body's polar axis. The cone is either tangent to the sphere or intersects it at two standard parallels of latitude. This projection is most useful for midlatitude areas extending farther in the east-west direction than north-south.

The reference surface for the Stereographic Projection is a plane tangent or secant to the spheroid at a point. Although in principle the Stereographic Projection can be constructed at any point on the surface of the spheroid, it is most commonly used as a Polar Stereographic, as shown in Fig. 16d.

When an entire planetary body is mapped, the area is divided into a series of quadrangles that will result in reasonable map sheet sizes, dependent upon the size of the body, the scale of the maps, and the resolution of the imagery. The usual arrangement is one or more bands of Mercator Projections in the equatorial areas, one or more bands of Lambert Conformal Conic Projections in the midlatitude regions, and one or more bands of Polar Stereographic Projections for the polar areas. Figure 16e shows the arrangement selected for mapping Mars at the scale 1:2,000,000.

DIGITAL DATA SYSTEMS

Cartographic data acquisition systems, either imaging or altimeter, rarely collect data in a regular systematic pattern. To increase their utility, such data are resampled into fractional intervals of latitude and longitude compatible with the resolution of the records. Resampling consists of taking the actual data records—either DN, elevation, or any other parameter—in the vicinity of the point of interest and interpolating a new value representative for that point. A variety of interpolation algorithms are used for different purposes. Although they all result in minor diminution of the integrity of the data, the resulting convenience and ease of use make the effort worthwhile, if not essential. The resampling interval is taken as a rational fraction of a degree of latitude or longitude. The "digital scale" is specified as the fractional part of a degree per image pixel. The fraction is selected so that the area covered will be approximately equal to the surface resolution of the data in meters per pixel. Table 3 shows the meters per pixel for various fractions of a degree for solar system planetary bodies; the value obviously depends upon the radius of the body.

Resampled digital data are stored in a Sinusoidal Equal Area Projection, where each line is a parallel of latitude with its length compressed by the cosine of the latitude. Files of image data are referred to as Digital Image Models (DIMs); elevation data are called Digital Topographic Models (DTMs). For each data type, the entire database for a planet can be stored in a single array, called a Mosaicked Digital Image Model (MDIM), so that map projection boundaries and quadrangle limits of printed maps need no longer be of concern. The fractional degree image resolution is constant throughout the array. When the data are to be printed out in one of the standard map projections, the locations of the new pixels are simply determined by the particular projection transformation formulas.

Planetary geologists have found that five to eight pixels across a feature are required to identify and classify most landforms. The resolving power of the human eye and the capability of halftone reproduction are between 5 and 10 pixels/mm. These conditions, coupled with the surface resolution of the sensor data, dictate the scale at which a map should be printed. For example, the nominal resolution of the Mariner 9 images of Mars is about 0.5 km/pixel. Ten pixels would extend 5 km, which would be represented by 1 mm on the map, making the useful scale 1 mm = 5 km × 1,000,000 mm/km = 1:5,000,000. Table 4 shows the pixel size and map scales selected for various bodies in the solar system.

TABLE 3. Digital pixel dimensions.

		Digital Scale (deg/pixel) Pixel Size in m						
Planet/Satellite	Radius (km)	1/16	1/32	1/64	1/128	1/256	1/512	1/1024
Mercury	2439	2660		665				
Venus	6052	6602					206	
Mars	3385	3692				231		58
Phobos	11	12						
Deimos	6	7						
Gaspra	7	7						
Amalthea	88	96						
Io	1821	1986	993		248	124		
Europa	1565	1707	852		213	107		
Ganymede	2634	2874		719			90	
Callisto	2403	2622		657			82	
Mimas	199	217						
Enceladus	249	272						
Tethys	530	578						
Dione	560	611						
Rhea	764	833						
Iapetus	718	783						
Hyperion	148	161						
Miranda	236	257						
Ariel	579	631						
Umbriel	586	639						
Titania	790	862						
Oberon	762	831						
Triton	1352	1475		600	300			

The digital pixel dimension on the planetary surface for rational fractions of a degree of latitude and longitude depends on the radius of the body. Fractions are selected to be compatible with the resolution of the image sensor records.

Various kinds of thematic maps are compiled by interpretation of images and other types of sensor data. On these maps boundaries between classes are shown by lines, crosshatching, or other graphic symbols. Such line data can also be digitized by scanner devices and converted to the same coordinate system and digital format as the DIMs and DTMs. Useful products are then produced by overlaying the line data on the image data when the map is reproduced.

CARTOGRAPHIC PRODUCTS

The processing techniques and the hard- and soft-copy products involved in planetary cartography are described in the following paragraphs.

Corrected and Rectified Images

Systematic batch processing of the transmitted data produces several versions of each image frame. The first version is corrected for camera shading; contrast may be enhanced or stretched; and reseau marks, if present, may be removed. Radiometric corrections are made according to prelaunch calibrations of the sensor. On a second version, high-frequency image detail is enhanced by spatial filtering. On

TABLE 4. Image map scales.

	Map Scale			
Deg/pixel	1:10M-1:25M	1:5M	1:2M	≤1:500K
1/16	Iapetus Umbriel Titania	Tethys Dione Rhea Ariel	Mimas Enceladus Miranda	
1/32		Io Europa		
1/64		Mercury Ganymede Callisto		
1/128			Io Europa Triton	Ganymede Callisto
1/256			Mars	Io Europa
1/512			Venus	Ganymede Callisto
1/1024				Mars
1/2048				Venus

The image map scale for planetary bodies is selected so that the pixels in the digital image model (DIM) will be reproduced at 5–10 pixels/mm in order to produce a high-quality graphic product.

the final version, the image is geometrically corrected for calibrated distortions in the sensor. The image is also rectified to a vertical view of the planetary surface according to the predicted orientation of the sensor with respect to the map coordinate system. These corrected and rectified images are usually the first results the investigators see, and are most useful in evaluating spacecraft and sensor performance during the mission. They are not, however, truly orthographic views of the planetary surface, because they still contain the one- or two-dimensional perspective resulting from rectangular or linear array sensors and uncompensated spacecraft attitude errors.

Uncontrolled Mosaics

Single-sensor records seldom extend over an entire given area of interest. It is therefore necessary to mosaic several frames to cover the required area. With hard copy images, mosaics are assembled by simply pasting down overlapping frames, selecting the cut lines between frames to provide the best match of imagery and gray tones. Because of their geometric and photometric inadequacies, uncontrolled mosaics are not often published as formal cartographic products. Nevertheless, because they are the earliest regional coverage available to investigators, much valuable science is derived from them.

A slight refinement of the uncontrolled mosaic process results in a more useful product. The photographic prints to be assembled are made at scales predicted by the spacecraft tracking data, and placed in a geographic graticule of latitude and longitude derived from the spacecraft position data. These products are referred to as "semicontrolled" mosaics.

Controlled Mosaics

A network of image identifiable control points can be established on the planetary surface by the techniques of analytical photogrammetric triangulation. The image coordinates of conjugate points, usually craters or other clearly defined terrain features, are measured on overlapping frames covering large areas of the body. A large least-squares solution then results in the latitude and longitude, and sometimes elevation, for each terrain point whose image has been measured. It also produces refined values for the spacecraft position and the sensor attitude angles. These data permit more accurate scaling of the individual frames. Hard-copy mosaics can then be assembled, so that the images of the control points are made to coincide with their proper positions in the latitude-longitude graticule.

In modern digital cartography, controlled mosaics are compiled on image work stations where the operator can interact directly with the images. The control points are identified and coded with their positions derived from the triangulation. The image is moved about in the array for a "best fit" of the control points to their proper latitude-longitude positions in the selected map coordinate system. In the overlap area between adjacent frames, "tie" points are identified. The computer assures that these points will have the same terrain coordinates in both frames. Furthermore, it applies an algorithm to assure that the gray levels are identical and smoothly merged, so that cut lines between images are no longer apparent. The resultant MDIM is then formatted according to the selected map projection and quadrangle boundaries, the controlled mosaic is printed out on a film writer, and the map graticule lines are superimposed. This is a more accurate product than the uncontrolled or semicontrolled mosaic, but the individual images may still have some internal topographic distortions resulting from the perspective geometry of the sensor. Controlled mosaics are often issued as formal cartographic products, but they may not be available until many months after the images are acquired.

Topographic Contour Maps

If the imaging sequences of a planetary spacecraft—such as the Viking Mars Orbiter—provide overlapping stereo coverage with suitable geometry, it is possible to compile topographic contour lines. The hard-copy images are oriented in an analytical stereo plotting instrument so that the operator sees a three-dimensional stereo model of the terrain. A "floating mark" whose horizontal and vertical translations are controlled by the operator is introduced optically into the stereo model. The operator sets the mark at a given elevation and moves it horizontally while keeping it in contact with the perceived terrain, thus tracing out a contour line. Considerable skill is required to assure that the contours are logical and continuous between adjacent stereo models. The resulting contour maps provide the best quantitative description of topographic relief. Figure 17 shows contour data of Mars compiled by this technique.

In an alternate technique, the floating mark is driven automatically along horizontal parallel lines in the stereo model. The operator uses stereo vision to keep the mark in contact with the perceived terrain, thus producing a series of parallel profiles. Some progress has been made in automatic terrain profiling using computer-controlled stereo correlation, but operator assistance is usually required to achieve full coverage.

In addition to stereo compilation, digital terrain information may be acquired by altimetry from spacecraft. However, whether acquired stereoscopically or by altimetry, the information is not in the format required by the standard DTM. Computational resampling and interpolation programs are employed to derive a regularly spaced DTM from contours, profiles, or altimetry. It is also possible to automatically compile contours from DTMs.

Orthoimage Maps

An orthoimage map has each pixel located in its correct map position. The DTM must be resampled and interpolated to produce an elevation value for each pixel. Photogrammetric computations then eliminate the internal image distortions resulting from the terrain relief and the perspective geometry of the imaging sensor. The resulting orthoimage map has the highest planimetric accuracy and also has the photometric integrity of the controlled mosaic. The contours, the geographic graticule, and other interpretive line data can be superimposed on the printed image map. Because of the large amount of processing involved and the marginal increase in utility compared to controlled mosaics, only a handful of orthoimage planetary maps have been published as formal cartographic products (see Fig. 17).

Shaded Relief Image Maps

Compilation of large area planetary maps often involves use of several image datasets acquired at different time periods, between which the illumination geometry and image scale may have changed considerably. Thus different parts of image mosaics will have inconsistent resolutions, shadow directions, and terrain relief representation. To overcome these difficulties, shaded relief maps are compiled.

Most shaded relief maps are made by specially trained cartographers skilled in the use of an airbrush. The technique produces a composite painting that shows essential terrain information extracted from large and awkward datasets. Airbrush cartography is a long and tedious process, and only a few people have developed the skill.

If a detailed DTM is available, it is possible to develop a shaded relief map digitally. A formula is derived that expresses the gray level as a function of the illumination direction, terrain slope, and aspect angle. The technique works fairly well for very-small-scale maps of extensive areas, but does not match the quality of renditions produced by skilled artists.

It is possible to derive excellent shaded relief images from SAR mosaics, when both right- and left-looking views are available. Since the regional radar albedo is nearly the same regardless of viewing direction, differences between the two images may be attributed to topography. Digital extraction of a shaded relief image from opposite-side SAR is therefore reasonably straightforward (Fig. 3c).

Shaded relief maps are probably the highest-level standard cartographic product. Shaded relief maps have recently been digitized by scanning and distributed in standard-format MDIMs. Investigators find them to be a useful base for interpretation of other terrain characteristics using computer-assisted viewing devices.

DERIVED CARTOGRAPHIC PRODUCTS

The great flexibility of digital imaging processing techniques has made it possible to produce a series of useful products derived from cartographic data files.

Perspective Views

Presuming that a suitable DTM and a DIM already exist, it is possible to produce any number of different perspective views of the area of interest, one of which is shown in Fig. 4. The simplest of these is known as a "wire frame model." In the same map coordinate system as the DTM a perspective viewpoint is chosen by specifying its azimuth and elevation angles and its distance from the center of the area (or, alternatively, its three-dimensional coordinates). The DTM consists of a rectangular grid, with an elevation "post" erected at each grid intersection. To exaggerate the relief impression, each elevation value can be multiplied by a suitable scalar. The computer connects the top of each elevation post with a line to the perspective center, and then computes the intersection of these lines with a picture plane which is normal to the viewing direction. The points in the picture plane are connected with the corresponding grid lines. The resulting wire frame model is helpful in visualizing the vertical relief in the area. Advances in computer capabilities now allow this procedure to be applied on a pixel-by-pixel basis to digital imaging data (Fig. 4), which can be combined to generate movies of simulated flight over the scene.

Synthetic Stereoscopic Images

The interpretation of landforms is greatly facilitated by examining image records in stereo, which makes topographic relief readily apparent. But because of the narrow field of view of most planetary imaging sensors, stereo with good viewing geometry is rarely obtained. However, if a good DTM and good monoscopic images are available, it is possible to create synthetic stereoscopic pairs. One image is produced as an orthorectified print in which all pixels are located in their correct cartographic position. For the second image, the parallax that would exist for the terrain relief at each pixel is computed. The stereomate is then printed using the same gray level pixels, but with the computed parallax displacements imposed. The direction of the stereo base can be freely chosen, and the base-to-height ratio can be selected to provide any required terrain height exaggeration. Such a stereomate can be prepared for the entire area covered by an orthophoto mosaic. This technique has been successfully applied to images of Venus using the digital images produced by the radar sensor and the DTM acquired by the altimeter.

Planetary Lander Images

Images acquired by lander spacecraft and cartographic products derived from them have provided the most detailed information about the surfaces of the Moon, Mars, and Venus.

The imaging system on the U.S. lunar Surveyors was a framing camera that recorded panoramas by means of a movable mirror. The U.S. Viking Mars Landers and the Soviet Luna, Lunokhods, and Veneras recorded scenes by scanning a single vertical line of pixels, then rotating the camera in azimuth through an angle equal to the angle subtended by a pixel, scanning another vertical line, and continuing in this fashion until the entire scene was recorded.

The simplest image processing step was to make an equivalent frame photograph by relocating and sizing the pixels to where they would intersect a picture plane rather than a sphere or cylinder. If the selected picture plane is vertical the resulting scene will look like the landscape in front of the spacecraft. If the picture plane is horizontal at some distance below the perspective center, the scene will look like a planimetric map of the area in front of the spacecraft. Because pixels close to the spacecraft cover a much smaller area than those near the local horizon, and since relief displacements of hills and rocks are not corrected, the resulting image has such widely varying resolution that it appears to be badly smeared. For this reason, line maps of the landing sites appear more acceptable than image maps.

Surveyor 6 carried a single camera, but at one point the spacecraft executed a little hop to one side in order to provide a stereo base. The Luna, Lunokhod, and Surveyor 7 systems utilized mirrors on the spacecraft to produce stereoscopic images from the real and virtual camera stations. The Viking Landers carried two cameras with a fixed stereo base. Stereo compilation from these pairs of images permitted correct planimetric placement of features and measurement of terrain heights and vertical dimensions of rocks.

Thematic Maps

Interpretation of planetary images by geologists, mineralogists, geophysicists, and other earth scientists results in a variety of line and text annotations to controlled mosaics, orthorectified image maps, and airbrush-shaded-relief maps. These annotations can be digitized by scanning and then superimposed on the digital image maps. Frequently the image base is subdued in order to make the final map product more readable.

Figures

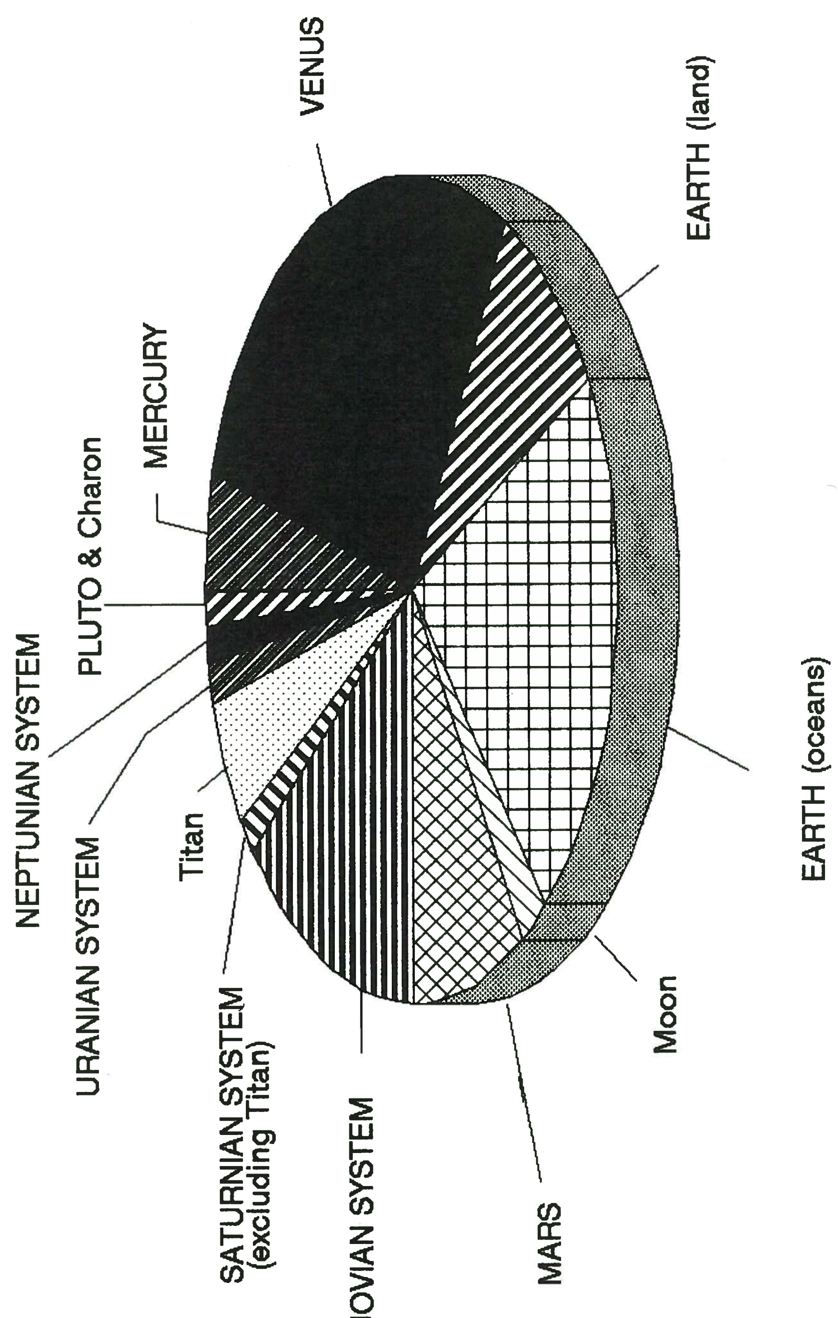


Fig. 1. *Surface area of planets and satellites in the solar system. The total is approximately 1.6×10^9 km^2. Jupiter, Saturn, Uranus, and Neptune do not contribute to the total because they do not have mappable surfaces. No attempt was made to incorporate the surface area of asteroids and comets in this diagram.*

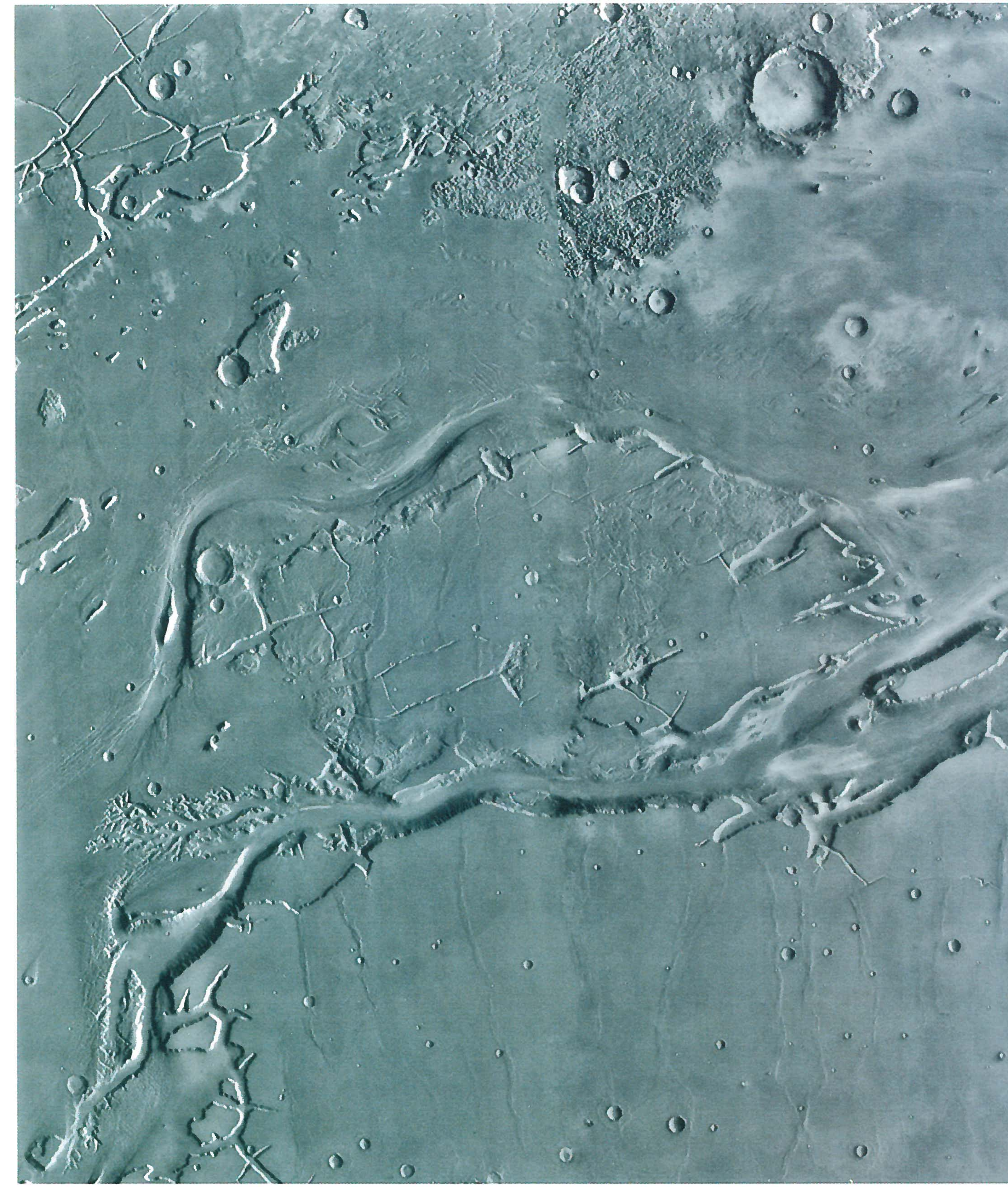


Fig. 2. *Mosaic of nine 1/64 deg/pixel image files from the DIM of Mars showing Kasei Vallis. Data are from volume 2 of the CD-ROM version of the Mars DIM released in 1991.*

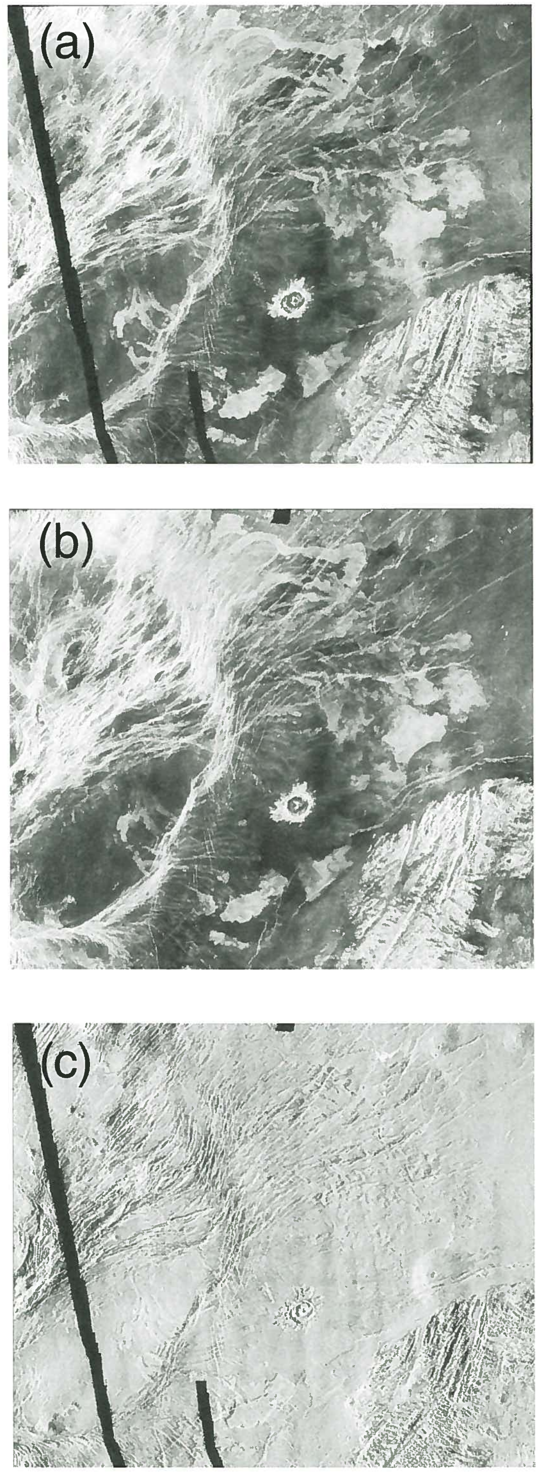


Fig. 3. *Examples of SAR image-map bases for geologic mapping. Most planetary images contain both relief and albedo information, as in Magellan SAR images. Base maps made with such images distort the colors normally used to delineate stratigraphic units on geologic maps. Shaded relief image maps, when they can be made, provide much clearer base materials. Such maps must usually be based on subjective interpretation and drawn manually with an airbrush. In the case of Magellan, a special digital processing technique can be used over 50% of Venus, where both left-looking and right-looking SAR images cover the same surface area. The image is about 350 km across, and shows part of the Eithinoha Corona. Guilbert Crater is near the center of the map segment. (a) Image mosaic made with left-looking Magellan radar images. (b) Image mosaic made with right-looking radar images. (c) Shaded relief image derived from (a) and (b) by digital processing.*

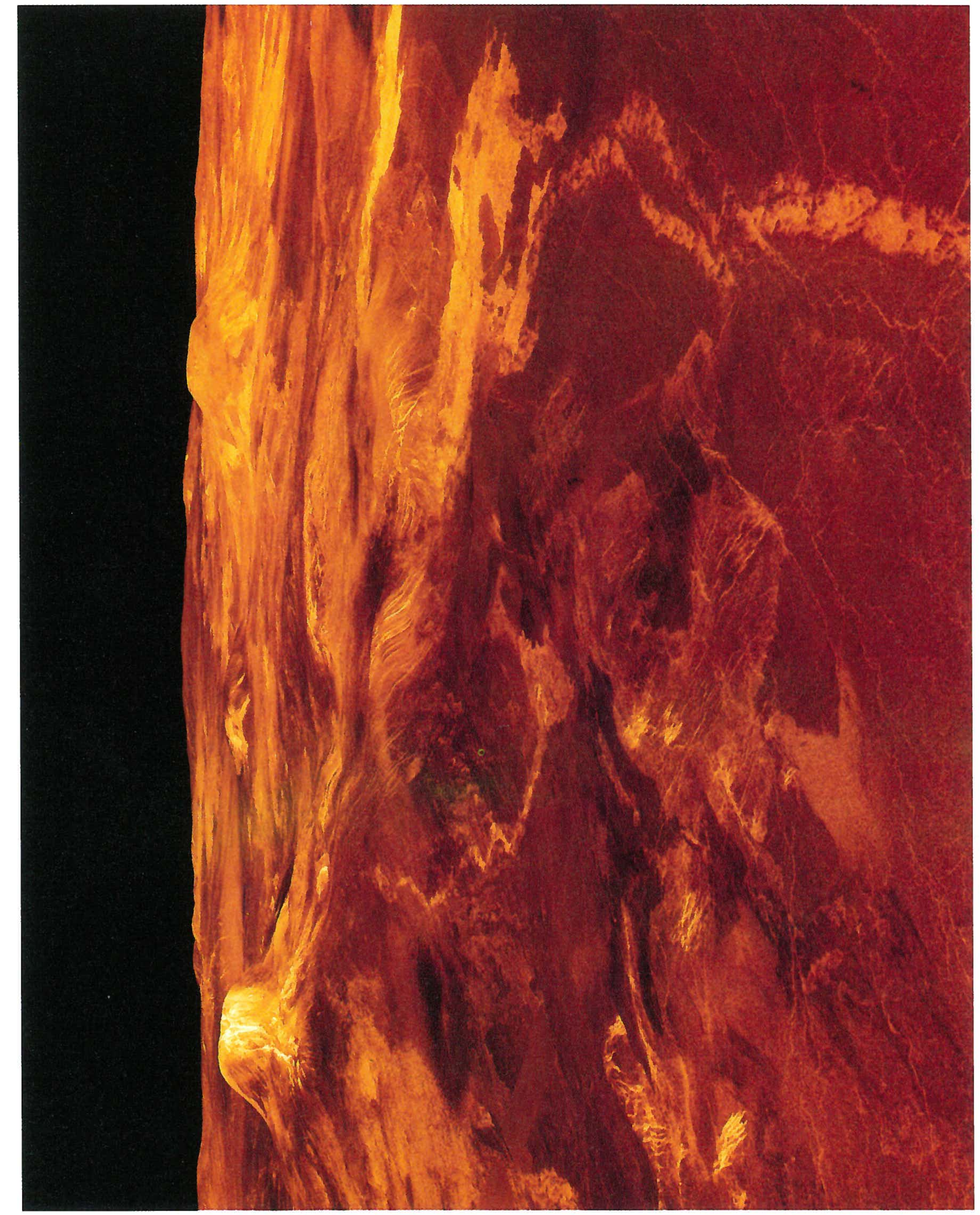


Fig. 4. *Three-dimensional perspective view of western Eistla Regio on Venus. Gula Mons (left) and Sif Mons (right) are two volcanos that rise 3 km and 2 km respectively above the plains. Magellan radar image data were combined with radar altimetry to generate this view, which has a vertical exaggeration of about 20.*

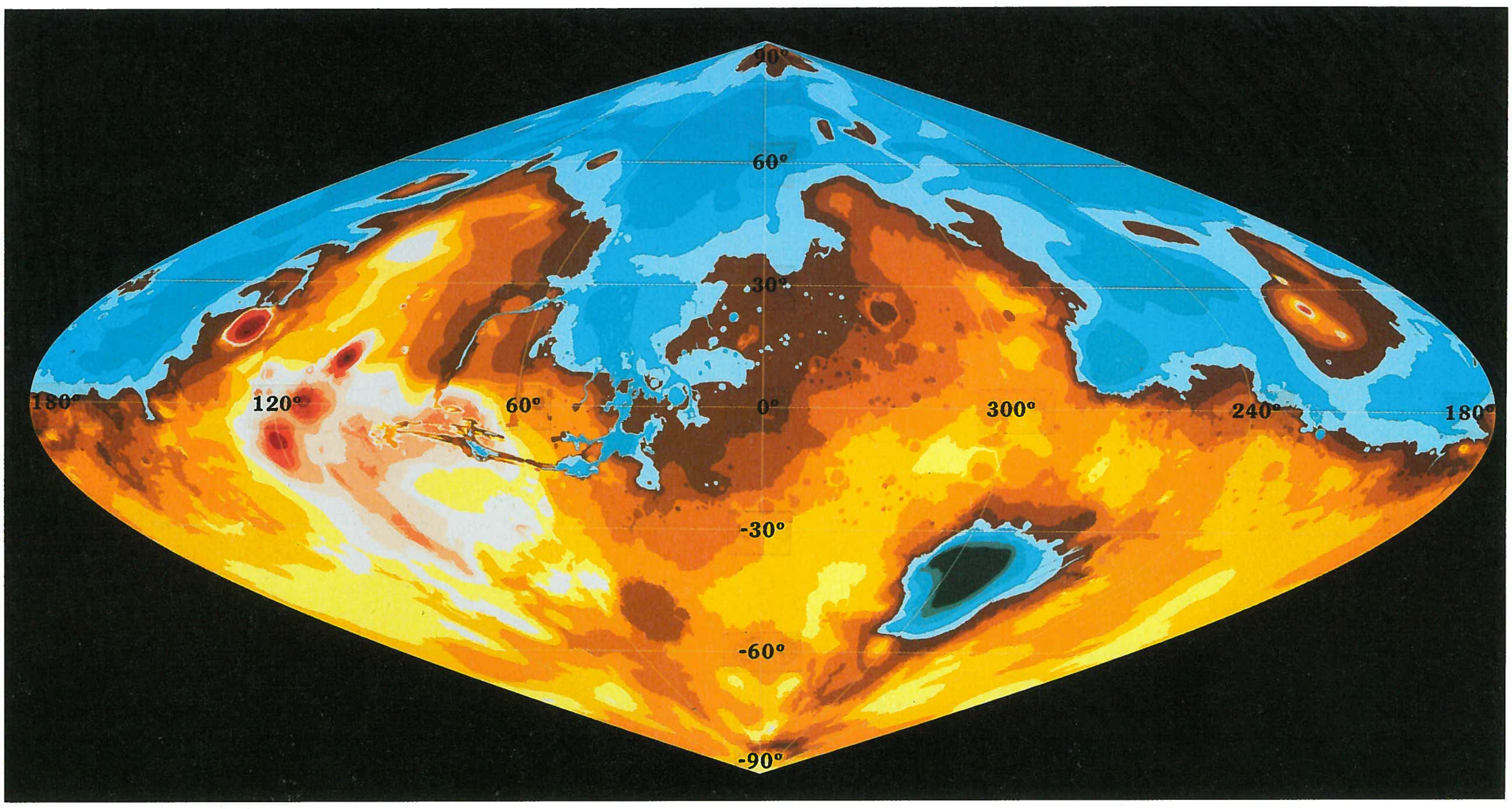


Fig. 5. Color-coded global topographic map of Mars (Sinusoidal Equal-Area Projection). The map was generated using a DTM derived from the global topographic map of Mars at 1:15,000,000 scale, 1-km contour interval.

Fig. 6. Stereo data obtained from Magellan radar images of Venus. The three images show the 24-km-diameter Riley Crater. From left to right, the images are from the first and third mapping cycles, which used two different look angles, and an orthorectified view color-coded with a digital elevation model derived from the displacements in the first two scenes.

Fig. 7. Geologic map on Mars showing relations of several small channels to geologic units having a wide range of ages. Uppercase letters of unit symbols denote system of martian timescale: N, Noachian (oldest); H, Hesperian (intermediate); A, Amazonian (youngest). Lowercase letters and numbers denote specific map units. The Nestus Vallis area is also shown in Fig. 14. Map is on a photomosaic base. Excerpt from Chapman et al. (1991) Geologic Map of Science Study Area 1B, West Mangala Valles Region of Mars, *U.S. Geol. Surv. Misc. Inv. Series Map I-2087, scale 1:500,000.*

Fig. 8. Image of a digital geologic map of Mars. Map units have been stored in digital form and can be reproduced in any desired form and correlated with other digital maps.

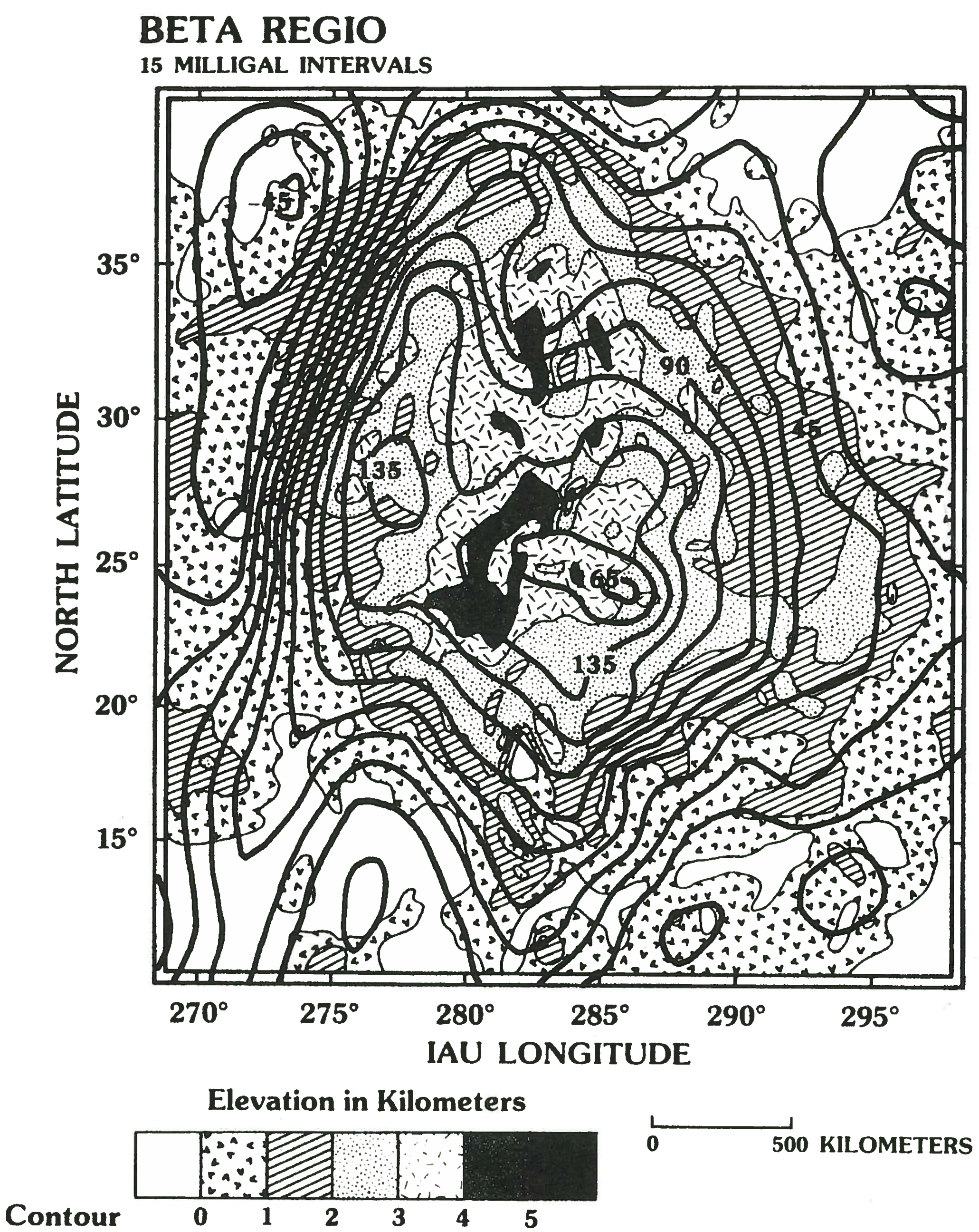


Fig. 9. *Overlay of gravity data on topographic data for Beta Regio on Venus [Fig. 13 from Phillips R. J. and Malin M. C. (1983) The interior of Venus and tectonic implications, in* Venus *(D.M. Hunten et al., eds.), Univ. of Arizona, Tucson]. Vertical gravity is evaluated at 200 km altitude, with a contour interval of 15 mgal. Topographic data are from the Pioneer Venus Altimeter, shaded in 1-km intervals. Note the strong correlation between local gravity and topography highs. Reprinted by permission of the University of Arizona Press.*

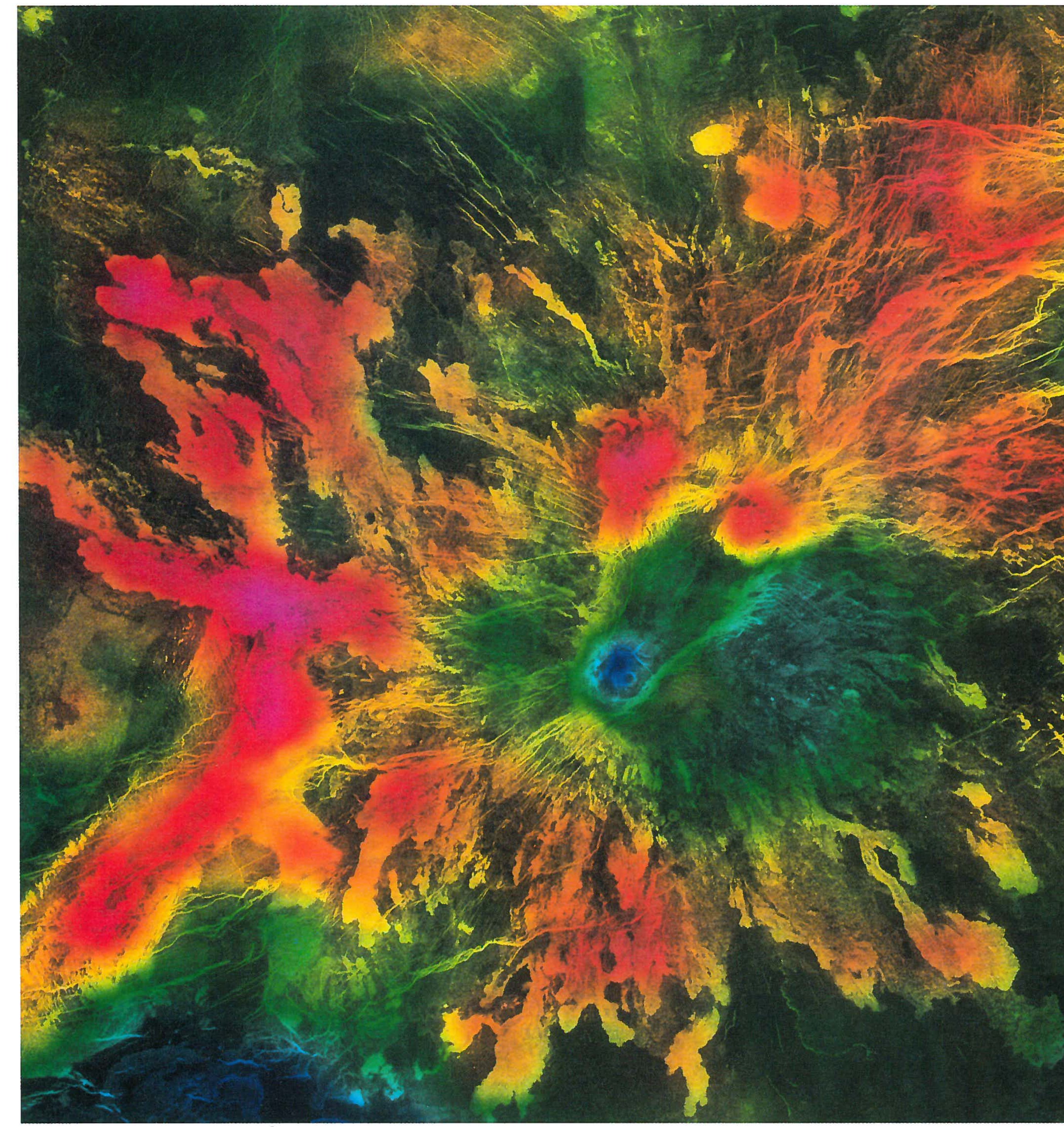


Fig. 10. *Magellan radar image data combined with radiothermal emission data. The area shown is 590 km wide and is located southeast of Phoebe Regio on Venus, centered at 12.5°S, 261°. Red corresponds to high emissivity while blue corresponds to low emissivity.*

Fig. 11. *Segment of a controlled image mosaic of Triton showing a dark volcanic plume. U.S. Geol. Surv. Misc. Inv. Map I-2275.*

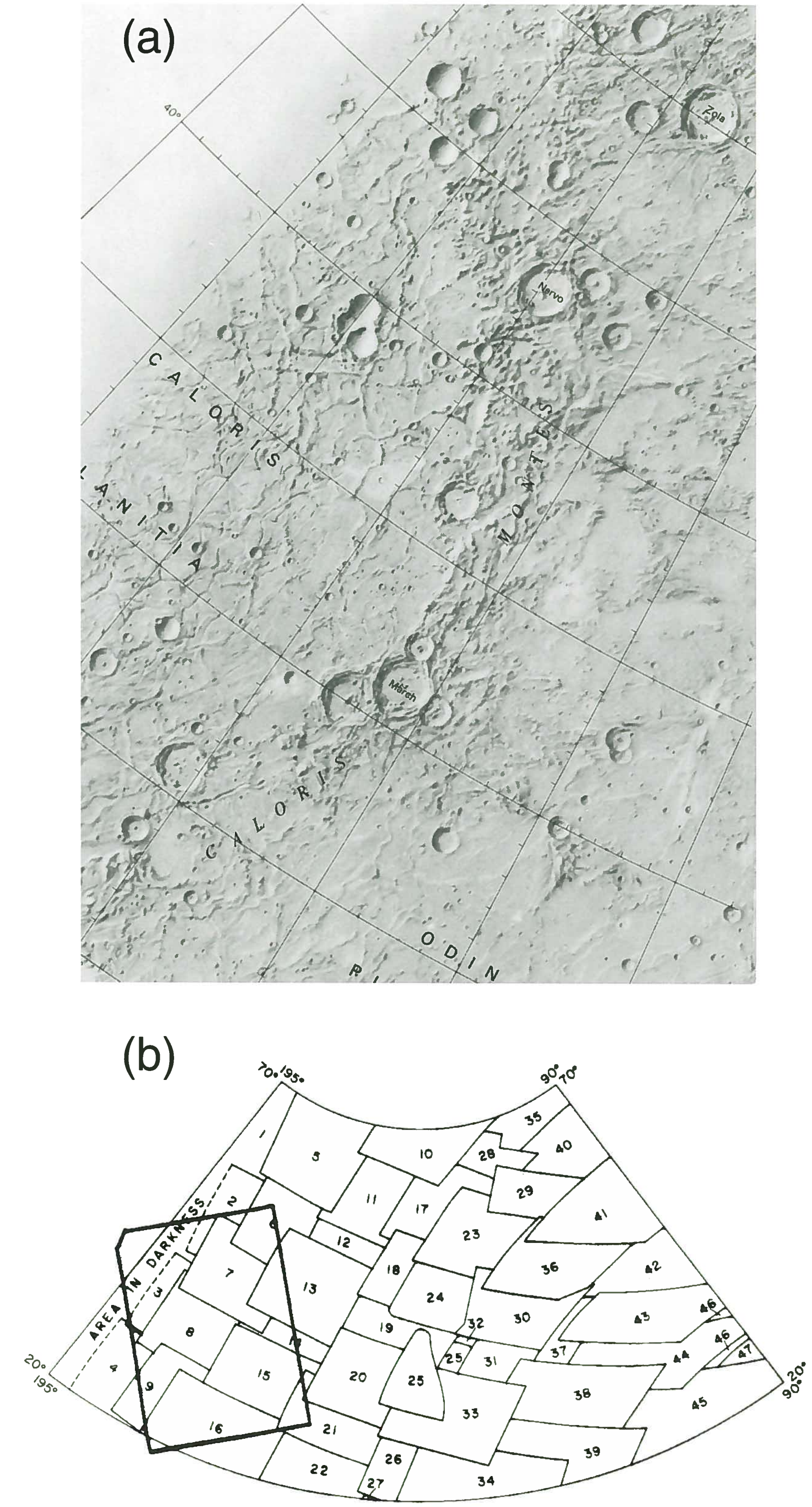


Fig. 12. *(a) Segment of the Shakespeare quadrangle of Mercury, showing part of the Caloris Planitia region. (b) A "cutline" index of Mariner 10 images used to make the map.*

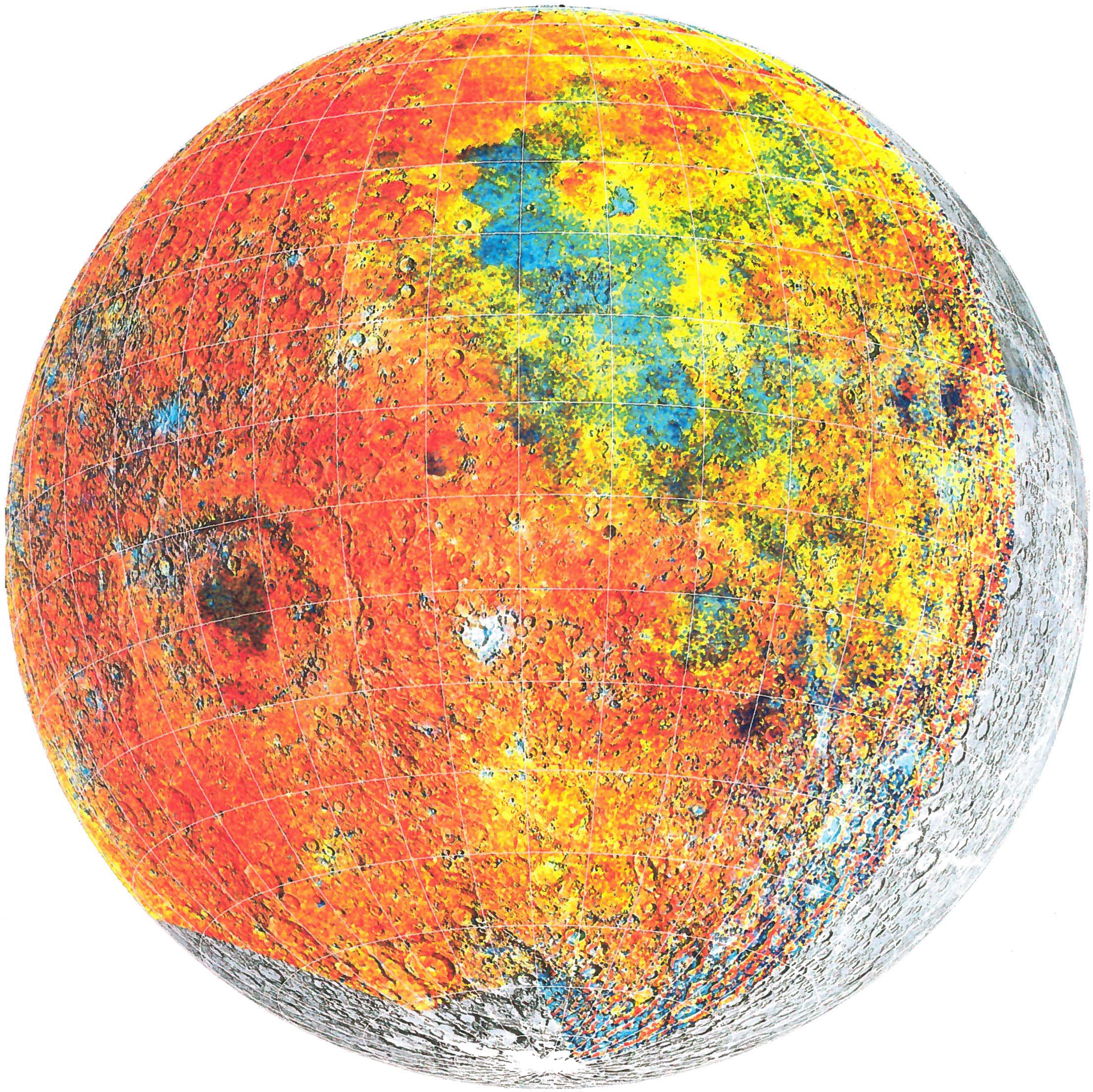


Fig. 13. Composite image of part of the western hemisphere of the Moon, made with a digitized shaded relief map and multispectral images returned by the Galileo spacecraft (U.S. Geological Survey).

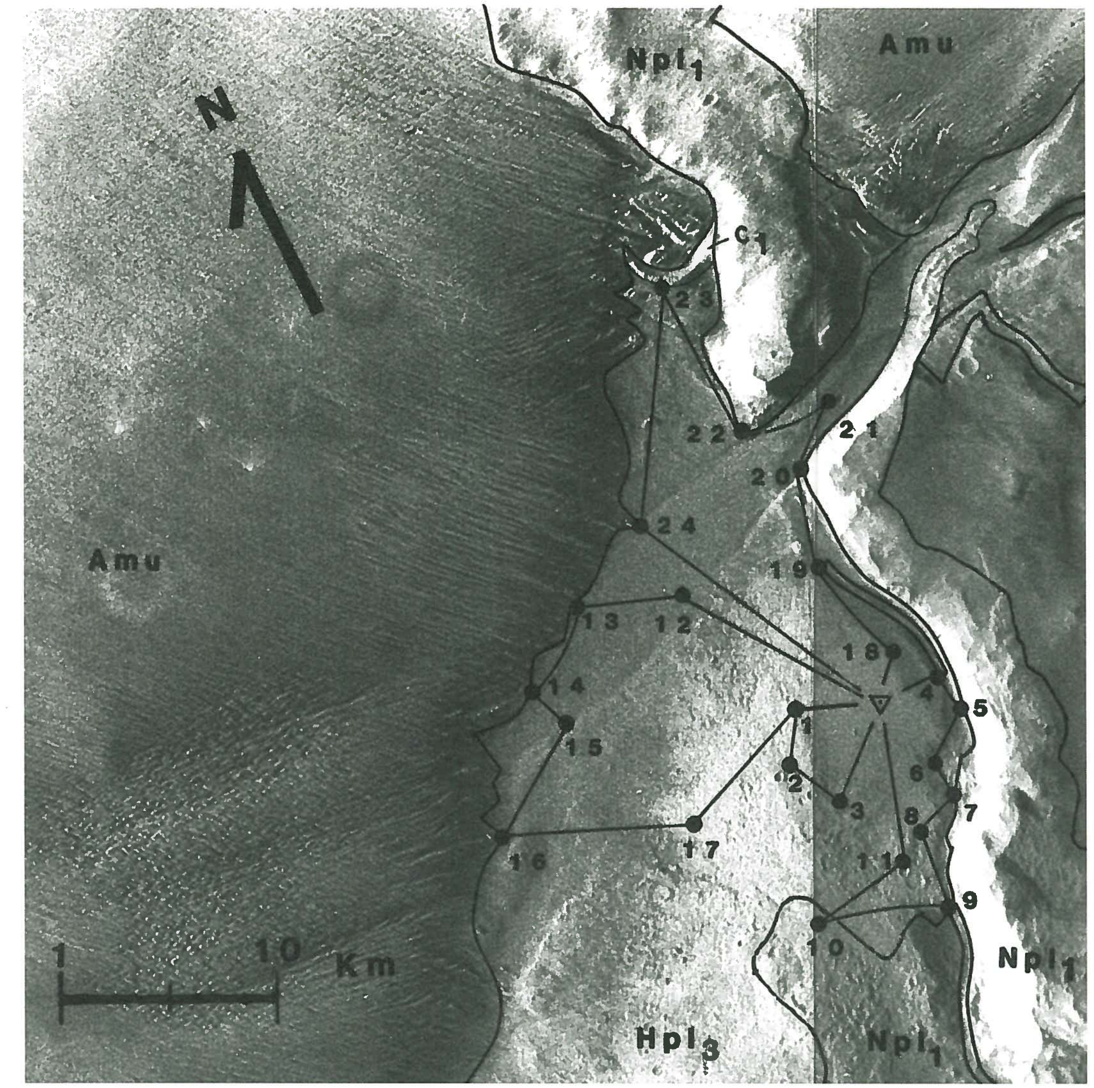


Fig. 14. Rover traverse and sample stations (numbers) in area of candidate landing site (triangle) in Nestus Vallis, Mars. Four traverse loops that begin and end at landing site are shown. Letter symbols denote geologic units; dark areas denote degraded channel material (compare with Fig. 7). From Chapman et al. (1991) Geologic Map of Science Study Area 1B, West Mangala Valles Region of Mars, *U.S. Geol. Surv. Misc. Inv. Series Map I-2087, scale 1:500,000.*

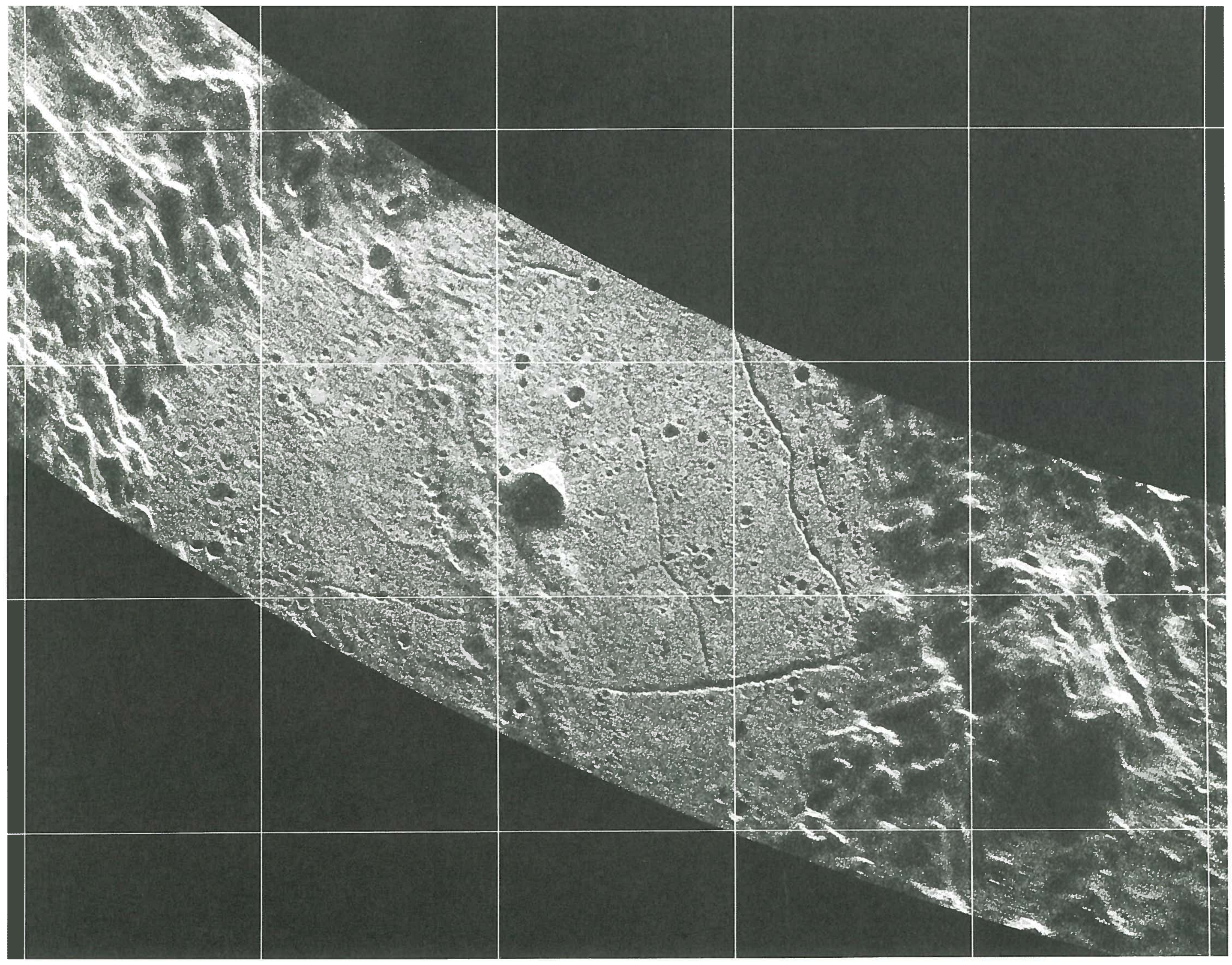


Fig. 15. *A high-resolution, Earth-based radar image of the lunar crater Alphonsus (119 km diameter), collected at Haystack Observatory. Image resolution is about 65 m/pixel. Bright areas occur where the surface is tilted toward the radar, or in regions that are very rough. Alphonsus has a large central peak and numerous narrow fractures in its floor. A few of the pits seen along these cracks are caused by explosive volcanic eruptions.*

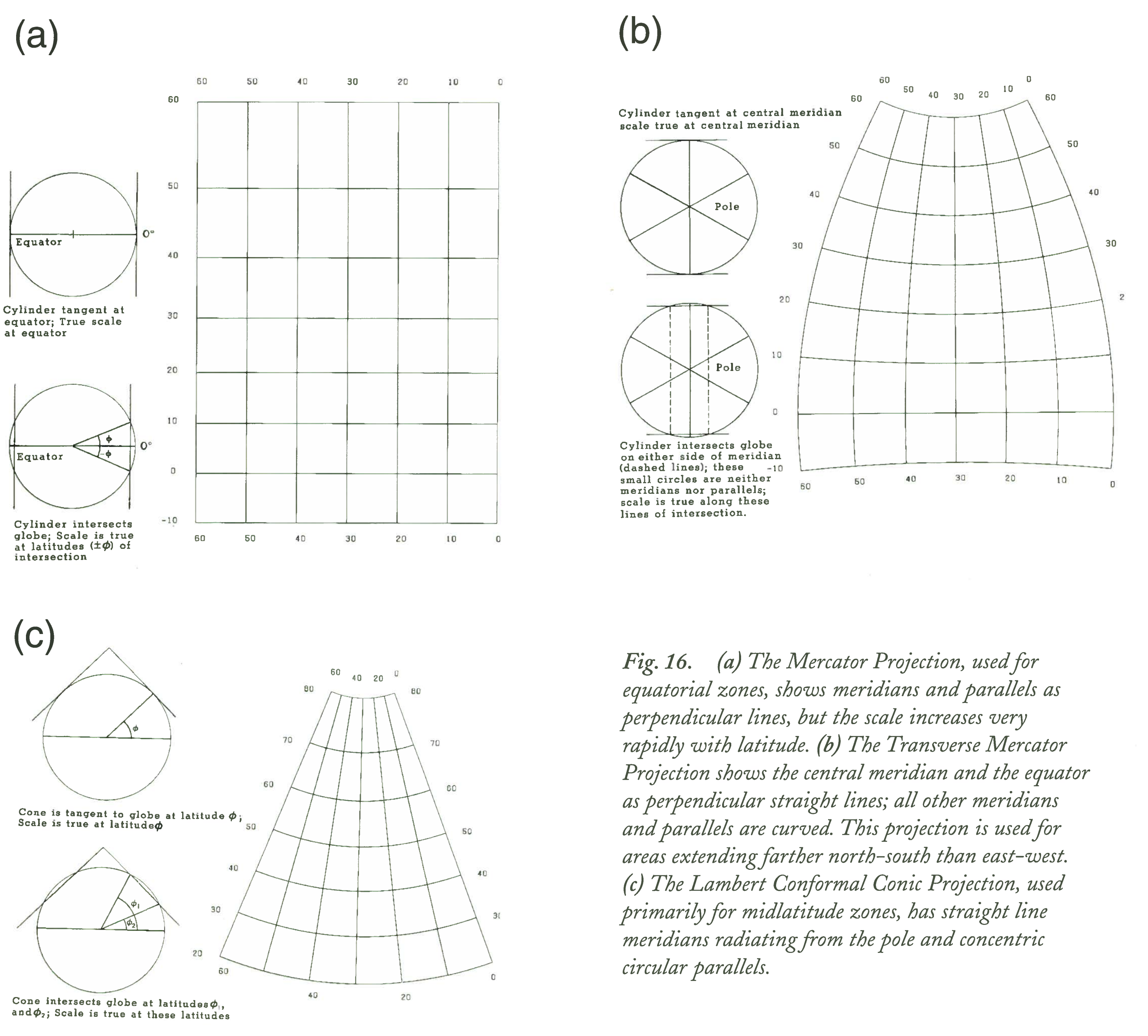
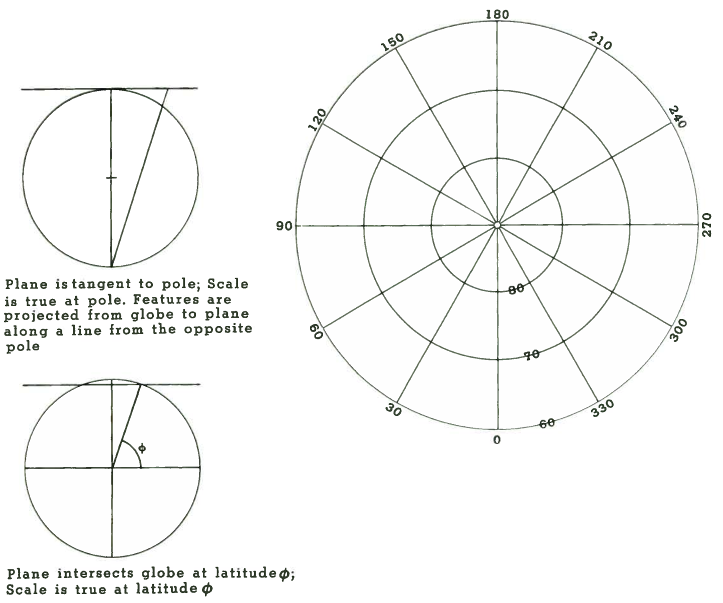
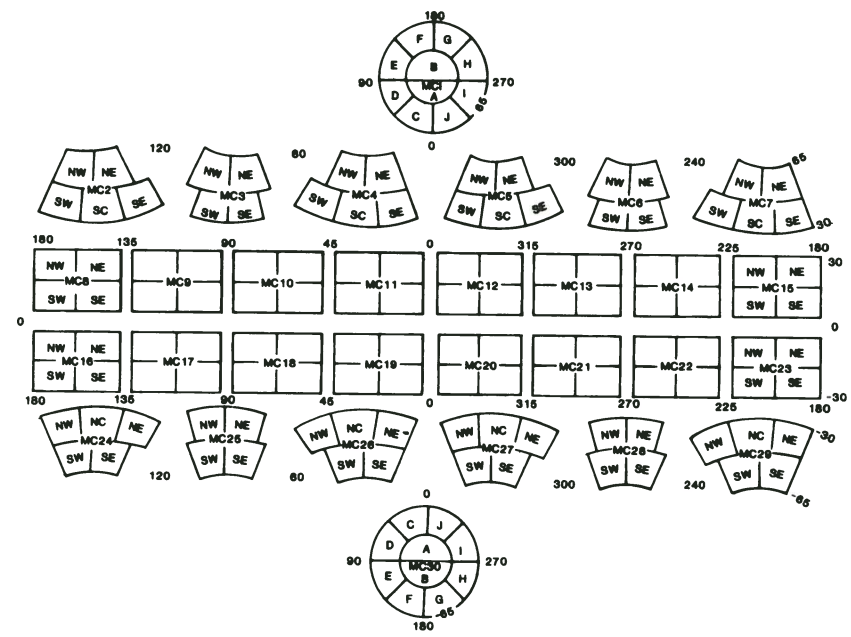


Fig. 16. ***(a)*** *The Mercator Projection, used for equatorial zones, shows meridians and parallels as perpendicular lines, but the scale increases very rapidly with latitude.* ***(b)*** *The Transverse Mercator Projection shows the central meridian and the equator as perpendicular straight lines; all other meridians and parallels are curved. This projection is used for areas extending farther north–south than east–west.* ***(c)*** *The Lambert Conformal Conic Projection, used primarily for midlatitude zones, has straight line meridians radiating from the pole and concentric circular parallels.*

(d)



(e)



(d) The Polar Stereographic Projection has meridians as straight lines radiating from the pole, while the parallels are concentric circles at equal spacing. (e) Mercator, Lambert Conic, and Polar Stereographic Projections are selected for 1:2,000,000-scale map series of Mars. Quadrangle limits are arranged to provide map sheets of approximately equal size.

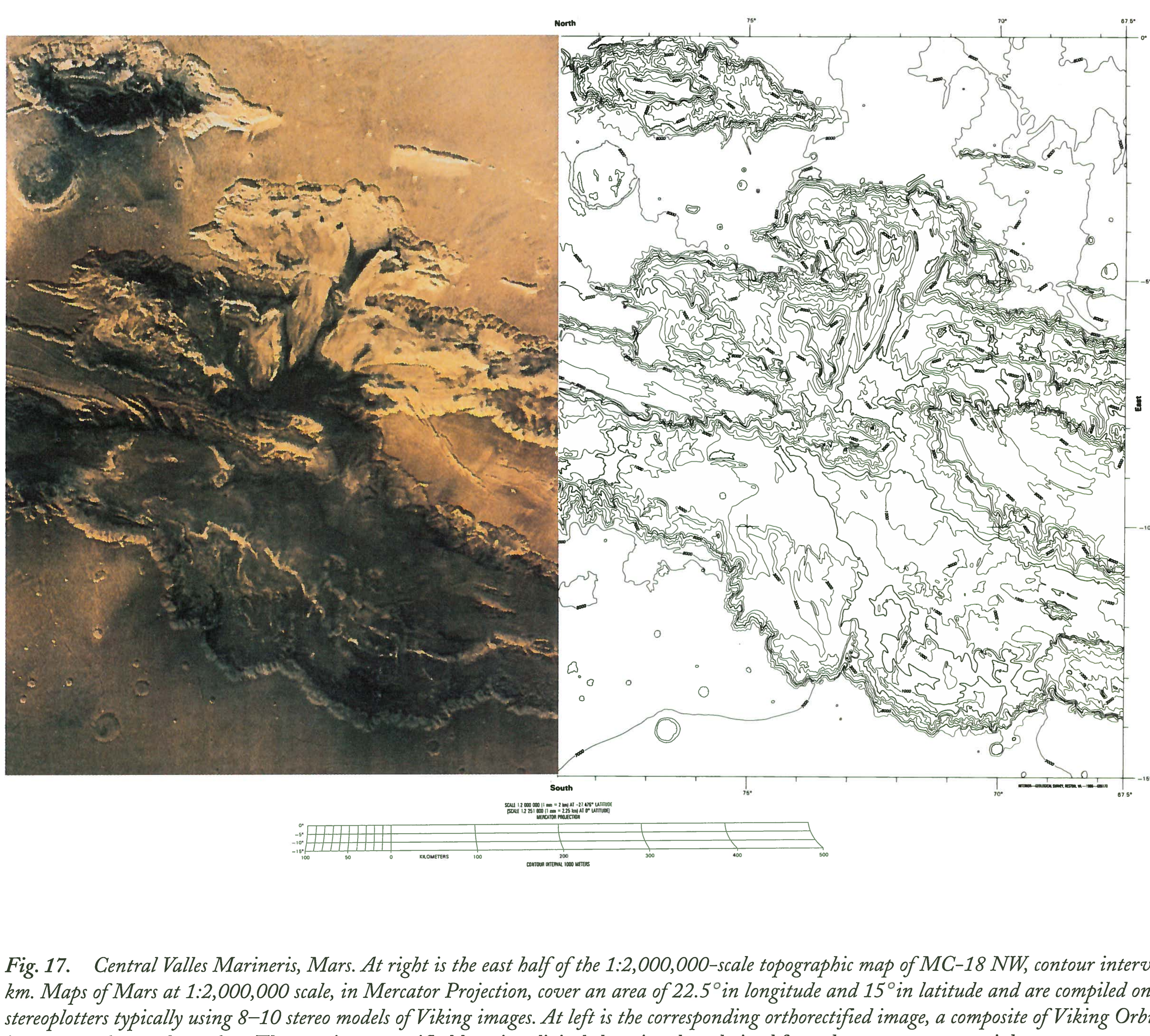


Fig. 17. *Central Valles Marineris, Mars. At right is the east half of the 1:2,000,000-scale topographic map of MC-18 NW, contour interval 1 km. Maps of Mars at 1:2,000,000 scale, in Mercator Projection, cover an area of 22.5° in longitude and 15° in latitude and are compiled on stereoplotters typically using 8–10 stereo models of Viking images. At left is the corresponding orthorectified image, a composite of Viking Orbiter images 663A42 and 663A44. The mosaic was rectified by using digital elevation data derived from the contour map on right.*

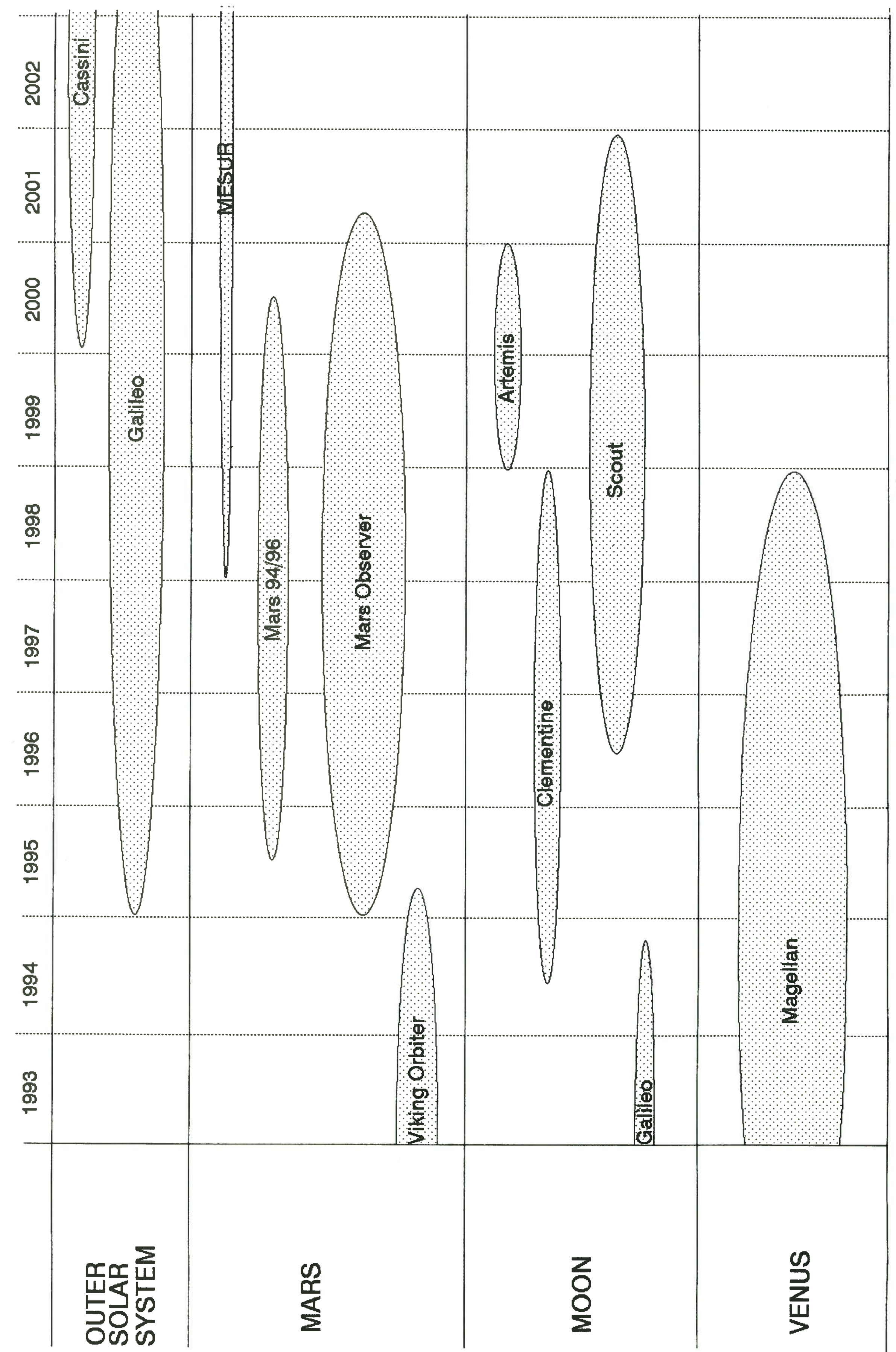


Fig. 18. Predicted levels of effort in planetary cartography.

PART 4

Cartographic Database

The modern planetary mapping program started with a major project to map the nearside of the Moon employing telescopic information. Many of the methods and techniques currently used in planetary mapping were developed during this period (see Part 3). Since that time, spacecraft missions have provided data to expand the mapping program, and refined methods and techniques have been developed to improve the cartographic products. The most important current and planned missions from this point of view are listed in Table 1.

In order to carry out the current program, coordinate systems must be defined, geodetic control must be established, and map nomenclature must be created.

MOON

For mapping the Moon the most significant missions were Apollo 15, 16, and 17, which carried excellent mapping and high-resolution panoramic cameras but obtained only limited coverage. Full coverage is obtained by adding Lunar Orbiter 4 and 5 photographs and Earth-based telescopic photographs to the Apollo data. The Soviet Zond 6 and 8 photographs of the western zone of the Moon were taken with a mapping camera and complement the Apollo images of the eastern zone. However, these disparate systems prevent uniform mapping at the desirable scales and resolutions. The early Lunar Orbiter (1, 2, and 3) and Apollo (8, 10, 11, 12, 13, and 14) missions acquired excellent photographs of both small and large regions of the farside and nearside, but lacked capability for accurate geodesy. This is also true of the Ranger missions. Earth-based radar images and altimetry data from the Apollo 15, 16, and 17 missions provide accurate elevation data and are a vital part of the lunar mapping effort.

There is an increasing likelihood that new lunar cartographic data will be obtained before the end of the decade from one or more programs. This may involve dedicated high-resolution stereo mapping, or laser altimetry and imaging, or both stereo and laser altimetry, as well as global multispectral mapping. The programs are not well defined at the moment, but there is a strong possibility that significant progress can be made late in the decade on lunar coordinates and topography.

MERCURY

The Mariner 10 spacecraft flew by Mercury three times at the same orbital longitude, giving essentially the identical illumination with each flyby. Because Mercury rotates very slowly on its axis (a period of 58.6 days), and because the high-resolution imaging data were obtained during a short period around the encounters, it was not possible to obtain images at all longitudes. The mapped region extends only from 10° to 190° longitude. Earth-based radar measurements of mercurian topography are valuable, and Mariner 10 radio occultation measurements of Mercury's radii are a significant contribution to the mapping program.

VENUS

Radar is the only sensor capable of imaging the surfaces of cloud-covered bodies such as Venus and Titan. The Magellan mission provided radar images of much of the surface of the planet at 100 m resolution, and has thereby significantly increased our cartographic database for Venus. The volume (more than all previous planetary missions combined) and accuracy of these data mean that Venus has become the most intensively mapped planet other than the Earth. The complex array of features seen in the Magellan data emphasize the need for good mapping of all the area in order to make sense of the geology of this planet. Earth-based radar images of Venus continue to provide valuable cartographic information that is complementary to the Magellan data.

MARS

Planetwide mapping coverage of Mars was accomplished by Mariner 9 using its wide-angle vidicon camera during the year that it was active in orbit. Viking Orbiters 1 and 2 imaged Mars at higher resolutions than Mariner 9 and with better-quality images; stereoscopic pictures were also taken. The Viking dataset is very large, with multiple coverage of selected regions and many areas sampled at very high resolution. The Soviet Mars 4 and 5 and Phobos 2 missions acquired images of selected regions; however, the dataset was small and did not support a large mapping effort. Planetary radii computed from radio occultations of Mariner 9 and the Viking Orbiters have been useful in compiling the global topographic maps. Radii computed from Earth-based radar are also important to the topographic mapping effort.

GALILEAN SATELLITES

The two Voyager spacecraft explored the Galilean satellites of Jupiter; Io and Europa are approximately the size of the Moon, and Ganymede and Callisto are approximately the size of Mercury. As the spacecraft approached, images of the entire surface areas of these bodies were taken as they rotated on their axes. The resolution of the images varies greatly with longitude, however, and in some places the distance was so great that the pictures were of very limited use for mapping. The best images of Io were taken by Voyager 1, and those of Europa were taken by Voyager 2. Both Voyager 1 and 2 took excellent images of

Ganymede and Callisto at different longitudes. Between these regions of good resolution the quality falls off rapidly because the satellites rotate so slowly that little new area was revealed while the spacecraft were close enough to take high-resolution images. The Galileo mission should fill in many areas of poor coverage and improve the best resolution by factors of 10 to 100.

SATURNIAN SATELLITES

The two Voyager spacecraft provided all the mapping data for the satellites of Saturn. The largest satellite, Titan, is cloud covered, so its surface could not be imaged. However, images encompassing all longitudes of Mimas, Tethys, Dione, and Rhea are recorded, and excellent pictures of interesting areas on Enceladus, Hyperion, and Iapetus were obtained. Again, the quality of the data varies greatly with longitude.

No new spacecraft data of the saturnian satellites are expected during the 10-year period covered by this report.

URANIAN SATELLITES

Images of the uranian satellites taken by Voyager 2 constitute the data for mapping these objects, and because of the high solar latitude at time of encounter, are limited to the southern hemispheres of these objects. Resolutions vary widely among the satellites, from 4 km on Titania down to 300 m on parts of Miranda. The best images of Miranda allowed stereoscopic mapping of parts of this satellite. No new spacecraft data on the uranian satellites are expected for well over a decade.

NEPTUNIAN SATELLITES

Image data from Voyager 2 with resolutions down to 1 km are the basis for maps of about half of Triton. Because of the active nature of the surface of Triton these have been of particular importance, and will be for reference to any data from a later Neptune Orbiter mission (data from which are more than 20 years away). Only one image shows surface features on the small satellite Proteus.

ASTEROIDS

The Galileo spacecraft obtained the first closeup images of an asteroid (Gaspra) in October 1991. About one-third the object was imaged at high enough resolution to make useful maps, and stereo coverage of this portion allows a good shape and digital topographic model to be developed. The Galileo spacecraft is scheduled to encounter the larger asteroid Ida on its final trajectory toward Jupiter. A mission to rendezvous with a near-Earth asteroid (NEAR) is the second scheduled flight of the Discovery series, and other Discovery missions may map other asteroids or comet nuclei. All these objects require use of techniques for mapping irregularly shaped objects.

PART 5

Current Status of Planetary Cartography

CONTROL NETWORKS

Control networks are composed of easily identified features whose coordinates have been determined by triangulation to provide reference points for mapping the surface and locating images. The control points are usually features, such as craters, whose shape is easily modeled so accurate image coordinates may be obtained. The accuracy of control networks varies widely because the camera calibrations and image resolutions vary substantially. Planetwide control networks exist for a few planets and satellites; however, most cover only a part of the surface imaged by a particular spacecraft.

Compilation of control networks of planetary bodies other than the Earth began with micrometer measurements of features on the Moon from telescopes. Later work used photographic prints and plates for measurements. Images taken by spacecraft (Zond 3, 6, 8; Lunar Orbiter 1–5; Apollo 15–17; Mariner 10; and Galileo) allow measurement of networks over the entire Moon. However, these control networks usually cover select regions and are not tied together. Thus there is still not a single unified control network of the entire lunar surface.

The control network of Mars is based on images taken from orbiting spacecraft (Mariner 9 and Viking 1 and 2). The initial control network (Mariner 9) was designed to achieve planetwide coverage for control of planimetric mosaicking at moderate resolution. Once higher-resolution Viking pictures were acquired, a planetwide network was derived for control of contour maps. A high-resolution (9 m/pixel) strip across the Viking 1 lander has been tied to stereo images providing local coordinates accurate to about 100 m.

The control network of Mercury covers about 45% of its surface and is based on the images taken by Mariner 10 on its three flybys.

During their tour of the outer planets, the Voyager spacecraft took images of many of the satellites that led to control networks and maps. Control networks of varying resolution and accuracies have been computed for all the large, ellipsoidal satellites of the outer planets.

A preliminary control network of Venus was constructed based on Arecibo and Venera 15/16 data. Magellan data are being used to substantially expand this network. Currently the Magellan north polar control network contains 654 points, and will eventually contain on the order of 1200 points.

MAP TYPES

Part 3 describes several types of maps that may be prepared at a given scale. Each of these types may be prepared at different scales, depending on scientific need and on data availability. Synoptic, or planetwide, maps are usually prepared at scales of 1:15,000,000–1:50,000,000 for planets of the size of Mars and Venus to 1:5,000,000 or even 1:2,000,000 for satellites as small as Mimas or Enceladus. The larger bodies are subdivided into map quadrangles at scales of 1:5,000,000, 1:2,000,000, and 1:500,000. "Topo only" refers to a contour map that has neither photomosaic nor shaded relief base. Feature nomenclature, map graticule, and other information may be included. "Relief" designates a shaded relief map prepared by airbrush techniques. Such a map usually contains no information other than feature nomenclature and map projection graticule. "Albedo" refers to a map showing surface brightness markings, in either black and white or in color. Albedo maps are drawn with an airbrush, with the albedo markings superimposed on a shaded relief map. Feature nomenclature and map graticule (but not topographic contour lines) are included. "Mosaics" are made from images that have been geometrically transformed and tied to map control on mathematically defined map projections. They may be assembled by hand with paper prints or in a computer from digital image files. Only feature nomenclature and map graticules are shown on mosaics. "Composite" maps are composed of shaded relief, albedo, or mosaics with superimposed topographic contour lines. Composite maps also show feature nomenclature, map graticules, and other pertinent information.

PUBLISHED PLANET AND SATELLITE MAPS

Since 1962 more than 1600 planet and satellite maps have been published (Table 5). Most of the maps are of the Moon (50%) and Mars (43%). The large number of lunar maps reflects the preparation for Surveyor, Lunar Orbiter, and Apollo programs. The production of lunar maps largely ceased after production of orthophotomosaics for Apollo 15,16, and 17.

Since the last 10-year plan was published, a much larger fraction of the data are being made available in digital format to include CD-ROM distribution.

ACCURACY AND QUALITY OF MAPS

The accuracy and quality of maps depend not only on the original data but on the techniques and resources available to turn the raw data into finished maps. Tables 6 and 7 give overviews of the status of accuracies of maps for different groups of objects that have been or soon will be mapped.

Optimum support of scientific research would be provided by maps that meet the following specifications, listed in order of priority:

1. *Global coverage with pixel size less than 1 km, uniformly distributed over the planet.* Many datasets contain a wide mix of resolutions, permitting global small-scale mapping but large-scale mapping only in a few areas. It is not possible to characterize the geology of a planet adequately with less than about 60–70% coverage. Diagnostic landforms typically have slope lengths of only 1 or 2 km. Landform slopes must also be resolved in order to distinguish morphology (for analysis of geologic structure) from albedo and surface coloration (containing compositional evidence).

2. *Global altimetry.* These data are used in geophysical study and regional geologic work. Quantifying geologic processes is not possible without slope and relief data. For example, which way would fluids flow on a given surface? Has the slope on a surface changed with time, as evidenced by outflow channels that now slope "the wrong way"?

3. *High-resolution metric relief information commensurate with image resolution for local areas.* This allows quantification of local textures, slopes, and volumes.

PLANETARY AND SATELLITE ATLASES

Atlases of planetary data have been published for nearly a century and reflect many different data sources and purposes. With the increasing volume and variety of spacecraft data, atlases have a growing role of providing overviews of solar system objects and of data collections. The following is a list of some of the planetary atlases that have been published.

Mercury

- *Atlas of Mercury*, Merton E. Davies et al., NASA SP-423, 1978.
- *The Atlas of Mercury*, Charles A. Cross and Patrick Moore, 1977.

Moon

- *Atlas of the Far Side of the Moon*, I. P. Lipskii, 1975.
- *Lunar Orbiter Photographic Atlas of the Moon*, David E. Bowker and Kenrick Hughes, NASA-SP 206, 1971.
- *Atlas of the Reverse Side of the Moon*, Part II, Y. N. Lipskiy et al., NASA-TF-514, 1969.
- *A New Photographic Atlas of the Moon*, Zdenek Kopal, 1971.
- *Lunar Atlas*, Dinsmore Alter, 1968.
- *Photographic Atlas of the Moon*, Zdenek Kopal, Joseph Klepe and Thomas W. Rackham, 1965.
- *Moon Atlas*, Valdemar A. Firsoff, 1962.
- *An Atlas of the Moon's Far Side: The Lunik III Reconnaissance*, N. P. Barabashov, A. A. Mikhailov, and Y. N. Lipskiy, 1961.
- *The Moon*, H. Percy Wilkins and Patrick Moore, 1961.
- *Photographic Lunar Atlas*, Gerard P. Kuiper, 1960.
- *Mond-Atlas*, Johan N. Krieger, 1912.
- *Atlas Photographique de la Lune*, 12 Vol., 1896–1910.

Mars

- *Images of Mars: the Viking Extended Mission*, Michael Carr and Nancy Evans, 1980.
- *Atlas of Mars*, the 1:5,000,000 map series, R. M. Batson, P. M. Bridges, and J. L. Inge, 1979.
- *Atlas risunkov Marsa*, N. P. Barabashov, 1961.

Saturn

- *Voyager 1 and 2 Atlas of Six Saturnian Satellites*, Raymond M. Batson et al., NASA SP-474, 1984.

Uranus

- *Atlas of Uranus*, Garry Hunt and Patrick Moore, 1989.

TABLE 5a. Status of planetary mapping.

Scale	Series	Percentage of Globe Covered	Number of Sheets	Date
Mercury				
1:5M	Special Caloris Basin map	<5	1	1979
1:5M	Shaded relief	45	9	1976–1977
1:10M	Special global	45	2	1987
1:10M	Mariner 10 reference mosaic	40	1	1974
1:15M	Shaded relief, albedo	45	2	1979
Venus				
1:15M	Northern hemisphere; shaded relief, Venera 15/16 radar image mosaic, geomorphology/geology (U.S./U.S.S.R. joint mapping project)	25	4	1989
1:50M	Altimetry map from Pioneer Venus, including VRM (MGN) planning chart	70	3	1980–1984
Moon				
<1:1M	Special area maps, contour maps in Apollo suborbital areas, etc.	<25	652	1962–1979
1:1M	Shaded relief and albedo (LAC series), some with contours	45	58	1962–1979
1:2M–1:2.75M	Shaded relief and albedo	75	16	1962–1971
1:5M	Shaded relief and albedo	90	9	1967–1992
1:10M	Shaded relief and albedo	90	5	1960–1970
Mars				
1:500K	High-resolution mosaics; from Viking Orbiter	15	172	1984–1991
1:250K–1:1M	Special area maps; from Mariner 9 and Viking Orbiter	10	19	1975–1980
1:2M	Controlled photomosaics; from Viking Orbiter	100	59	1979–1985
1:2M	Contour maps; from Viking Orbiter	50	64	1991–1992
1:5M	Shaded relief, some with albedo and contours; from Mariner 9 and Viking Orbiter; photomosaics from Viking Orbiter	100	77	1975–1992
1:15M	Shaded relief, some with albedo and contours; from Viking Orbiter	100	14	1985–1991
1:25M	Shaded relief, some with albedo and contours; from Mariner 9 and Viking Orbiter	100	15	1967–1991
Galilean Satellites				
1:1M–1:2M	Io controlled mosaic	5	2	1983–1987
1:5M	Io pictorial (airbrushed image map)	80	6	1984
1.5M	Europa pictorial + mosaic	35	4	1985
1:5M	Ganymede pictorial + mosaic	75	30	1984–1988
1:5M	Callisto Controlled Mosaic	60	14	1990
1:15M	Io shaded relief, color mosaic, pictorial	90	3	1987
1:15M	Ganymede pictorial	75	1	1991
1:15M	Callisto controlled mosaic	60	1	1991
1:25M	Pictorial: preliminary Voyager 1, Voyager 2, Io, Europa, Ganymede, Callisto	Io: 90 Eu: 35 Ga: 75 Ca: 60	4	1979
Saturnian Satellites				
1:2M, 1:5M	Mimas global pictorial	65	3	1981–1991
1:2M	Enceladus global pictorial, mosaic	60	3	1981–1991
1:5M, 1:10M	Dione global pictorial, mosaic	50	4	1981–1991
1:5M, 1:10M	Tethys global pictorial, mosaic	70	4	1981–1991
1:5M, 1:10M	Rhea global pictorial, mosaic	80	4	1981–1988
1:10M	Iapetus global pictorial, mosaic	30	3	1982–1991

TABLE 5a. (continued).

TABLE 5a. (continued).

Scale	Series	Percentage of Globe Covered	Number of Sheets	Date
Uranian Satellites				
1:2M	Miranda southern hemisphere pictorial, mosaic	35	3	1988
1:5M	Ariel southern hemisphere pictorial, mosaic	25	3	1988
1:10M	Umbriel southern hemisphere pictorial, mosaic	30	3	1988
1:10M	Titania southern hemisphere	30	3	1988
1:10M	Oberon southern hemisphere	25	3	1988
Neptunian Satellites				
1:5M	Triton pictorial, mosaic	40	2	1991
1:15M	Triton global pictorial	40	1	1991

TABLE 5b. Existing digital map series.

Scale (deg/pixel)	Series	Format	Percentage of Globe Covered	Number of Sheets	Dates
Mars					
1/256	Medium-resolution global	DIM	100	6	1991
1/64	Moderate and high-resolution topography	DTM	100	1	1992

TABLE 6. Estimated absolute accuracies of positions relative to coordinate systems achievable with various datasets.

	Horizontal	Vertical	Source of Data
Mercury	2[*] km	—	Mariner 10
Venus	50 km	0.5 km	Pioneer Venus
	5 km	0.5 km	Venera 15/16
	1 km	0.1 km	Magellan
Moon	2 km	—	Telescopic (nearside)
	10[†] km	—	Lunar Orbiter (farside)
	0.5[‡] km	0.1 km	Apollo Orbiter
Mars	5 km	1 km	Viking Orbiter
	1 km	0.2 km	Mars Observer
Jovian Satellites	5 km	1 km	Voyager
	1 km	0.2 km	Galileo
	5 km	—	Voyager
Saturnian Satellites	5 km	1 km	Voyager
Uranian Satellites	5 km	5 km	Voyager
Neptunian Satellites			

Relative accuracies are generally at least an order of magnitude higher than absolute accuracies. National Map Accuracy Standards require horizontal placement of 90% of features to be accurate to 0.5 mm at map scale, and vertical accuracies of 1/2 contour interval over 90% of the map area. These accuracies are not yet achievable in planetary mapping because of constraints in the nature of the data.

[*] Existing Mercury maps were compiled before geodetic control computations, on incomplete nets. Accuracies achieved are at least an order of magnitude below theoretical limits. New mapping with existing data could achieve the accuracies shown in the table.

[†] The lunar farside control net has not been refined to its potential accuracy. Discrepancies as large as 50 km exist in the base mosaic from which the most recent 1:5,000,000 map was compiled. New mapping with existing data on a recomputed control net could achieve the accuracy shown in the table.

[‡] A calibrated mapping camera was carried on the orbiting Command Modules of Apollo 15, 16, and 17, and was used to photograph about 20% of the eastern equatorial region of the Moon. High internal accuracies are achievable with this system, but in the absence of precise bench marks, the block of images "floats" on a far less accurate net.

TABLE 7. Status and future of map dataset quality.

	Coverage at 1 km Resolution		Global Altimetry		High-Resolution Topography	
	Existing	Potential	Existing	Potential	Existing	Potential
Mercury	45%	—	90%	—	—	—
Venus	—	100%[*]		100%[*]	—	TBD[†]
Moon	95%	—	90%	—	20%	—
Mars	100%	—		100%[‡]	1%	TBD[§]
Jovian Satellites	35%	75%	—	—	—	TBD[¶]
Saturnian Satellites	30%[**]	TBD[††]	—	—	—	TBD[‡‡]
Uranian Satellites	30%	—	—	—	1%	—
Neptunian Satellites	25%	—		—	—	—

The table shows the percentages of areas that have been (or can be) mapped according to criteria described in the text. "Existing" column includes mapping in current program. "Potential" column includes data from future programs, with technology that shows promise but may not have been fully demonstrated. Data-gathering sequences for mapping have not been fully defined for any future program except Magellan; mapping potential depends upon how data are actually collected.

* Magellan SAR.
† Undemonstrated potential exists for radargrammetric, radarclinometric, and interferometric mapping of topography at high resolution with Magellan SAR images.
‡ Mars Observer laser altimeter.
§ Undemonstrated potential for high-resolution photogrammetry with images from Mars Observer camera and Soviet Mars '94 three-line scanner.
¶ Possibility for stereophotogrammetry and photoclinometry with Galileo Solid State Imager.
** Does not include Titan.
†† Cassini mission may have potential for mapping small satellites with imaging systems, and for mapping Titan with SAR, depending on payload specification, but will not return these data before 2004.
‡‡ Potential for radar/photoclinometry, radar/photogrammetry with Cassini, depending on payload specification.

PART 6

Planetary Cartography Ten-Year Plan

This 10-year plan is designed to guide the production of cartographic products that support scientific research, planning for future planetary missions, and educational activities. The products are largely in four general categories: controlled image photomosaics, shaded relief and albedo maps, topographic maps, and selected thematic maps. All can be produced on paper, in digital form, or both.

The number of planetary cartographic products that could be compiled from existing and anticipated data exceeds the resources available to produce them. Maps listed are the basic materials of scientific research and exploration. Major map series provide the global and regional foundations required to characterize the surface of a planet or satellite, whereas special high-resolution maps are required to address topical issues. These are specified on an individual basis depending on scientific requirements. Also needed are special maps to select and certify landing sites, traverse the surface, and establish base sites. Once these sites are selected, additional specialized mapping will be required for engineering purposes, but such maps will require acquisition of new data and are therefore not dealt with in this report.

During the period covered by this report, new data from the Magellan (1990–1993) mission is on hand, and at least two U.S. planetary missions are scheduled to return significant data: Galileo (1995–1997) and Mars Observer (1997+). Additional major mapping missions to the Moon, Mars, and asteroids are possible during this interval, but are not yet approved. Other nations' spacecraft may yield data of relevance to this plan (such as the Russian Mars '94 mission), but these data are not dealt with specifically in this report.

This 10-year plan endorses the perspective that new or revised maps are essential for mission data analysis and for expeditious publication of scientific findings. Therefore, the PCWG makes the following recommendations.

GENERAL RECOMMENDATIONS

1. In the near future the planetary cartography effort should concentrate on the production of image and topographic maps of Venus with Magellan radar data and refining map bases for topical studies of Mars based on available data. Addi-

tional priorities include the preparation of lunar thematic maps, especially from the Galileo fly-bys and Earth-based data, and the production of digital image models of the large satellites of Jupiter from Voyager data to support the Galileo mission.

2. In the second half of the decade, the emphasis should be placed on mapping Mars based on Mars Observer data and on mapping Jupiter's satellites using Galileo data. Additionally, mapping of Venus, the Moon, and small solar system bodies should be continued.

3. A new era of planetary science may begin with a renewal of lunar exploration. Detailed models of basin-forming processes and of subkilometer crustal morphology are only two of many possible examples. Although small pieces of these puzzles can be examined with existing lunar data, new expeditions should provide precise data over the entire lunar surface.

Any meaningful lunar investigations will require development of a much more precise and consistent geodetic and cartographic base than the one that remained after the Apollo program was completed. Substantial improvement in that base should be made with existing data, but the resolution and accuracy would remain inconsistent and unsuited for supporting new scientific exploration. Cartographic data should be key objectives of forthcoming lunar and asteroidal missions.

RECOMMENDED MAP PRODUCTS

Although many map products will be compiled from data yet to be acquired, our knowledge of the target objects and of mission limitations allows the desirable products to be well defined. Because the Galileo satellite tour has not been finalized, the coverage of Jupiter's satellites is not as well constrained as those for Mars Observer. New phenomena or problems encountered after data acquisition will control the preparation of geologic maps or other special products; however, these unforeseen circumstances are unlikely to cause recasting of the basic plan.

The greatest uncertainties are associated with new targets, such as asteroids, with new instruments such as imaging radar and laser altimeters, and variable mission durations. Analysis of asteroid data may present wholly unexpected science problems requiring modification of mapping technologies. Mars Observer may have a significantly extended mission that could provide opportunity for additional map products.

Mapping products are increasingly needed in digital form, but it is mandatory that most materials also be provided in traditional paper format. DTMs are also required for studies of the surface of a planet where quantitative measurements of elevation, slope, volume, or aspect are required for effective scientific analysis. All cartographic products should therefore be distributed on traditional and digital (CD-ROM) media.

The scientific rationales of the various map products are given below and summarized in Tables 8 and 9. The level of estimated effort is shown in Fig. 18.

SCIENTIFIC RATIONALES FOR CARTOGRAPHIC PRODUCTS FROM EXISTING DATA

This section presents a short summary of some of the scientific rationales for the various planetary map products needed in the next decade. This is an overview of

TABLE 8. Planned convention map series.

Scale	Series	Justification	Number of Sheets	Dates
1:50M	Shaded relief, contours	Global characterization of surface morphology on a continental scale	1 prelim 1 final	1992 1996
1:50M	SAR mosaic, contours	Global cartographic database to support preliminary science analysis	1 left-look 1 right-look 1 composite	1992 1993 1993
1:10M	SAR mosaic, contours	Regional-scale, global cartographic base to support preliminary regional science analysis	8 left-look 5 right-look 6 composite	1992 1993 1993
1:10M	Shaded relief, contours	Global characterization of morphology at regional scale	8 prelim 8 final	1993 1996
1:10M	Digital shaded relief *	Characterization of regional morphology in area of available data	2 final	1993
1:5M	SAR mosaic, contours	Base maps for regional geologic mapping of entire planet	32 prelim 62 final	1993 1994
1:5M	Digital shaded relief *	Characterization of morphology in area of available data	21 final	1994
1:1.5M	SAR mosaic, full resolution	Full-resolution archive of Magellan SAR images	100 prelim 334 final	1993 1995
1:1.5M	SAR mosaic, contours	Full-resolution precision metric topography in areas of available stereoscopic SAR images	2 prelim 5 prelim 25 final	1993 1994 1999
1:1.5M	Digital shaded relief *	Full-resolution characterization of morphology in area of available data	3 prelim 80 final	1992 1996
Moon				
1:2M	Image mosaics, contours (Scout)	Systematic cartographic/topographic database of Moon—supports all future lunar exploration	37	1997–2002
1:5M	Shaded relief, contours	Regional-scale topography, shaded relief	3	1997–1998
Mars				
1:500K	Image mosaics (Viking Orbiter)	Supports Mars geological mapping/topical studies program	16 yr	1992–1995
1:500K	Image mosaics, contours (Mars Observer, Mars '94/96)	Supports Mars geological mapping/topical studies program	5 prelim 5/yr final	1995 1996–2000
1:5M	Shaded relief, albedo, contours (Viking Orbiter)	Supports Mars regional studies, data acquisition sequencing from Mars Observer and Mars 94/96	60	1992 1995
1:5M	Image mosaics (Viking Orbiter), contours (Mars Observer, Mars '94/96)	Provides independently controlled, high-density global topographic base; provides quantitative control of existing cartographic base	30	1995–1998
1:15M	Shaded relief and albedo (Viking Orbiter), contours (Mars Observer, Mars '94–96)	Provides independently controlled, high-density global topographic base; provides quantitative control of existing cartographic base	1 prelim 1 final	1995 1998

TABLE 8. (continued)

Scale	Series	Justification	Number of Sheets	Dates
Galilean Satellites†				
1:15M	Shaded relief, albedo, contours	Global characterization of surface morphology and coloration	4 prelim 4 final	1997 2000
1:15M	Color mosaic, contours	Global cartographic database to support science analysis	4 prelim 8 final	1997 2000
1:5M	Color mosaic, contours	Base maps for regional geologic mapping	38 prelim 76 final	1996–2005
1:2M–1:100K	Color mosaic, contours	Full-resolution photo archive	10 prelim 50 final	1997 2005
TBD Special Maps (Any Planet, Satellite, or Asteroid)				
TBD	Shaded relief, albedo, contours	Global characterization of surface morphology and coloration	≈5 prelim ≈10 final	1993–2005
TBD	Color mosaic, contours	Global cartographic database to support science analysis	≈10 prelim ≈20 final	1993–2005
1:2M–1:50K	Color mosaic, contours	Full-resolution photo archive of best-resolution images for topical studies	≈10 prelim ≈50 final	1993–2005

* Shaded relief derived by digital processing of left- and right-looking SAR images of the same area—possible over only 25% of Venus.
† All series based on Voyager and Galileo data as appropriate.

TABLE 9. Planned digital map series.

Resolution (deg/pixel)	Series	Justification	Number of CD-ROMs	Date
Venus				
1/4, 1/16, 1/64	DIM, digitized shaded relief	Index images, global characterization of surface morphology	None; used as index files on other CD-ROMs	1995
1/64	DIM, nomenclature, contours	Regional-scale, global cartographic base to support regional science analysis	1 left-look 1 right-look 1 composite	1993 1994 1994
(75 m/pixel)	Digital shaded relief*	Characterization of morphology in area of available data	40	1995
(75 m/pixel)	DIM	Full-resolution archive of Magellan in SAR images	220	1993–1996
(75 m/pixel)	DTM	Full-resolution precision metric topography in areas of available stereoscopic SAR images	50	1993–1998

TABLE 9. (continued)

Resolution (deg/pixel)	Series	Justification	Number of CD-ROMs	Date
Moon				
1/16, 1/64, 1/256	DTM, multispectral DIMs, digitized shaded relief (Apollo)	Precision topography to support current scientific investigations and to strengthen geodetic computations with data from Scout, Clementine, and Artemis	1	1993
1/256–1/2024	DTM, multispectral DIMs (Scout, Clementine)	Global lunar digital database	>100	1996
Mars				
1/16, 1/64	DIM, digitized shaded relief	Index images, global characterization of surface morphology	None; used as index files on other CD-ROMs	1998
1/1024–1/8192	DIM (Viking Orbiter, Mars Observer, Mars '94/96)	High-resolution images to support special mapping requirements and Mars geological mapping	5/yr	1993–2002
1/256	DTM (Mars Observer)	Full-resolution precision metric topography to support special mapping requirements and Mars geological mapping	prelim 6 final	1997–2002
Galilean Satellites				
1/32	DIM (Voyager)	Global cartographic database to support current science analysis and Galileo data acquisition	2	1994
1/16, 1/64, 1/256	DIM, digitized shaded relief	Index images, global characterization of surface morphology on a regional basis	None; used as index files on other CD-ROMs	1998
1/256	DIM (Galileo/Voyager)	Global cartographic database to support science analysis	12	1997–2002
1/64	DTM (Galileo)	Best-resolution topography	4 prelim 4 final	1997–2002

* Shaded relief derived by digital processing of left- and right-looking SAR images of the same area—possible over only 25% of Venus.

important scientific questions; it is not a research plan. Examples of scientific studies that depend on map products are given for each scientific question. The list will evolve greatly as knowledge increases. All studies require global, regional, and higher-resolution products in some proportion. Products include image maps, topographic maps, DIMs, and DTMs.

Venus (Magellan, Arecibo, and Venera 15/16 Data)

1. *Model the process of crustal evolution on a planetary body of size and composition similar to the Earth.* Scientific studies should be to (a) characterize the stratigraphy and morphology of the venusian surface by making geological maps based on radar images, stereoscopic views, and backscatter characteristics; (b) characterize tectonic processes on Venus' surface and relate the resultant landforms to possible forcing mechanisms; (c) identify diverse volcanic processes to understand the methods of internal heat loss and the role that volcanism has played in creating the present-day surface; (d) correlate the gravity field with surface topography and morphology to investigate compensation mechanisms; and (e) search for temporal changes in volcanic activity, tectonism, and eolian processes. Global, regional, and high-resolution planimetric and topographic maps, DIMs, and DTMs are necessary for these studies.

2. *Determine the age of the surface of Venus.* Scientific studies should be to (a) generate cumulative impact crater size/frequency distribution curves for major geologic units; and (b) identify and tabulate any other indicators of age such as states of erosion, superposition of units, and tectonic modification of units. DIMs and DTMs at various scales are most important for this work.

3. *Model the effects on surface processes of the high-temperature, high-pressure environment on Venus.* Scientific studies should be to (a) determine geometries and volumes of volcanos to determine magnitude of erupted magma, (b) determine the distribution of surficial sediments and erosional forms, and (c) model the weathering processes at different altitudes on Venus. DTMs, high-resolution DIMs, and thematic maps are most important for this work.

4. *Model the mechanics of cratering and the mechanics and rheology of crustal materials on Venus.* Scientific studies should be to (a) measure impact crater depth/diameter ratios and other shape parameters to model impact cratering mechanics on a "hot" planet with a high gravity and dense atmosphere, and (b) model the rheology of crustal materials on Venus based on the estimated ages and accurate elevations of surface morphology. High-resolution DIMs and DTMs are particularly relevant to these studies.

Mars (Earth-based Radar and Viking Data)

1. *Model effects of climate evolution or change on surface geology.* Scientific studies should be to (a) determine slopes and cross sections of landforms such as probable fluvial channels and rock glaciers, and vertical relief of landforms such as polar caps, scarps, impact crater rims and floors; and (b) determine the volumes of sedimentary deposits and the altitudes and stratigraphic positions of possible paleo-shoreline features. High-resolution DTMs are required for this work.

2. *Refine existing models of the volcanic and tectonic history of Mars.* Scientific studies should be to (a) determine the tectonic structures by preparing high-resolution maps of scarps, joint and fracture patterns, faults, ridges, and similar features; and (b) determine the relative chronologies of these features. High-resolution products are particularly important to these studies.

3. *Identify topical problems uniquely amenable to solutions with data from Mars Observer and potential lander, rover, and sample return missions.* Scientific studies should be to (a) investigate local landforms and surface processes with the highest-resolution Viking Orbiter images, and (b) investigate geomorphic variability of the martian surface at subdecameter scale. Thematic maps and the highest-resolution DIMs and DTMs are particularly relevant to this work.

Moon (Galileo, Digitized Lunar Orbiter, and Earth-based Data)

1. *Investigate basin-forming processes associated with Mare Orientale and other lunar farside basins.* Scientific studies should be to (a) determine the distribution and diversity of highland materials surrounding the Orientale impact basin, and (b) map the distribution and spectral properties of mare deposits on the lunar farside. Galileo multispectral data are important for this effort.

2. *Investigate the subkilometer surface morphology of the Moon to study the geologic processes operating at this scale.* Scientific studies should be to (a) determine the detailed spatial distribution of impact and pyroclastic ejecta on the lunar nearside, and (b) determine local topography in support of siting of lunar bases.

Galilean Satellites (Voyager 1 and 2 Data)

1. *Characterize the tectonic processes on Ganymede using full resolution digital mosaics and the J2000 coordinate system.* Scientific studies should be to (a) measure horizontal displacements and poles of rotation of crustal block on Ganymede, and (b) model regional effects of basin-forming impacts.

SCIENTIFIC RATIONALES FOR CARTOGRAPHIC PRODUCTS USING DATA FROM FUTURE MISSIONS

Mars (Mars Observer and Mars '94 Data)

1. *Refine the global topography and geophysics of Mars.* Scientific studies should be to (a) establish global and regional relations between topography and gravity for fundamental characterization of martian tectonic behavior, and (b) determine amounts of volcanic and sedimentary materials to permit the modes of compensation to be modeled using the topographic and gravity data.

2. *Investigate the history of cratering, tectonics, erosion, and volcanism on Mars.* Scientific studies should be to (a) determine the distribution and relative chronology of craters, surfaces, deposits and structures; (b) determine the spatial distribution and compositions of surface materials to study the volcanic and sedimentary history of Mars; (c) refine existing models of surface processes using high-resolution data [the 2-m resolution of the high-resolution Mars Observer Camera (MOC), combined with topographic data from the wide-angle MOC and the Mars Observer Laser Altimeter (MOLA), will allow many quantitative studies of the martian surface]; (d) investigate the morphologic expression of regolith volatiles by topographic mapping of polar deposits, rampart craters, debris flows,

fluvial channels, and periglacial features; and (e) model the rheological properties of lava flows using high-resolution topography to measure slopes.

3. *Determine the types and distribution of mobile surface materials on Mars and document the amounts and patterns of their temporal variability.* Scientific studies should be to (a) model the seasonal changes in martian surface materials such as dust, sand, and frost, and their relationship to topography and to general wind patterns; and (b) measure the topography of various deposits and superposed erosional forms that are related to the deposition or erosion of the mobile materials.

Galilean Satellites (Galileo)

1. *Investigate temporal change on the volcanically active moon Io.* Scientific studies should be to (a) search for changes in the distribution of landforms and albedo features on Io since the Voyager observations using image and topographic comparisons, (b) map the thermal distribution of hot spots such as calderas and recent lava flows on Io using the Near-Infrared Mapping Spectrometer (NIMS) data, (c) search for small impact craters, (d) establish the full range of volcanic features and their relations to resurfacing mechanisms and rates, and (e) relate tectonic structures to volcanic features.

2. *Refine models of the tectonic and cratering history of the icy satellites, particularly Europa and Ganymede.* Scientific studies should be to (a) determine the morphologies and temporal relations of structures on Ganymede and Europa, and (b) determine the relative ages of surface units on the icy satellites based on crater densities.

3. *Model the physical properties of the icy satellites.* Scientific studies should be to (a) map the distribution of surface materials based on quantitative photometric study, and (b) model the rheology of crustal materials on the icy satellites on the basis of their three-dimensional morphology. These models require stereoscopic surveys from which DTMs can be derived.

Small Bodies (Galileo, NEAR)

1. *To determine the density, overall mechanical properties, regolith properties and distribution, and geologic histories of small bodies such as asteroids and the small moons of Jupiter.* Scientific studies should be to (a) model the relationship between overall shape, crater morphologies, crater ejecta, and structural features; (b) model the physical properties of surface materials on asteroids and small satellites; and (c) measure the morphology of impact craters to model cratering mechanics at very low gravity. DTMs are critical to these investigations.

This report does not include the possible effects of a significant program to send humans to the Moon or Mars. Requirements and priorities for any such programs will be dealt with separately as required.

PLANET AND SATELLITE ATLASES

Atlases are important references because they provide in a single volume a compendium of cartographic information. Such a format is convenient for both professional investigators and the general public. Atlases may contain photomosaics, shaded relief maps, topographic maps, individual images, photoindexes, and written descriptions of our understanding of planets and satellites. Many publications have been titled "atlas," but to date only four publications can be considered true comprehensive planetary atlases: *Atlas of Mercury* (NASA SP-423), based on information from Mariner 10, *Atlas of Mars* (NASA SP-438), based on information from Mariner 9, *Atlas of Mars: The Viking Global Survey* (NASA SP 506), and *Voyager 1 and 2 Atlas of Six Saturnian Satellites* (NASA SP-474). Because planetary atlases are such important references, the PCWG recommends the publication of atlases of planets or satellite systems as missions complete significant surveys, such as those of Venus, Mars, and the Galilean satellites.

ESTIMATED LEVEL OF EFFORT

The estimated level of effort for the recommended plan is shown in Fig. 18. Amounts are based upon expectations of some extensions of the nominal missions of Magellan and Mars Observer. There is less opportunity, proportionately, for extending the Galileo mission. As noted above, any impact of a major lunar or Mars initiative is not dealt with in this figure.

TABLE 10. Required conventional map series from programs that are as yet undefined.

Scale	Series	Justification	Number of Sheets	Dates
Moon				
≥1:500K	Image maps, contours	Selection and qualification of scientifically important sites for landings, bases, and traverses	100?	1996–2005
Mars				
1:15M	Image map, contours	Global planning map for landings, bases, and traverses	3	2000
1:5M	Image maps, contours	Regional-scale scientific evaluation of potential sites for landings, bases, and traverses	5	2000–2015
1:2M	Image maps, contours	Regional-scale scientific evaluation of potential sites for landings, bases, and traverses	20	2005–2015
≥1:500K	Image maps, contours	Selection and qualification of scientifically important sites for landings, bases, and traverses	100?	2005–2015
1:100K	Phobos, Deimos: image maps, contours	Scientific planning for utilizing the satellites of Mars as a part of martian exploration	8	2005–2015
Asteroids and Comets				
1:100K	Image maps, contours	Scientific planning for explorations, rendezvous, and landings on asteroids and comets	20?	2000–?

TABLE 11. Required digital map series from programs that are as yet undefined.

Resolution	Series	Justification	Number of CD-ROMS	Dates
Mars				
1/4096 deg/pixel; ≈15 m/pixel	DIM	Selection and qualification of scientifically important sites for landings, bases, and traverses	3000	2005–2015
1/256 deg/pixel; 231 m/pixel; ±50 m vertical	DTM	Selection and qualification of scientifically important sites for landings, bases, and traverses	50	2005–2015
1/16 deg/pixel; ≈5–12 m/pixel	Phobos, Deimos: DIM	Scientific planning for utilizing the satellites of Mars as a part of martian exploration	1	2005–2015
1/16 deg/pixel; ≈5–12 m/pixel; ±50 m vertical	Phobos, Deimos: DTMs	Scientific planning for utilizing the satellites of Mars as a part of martian exploration	1	2005–2015
Asteroids and Comets				
1/16 deg/pixel; ≈5–12 m/pixel	DIM	Scientific planning for explorations, rendezvous, and landings on asteroids and comets	5?	2000–?
1/16 deg/pixel; ≈5–12 m/pixel; ±50 m vertical	DTM	Scientific planning for explorations, rendezvous, and landings on asteroids and comets	5?	2000–?