PLANETARY CARTOGRAPHY IN THE NEXT DECADE (1984-1994)

NASA

PLANETARY CARTOGRAPHY

IN THE

NEXT DECADE (1984-1994)

THE PLANETARY CARTOGRAPHY WORKING GROUP

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Contents

Introduction

The Planetary Cartography Working Group has assessed the cartographic products required to support science and planetary exploration during the next ten years. To aid in this task, the Working Group solicited suggestions and recommendations from the general planetary science community to help identify and establish priorities for map products required for research projects in a variety of disciplines (appendix A). The objective of the plan contained in this report is to keep the number of map sheets to a minimum while still supporting the requirements of the entire user community, and to do so within the constraints imposed by available financial and institutional resources.

The Working Group considered only major map series or first-order maps needed to characterize the surface physiography of a planet or satellite. Included in these considerations are maps needed as bases for plotting geologic, geophysical, geochemical, and atmospheric phenomena and for planning future planetary exploration. These products consist of three types of maps: controlled photomosaics, shaded relief maps, and topographic contour maps. All of these maps should be published so that they are available to the scientific community and to the general public. Interpretive maps, such as geologic maps, and special purpose maps have not been considered by the Working Group.

The total mappable surface area of planets and satellites in the solar system is approximtely 1.6×10^9 km^2. This area is distributed as shown in figure 1. During the past twenty years, an enormous amount of information on these surfaces has been acquired by various space missions. High-resolution (10-100 m) Viking images of Mars, Voyager images of the satellites of Jupiter and Saturn, Mariner 10 images of Mercury, and Lunar Orbiter and Apollo photographs of the Moon are currently available for production of cartographic products. In the next decade (1984-1994), these data will be augmented by a large quantity of new information from existing or planned planetary missions (table 1). Voyager will acquire images of the satellites of Uranus and Neptune in 1986 and 1989, Galileo will return high-resolution images of the Galilean satellites of Jupiter beginning in 1988, and the Venus Radar Mapper will return 1-km resolution radar images of more than 90 percent of the surface of Venus, also beginning in 1988. In addition, a Mars Geoscience/Climatology Orbiter (MGCO) may begin transmitting data in 1991. This mission will require a comprehensive Mars data base for analysis and display of its scientific return and may provide significant radar altimetry data.

The most important cartographic data from past and future missions consist of 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 data sets and examined by various analysis techniques—is it possible to achieve a comprehensive view of a planet or satellite and an understanding of its evolution.

Controlled photomosaics provide the user with a scaled regional image formatted to a given map projection. They consist of many mosaic images that have been computer enhanced, and scaled and geometrically transformed with respect to a mathematically defined coordinate system. Photomosaics contain only one version of an image that is usually processed for maximum discrimination of surface structure. As a result, low-frequency regional relief and albedo patterns are suppressed.

Shaded relief maps are renditions of the topography and albedo constructed with an airbrush by a skilled cartographer. They compliment photomosaics by displaying other types of information such as albedo, by eliminating image and mosaic artifacts, and by converting sun-angle, photometric, and rectification effects into easily interpretable topography. Shaded relief maps are usually the only practical way to display planet-wide topography and albedo because available images have large variations in resolution or illumination. They also provide an ideal base upon which topographic contours and other data sets can be displayed.

Topographic contour maps provide a third dimension to mapping. They furnish quantitative information on landform elevations, volumes, profiles, and slopes required to formulate models of geologic and geophysical processes. Topographic contour maps can be constructed by photogrammetric methods or from radar altimetry data.

The digital map is a cartographic product that will become extremely important in the next decade. These maps consist of digital arrays of map data such as elevations and geochemistry that are geometrically ar-

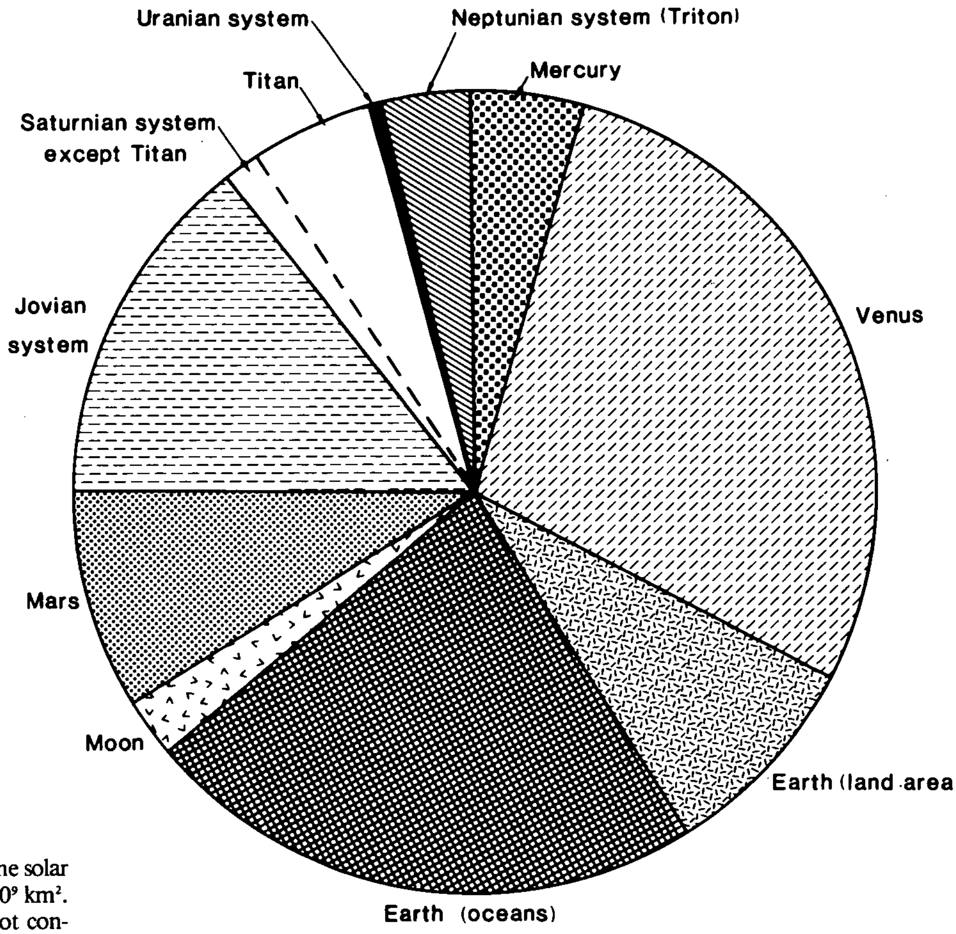


Figure 1.

Solid 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. Asteroids and comets are very small compared to the other bodies and would add a negligible area.

ranged in ways that facilitate coregistration of different data sets. Few versions of this type of map are printed; they exist as digital arrays in mass storage devices and are used on interactive computer terminals. This kind of usage, however, requires user access to elaborate computer hardware, software, and training.

The general-purpose printed maps considered in this report will always be required because they constitute a carefully compiled, widely available synopsis of map data, and because many users have neither the capability nor the need for digital coregistration of data sets. This report is therefore restricted to identifying requirements and products that can be addressed with currently operational cartographic technology. At present the methods for producing and using digital data sets are insufficiently defined to allow meaningful evaluation by the Working Group. Publishable map products derived from digital data sets will be considered in a future revision of this report.

Although maps are essential to planetary science, they also serve other broad purposes. They are required for planning future exploration, for indexing photography and other science data, for education, and for fostering a better public awareness and understanding of the solar system.

This report comprises five parts. The first part summarizes the recommendations of the Working Group. The second part reviews the uses of planetary cartography and its importance to mission support, science data analysis, education, and as an indexing base. The third part deals with the current and anticipated data base from which maps can be compiled. The current status of planetary cartography is outlined in part four. Part five consists of the recommendations of the Working Group for map products to be produced during the next ten years. These recommendations may need revision as future missions become better defined or changed, particularly those for the 1989 to 1994 time period. The entire report will be revised periodically as map data bases, mission planning, and cartographic technology evolve.

Table 1. Planned (January 1984)
Planetary Missions Returning Mapping Data
During the Next Ten Years

Planet	Mission	Encounter	Expected Data
Uranus Satellites	Voyager	1986	High- to medium-resolution images of Miranda and Ariel
Venus	Venus Radar Mapper	1988	High-resolution radar images and altimetry covering about 90 percent of surface
Galilean Satellites	Galileo	1988	High-resolution images of Callisto, Ganymede, Europa, and Io
Neptune Satellites	Voyager	1989	High- to medium-resolution images of Triton
Mars	Mars Geoscience/Climatology Orbiter	1991	Global high-resolution altimetry, geochemical and geophysical data

Part 1

Summary of Recommendations

This section is a summary of the recommendations contained in part 5 of this report. There are four general recommendations concerning the prioritization of the Planetary Cartography Program, and recommendations for specific maps and atlases to be produced during the ten-year period covered by this report. The recommendations for specific map products are listed by map type within two five-year periods. They are not listed in order of priority and are discussed in detail in part 5.

General Recommendations

The following are the general recommendations for the prioritization of the Planetary Cartography Program:

- The five-year period between 1984 and 1989 should be used to complete the mapping of Mars from Viking data and of Galilean and Saturnian satellites from Voyager data.
- In 1986, the highest priority should be Uranian satellite maps for the support of Voyager science.
- From 1989 through 1993, the highest priority should be assigned to compiling maps of Venus from Venus Radar Mapper (VRM) data, the Galilean satellites from Galileo data, and the Neptunian satellites from Voyager data to support the science requirements of these missions.
- During the period 1991 to 1993, cartographic products derived from the Mars Geoscience/Climatology Orbiter should have a high priority.

Recommended Map Products (1984-1989)

The recommended map products for the five-year period between 1984 and 1989 are presented in table 2.

Recommended Map Products (1989-1994)

The recommended map products for the five-year period between 1989 and 1994 are presented in table 3.

Planet and Satellite Atlases

The Planetary Cartography Working Group recommends the production of planet and satellite atlases as soon as the map products required to complete them are available. Specifically, a revised atlas of Mars based on Viking data and a revision of the atlas of Saturnian satellites should be completed no later than 1989. An atlas of Venus based on the Venus Radar Mapper data and an atlas of the Galilean satellites based on Voyager and Galileo data should be compiled when the appropriate cartographic products are available ($\sim$1994).

Table 2. Recommended Map Products (1984-1989)

Controlled Photomosaics	Shaded Relief and Albedo Maps	Topographic Contour Maps
Mars 1:2 000 000 Mars 1:500 000 Rhea 1:5 000 000 Uranus Satellites 1:5 000 000	Galilean Satellites 1:15 000 000 Galilean Satellites 1:5 000 000 Uranus Satellites (Synoptic) Saturn Satellites (Synoptic) Mars 1:5 000 000 Lunar 1:5 000 000 Revised Frontside Mercator	Mars 1:2 000 000 Mars 1:500 000

Table 3. Recommended Map Products (1989-1994)

Controlled Photomosaics	Shaded Relief and Albedo Maps	Topographic Contour Maps
Venus 1:5 000 000 Radar Galilean Satellites 1:2 000 000 Triton Mosaics (Synoptic)	Venus Global (Synoptic) Venus 1:5 000 000 Galilean Satellites 1:5 000 000 Triton (Synoptic)	Venus Global (Synoptic) Venus 1:5 000 000

Part 2

Utilization of Planetary Cartography

Cartographic products are essential for planetary exploration, scientific data analysis, and major decision-making processes. They provide a permanent record of knowledge that may be analyzed, compared, generalized, and abstracted. Planetary maps display surface features within standard coordinate systems that provide precise locations and in some cases elevations. In addition to surface features, other data that can be displayed include geology, surface chemistry, geophysical measurements, and surface atmospheric effects. Three-dimensional displays derived from elevation data allow quantitative description of surface features necessary for deciphering the geologic and geophysical evolution of planetary surfaces and interiors. Planetary maps are also essential for planning more detailed exploration of a planet or satellite by orbiters, probes, landers, rovers, and return samplers; for indexing photographic records and other science data; for the education of future scientists; and for a better public understanding of the solar system and our place in it.

Science Data Analysis

The study of the evolution of the planets depends heavily on analysis of the dimensions and areal distributions 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, as well as individual photographs, are commonly used for geologic interpretation of volcanic, impact cratering, tectonic, eolian, and fluvial processes (fig 2). Cartographic products at various scales are the basis for systematic geologic mapping of the Moon, the terrestrial planets, and outer planet satellites (figs. 3, 4, 5, and 6). Shaded relief quadrangle maps and photomosaics have supported geologic mapping programs of the Moon, Mars, Mercury, and the Galilean satellites (figs. 7 and 8). Topical studies such as crater morphology, fluvial channels, volcanic flows and vents, and erosion of buried surfaces can be shown on special maps or in three-dimensional displays with selected vertical exaggeration (fig. 9). Contour maps provide important information on the spatial distribution of heights from which slopes and volumes can be derived (figs. 10 and 11). These quantitative data are important for interpreting geologic and geophysical phenomena and for devising models to explain them.

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 (figs. 12 and 13).

Display of orbital geochemical data also requires cartographic products. X-ray fluorescence, gamma ray, and multispectral color information must be plotted on maps to determine the relationship of the geology of a planet or satellite (fig. 14). Such geologic/geochemical relationships provide insight into the genesis and history of complex regions.

Atmospheric sciences also benefit from cartographic

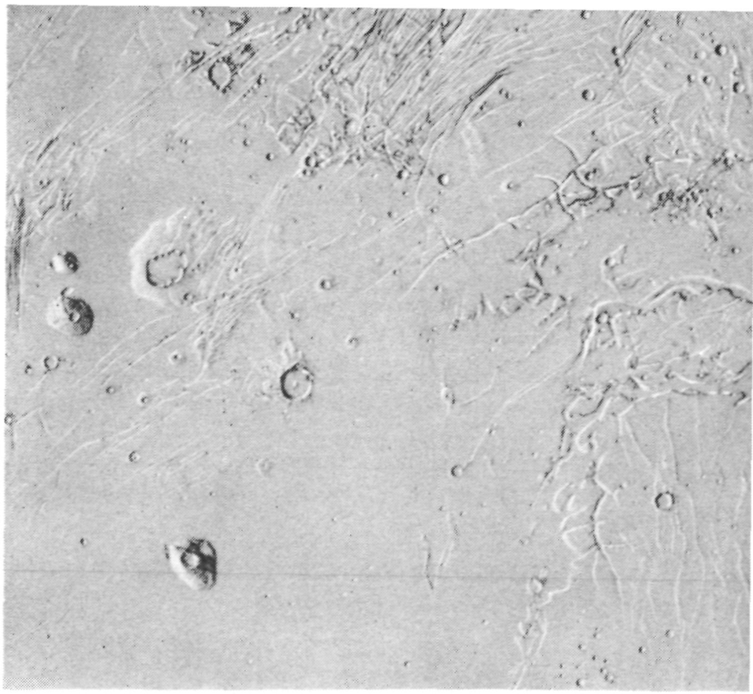


Figure 2.
Controlled photomosaic of part of the Phoenicis Lacus NE quadrangle of Mars. Viking Orbiter images were used to make this mosaic (USGS map I-1206).

Figure 3.
Part of a synoptic map of Mars. This map shows the Kasei Vallis region as it appears on the 1:15 000 000 shaded relief map of Mars (USGS map I-1320). This map segment covers approximately 1900 by 3000 km.

products. Studies of the distribution and directions of Martian wind streaks provided information on the near-surface atmospheric circulation of Mars (fig. 15). Local and regional topographic information is used to explain orographic effects in the atmosphere.

Indexing

Data returned from spacecraft are intractable until placed in their correct spatial context. For example, hundreds of images are often used in the compilation of a single map. "Footprint" plots and cutline diagrams (figs. 16 and 17) are compiled as overlays to aid researchers in determining the scale and location of images of features they wish to study in detail.

Similarly, nonimaging data such as radar tracks or footprints of spectroscopic sensors must be plotted on maps if the data are to be applied to the study of specific surface features or processes. For example, data from the Mars Geoscience/Climatology Orbiter and from the Lunar Geoscience Orbiter will be plotted at 1:5 000 000 and other scales.

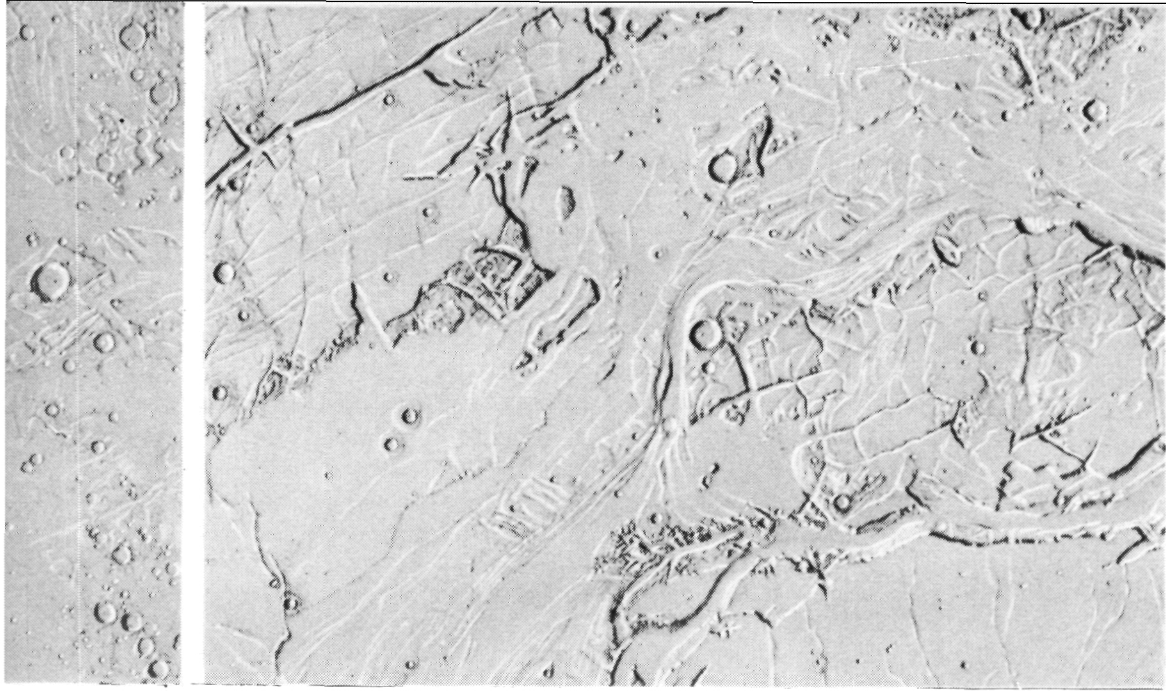


Figure 4.
Part of a 1:5 000 000 quadrangle. This map shows the Kasei Vallis region as it appears on the shaded relief version of the *Lunae Palus quadrangle on* Mars (USGS map I-1511). The map segment covers approximately 1000 by 650 km.

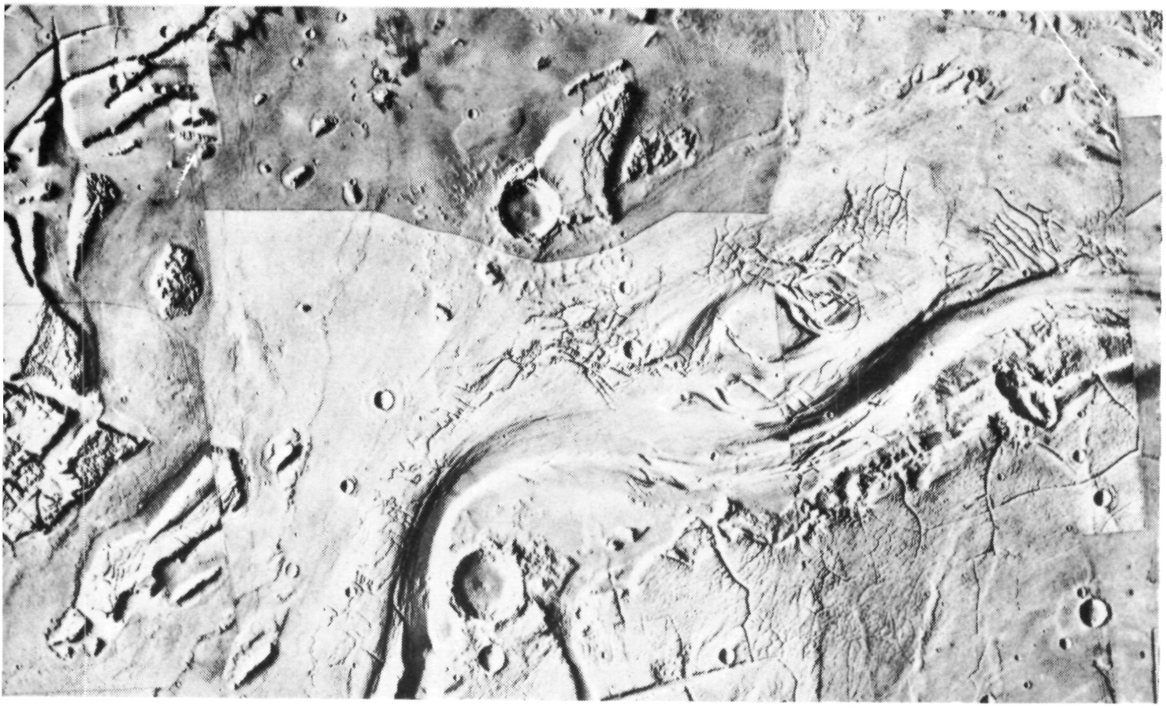


Figure 5.
Part of a 1:2 000 000 quadrangle. This map shows part of the Kasei Vallis region as it appears on the controlled photomosaic of the Lunae Palus NW quadrangle of Mars (USGS map I-1303). The map segment covers approximately 450 by 250 km.

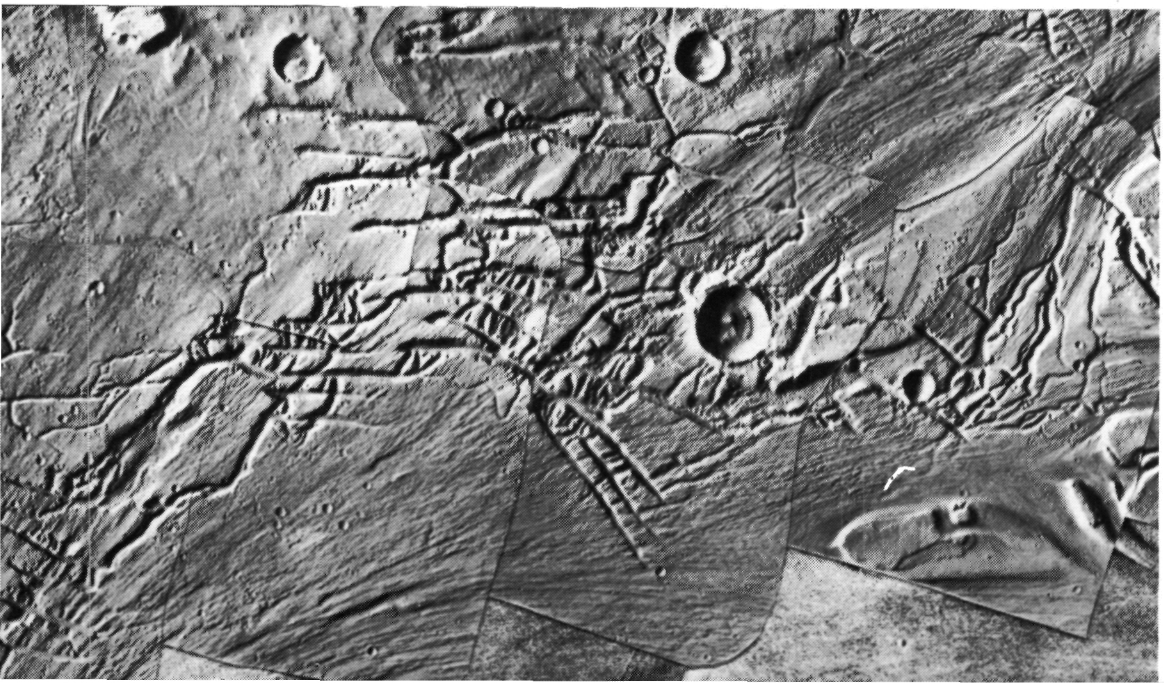


Figure 6.
Part of a 1:500 000 quadrangle. This map shows part of the Kasei Vallis region of Mars as it appears on the 1:500 000 controlled photomosaic of part of the Lunae Planum region of Mars (USGS map I-1588). The map segment covers approximately 110 by 60 km.

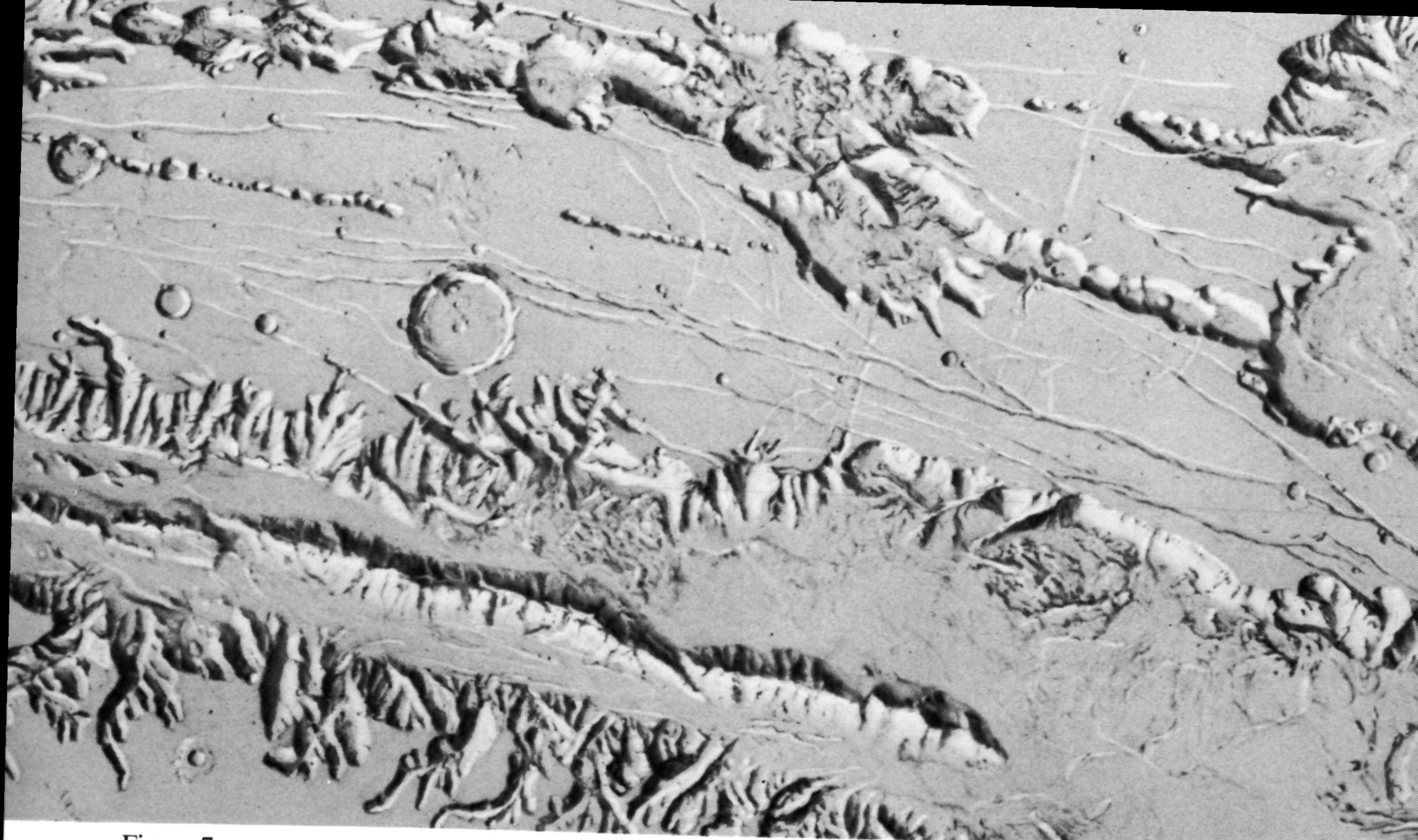


Figure 7.
Part of a shaded relief map of the Coprates NW quadrangle of Mars. This map was made with Mariner 9 and Viking Orbiter images. Only surface landforms are shown. Albedo markings are intentionally omitted (USGS map I-1295).

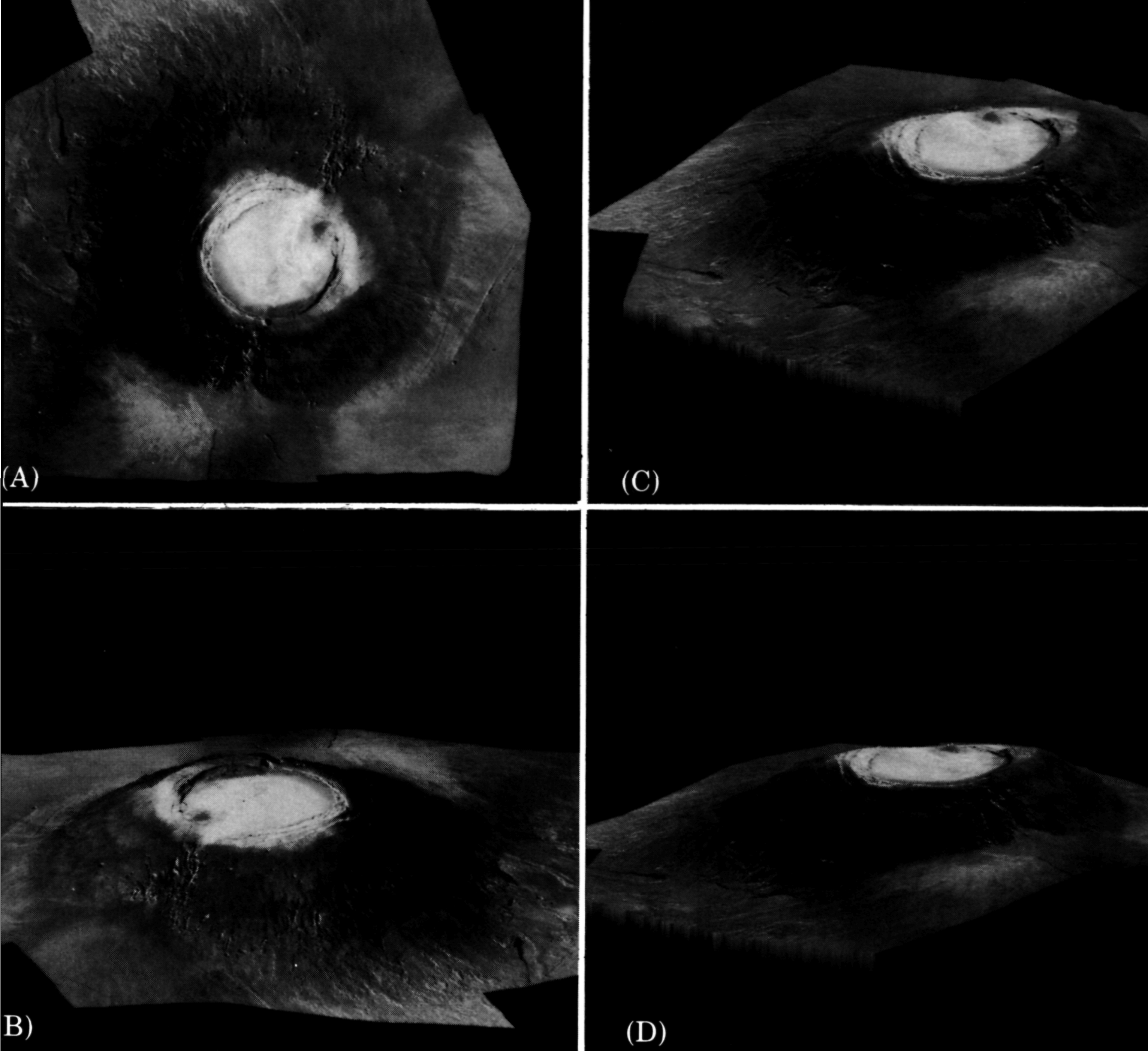


Figure 9.
Three-dimensional transformations of the Arsia Mons volcano on Mars. The different views were made by digitally projecting Viking Orbiter images onto a digital terrain model (a raster of surface elevations derived by stereophotogrammetry), and then rotating the composite file in the computer. (A) Orthographic view. (B) View from 25° above the northern horizon. (C) View from 25° above the southwestern horizon. (D) View from 15° above the southwestern horizon.

Figure 8.
Part of an albedo map of the Memphis Facula quadrangle of Ganymede. Albedo is combined with landform delineation on this kind of map. Resolution varied widely in data available for this compilation, resulting in much less detailed portrayal in the eastern part of the map segment. Different colored inks are used to print airbrushed maps of each planet or satellite for easy identification and to facilitate discrimination of black lines and type. The colors are not intended to represent the true color of the surface (USGS map I-1498).

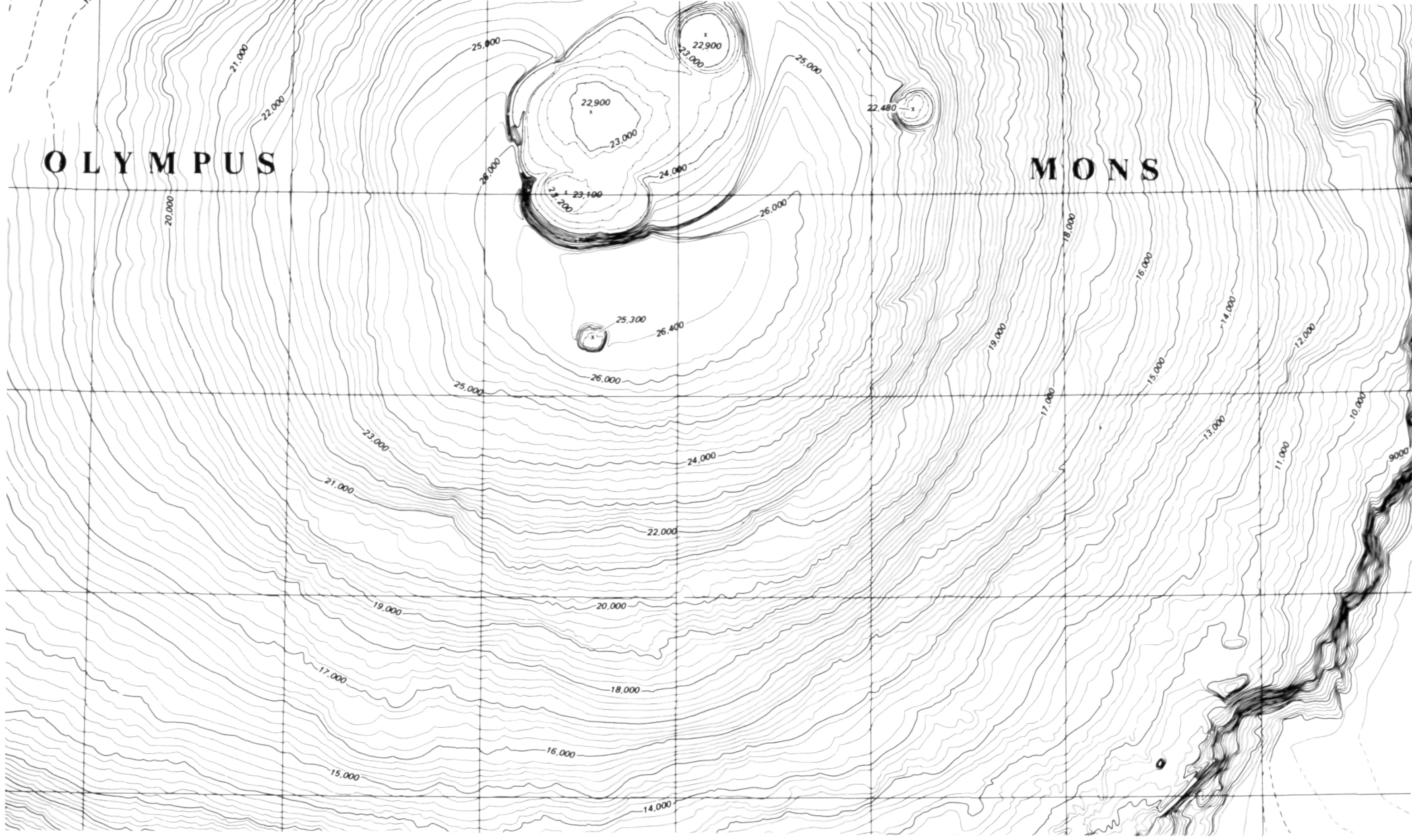
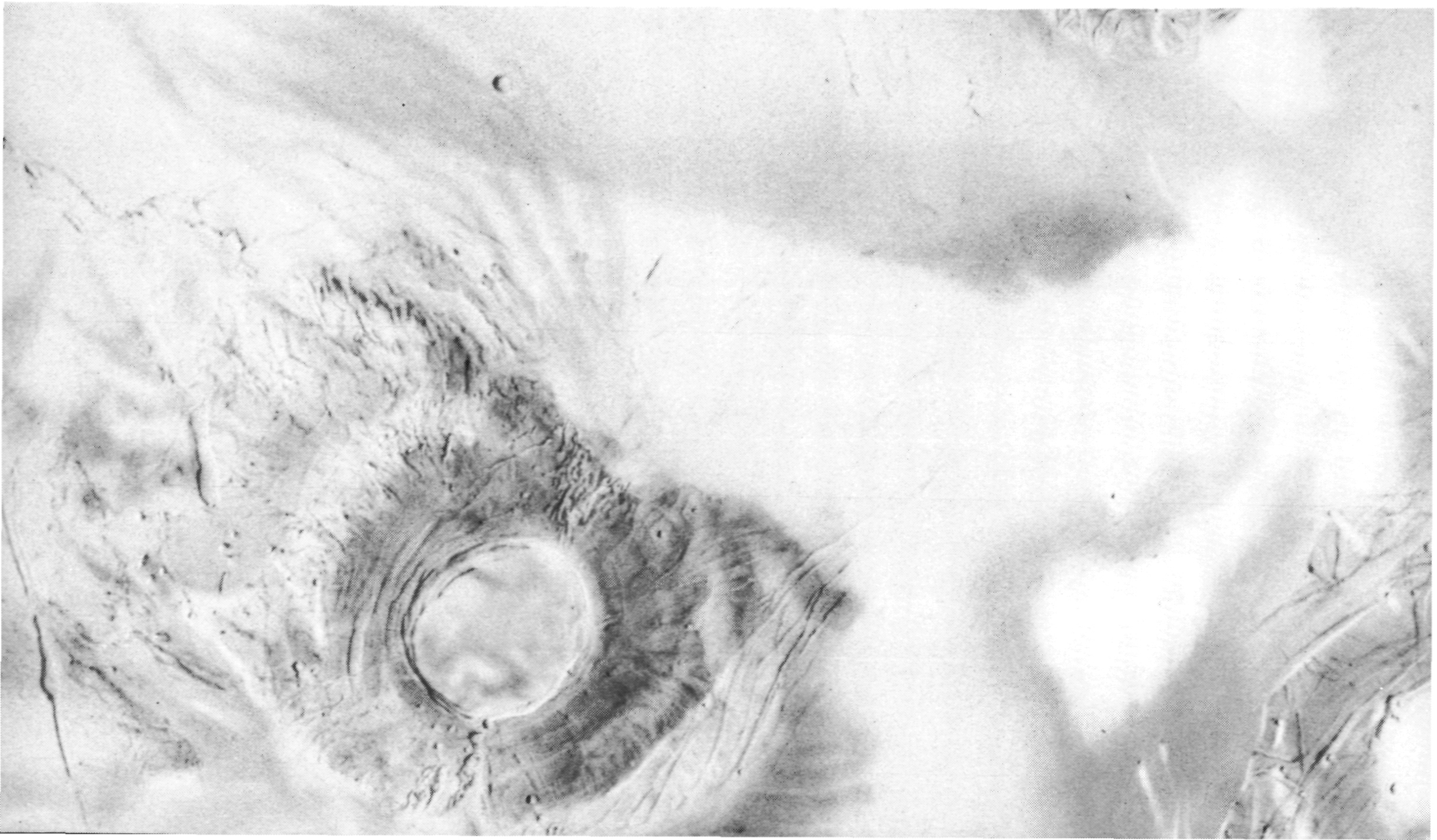


Figure 10
Topographic map of part of the Olympus Mons volcano on Mars. The contour lines were compiled by photogrammetry with stereoscopic Viking Orbiter images. This map has been used as an illustration in reports, but has not yet been published separately.

Figure 11.
Part of a composite map of the Phoenicis Lacus quadrangle of Mars. Topographic contour lines are overprinted on an airbrushed shaded relief and albedo base (USGS map I-984).



Mission Planning

Maps prepared from data obtained on early reconnaissance missions have been used to select landing sites for later missions. In the case of Ranger, Earth-based telescopic maps were used to plan high-resolution photography of scientifically interesting areas to be acquired by the spacecraft. Lunar maps made from Earth-based observations were used extensively in planning the 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. For Surveyor, the lunar maps were used in numerous unpublished studies that eventually resulted in the selection of the seven landing sites. Similarly, 37 lunar charts and maps were produced to aid the Apollo site-selection process and for planning the lunar rover traverses (fig. 18). Maps prepared from photographs acquired by early Apollo missions were used to choose landing sites for later Apollo missions.

Photomosaics and maps compiled from lander spacecraft have been used to determine the areal distribution of fine-scale features, locate and document sample sites, and plan traverses. Lunar photomosaics from Surveyors 5 and 7 were used in deploying the Alpha backscatter instrument that obtained chemical measurements of lunar soil and rocks. On the manned Apollo missions, surface science instruments and rock, soil, and core samples were recorded by photographs and located on detailed maps. Lunar Rover traverses and sample sites were plotted on orbital images with the use of ground photography so that sample sites and measurements could be correlated with the local geology.

Maps and other Mars data from Mariner 9 were used to select candidate Viking landing sites, after which near-real-time Viking Orbiter data were used to refine the locations of safe landing sites. Essential cartographic requirements for Viking site selection were topographic maps, because only in the topographically lowest regions of Mars was atmospheric density sufficiently high for the parachute to slow the Viking Landers effectively. Also, the likelihood of finding life was expected to be enhanced if Viking could land in a region where the atmospheric pressure was high enough to prevent liquid water from boiling. At present, possible future Mars landing sites are being studied by using high-resolution Viking images and related map products. Mars Rover traverses and sites for possible sample return are being evaluated (fig. 19). Because of the limited ranges of planned roving vehicles, absolute map coordinates must be accurate to a few kilometers and relative map coordinates to a few tens of meters.

Panoramas of the surface of Mars were obtained by Viking Landers 1 and 2. Various charts, including contour maps, were made from the Viking Lander images. These detailed maps were used to plan the acquisition of samples for chemical and biologic analyses and to select sites for trenching to acquire data on the physical properties of Martian surface materials. From these maps the detailed geochemistry, petrology, and geophysics of the landing sites could be extrapolated to larger areas of the planet using the remote sensing instruments on orbital spacecraft.

Earth-based radar images of Venus, Pioneer Venus altimetry, and radar maps of surface roughness, slopes, reflectivity, and emissivity were used to select the USSR Venera 13 and 14 landing sites. These data are also being used to choose the Venera 17 and 18 landing sites of the VEGA mission to be launched in 1984. Correlations have been made between the chemical and imaging data of the USSR Venera landers and the radar data from the Pioneer Venus Orbiter and from Earth-based facilities. Planning data-gathering sequences for the VRM mission will require planning charts based on Pioneer Venus data and Earth-based radar observations (fig. 20). These include maps of the topography and radar reflectivity. Mission operations and the assembling of image map products will require a Venus geodetic control network derived from spacecraft and Earth-based radar with positions defined to about 5 km.

Maps of the Galilean satellites of Jupiter derived from Voyager observations are being used to determine an optimum satellite tour for the Galileo mission in 1988. This mission will acquire much higher resolution images (10 to 100 times) than were obtained by Voyager, together with infrared and ultraviolet spectral and photopolarimeter data. Consequently, much higher resolution maps of the Galilean satellites can be compiled. Comparison with maps of Io based on Voyager images will be essential for understanding the rates and characteristics of active volcanic processes.

Planned future missions not within the period covered by this report will also require map products. Comet rendezvous and asteroid flyby missions will involve detailed imaging of their surfaces. A Saturn/Titan mission will acquire higher-resolution data on the Saturnian satellites than did Voyager, allowing much more detailed maps to be compiled. This mission may also obtain low-resolution radar images of Titan's surface that will allow interpretation of the geologic history of that unusual satellite.

The Earth's Moon will probably be explored again by manned and unmanned missions. Although much of the necessary cartographic data were acquired by

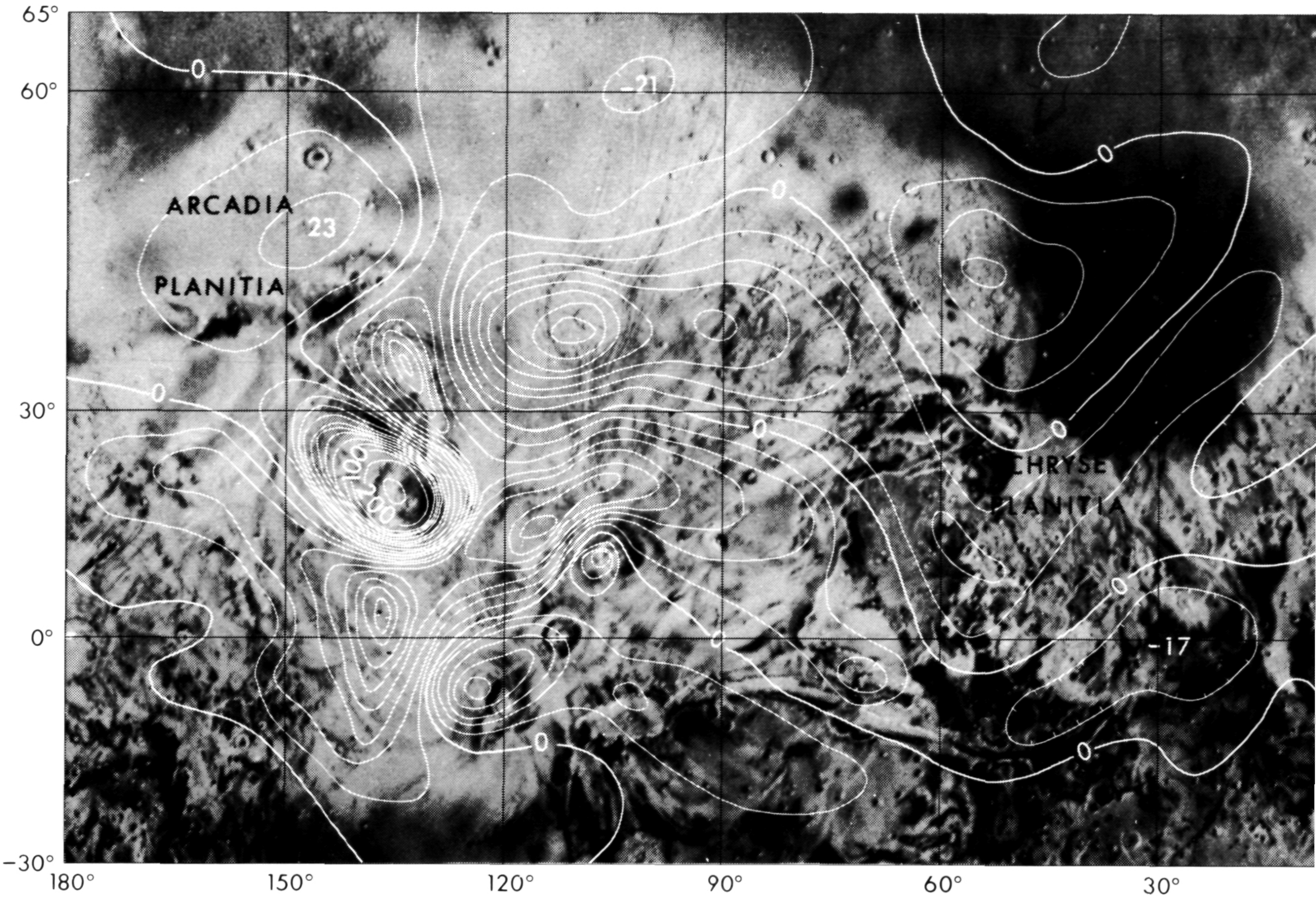


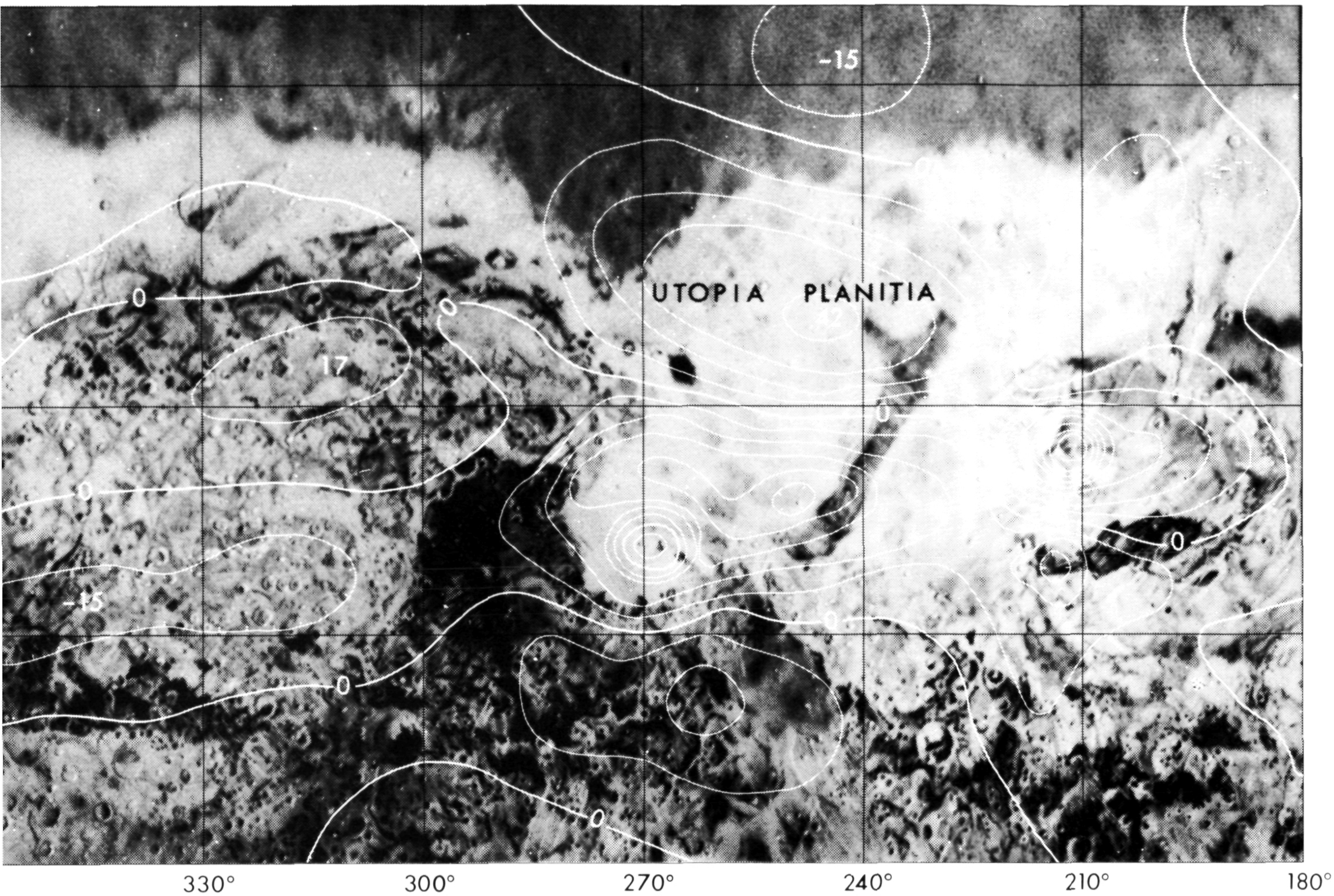
Figure 12.
Gravity map of Mars with 10-milligal contour interval.

Apollo and by Lunar Orbiter, additional high-quality maps will be needed for mission planning and data analyses. A unified geodetic control net, an accurate map of the global topography, and a much needed revision of the 1:5 million lunar frontside map are still lacking. The proposed Lunar Geoscience Orbiter would carry a complement of geoscience instruments similar to those carried by a Mars Geoscience/Climatology Orbiter and would acquire geochemical and geophysical data that must be plotted on accurate base maps to be 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 (current circulation of 10 million), in books like *Our Universe* which 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' *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, the planetary maps as individual sheets have had a continuing high sales record. More than 300 000 copies have been sold through distribution centers (appendix B).

At the university level, more courses in planetary science at the undergraduate and graduate levels are being established because of the great student interest in this subject. For example, at the University of Arizona three new courses in planetary science have been added to the curriculum during the past four years, and a lower-division course has been expanded to two sections in order to accommodate the more than 100 students who request the course each semester. 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 processses operate on a regional or global scale.

Regional Planetary Image Facilities

Currently, there are nine Regional Planetary Image Facilities located throughout the United States and two centers in Europe (table 4). These facilities contain images of planets and satellites acquired from various space missions and the cartographic products derived from these images. Smaller collections are maintained at three branch facilities. The image facilities are intended for the use of individuals or groups who require photographic and cartographic materials for research, education, or public information, but who have only limited or no access to such material. About 6000 users and visitors utilize these facilities each year.

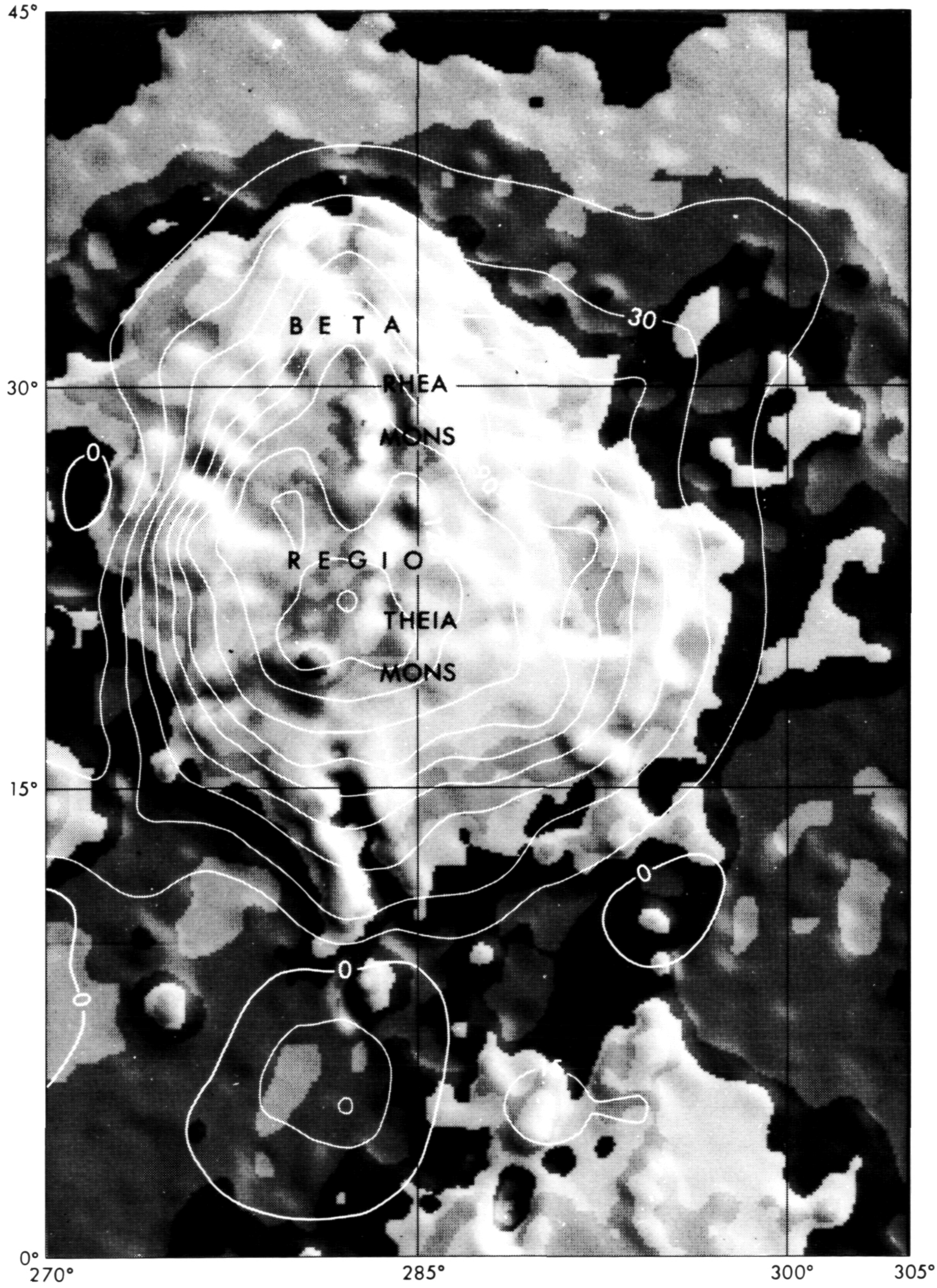


Figure 13.

Gravity map of Beta Regio on Venus with 15-milligal contour interval.

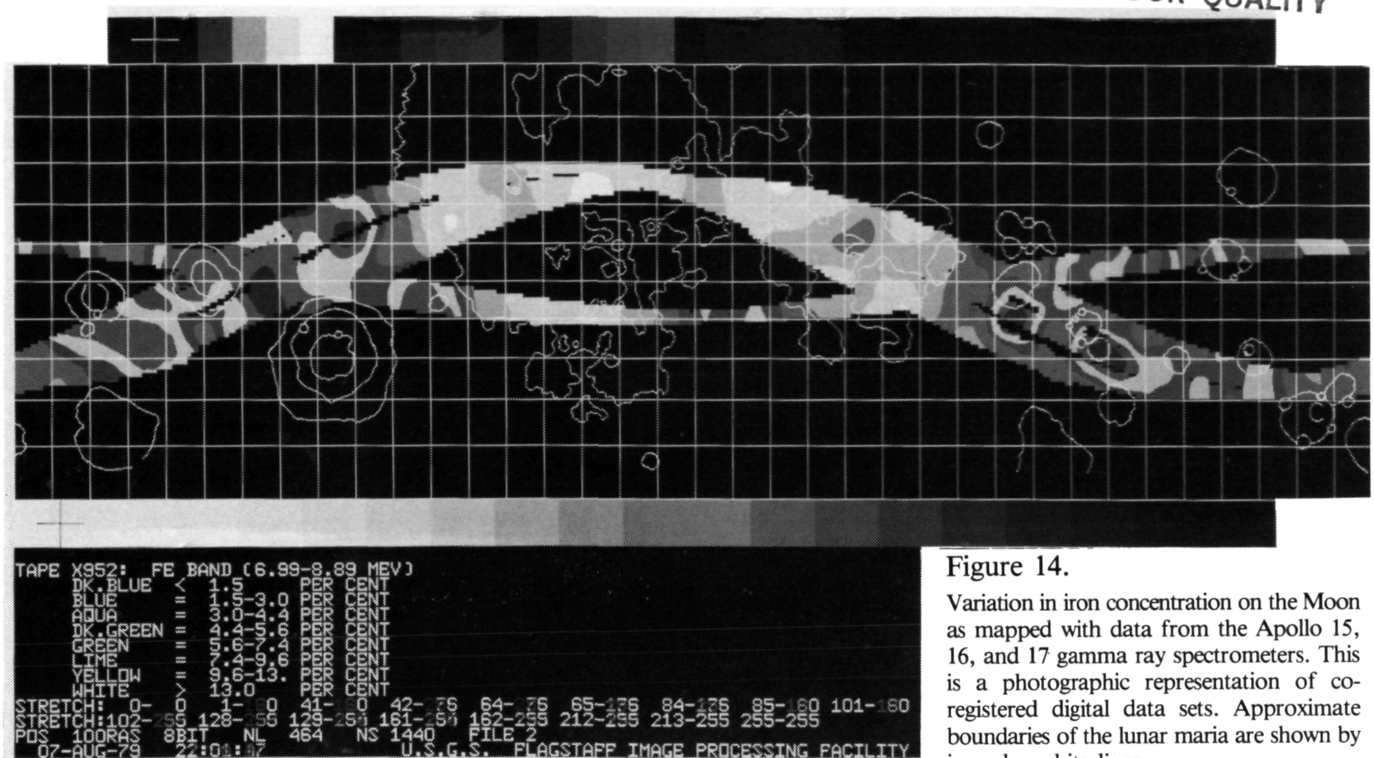


Figure 14.

Variation in iron concentration on the Moon as mapped with data from the Apollo 15, 16, and 17 gamma ray spectrometers. This is a photographic representation of co-registered digital data sets. Approximate boundaries of the lunar maria are shown by irregular white lines.

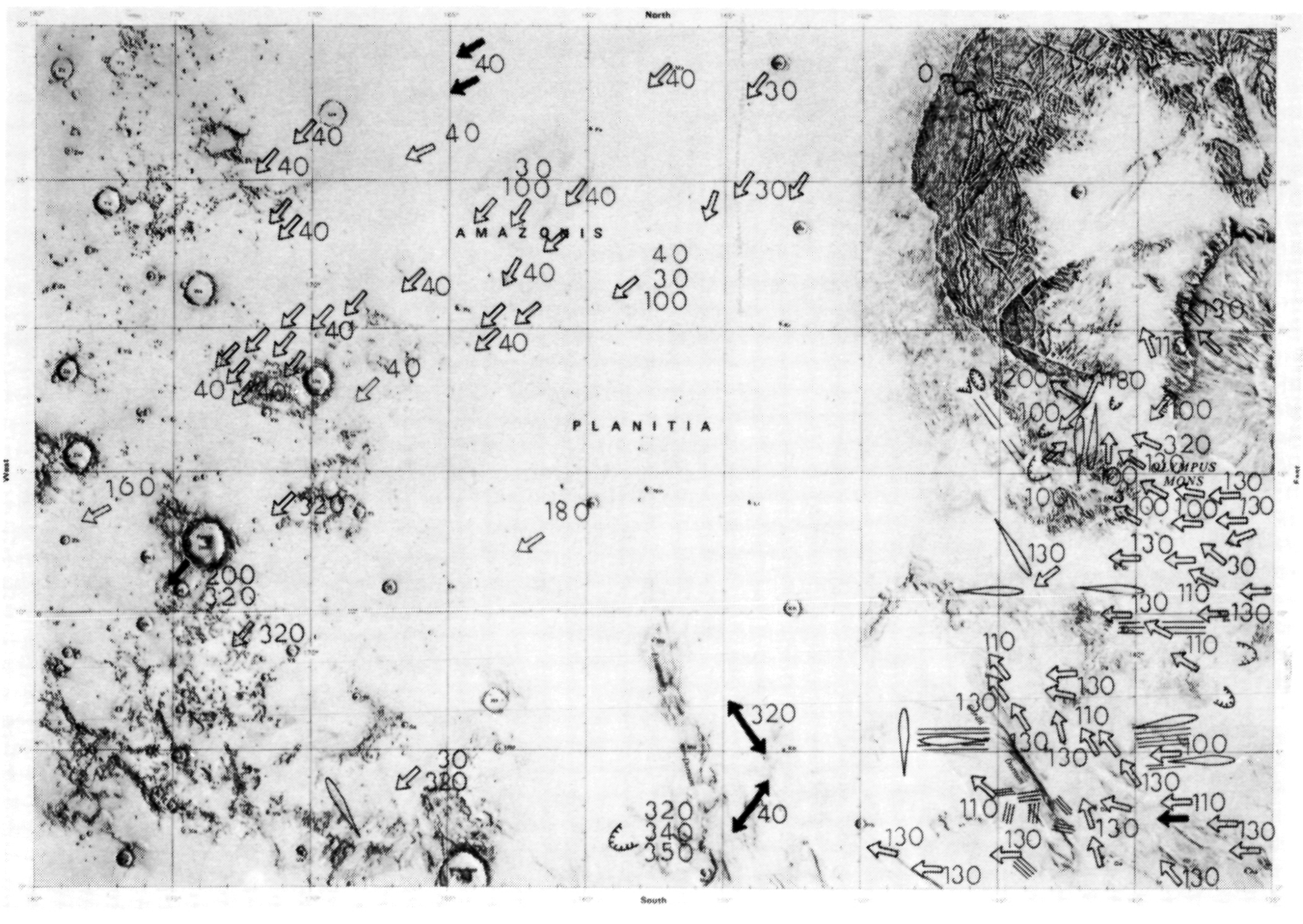


Figure 15.

Map of Mars showing the distribution and direction of wind streaks west of Olympus Mons.

Table 4. Regional Planetary Image Facilities

Name	Location	Director
Space Imagery Center	University of Arizona Tucson, Arizona	Robert G. Strom
Spacecraft Planetary Imaging Facility	Cornell University Ithaca, New York	Joseph Veverka
Brown Regional Planetary Data Center	Brown University Providence, Rhode Island	James Head
Planetary Image Center	Lunar and Planetary Institute Houston, Texas	Peter Schultz
Planetary Image Facility	Jet Propulsion Laboratory Pasadena, California	R. Stephen Saunders
Regional Planetary Image Facility	Washington University St. Louis, Missouri	Raymond Arvidson
Planetary Data Facility	United States Geological Survey Flagstaff, Arizona	Elliot Morris
Planetary Image Facility	National Air and Space Museum Washington, D.C.	Ted A. Maxwell
Planetary Data Center	University of Hawaii Honolulu, Hawaii	B. Ray Hawke
	Branch Facilities	
Space Photography Lab	Arizona State University Tempe, Arizona	Ronald Greeley
Planetary Image Facility	Louisiana State University Baton Rouge, Louisiana	Dag Nummedal
Planetary Image Facility	Oregon State University Corvallis, Oregon	Paul D. Komar
	Foreign Facilities	
Southern Europe Regional Planetary Image Facility	Istituto Astrofisica Spaziale Rome, Italy	Marcello Fulchignoni
Planetary Image Facility	University of London Observatory London, England	John Guest

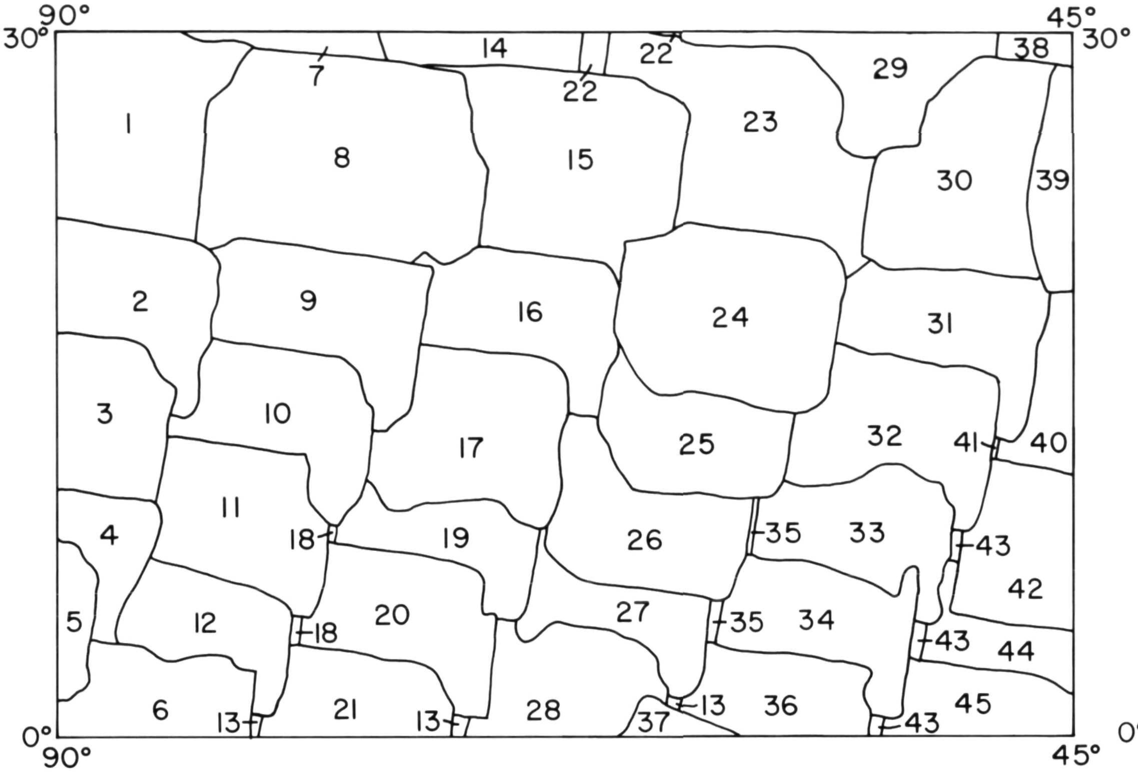


Figure 16.

Cutline diagram, showing layout of Viking Orbiter frames used to make the controlled mosaic of the Coprates quadrangle of Mars. The numbers in this diagram are keyed to a listing of image identification numbers. Such diagrams and listings are usually printed on the borders of planetary maps.

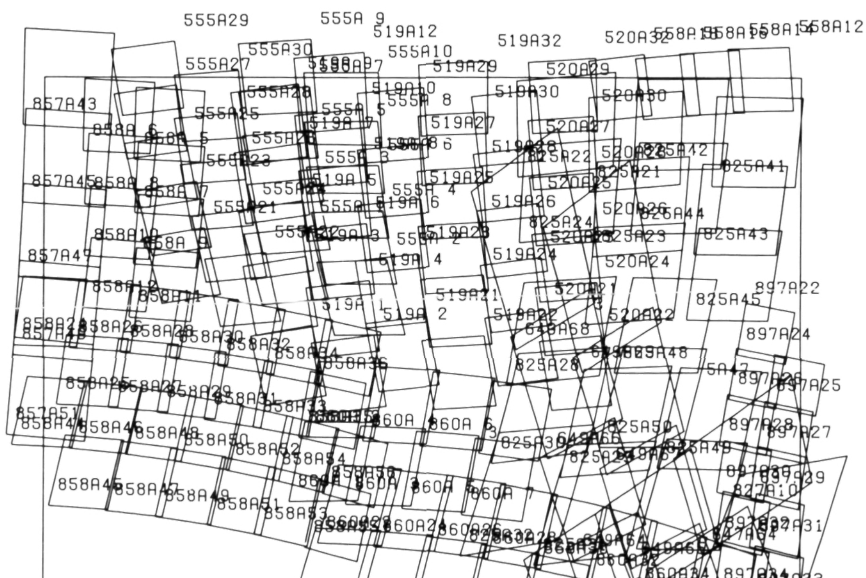


Figure 17.

Footprint plot, showing approximate locations of all Viking Orbiter frames with resolutions of 100 to 300 meters per pixel. Unlike a cutline diagram, a footprint plot delineates the entire outline of a spacecraft frame, rather than just the part used in a photomosaic.

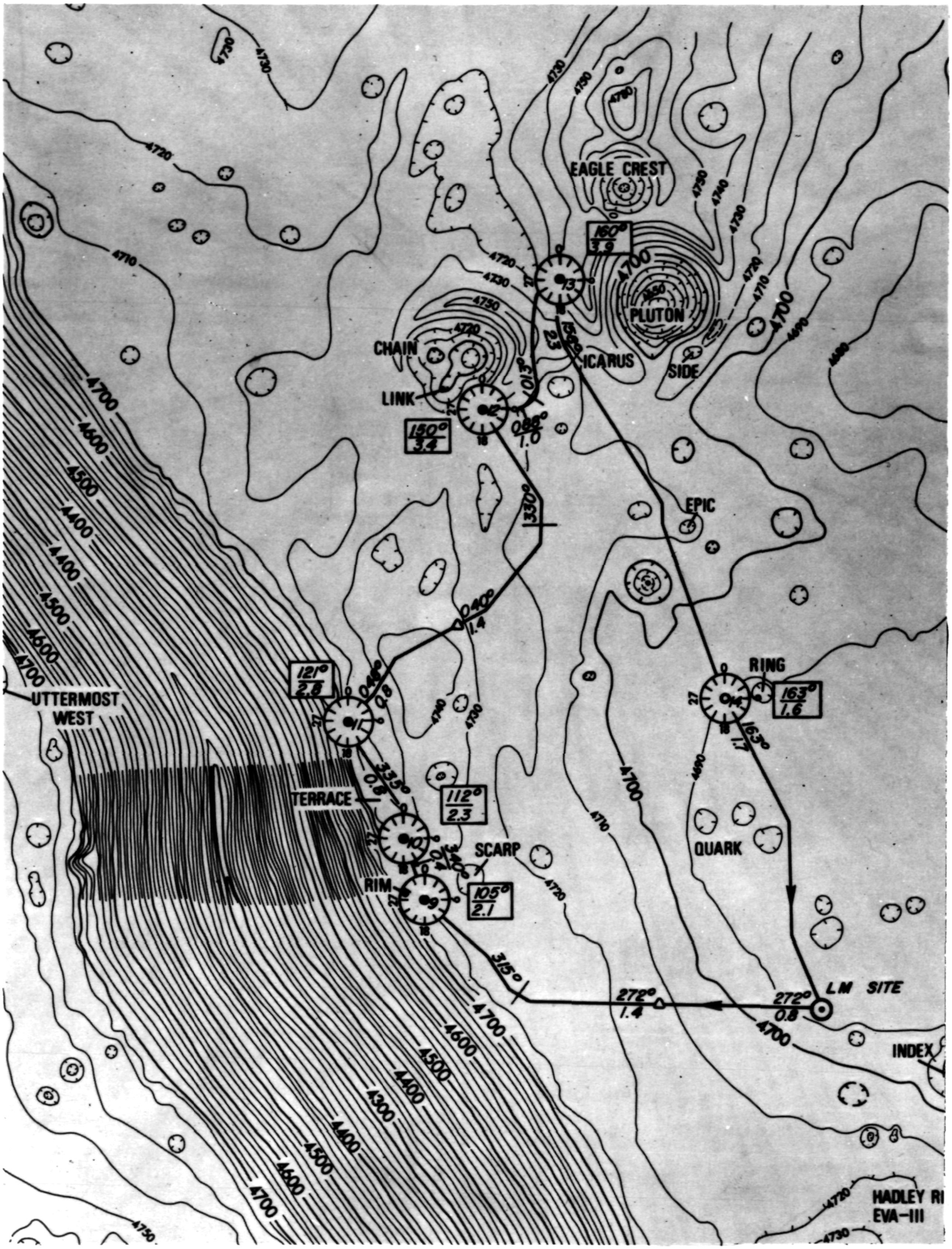


Figure 18A.

Apollo 15 landing site near Hadley Rille. These maps were used on the Moon by the Apollo 15 astronauts. The landing site is shown for the Lunar Module (LM). Also shown is the planned Lunar Rover traverse for Extra Vehicular Activity III (EVA), and small named craters that assisted the astronauts in locating their positions on the lunar surface. (A) Topographic map.

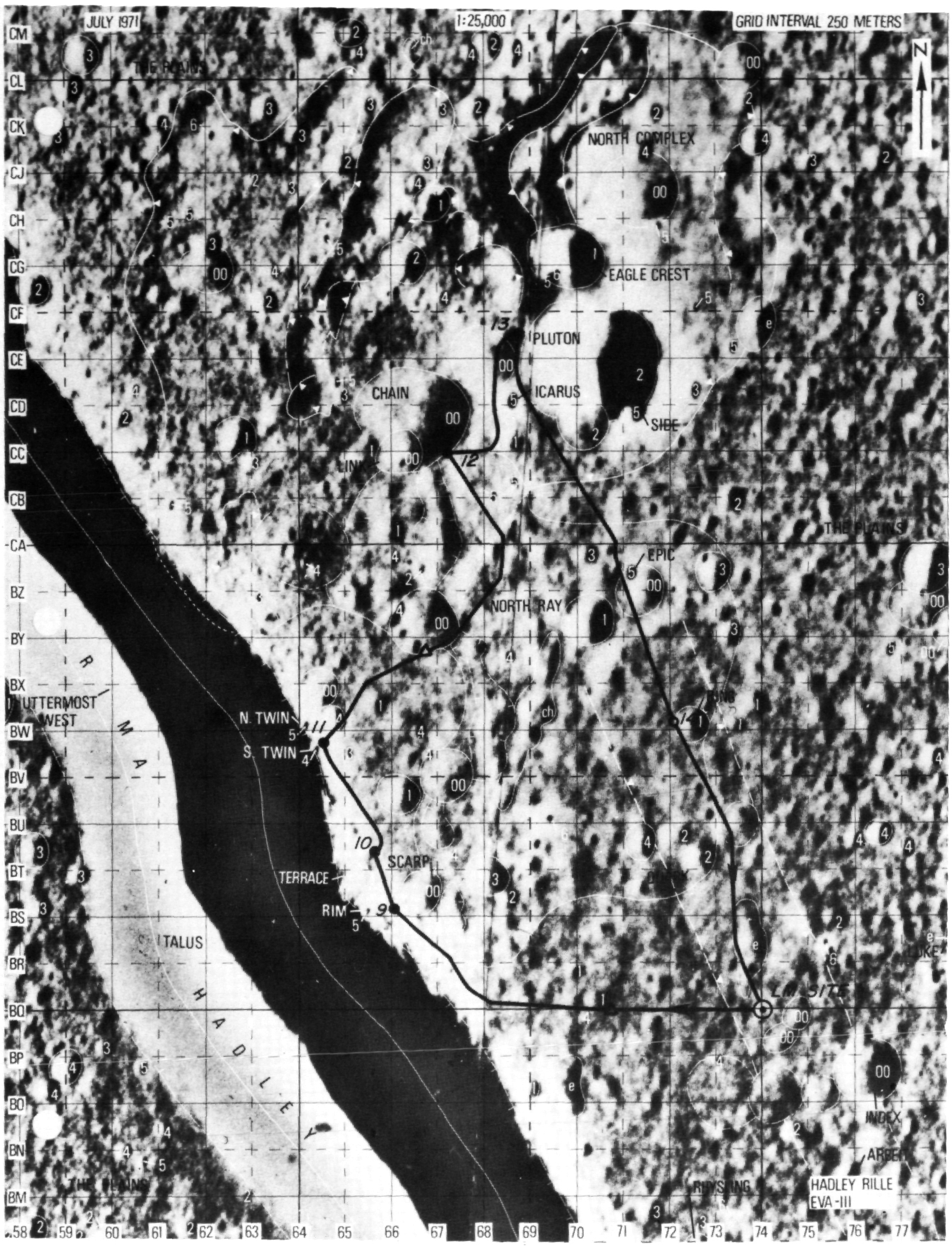


Figure 18B.
Photomosaic.

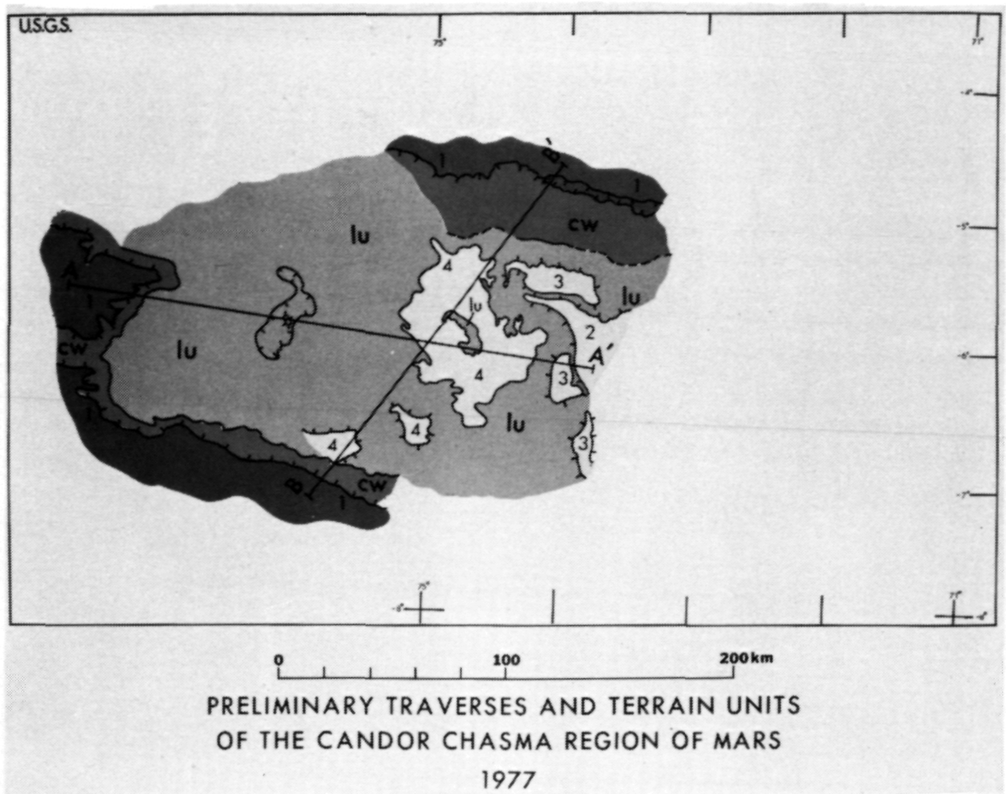
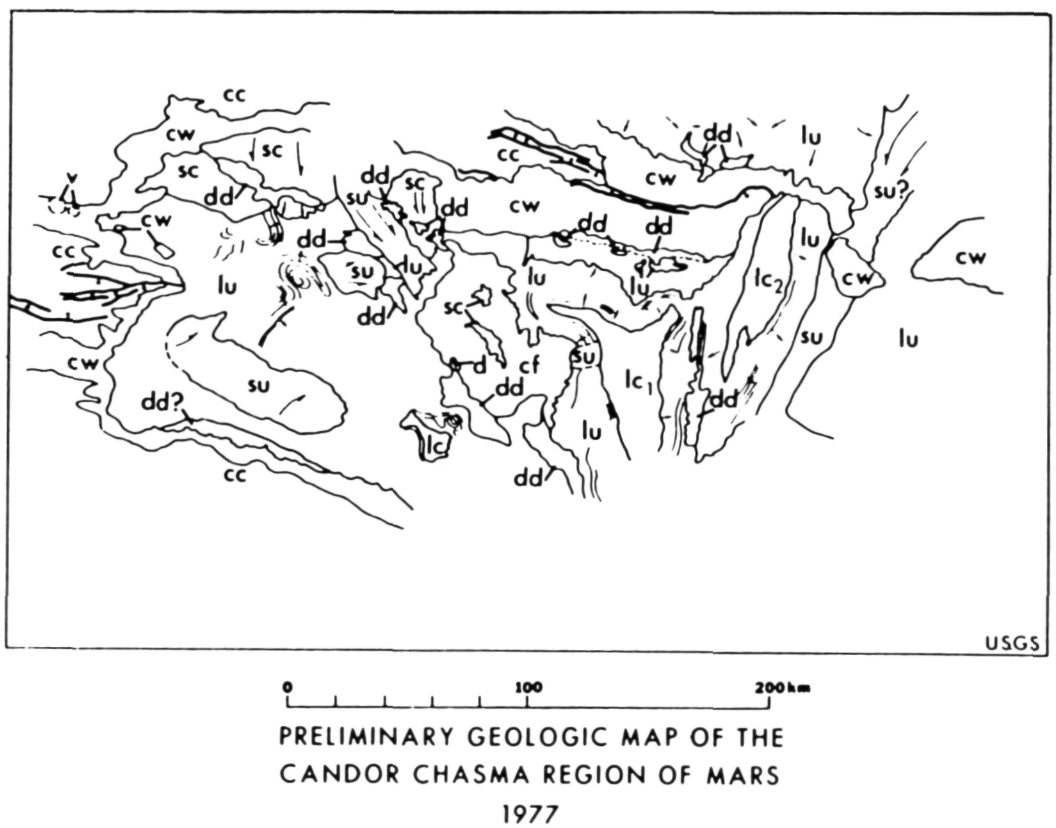


Figure 19A.

Traverse mapping and planning for a proposed Mars roving vehicle. (A) Terrain units in the Candor Chasma region of Mars (1977).

Figure 19B.

Preliminary geologic map (1977) of the area in (A).



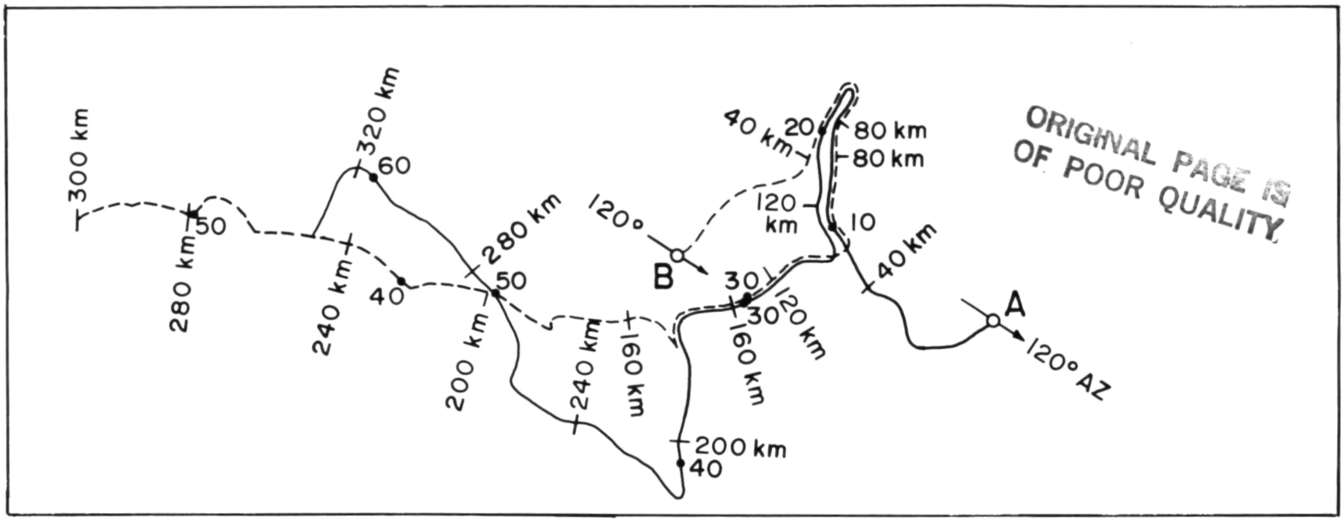
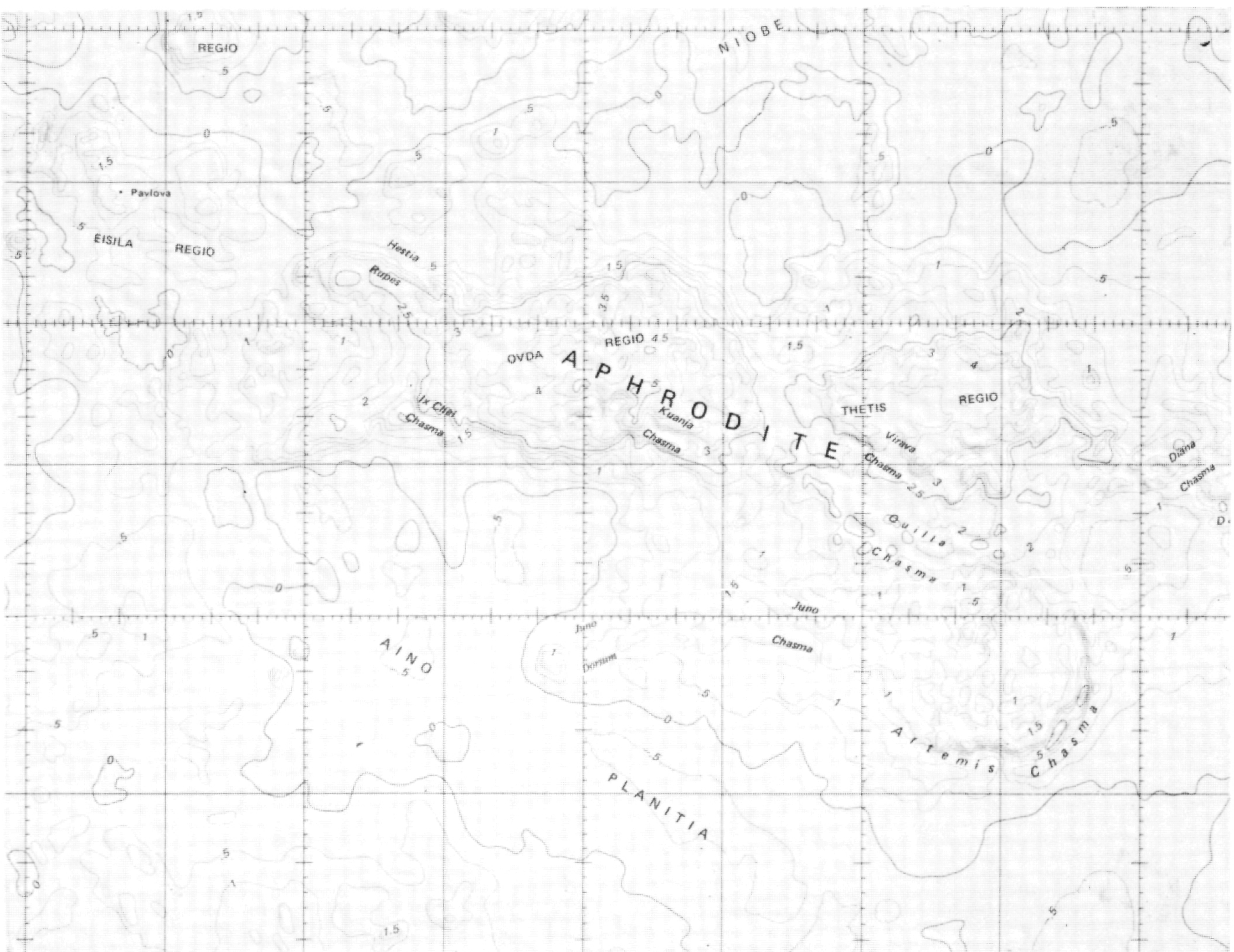


Figure 19C.

Proposed traverse routes and sampling sites.

Figure 20.

Part of the planning chart for the Venus Radar Mapper mission. Relief and linework, derived from Venus Pioneer data, have been intentionally subdued to facilitate plotting of VRM data (USGS I-1562). The topographic contour interval is 500 m.



Part 3

Cartographic Data Base

The modern planetary mapping program started with a major project to map the near side of the Moon employing telescopic information. Many of the methods and techniques currently used in planetary mapping were developed during this period. Since that time, spacecraft missions to the Moon, Mars, Mercury, Jupiter, and Saturn have provided data to expand the mapping program, and refined methods and techniques have been developed to improve the cartographic products. The most important missions from this point of view are listed in table 5. In order to carry out the current program, coordinate systems must be defined, geodetic control must be established, and map nomenclature must be created. These elements of the current program are defined in appendix C.

Data Reduction

Data reduction is a necessary first step in the compilation of any map. An extensive catalog of imaging support data is required to assess efficiently the large amount of information resulting from modern planetary missions. These data include parameters such as the orientation and range of the spacecraft and the aiming direction, shutter speed, and filter setting of the camera. This information is used in a variety of processing techniques that must be applied to new spacecraft images before maps can be compiled.

One of the fundamental problems in using spacecraft images for mapping is the correction of geometric distortions. The only low-distortion mapping camera placed on planetary spacecraft to date was the 76-mm focal length Apollo mapping camera. Pictures taken by this camera can be used directly in conventional stereoplotting equipment. Although the image resolution on Lunar Orbiter pictures is excellent, their geometry was seriously degraded by segmenting them into strips for transmission. After Lunar Orbiter 1, a reseau was preexposed on the flight film, allowing some measure of control; however, in general, the Lunar Orbiter pictures are extremely difficult to use photogrammetrically.

Digital television imaging systems have been employed on all planetary missions beyond the Moon. Digital images lend themselves to rigidly controllable computer processing, including noise removal, correction of internal image geometry, contrast enhancement, spatial frequency filtration, and geometric transformation to any desired map projection. Digital image processing has thus become a fundamental part of planetary mapping programs, and the algorithms designed for planetary mapping have now become an important element in the processing of Landsat images of the Earth.

Digital television images are transformed in computers to the desired map projection for constructing controlled photomosaics. Most of these mosaics have been assembled by hand, but many are now combined in the computer and produced as a single image. Although this method is expensive, it has the advantage that a variety of image processing programs can be applied to an entire map rather than to each in-

Table 5. Missions Important to the Planetary Mapping Program

Body	Mission	Camera Design	Camera Type	Lens Focal Length (mm)	Lens Angular Coverage (deg)	Lens Aperture	Image Format (mm)
Moon							
Primary Sources	Lunar Orbiter 4, 5	Eastman	70-mm film readout	80	37°.9 × 44°.2	f/5.6	55 × 65
	Apollo 15, 16, 17	Fairchild	127-mm film return	76	74° × 74°	f/4.5	114 × 114
	Soviet Zond 6, 8		190-mm film return	400	18°.5 × 25°.4	f/6.3	130 × 180
Also Important	Apollo 15, 16, 17	Itek pan	127-mm film return	610	10°.7 × 108°.0	f/3.5	114 × 1148
	Apollo 8-17	Hasselblad	70-mm film return	various			55 × 55
	Apollo 14	Hycon	127-mm film return	457	14°.2 × 14°.2	f/4	114 × 114
	Lunar Orbiter 1-5	Eastman	70-mm film readout	610	5°.2 × 20°.4	f/5.6	55 × 219
	Lunar Orbiter 1-3	Eastman	70-mm film readout	80	37°.9 × 44°.2	f/5.6	55 × 65
Mercury	Mariner 10	JPL	Vidicon	1500	0°.4 × 0°.5	f/8.5	9.6 × 12.35
Mars	Mariner 9	JPL	Vidicon	52, 500	10°.5 × 13°.5, 1°.1 × 1°.4	f/4, f/2.4	9.6 × 12.5
	Viking 1, 2	JPL	Vidicon	475	1°.5 × 1°.7	f/3.5	12.5 × 14.0
Jupiter Satellites	Voyager 1, 2	JPL	Vidicon	200, 1500	3°.2 × 3°.2, 0°.4 × 0°.4	f/3.5, f/8.5	11.14 × 11.14
Saturn Satellites	Voyager 1, 2	JPL	Vidicon	200, 1500	3°.2 × 3°.2, 0°.4 × 0°.4	f/3.5, f/8.5	11.14 × 11.14

dividual picture. Digital terrain elevation models, when available, can be used to correct relief distortions in monoscopic images for the complete generation of orthophoto mosaics.

In planning a map or a map series, it is important to select a map scale that takes advantage of the resolution of the available pictures or photomosaics. In general, the map scale should be chosen so that there is an uncluttered cartographic portrayal of all pertinent information larger than 0.5 mm in diameter at the map scale. For instance, if 5 pixels are required to define a 0.5 mm diameter, the map scale can be computed as:

$$\text{Map scale} = 10\,000 \times \text{the surface pixel dimension (in meters)}$$

A variety of controlled photomosaics can be compiled. Many scientists prefer mosaics with high-frequency detail enhanced, although this has the disadvantage that all relief receives equal emphasis. Other versions are therefore made with no spatial filtering and with photometric corrections applied to the pictures.

Photomosaics can be used as photomaps to portray landscape information or as guides for the airbrush cartographer to portray the landscape on shaded relief maps. The airbrush cartographer is able to incorporate into the portrayal information from many sources, such as high-resolution pictures. Albedo overprints for shaded relief maps are characteristically made with the airbrush.

Sufficient elevation information has been acquired so that contour lines have been added to some maps of Mars and the Moon. Special maps of regions of high topographic relief have been produced that show only contour lines, with no distraction of landscape portrayal.

When a planet or satellite is explored for the first time, it is important to produce rapidly a preliminary planetwide base map for various scientific studies and planning functions. This map is preliminary, because it will be replaced by one with greater positional accuracy and a more detailed portrayal of surface features.

Commonly used map projections are employed in the planetary program (appendix D). Perhaps the most popular are the equatorial Mercator and polar stereographic projections. The Lambert conformal conic projection is convenient in the middle latitudes. The transverse Mercator projection is often suitable for large-scale map series.

For convenience, planetary maps can be categorized as global, regional, and special area maps. Since the mapping program is ongoing and dynamic, updated versions of old maps are often produced, new bodies are mapped, new systematic mapping series are introduced, and special maps are prepared for particular scientific investigations. A list of global planet and satellite maps is contained in table 6. The following is a brief summary of the existing and anticipated data from which planet and satellite maps can be compiled.

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

Table 6. Global Maps of the Planets and Satellites

Planet or Satellite	Map Scale	Projections	Characteristics	Number of Sheets	Publication Date
Mercury	1:15 000 000	Mercator, polar stereo	Shaded relief, albedo	1	1979
Venus	1:50 000 000	Mercator	Contours only	1	1981
Moon	1:10 000 000	Mercator, polar stereo	Shaded relief, albedo	1	1979
	1: 5 000 000	Mercator, polar stereo	Shaded relief, albedo	3	1970, 1980, 1982
Mars	1:25 000 000	Mercator, polar stereo	Shaded relief, albedo, contours	1	1976
	1:15 000 000	Mercator, polar stereo	Shaded relief, albedo	3	1982
Io	1:25 000 000	Mercator, polar stereo	Shaded relief	1	1979
	1:15 000 000	Mercator, polar stereo	Shaded relief	1	1983
	1: 5 000 000	Mercator, polar stereo	Shaded relief	3	1983
Europa	1:25 000 000	Mercator, polar stereo	Shaded relief	1	1979
	1:15 000 000	Mercator, polar stereo	Shaded relief	1	1983
	1: 5 000 000	Mercator, polar stereo	Shaded relief	2	1983
Ganymede	1:25 000 000	Mercator, polar stereo	Shaded relief	1	1979
	1:15 000 000	Mercator, polar stereo	Shaded relief	3	1983
Callisto	1:25 000 000	Mercator, polar stereo	Shaded relief	1	1979
	1:15 000 000	Mercator, polar stereo	Shaded relief	3	1983
Mimas	1: 5 000 000	Mercator, polar stereo	Shaded relief	1	1982
Enceladus	1: 5 000 000	Mercator, polar stereo	Shaded relief	1	1982
Tethys	1:10 000 000	Mercator, polar stereo	Shaded relief	1	1982
Dione	1:10 000 000	Mercator, polar stereo	Shaded relief	1	1982
Rhea	1:10 000 000	Mercator, polar stereo	Shaded relief	1	1982
Iapetus	1:10 000 000	Mercator, polar stereo	Shaded relief	1	1982

desirable scales and resolution. 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 far and near sides, but they do not contribute significantly to global mapping. 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.

No new lunar data requiring maps are expected during the period covered by this report. However, in the mid-1990's, a Lunar Geoscience Orbiter may return high-resolution radar altimetry and geochemical data that will probably require new base maps and topographic contour maps.

Mercury

The Mariner 10 spacecraft flew by Mercury three times. Mercury was encountered at the same orbital longitude each time, giving essentially the identical illumination with each flyby. The first and third encounters passed by the night side of Mercury, whereas the second encounter passed by the lit side and took pictures of most of the illuminated hemisphere. Because Mercury rotates very slowly on its axis (58.6 days) and because the high-resolution imaging data were obtained during a short period around the encounter, 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.

No new spacecraft data of Mercury will be acquired during the next ten years. However, the Space Telescope may be able to obtain images at about 30-km resolution of Mercury's surface not seen by Mariner 10. If this is the case, then an updated version of the global 1:15 000 000 map will be necessary.

Mars

Planetwide mapping coverage of Mars was accomplished by Mariner 9 using its wide-angle vidicon camera during the year 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 at lower resolution were also taken. The Viking data set is very large, with multiple coverage of selected regions and many areas sampled at very high resolution. The Soviet Mars 4 and 5 acquired a few pictures of a small region; however, the data set was small and did not support a large mapping effort. Planetary radii computed from radio occultations of Mariner 9 and the Viking Orbiters are very useful. Radii computed from Earth-based radar are also important to the mapping effort.

A Mars Geoscience/Climatology Orbiter may begin returning high-resolution radar altimetry and geochemical data as early as 1991. This mission will make possible the compilation of new topographic and geochemical maps of Mars.

Venus

Radar is the only sensor capable of imaging the surfaces of cloud-covered bodies such as Venus and Titan. The large Earth-based radars at Arecibo and Goldstone have already obtained images and measured topographic relief of particular regions on Venus. In addition, planetary radii and large-scale relief have been measured over most of the surface of Venus by the Pioneer Venus radar altimeter.

Radar data suitable for map compilation may become available from the recent USSR Venera 15 and 16 missions, but at this time the extent and availability of these data are not known. The new Venus Radar Mapper mission will carry out a comprehensive planetwide exploration using synthetic aperture radar and high-resolution altimetry measurements. This mission will provide the data for compilations of detailed maps of Venus.

Galilean Satellites

The two Voyager spacecraft explored the large 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 sometimes the distance was so great that the pictures were almost valueless 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 on their axes that little rotation took place when the spacecrafts were close enough to take high-resolution images.

The Galileo mission will be the source of an enormous amount of new data on the Galilean satellites. New and revised Galilean satellite maps can be compiled from these data.

Saturn Satellites

As the Voyager spacecraft encountered Saturn they took pictures of many of the planet's satellites. 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 were 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 ten-year period covered by this report.

Part 4

Current Status of Planetary Cartography

Control Networks

Planetwide control networks have been computed only for Mars, Io, Europa, Ganymede, Callisto, Mimas, Tethys, Dione, and Rhea. 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 at moderate resolution. Since that time higher-resolution Viking pictures have been used to improve the accuracy of the network and to increase the density of control points in many areas. This work is continuing, and the network is updated periodically and the results published. The control networks of the Jovian and Saturnian satellites are based on Voyager images. However, the resolution of the pictures and hence the density of the control points vary greatly with longitude.

Regional control networks have been computed for Mercury, the Moon, Enceladus, and Iapetus. The control network of Mercury is based on images taken by the Mariner 10 spacecraft on its three flybys of Mercury; about 45 percent of the surface was observed. A series of regional independent control networks of the Moon have been computed. These regional networks are composed of telescopic, Apollo 15, 16, and 17, Lunar Orbiter, Zond 6 and 8, and Mariner 10 images of the lunar near and far sides. However, the networks have not been assembled into a single coordinated global network with the origin at the center of mass. Work on the project is just starting. The regions of Enceladus and Iapetus observed in the images taken by the Voyager spacecraft were rather limited, and for Iapetus there are no overlapping areas between Voyager 1 and 2 coverage. Therefore, the control networks of these Saturnian satellites are limited to relatively small regions. A review of the status and references of all planet and satellite control networks is given in appendix C.

Published Planet and Satellite Maps

Since 1962, more than 1000 planet and satellite maps have been published (table 7). Most of these maps are of the Moon (79 percent) and Mars (18 percent). More than 800 lunar maps were prepared to support data analysis and mission planning for the Surveyor, Lunar Orbiter, and Apollo programs. The production of lunar maps was essentially terminated in 1974 after the completion of orthophotomosaics of areas covered by the mapping cameras on Apollo 15, 16, and 17. Since that time only seven maps have been produced, including a shaded relief compilation of the lunar farside and poles at a scale of 1:5 000 000.

Maps in Preparation or in Press

Other planet and satellite maps are in various stages of compilation. Table 8 lists the maps in preparation or those completed and awaiting publication. Preliminary photocopies of completed maps are distributed to Regional Planetary Image Facilities (see table 4) for interim scientific use. Currently (January 1984), 122 maps, mostly of Mars and the Galilean satellites, are in preparation or in press.

Table 7. Number of Planet and Satellite Maps Published as of January 1, 1984

Series	Mercury	Venus	Moon	Mars	Io	Europa	Ganymede	Callisto	Mimas	Enceladus	Tethys	Dione	Rhea	Iapetus	Totals
Synoptic maps (formats A,B,C)															
Mosaic	1	—	—	—	—	—	—	—	—	—	—	—	—	—	1
Relief	1	—	—	5	—	—	—	—	—	—	—	1	—	—	7
Albedo	1	—	2	2	1	1	1	1	2	1	2	2	2	1	19
Composite	—	1	—	1	—	—	—	—	—	—	—	—	—	—	2
Totals	3	1	2	8	1	1	1	1	2	1	2	3	2	1	29
1:5M quads (formats D,E,F,G)															
Relief	9	—	2	44	—	—	—	—	—	—	—	—	—	—	55
Albedo	—	—	5	—	—	—	—	—	—	—	—	—	—	—	5
Totals	9	—	7	44	—	—	—	—	—	—	—	—	—	—	60
1:2M quads (formats H,J,K)															
Mosaic	—	—	—	107	—	—	—	—	—	—	—	—	—	—	107
Relief	—	—	—	2	—	—	—	—	—	—	—	—	—	—	2
Totals	—	—	—	109	—	—	—	—	—	—	—	—	—	—	109
Miscellaneous specifications (format M, etc.)															
Mosaic	—	—	478	5	—	—	—	—	—	—	—	—	—	—	483
Relief	1	—	55	8	—	—	—	—	—	—	—	—	—	—	64
Albedo	—	—	20	1	—	—	—	—	—	—	—	—	—	—	21
Composite	—	—	273	7	3	—	—	—	—	—	—	—	—	—	283
Totals	1	—	826	21	3	—	—	—	—	—	—	—	—	—	851
Totals	13	1	835	182	4	1	1	1	2	1	2	3	2	1	1049

Table 8. Number of Planet and Satellite Maps in Compilation or in Press as of January 1, 1984

Series	Mercury	Venus	Moon	Mars	Io	Europa	Ganymede	Callisto	Mimas	Enceladus	Tethys	Dione	Rhea	Iapetus	Totals
Synoptic maps (formats A,B,C)															
Mosaic	—	—	—	—	2	—	—	—	—	—	—	—	—	—	2
Relief	—	1	—	—	—	—	—	—	—	—	—	—	—	—	1
Albedo	—	—	—	2	1	1	—	—	—	—	—	—	—	—	4
Composite	—	1	—	—	—	—	—	—	—	—	—	—	—	—	1
Totals	—	2	—	2	3	1	—	—	—	—	—	—	—	—	8
1:5M quads (formats D,E,F,G)															
Relief	—	—	—	4	—	—	—	—	—	—	—	—	—	—	4
Albedo	—	—	—	—	3	2	8	—	—	—	—	—	—	—	13
Totals	—	—	—	4	3	2	8	—	—	—	—	—	—	—	17
1:2M quads (formats H,J,K)															
Mosaic	—	—	—	47	—	—	—	—	—	—	—	—	—	—	47
Totals	—	—	—	47	—	—	—	—	—	—	—	—	—	—	47
1:500K quads (format L)															
Mosaic	—	—	—	36	—	—	—	—	—	—	—	—	—	—	36
Totals	—	—	—	36	—	—	—	—	—	—	—	—	—	—	36
Miscellaneous specifications (format M, etc.)															
Relief	1	1	1	1	1	1	1	1	1	1	1	1	1	1	14
Totals	1	1	1	1	1	1	1	1	1	1	1	1	1	1	14
Totals	1	3	1	90	7	4	9	1	1	1	1	1	1	1	122

Map Types

Tables 7, 8, and 11 and appendix D list 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 to 1:50 000 000 for planets of the size of Mars and Venus (fig. 3) 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 (figs. 4, 5, and 6). "Topo only" refers to a contour map that has neither photomosaic nor shaded relief base (fig. 10). Feature nomenclature, map graticule, and other information may be included. "Relief" designates a shaded relief map prepared by airbrush techniques (fig. 7). 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 (fig. 8). 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 (fig. 2). "Composite" maps are composed of shaded relief, albedo, or mosaics with superimposed topographic contour lines (fig. 11). Composite maps also show feature nomenclature, map graticules, and other pertinent information.

Published U.S. Geological Survey planet and satellite maps can be obtained from the following organizations:

Branch of Distribution
U.S. Geological Survey
1200 S. Eads Street
Arlington, Virginia 22202

Branch of Distribution
U.S. Geological Survey
Federal Center
Denver, Colorado 80225

The *Atlas of Mercury* (NASA SP-423), the *Atlas of Mars* (NASA SP-438), and other NASA Special Publications can be obtained from the Superintendent of Documents at the following address:

Superintendent of Documents
U.S. Government Printing Office
Washington, D.C. 20402

Lunar maps prepared for NASA by the Defense Mapping Agency and primarily based on Apollo data can be obtained from:

National Space Science Data Center
Code 601
Goddard Space Flight Center
Greenbelt, Maryland 20771

Part 5

Planetary Cartography Ten-Year Plan

The plan that follows is designed to produce cartographic products that directly support planning for future planetary missions, scientific research, and preservation of spacecraft data. These products comprise three general categories of maps which are compiled by three different groups within the U.S. Geological Survey. Each group generally works independently of the others, so that each type of map can be compiled simultaneously. The three cartographic categories are controlled photomosaics, airbrush shaded relief and albedo maps, and topographic contour maps. A control network is essential for the production of all three types of maps (appendix C).

The number of planetary cartographic products that can be compiled from existing and anticipated data is very large and far exceeds the resources available to produce them. The Working Group has recommended only those products that it considers important or essential to support scientific research or future mission planning. These products are major map series or first-order maps needed to characterize the surface of a planet or satellite. Special-purpose maps will be considered by the Working Group on an individual basis depending on scientific requirements. Individuals requiring special maps, including Mars 1:500 000 controlled photomosaics of specific areas, should send their requests with full justification to the Chairman, Planetary Cartography Working Group, c/o Joseph M. Boyce, Code SL-4, NASA Headquarters, Washington, D.C. 20546.

General Recommendations

During the ten-year period covered by this report, three approved missions and several planned missions will return new data from planetary bodies. In 1986, Voyager will return a limited number of images of the Uranian satellites. In 1988, the Galileo and Venus Radar Mapper missions will begin returning an enormous number of images of the Galilean satellites and Venus. Voyager will acquire images of the Neptunian satellites (primarily Triton) in 1989, and a Geoscience/Climatology Orbiter may begin returning high-resolution altimetry and other data from Mars as early as 1991. The data from these missions will support new or augmented versions of existing maps.

The Working Group considers that map products to support the science requirements of active missions should have the highest priority. These new or revised maps are essential for mission data analysis and the expeditious publication of mission results. As a consequence, the Planetary Cartography Working Group makes the following general recommendations:

- During the five-year period 1984 to 1989, the planetary cartography effort should complete the mapping of Mars from Viking data and of Galilean and Saturnian satellites from Voyager data.

- In 1986, the highest priority should be assigned to Uranian satellite maps for the support of Voyager science.

- From 1989 through 1993, the highest priority should be assigned to compiling maps of Venus from VRM data, the Galilean satellites from Galileo data, and Neptunian satellites from Voyager data to support the science requirements of these missions.

- During the period 1991 to 1993, cartographic products derived from the Mars Geoscience/Climatology Orbiter should have a high priority.

Recommended Map Products

The map products using existing spacecraft images through the 1984-1989 time period are well defined. The only exception is the maps to be produced from the Voyager Uranus data that are to be returned in 1986. The products that can be produced from existing data include controlled photomosaics or shaded relief maps of Mercury, Mars, the Moon, and the satellites of Jupiter and Saturn. Map series of these bodies are in various states of completion. The map products of Mars, in particular, should be completed in time to support the anticipated Mars Geoscience/Climatology Orbiter (possible encounter in 1991). Topographic contour maps recommended for this time period depend on images that are suitable for stereo photogrammetric measurement; to date, these data are available only for parts of the Moon and Mars.

Mapping products through the 1989-1994 time period are less well defined because they depend on data which are anticipated but not yet available. In addition to images, the acquisition of extensive high-resolution altimetry data for Venus and Mars is planned, which will permit planetwide topographic mapping by nonphotogrammetric methods. The following recommendations for specific map products are therefore divided into two five-year time periods: the period 1984 to 1989, when map series are to be completed with existing data; and the period 1989 to 1994, when mapping will be done with new data acquired primarily from the Galileo, Venus Radar Mapper, and Mars Geoscience/Climatology Orbiter missions. The recommendations are based on the view that data returned from future missions will be optimum for cartography. Because this will almost certainly not be the case, plans will be modified after data actually become available. The recommendations are further divided into three types of products: controlled photomosaics, airbrush shaded relief and albedo maps, and topographic contour maps. Figure 21 is a diagrammatic representation of existing and recommended mapping of the planets and satellites.

Preliminary mapping and mapping for which original data do not fully justify map scale are not included. For example, a synoptic map of Venus has been published at 1:50 000 000, but it is not represented in the figures because the horizontal resolution of compilation data is on the order of tens of kilometers. Resolutions between 5 and 10 km per image element are normally required to justify a scale of 1:50 000 000.

Solid color indicates mapping that is complete or in progress. Hatched areas are planned for mapping with data now in hand, and stipled areas must be compiled with data to be gathered in the future, with approved missions.

Only mapping recommended in this report is shown. In many cases, data are available or can be expected to become available that will support mapping not shown here. For example, nearly all of the Moon could be mapped at 1:2 000 000 with data now in hand.

Planetary Cartography Recommendations (1984-1989)

The planetary cartography recommendations for the five-year period between 1984 and 1989 are presented in table 9.

Planetary Cartography Recommendations (1989-1994)

The planetary cartography recommendations for the five-year period between 1989 and 1994 are presented in table 10.

Table 11 lists the estimated number of specific maps based on existing data or data from future missions that are recommended in this report. In some cases (for example, Mars), many of these maps have already been published or are in various stages of completion (tables 7 and 8). Table 11 lists all maps that are scientifically important, including those which could become available under ideal circumstances. It is assumed, for example, that Galileo images will permit mosaics to be compiled for all 1:2 000 000 quadrangles on the Galilean satellites. Although imaging sequences have not yet been finalized, it is very unlikely that the data set will be as complete as shown. Similarly, it is unlikely that Voyager coverage of Triton will allow compilation of the three versions of all fifteen 1:5 000 000 quadrangles. Because the table shows this optimistic view and also lists maps published or in compilation, the total number of maps that is likely to be published during the next decade probably will be less than that shown. Furthermore, the table lists numbers of map sheets to be published, but many of these sheets are actually multiple versions made from single compilations. The cost of these versions is negligible compared

Table 9. Planetary Cartography Recommendations (1984-1989)

Controlled Photomosaics			
Mars 1:2 000 000	Mars 1:500 000	Rhea 1:5 000 000	Uranus Satellites (Synoptic)
• Priority — First • Justification — This series constitutes the primary contiguous photographic data base for Mars. It is essential for most research dealing with the surface or subsurface. The series is also necessary for planning future Mars missions. • Complete by — 1985	• Priority — Second • Justification — This series constitutes the highest-resolution base maps for detailed Martian studies. It provides the most reliable base for scientific and engineering studies to select lander, rover, and sample-return sites. • Complete by — Maximum effort from 1984 to 1988; small effort after 1988	• Priority — Third • Justification — This product constitutes the highest-resolution images of any Saturn satellite that can be mosaicked. These mosaics are important for detailed studies of Rhea. • Complete by — 1985	• Priority — Highest on receipt of data • Justification — These mosaics of Ariel and Miranda will constitute the highest-resolution images of the Uranian satellites. They are important for detailed studies of the Uranian satellites and for comparison with the Saturnian satellites. • Complete by — 1987

Shaded Relief and Albedo Maps		
Galilean Satellites 1:5 000 000	Galilean Satellites Global 1:15 000 000	Saturn Satellites (Synoptic)
• Priority — First • Justification — These base maps are needed for systematic geologic mapping, for topical studies of areas of special interest, and for comparative satellite studies. They are also needed to support planning and operations for the Galileo mission. • Complete by — 1987	• Priority — Second • Justification — These maps are important for global studies of the Galilean satellites. They are also needed to support planning and operations for the Galileo mission. • Complete by — 1987	• Priority — Third • Justification — The preliminary maps done for the Voyager Project were completed to meet initial project reporting schedules (30-day report). They are not tied to a control network and therefore contain unacceptable positional discrepancies up to 5°. The error can be reduced to approximately 0.5° latitude and longitude, and the level of detail portrayed can be significantly improved. These maps are important for Saturn satellite surface studies and to support future mission planning. • Complete by — 1985

(continued on next page)

Table 9. *(continued)*

Shaded Relief and Albedo Maps *(continued)*		
Uranus Satellites (Synoptic)	Mars 1:5 000 000	Moon 1:5 000 000 Revised Frontside Mercator
• Priority — Highest on receipt of data • Justification — These map products are vital to support Uranus data analysis. They will be the base maps on which the detailed geologic, geophysical, geochemical, and correlative data consortia activities will be focused. They are also important for comparative satellite and future mission studies. • Complete by — 1987	• Priority — Fifth • Justification — The original maps were based on Mariner 9 images and are published as individual sheets and in the *Atlas of Mars.* Revisions using Viking data provide great improvement at this scale. These maps are needed to support planning for future Mars missions, as a base for a possible new generation of geologic maps, and as a base for plotting the Mars Geoscience/Climatology Orbiter data. • Complete by — 1987	• Priority — Sixth • Justification — This map is the last of three sheets required to complete the 1:5 000 000 map series of the Moon. The series is a major revision of the initial 1:5 000 000 global maps and is important for planning the next lunar missions, and as a base for plotting the Lunar Geoscience Orbiter data. • Complete by — 1988

Topographic Contour Maps	
Mars 1:2 000 000	Mars 1:500 000
• Priority — First • Justification — Topographic information provides critical data for quantitative geologic and geophysical characterization of Mars at a scale and resolution that effectively utilize most of the Viking data set. • Complete by — 1987	• Priority — Second • Justification — In several areas of complex geology the planning of rover traverses to collect samples is dependent on slope information that might be derived from these maps. They also provide the highest-resolution topographic data from which quantitative measurements and stratigraphic relationships can be derived. • Complete by — 1987

to the original compilations. For example, the 1:15 000 000 Venus map will be compiled in eight sheets on format C and the same compilation will be published at reduced scale on formats A and B (appendix D). Also, the Venus 1:5 000 000 composite maps will be topographic maps superimposed on mosaics or shaded relief maps. Although nearly 2000 Mars 1:500 000 mosaics could be compiled, only a small selection of these maps will be produced. This selection will be based on areas of great scientific interest covered by high-resolution images and chosen with the aid of recommendations solicited from the planetary science community. Because surface changes on Io occur rapidly, it is likely that several versions of a given map will be required to depict the changes of the surface as a function of time.

The Working Group has not considered in detail the possible map products derived from a Mars Geoscience/Climatology Orbiter, because this mission has not yet been fully defined. It is likely, however, that high-resolution radar altimetry data will require topographic maps printed as stand-alone contour maps and as composite maps on previously compiled Viking cartographic products. The number of such maps could be 300 or more, depending on the resolution of the altimetry data. This problem will be addressed in a future revision of this report when the Mars Geoscience/Climatology Orbiter mission is better defined.

Appendix D shows the map formats to be used in the mapping program, together with lists of maps published (PUB), in preparation (IPR), and recommended in this report (PLAN). Also listed are maps

Table 10. Planetary Cartography Recommendations (1989-1994)

Controlled Photomosaics

Galilean Satellites 1:2 000 000 (Galileo Mission)	Venus 1:5 000 000 (Venus Radar Mapping Mission)	Triton (Voyager)
• Priority — High • Justification — These maps will constitute the primary regional photographic data base for the Galilean satellites. They will be essential for most research dealing with the surface and subsurface. • Complete by — approximately 1994	• Priority — High • Justification — These maps will constitute the primary radar image data set for the foreseeable future. They are essential for most research dealing with the surface and subsurface and will support the systematic geologic mapping of Venus. • Complete by — approximately 1995	• Priority — Third • Justification — The number of images that can be mosaicked is not known at this time, but they could constitute the primary photographic data base for Triton. • Complete by — approximately 1992

Shaded Relief and Albedo Maps

Galilean Satellites 1:5 000 000 (Galileo Mission)	Venus Global (Synoptic)	Venus 1:5 000 000 (Venus Radar Mapper)	Triton (Synoptic)
• Priority — High • Justification — This series will be a revision of the Voyager maps based on the new Galileo data. It will constitute the primary map product of the Galilean satellites for the foreseeable future. The series is important as a base for the revision of geologic maps, for topical studies, and for comparative studies of outer planet satellites. • Complete by — approximately 1994	• Priority — High • Justification — These maps will provide a conventional map rendition of Venus on a global scale. They are important for global geologic and geophysical studies and provide a base upon which global topographic contours and other data can be superimposed. • Complete by — approximately 1992	• Priority — High • Justification — These maps will provide a conventional map rendition of Venus based on the radar images. Radar images can contain distortions, such as fold-over, that may be removed by the airbrushing technique. These maps will be most widely used to illustrate Venus surface relief, because they will be interpretable by those unfamiliar with radar images. • Complete by — approximately 1995	• Priority — Highest on receipt of data • Justification — These maps are vital to support Triton data analysis. They will be the fundamental base maps upon which the detailed geologic, geophysical, geochemical, correlative data consortia, and nomenclature activities will be focused. They are also important for comparative satellite and future mission studies. • Complete by — approximately 1992

Topographic Contour Maps

Venus Global (Synoptic)	Venus 1:5 000 000 (Venus Radar Mapper)
• Priority — First • Justification — This series will feature global topographic contours from VRM radar altimetry, small-scale roughness, rms slope, and radar backscatter cross-section maps. These maps will be the primary bases for all global studies of Venus. • Complete by — approximately 1992	• Priority — Second • Justification — These maps are required to show the full resolution of VRM altimeter data. The topographic contours will aid in preparation of the 1:5 000 000 shaded relief maps and as overlays on these maps. These contour maps will provide quantitative information that can be used in conjunction with the radar images to facilitate geologic and geophysical interpretations. They are a fundamental data base for various geologic, geophysical, and atmospheric studies. • Complete by — approximately 1992

(FUT) that may be desirable from future missions and from existing or anticipated data, but not specifically recommended in this report. These cartographic products should be considered by the Working Group during the next revision of this report.

Although it has not made a specific recommendation, the Working Group believes that new maps may be required early in the next decade to support future missions not considered in this report. For example, new maps of the Moon and Mars may be necessary to support a Lunar Geoscience Orbiter and a Mars Surface Probe. Also, maps of small irregularly shaped satellites (for example, Phobos) may be useful for comparison with similar maps of asteroids and comet nuclei compiled from data returned by missions to such objects. The Working Group should consider such products during the next revision of this document.

Planet and Satellite Atlases

Atlases are important references because they provide a single-volume compendium of cartographic information of planets or satellites. Such a format is convenient and readily accessible to the scientist and the general public. Atlases may contain photomosaics, shaded relief maps, topographic contour maps, individual images of high scientific interest, photo-indices, and a written summary of the current understanding of the planet or satellite. A number of publications have been titled "atlas," for example, *Atlas and Gazetteer of the Near Side of the Moon;* but most of these volumes do not contain the comprehensive cartographic information that would classify them as true atlases. Although these publications may be very useful for specific applications, they do not give a comprehensive overview of a planetary surface. To date, only three publications can be considered true comprehensive planetary atlases: *Atlas of Mercury* (NASA SP-423), *Atlas of Mars* (NASA SP-438), and *Voyager 1 and 2 Atlas of Six Saturnian Satellites* (NASA SP-474). The cartographic information derived from Mariner 10 is contained in the *Atlas of Mercury,* whereas that from Mariner 9 is contained in the *Atlas of Mars.* The Saturn satellite atlas is based on Voyager data. Because planetary atlases are such important references, the following recommendation is made:

- The Planetary Cartography Working Group recommends the production of planet and satellite atlases as soon as the map products required to complete them are available. Specifically, a revision of the *Atlas of Mars* based on Viking data and a revision of the *Atlas of Six Saturnian Satellites* should be completed no later than 1989. An atlas of Venus based on the Venus Radar Mapper data and an atlas of the Galilean satellites based on Voyager and Galileo data should be compiled when the appropriate cartographic products become available (approximately 1994).

Estimated Level of Effort

The estimated relative level of effort required for the recommended mapping plan is shown by the area encompassed by each planet or satellite system in figure 22. From 1984 to about mid-1988, the total level of effort will remain constant. However, beyond 1988, the level of effort is expected to increase in order to accommodate map compilation of Venus and the Galilean satellites from the VRM and Galileo data. Both of these missions will be returning enormous amounts of data during the same time period. The amount of this increase will be dictated by budgetary considerations, which could affect map production scheduling. Although the mapping effort for Mars and other bodies will decline, the number of maps requiring simultaneous compilation to support both Galileo and VRM data analysis will increase. This demand will be exacerbated by the requirement to produce at the same time maps of Triton for Voyager data analysis. The level of effort for Mars and the Moon is likely to increase beyond about 1992 to accommodate map products derived from the Mars Geoscience/Climatology Orbiter and for support of a possible Lunar Geoscience Orbiter.

Acknowledgments

The Planetary Cartography Working Group greatly appreciates the prompt reviews and useful comments and suggestions by Ronald Greeley (Arizona State University), Richard Rapp (Ohio State University), Arden Albee (JPL/California Institute of Technology), and Peter Schultz (Lunar and Planetary Institute). The assistance of Lila Mager (Lunar and Planetary Institute) in arranging meetings and other logistical tasks, and the enormous efforts of Debby Welsch and Margaret Brahm (Lunar and Planetary Laboratory, University of Arizona) in typing and editing this report are gratefully acknowledged. Finally, we thank the people who responded to our planetary cartography questionnaire.

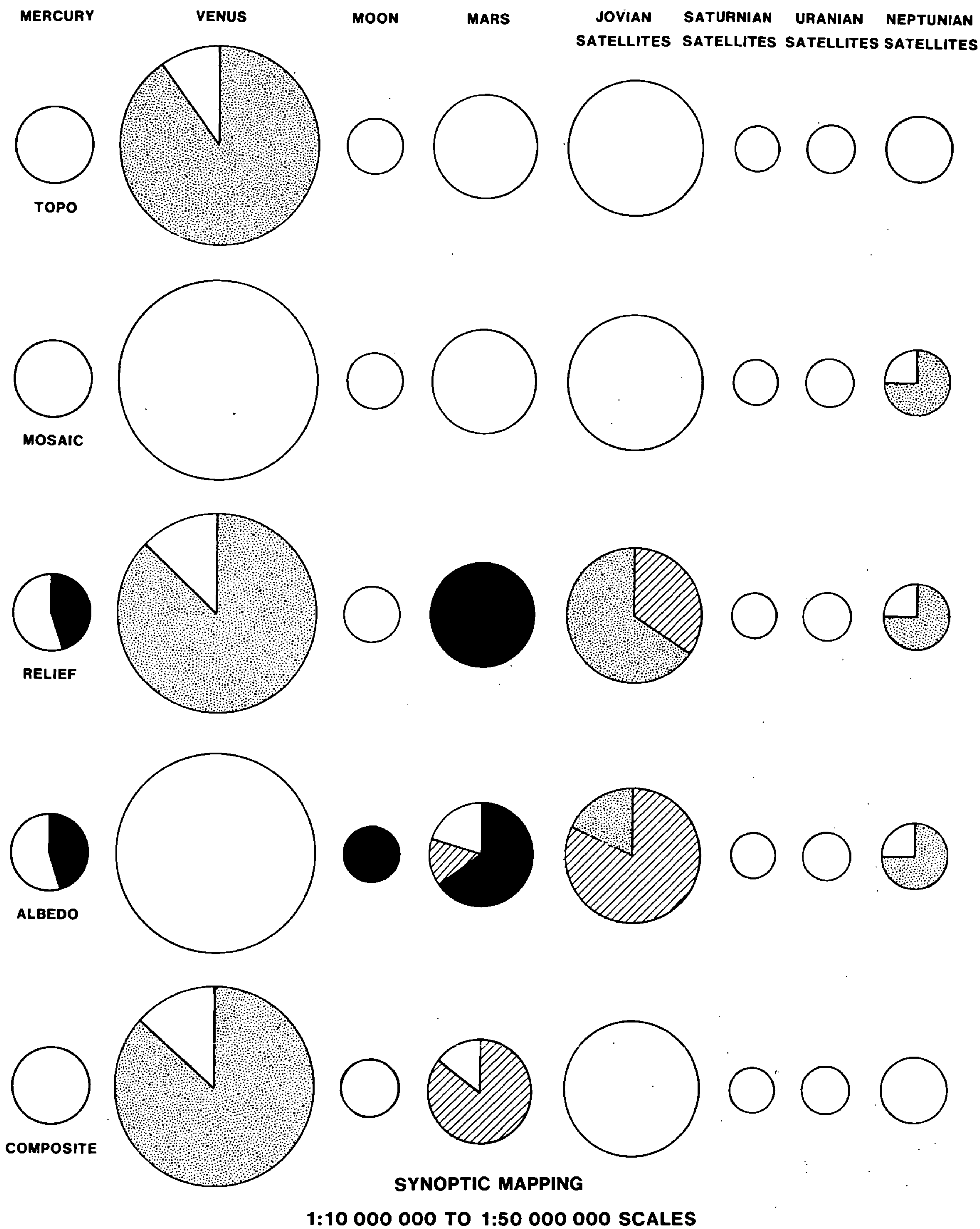


Figure 21A.

Existing and recommended mapping of the planets and satellites. The area of each circle is proportional to the area of the planet, satellite, or satellite system specified. Areas delineated on the diagrams represent area mapped, not the number of map sheets. (A) Synoptic mapping, at 1:10 000 000 to 1:50 000 000 scales.

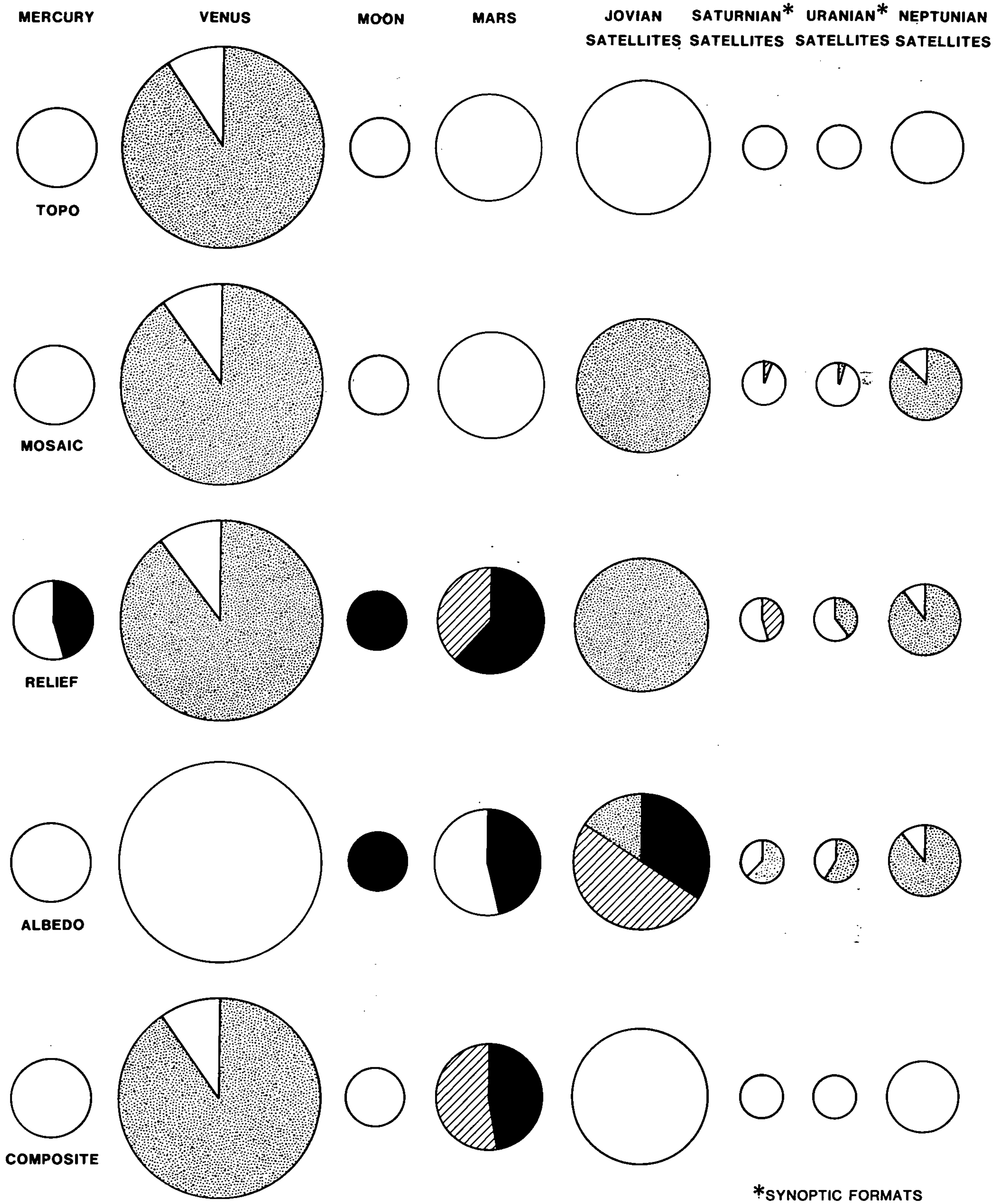


Figure 21B.
1:5 000 000 mapping, in synoptic or quadrangle formats.

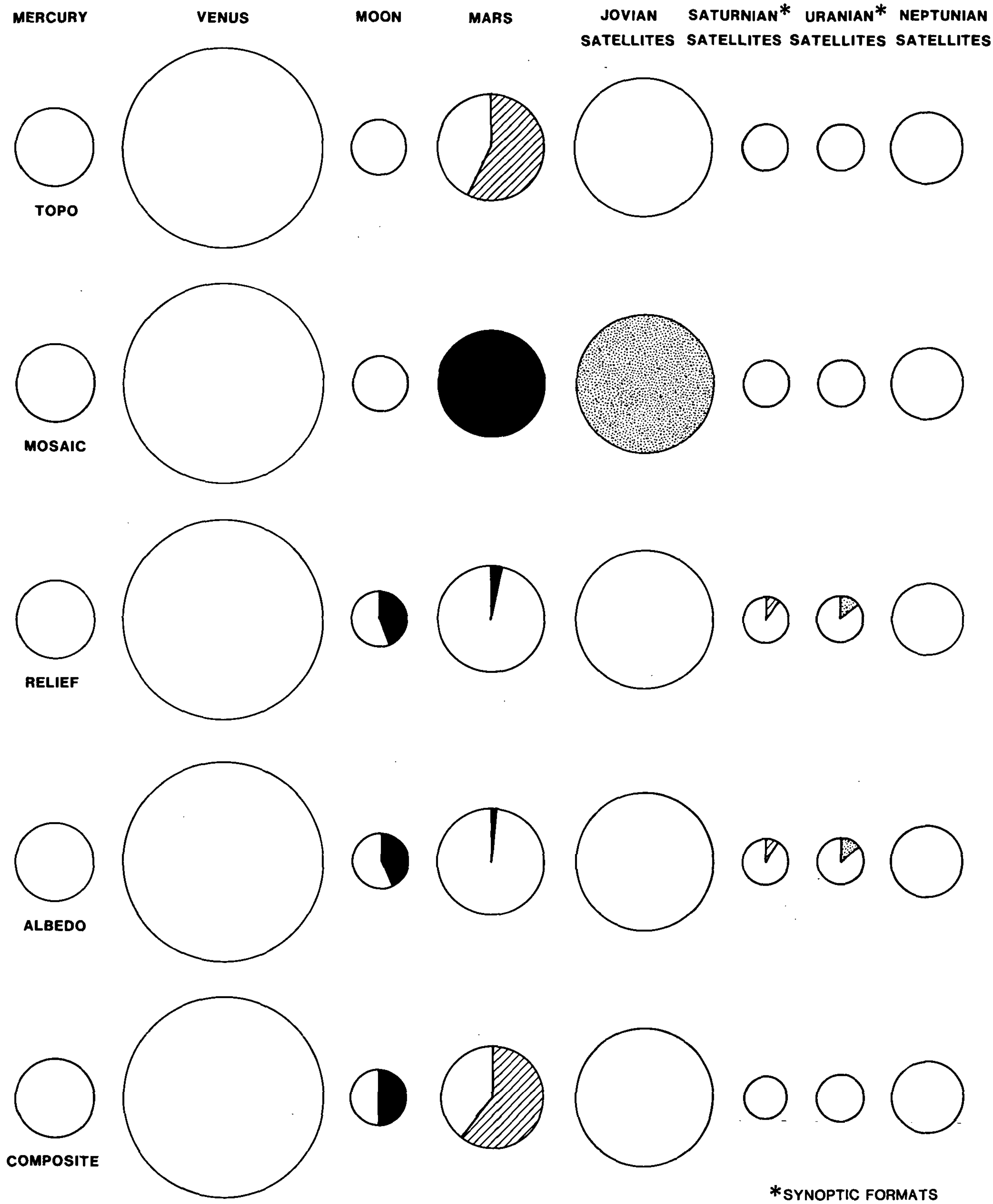


Figure 21C.
1:2 000 000 and larger-scale mapping in synoptic, quadrangle, or special formats.

Table 11. Recommended Maps from Existing and Future Data

Planet or Satellite	Number of Maps	Planet or Satellite	Number of Maps
Mars		Io	
Mosaics		Mosaics	
1:2M	140	1:2M	∼37
1:500K	∼250	Relief	
Relief		1:15M	1
1:5M	30	1.5M	∼4
Albedo		Albedo	
1:15M	3	1:5M	∼4
Topo			∼46
1:15M	3		
1:2M	∼80	Europa	
1:500K	∼50		
Composite		Mosaics	
1:15M	3	1:2M	∼37
1:2M	∼80	Relief	
1:500K	∼50	1:15M	1
	∼689	1:5M	∼4
		Albedo	
Venus		1:5M	∼4
			∼46
Mosaics			
1:5M	62	Ganymede	
Relief			
1:50M	2	Mosaics	
1:25M	6	1:2M	∼70
1:15M	8	Relief	
1:5M	62	1:25M	1
Topo		1:15M	3
1:50M	2	1:5M	∼15
1:25M	6	Albedo	
1:15M	8	1:25M	1
1:5M	62	1:15M	3
Composite		1:5M	∼15
1:50M	2		∼108
1:25M	6		
1:15M	8	Callisto	
1:5M	62		
	296	Mosaics	
		1:2M	∼70
Moon		Relief	
		1:25M	1
Relief		1:15M	3
1:5M	1	1:5M	∼15
Albedo		Albedo	
1:5M	1	1:25M	1
	2	1:15M	3
		1:5M	∼15
			∼108

Table 11. *(continued)*

Planet or Satellite	Number of Maps	Planet or Satellite	Number of Maps
Saturn Satellites		Neptune Satellites (Triton)	
Mosaics			
1:5M	2	Mosaics	
Relief		1:15M	~3
1:10M	2	1:5M	~15
1:5M	2	Relief	
1:2M	2	1:15M	~3
Albedo		1:5M	~15
1:10M	2	Albedo	
1:5M	2	1:25M	1
1:2M	2	1:15M	~3
	14	1:5M	~15
			~55
Uranus Satellites			
Mosaics			
1:5M	~2		
Relief			
1:10M	1		
1:5M	2		
1:2M	1		
Albedo			
1:10M	2		
1:5M	2		
1:2M	2		
	~12		
Total =	~1376		

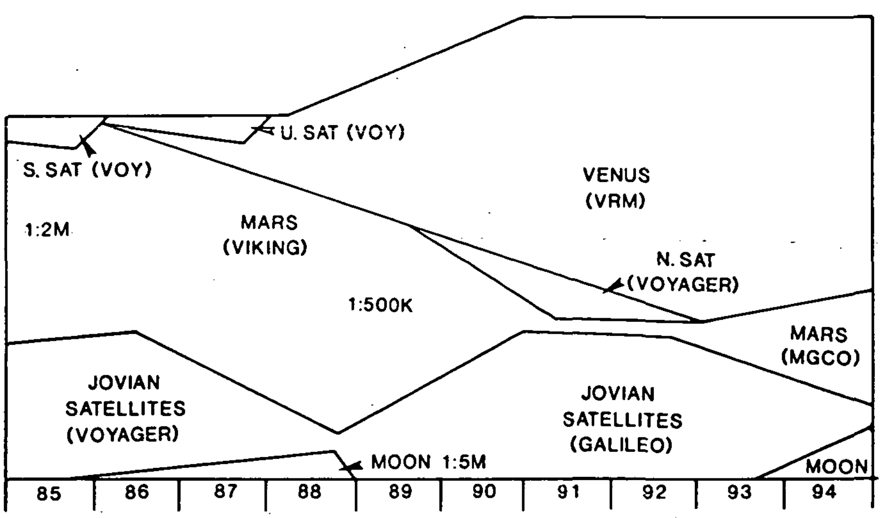


Figure 22.
Estimated level of effort for ten-year plan. The area shown by each planet or satellite system indicates the relative level of effort.

Appendices

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Appendix A: Responses to Planetary Cartography Questionnaire

RESPONSES

Total Number: 76

By Country:
Domestic = 63
Foreign = 13

By Discipline:

Planetary Geology	47	(62 percent)
Planetary Astronomy	9	(12 percent)
Planetary Geophysics	8	(11 percent)
Planetary Geochemistry	7	(9 percent)
Planetary Atmospheres	5	(6 percent)

TYPES OF MAPS FOUND MOST USEFUL (Listed in order of preference; number of responses in parentheses):

1. Planetwide (60)
2. Contour maps (58)
3. Controlled photomosaics (57)
4. High-resolution maps (54)
5. Medium-resolution maps (49)
6. Airbrush maps (45)
7. Footprint maps (44)
8. Digital data (27)
9. Uncontrolled photomosaics (26)

BODIES CURRENTLY CONSIDERED TO BE MOST IMPORTANT TO RESPONDENTS' RESEARCH (Listed in order of preference; number of responses in parentheses):

1. Mars (57)
2. Moon (47)
3. Venus (37)
4. Ganymede (33)
5. Io (33)
6. Europa (26)
7. Enceladus (24)
8. Mercury (24)
9. Callisto (23)
10. Iapetus (19)
11. Dione (19)
12. Mimas (18)
13. Rhea (16)
14. Tethys (16)
15. Saturn, Uranus, and Neptune (14)
16. Phobos (14)
17. Deimos (13)
18. Hyperion (9)

IMPORTANCE OF PLANETARY MAPS TO RESPONDENTS (10 = absolutely essential; 0 = not relevant; total number of responses in parentheses):

$$\left.\begin{array}{r} 10=(31) \\ 9=(13) \\ 8=(13) \end{array}\right\} \text{75 percent}$$

7 = (2)
6 = (6)
5 = (4)
4 = (1)
3 = (2)
2 = (3)
1 = (1)

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Planetary Mapping Requirements for 10-Year Plan

Name ____________________

Institution ____________________

Research Interest ____________________

1. Check the maps that you find useful:

_____ Uncontrolled mosaics
_____ Controlled mosaics
_____ Airbrush maps
_____ Contour maps
_____ Footprint maps and frame indexes
_____ Other (specify) __________
_____ Planetwide maps (1:10M to 1:100M)
_____ Medium-resolution maps (1:2M to 1:5M)
_____ High-resolution maps (1:100K to 1:1M)
_____ Digital map data

2. Which bodies are most relevant to your investigations?

_____ Mercury	_____ Venus	_____ Moon	_____ Mars
_____ Phobos	_____ Deimos	_____ Io	_____ Europa
_____ Ganymede	_____ Callisto	_____ Mimas	_____ Enceladus
_____ Tethys	_____ Dione	_____ Rhea	_____ Iapetus
_____ Hyperion	_____ Satellites of Uranus and Neptune		

_____ Others (specify) ____________________

3. Describe any current special mapping needs for your area of interest, particularly ones that are not currently being met (such as Mars channels, or hilly and lineated terrain on Mercury).

4. Describe future mapping needs you foresee for anticipated investigations. Note that it may take two or three years to produce preliminary work copies of many complicated maps or new map series.

5. Other comments.

6. On a scale of 0 to 10, how important are planetary maps to your investigations?
(0 = not relevant, 10 = absolutely essential) ____________________

Return the questionnaire to the registration desk prior to your departure, or send to:

Robert G. Strom
Lunar and Planetary Laboratory
University of Arizona
Tucson, Arizona 85721

Figure A1. Planetary and Cartography Questionnaire

Appendix B: Production and Public Sales of Planetary Maps Through June 1983*

	Mercury	Venus	Moon	Mars	Galilean Satellites	Saturnian Satellites	Totals
Synoptic Maps							
Number of maps	3	1	—	6	4	10	24
Number of copies printed	10 125	4 530	—	20 133	10 275	26 000	71 063
Number of copies sold	8 285	3 125	—	16 983	9 810	18 650	56 853
Average sales per map	2 762	3 125	—	2 831	2 453	1 865	2 369
1:5 000 000 Quads							
Number of maps	9	—	4	55	—	—	68
Number of copies printed	27 390	—	11 376	163 430	—	—	202 196
Number of copies sold	15 265	—	6 166	93 125	—	—	114 556
Average sales per map	1 696	—	1 542	1 693	—	—	1 685
1:2 000 000 Quads							
Number of maps	—	—	—	96	—	—	96
Number of copies printed	—	—	—	260 577	—	—	260 577
Number of copies sold	—	—	—	108 283	—	—	108 283
Average sales per map	—	—	—	1 128	—	—	1 128
Miscellaneous Special Maps							
Number of maps	1	—	1	22	—	—	24
Number of copies printed	3 100	—	2 800	68 235	—	—	74 135
Number of copies sold	1 875	—	400	37 526	—	—	39 801
Average sales per map	1 875	—	400	1 706	—	—	1 658
Totals							
Number of maps	13	1	5	179	4	10	212
Number of copies printed	40 615	4 530	14 176	512 375	10 275	26 000	607 971
Number of copies sold	25 425	3 125	6 566	255 917	9 810	18 650	319 493
Average sales per map	1 956	3 125	1 313	1 430	2 453	1 865	1 507
Atlases: number of copies sold **	3 416	—	—	6 980	—	—	10 396

* Sources: U.S. Geological Survey, Arlington, Virginia and Denver, Colorado (Only maps published by the U.S. Geological Survey are shown. Numbers are not available for lunar maps published by the Defense Mapping Agency.)

** Source: U.S. Government Printing Office, Washington, D.C.

Appendix C: Cartographic Elements and Principles

All cartographic products require control networks, coordinate systems, and a system of nomenclature. The following is a summary of the principles involved in deriving these essential cartographic elements.

Coordinate Systems of Planets and Satellites

In 1976, Commissions 4 and 16 of the International Astronomical Union (IAU) established a joint working group on cartographic coordinates and rotational elements of the planets and satellites. Reports of this group were presented at the IAU General Assemblies in 1979 and 1982 (Davies et al., 1980, 1983).

The IAU working group adopted the following guiding principles:

1. The rotational pole of a planet or satellite which lies on the north side of the invariable plane shall be called north, and north latitudes shall be designated positive.

2. The planetographic longitude of the central meridian, as observed from a direction fixed with respect to an inertial coordinate system, shall increase with time. The range of longitudes shall extend from 0° to 360°.

As a result of principle 2, bodies with prograde rotation, such as Mercury, Mars, and most of the satellites of Jupiter and Saturn, have longitudes from 0° to 360° that increase from east to west. The retrograde rotation of Venus and the satellites of Uranus, however, results in longitudes from 0° to 360° that increase from west to east. The exceptions to principle 2 are the Moon and Earth, where longitudes are measured from 0° to 180° east and west of the prime meridian.

The cartographic coordinate system is defined by reference to a planet's or satellite's axis of rotation and an arbitrarily defined prime meridian. In most cases, a clearly defined photo-identifiable surface feature is assigned a specific longitude. Small craters have been selected for this purpose: Hun Kal defines 20° on Mercury, Airy-O defines 0° on Mars, Cilix defines 182° on Europa, Anat defines 129° on Ganymede, Saga defines 326° on Callisto, and so forth. On Io, it was not obvious how to choose a small permanent feature for the definition of longitudes because of Io's extensive volcanic resurfacing; thus the astronomical definition is used—the prime meridian is the sub-Jupiter longitude at the first superior conjunction after 1950.0. The prime meridian of the Moon passes through the mean sub-Earth direction.

The rotational elements of the planets and satellites are derived relative to the standard Earth mean equator and equinox of the J1950.0 coordinate system, and time is measured in ephemeris days or Julian ephemeris centuries of 36525 days from the standard epoch of 1950 January 1.0 ET, or JED 2433282.5. The standard equatorial coordinates of J2000 and standard epoch 2000 January 1.5 or JD 2451545.0 TDB are also available. The direction of the north pole is specified by its right ascension, α_0, and declination, δ_0. The prime meridian is specified by the angle, W, measured along the planet's equator in an easterly direction from the ascending node, Q, of the planet's equator on the standard Earth equator to the point, B, where the prime meridian crosses the planet's equator (fig. C1). If W increases with time, the planet has direct rotation; if W decreases, the rotation is retrograde.

The mathematical expressions for α_0, δ_0, and W as a function of time are fairly simple for the planets because their precession periods are long and the distances between them are sufficiently great that their mutual gravitational perturbations are small. On the other hand, the expressions for the natural satellites of the planets are frequently long because the theory of their motions commonly necessitates many terms.

The reports of the IAU working group also contain recommended reference spheroids for mapping the planets and satellites. The values for the equatorial radii and flattening presented in this report are used to define the reference datums for bodies currently in the mapping program. Only for the Earth, Moon, Mars, and Venus is there sufficient information to prepare topographic contour maps. Currently, topographic contour maps of the Moon and Venus are spherical vertical datums. However, contour maps of Mars based on Mariner 9 data use a vertical datum defined by its gravity field and described in terms of the spherical harmonics of fourth degree and fourth order, combined with a 6.1-millibar surface of 3382.9-km radius (Wu, 1981). The International Association of Geodesy (IAG) has proposed the establishment of a joint working group to review current mapping practices and define reference systems for the planets and satellites. This working group will consist of representatives of the IAU, COSPAR, and IAG, and will consider horizontal and

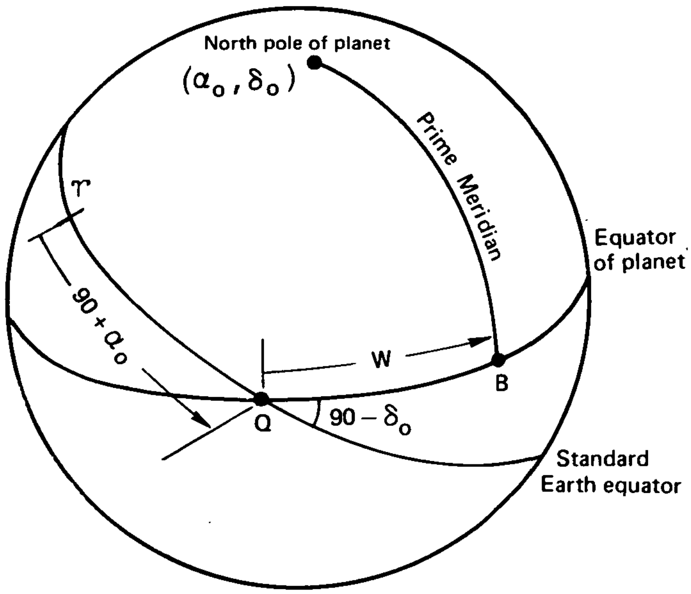

Figure C1.
Reference system used to define the orientation of a planet.

vertical datums, the gravity fields, and a coordinate connection to an inertial system.

Control Networks of Planets and Satellites

Control networks of the planets and satellites, required to compile any type of map, are computed photogrammetrically from location measurements of surface features made on images taken by spacecraft. Control points are selected on these images, their positions are measured (in millimeters on film images or pixels on electro-optical images), and their cartographic coordinates are computed using analytical triangulation computer programs. The programs are variations of the standard bundle method used in conventional Earth-mapping photogrammetric projects. The coordinates of the surface features (control points) are then used to position the latitude and longitude grid for maps.

The best images of the Moon were recorded on photographic film, whereas the images of Mercury, Mars, and the satellites of the outer planets were all taken with television cameras. The character of the data sets dictates to a large extent the design of the mapping project. On Earth, a conventional aerial mapping project would start with an aircraft flying in straight lines over the designated terrain and taking overlapping pictures with a photographic film aerial camera. Usually the mapping camera has a minimum distortion, wide-angle lens, and sometimes a calibrated reseau platen in the film plane. Because wide-angle lenses are used, accurate horizontal and vertical positions of points can be computed from overlapping stereoscopic pictures. The Fairchild mapping camera flown on Apollo 15, 16, and 17 was the only camera in the lunar and planetary program to satisfy conventional mapping requirements and procedures. The Soviet Zond 6 and 8 cameras were mapping cameras but their lenses did not have a field of view wide enough to permit accurate vertical measurements for points on the lunar surface. The Zond 6 and 8 pictures are, however, excellent for planimetric information. Although the Apollo mapping coverage was limited, the accuracy of the network in the mapped region is much greater than in any other area of the Moon (Schimerman et al., 1973; Schimerman, 1976; Doyle et al., 1976). Zond 6 and 8 images were tied photogrammetrically to points on the near-side telescopic net, thus extending the net into the eastern far side of the Moon (Bolijshakov et al., 1975; Ziman et al., 1975).

The Lunar Orbiters provided medium-resolution global coverage of the lunar surface. This camera system was not designed with photogrammetric applications as a primary objective. Measurements on the photographs required precise reassembly of the small framelets to the film reseau—a time-consuming and laborious task that fails to define the image geometry rigorously even when carefully done. A control network of the far side of the Moon was developed from the Lunar Orbiter data and published as the Lunar Positional Reference System (1974). Telescopic data are still essential for a complete control network on the near side of the Moon (Meyer, 1980) because better spacecraft data for positional measurements are not available except in the Apollo mapping region. The control networks are summarized in table C1.

Vertical control is computed photogrammetrically in the telescopic, Apollo, and Zond lunar nets; the Apollo laser altimeter is another source of very good vertical data. The coordinates of the lunar retroreflectors and the ALSEP transmitters left on the surface by the Apollo missions have been accurately determined (Bender et al., 1973; King et al., 1976; Ferrari et al., 1980); the Apollo 15 retroflector and the Apollo 16 and 17 transmitters have been located on the panoramic images and their locations transferred to the mapping pictures (Schimerman, 1976).

The horizontal control net of Mercury was computed photogrammetrically from images taken by the Mariner 10 spacecraft on its three encounters with Mercury (Davies and Katayama, 1976). All of the control points were constrained to lie on a sphere with a radius of 2439 km. This radius is consistent to within 0.7 km of the two occultation measurements made when the Mariner 10 spacecraft passed behind Mercury (Howard et al., 1974), and from measurements made by Earth-based radar (Ash et al., 1971).

The computation of the planetwide horizontal control nets of Venus will depend on data from the Venus

Table C1. Control Nets of Planets and Satellites Based on Pictures Taken by Spacecraft

Planet	Satellite	Spacecraft	Number of Points in Net	Number of Pictures in Net	Reference
Earth	Moon	Lunar Orbiter		41	Positional Reference System (1974)
		Apollo 15	4900		Schimerman et al. (1973)
		Apollo 15,16,17			Schimerman (1976)
		Apollo 15,16,17	5324	1244	Doyle et al. (1976)
		Zond 6,8	387		Bolijshakov et al. (1975)
		Zond 6,8	131	4	Ziman et al. (1975)
Mars		Mariner 9	6853	1811	Davies and Katayama (1983a)
		Viking 1,2			
		Mars 4,5	200		Tjuflin et al. (1980)
Mercury		Mariner 10	2378	788	Davies and Katayama (1976)
Jupiter	Io	Voyager 1,2	504	234	Davies and Katayama (1981)
	Europa	Voyager 1,2	112	115	Davies and Katayama (1981)
	Ganymede	Voyager 1,2	1547	282	Davies and Katayama (1981)
	Callisto	Voyager 1,2	439	200	Davies and Katayama (1981)
Saturn	Mimas	Voyager 1	110	32	Davies and Katayama (1983b)
	Enceladus	Voyager 2	71	22	Davies and Katayama (1983b)
	Tethys	Voyager 1,2	110	27	Davies and Katayama (1983c)
	Dione	Voyager 1,2	126	28	Davies and Katayama (1983c)
	Rhea	Voyager 1,2	351	84	Davies and Katayama (1983d)
	Iapetus	Voyager 1,2	62	80	Davies and Katayama (1984)

Radar Mapper mission in 1988. However, the radar altimeter on the Venus Pioneer mission provided good elevation data, so for the first time the vertical control on a planet is more advanced than the horizontal control.

The Mariner 9 spacecraft acquired images of the entire surface of Mars at approximately uniform resolution; thus, for the first time it was possible to compute a planetwide horizontal control net from a single source of data. Viking Orbiter 1 and 2 images were later included in the single-block analytical triangulation (Davies and Katayama, 1983a). The location of the Viking 1 Lander on the surface of Mars was identified on high-resolution Viking Orbiter images (Morris and Jones, 1980) so that accurate coordinates of the lander site (Michael, 1979) could be incorporated in the analytical triangulation. Vertical control on Mars was derived from many sources (Wu, 1978), including Mariner 9 and Viking 1 and 2 radio occultations; Earth-based radar observations using the Haystack, Arecibo, and Goldstone antennas; and measurements by the Mariner 9 ultraviolet spectrometer, infrared interferometer spectrometer, and infrared radiometer. Analysis of radio tracking data from both Viking landers has led to very accurate values for the direction of Mars' rotation axis, its rotation rate, and coordinates of the lander sites (Mayo et al., 1977; Michael, 1979; Reasenberg and King, 1979). Thus nonphotogrammetric data as well as the vertical network are fundamental to the development of the horizontal control network on Mars.

The Voyager 1 and 2 encounters with Jupiter provided images of the Galilean satellites Io, Europa, Ganymede, and Callisto. Measurements of points on these images are being used to establish horizontal control nets by analytical triangulation (Davies and Katayama, 1981). Because they were flyby missions, the resolution on the Galilean satellites varies greatly with longitude. Their mean radii were computed as additional unknowns in the analytical triangulation.

The Voyager 1 and 2 encounters with Saturn provided images of its major satellites except Titan, which is cloud covered. These images have been used to establish control networks on Mimas, Enceladus, Tethys, Dione, Rhea, and Iapetus (Davies and Katayama, 1983b,c,d). As with all flyby encounters, the resolution of the images varied with longitude, and it was not always possible to tie them together with common features. Thus the control network of Enceladus does not encircle the satellite, and the Voyager 1 and 2 images of Iapetus are not tied together. The control networks of Mimas, Tethys, Dione, and Rhea do, however, encircle the satellites.

Nomenclature

Before the space age, nomenclature had been assigned to topographic features on the Moon and albedo markings on Mars. The IAU periodically established committees to deal with nomenclature problems and questions that arose from the explorations of the Moon and Mars in the 1960s. By the early 1970s, it became apparent that the entire solar system was open to exploration by spacecraft.

In 1973, the IAU established a working group for Planetary Systems Nomenclature with Peter Millman of Canada designated president. Under the Working Group, Task Groups were established for the nomenclature of the Moon, Mercury, Venus, Mars, and the outer solar system. The Task Groups are responsible for nomenclature themes and name banks and the assignment of names to particular features. Those names can then be used on maps as "proposed names." The Working Group must then approve the recommendations of the Task Groups, and the IAU Executive Council must approve this report. Final approval is by the IAU General Assembly at which time the names can be shown on maps as "approved names." Harold Masursky of the U.S. Geological Survey is currently president of the Working Group; the chairmen of the Task Groups are V.V. Shevchenko, U.S.S.R., Moon; D. Morrison, U.S.A., Mercury; M. Ya Marov, U.S.S.R., Venus; B.A. Smith, U.S.A., Mars; and T.C. Owen, U.S.A., Outer Planets.

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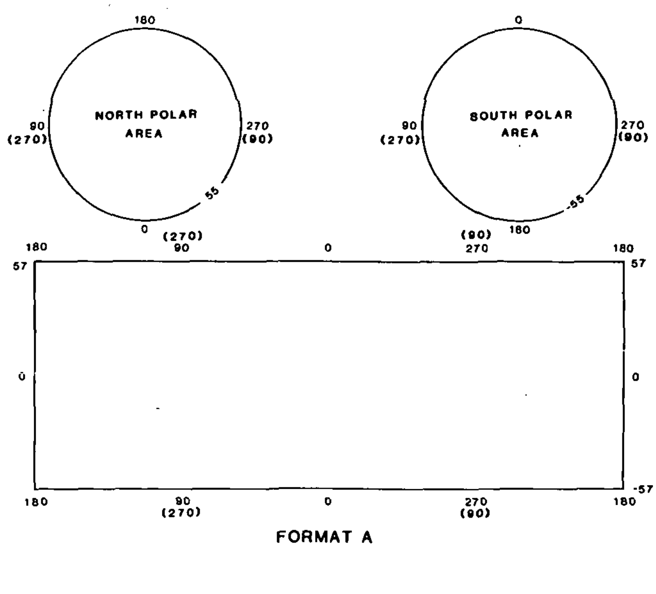
Appendix D: Planetary Map Formats and Products

The following diagrams and tabulations illustrate the formats of planetary maps and the status and plans for mapping. Maps that have been published, maps that are in press, and maps that are currently being compiled are shown in bold-face type. Map status is indicated by PUB for published maps, IPR for maps in preparation, PLAN for maps recommended in this report, and FUT for maps that may be important for later consideration. Plans for mapping from anticipated data are subject to large uncertainties.

More than one version of each map commonly is required for adequate cartographic representation. When the topographic contour interval is adequate to characterize landforms (very uncommon in planetary mapping), it is useful to print a separate version of the map without a photographic base to allow clear definition of the contour lines. Such versions are designated TOPO in the tabulations. Maps designated MOSAIC are made either by hand or in the computer with geometrically projected spacecraft images. They may be in color or in black and white. RELIEF maps are made by airbrush techniques and show only three-dimensional structures. ALBEDO maps are usually made with the airbrush and show albedo patterns superimposed on a shaded relief base map. COMPOSITE maps contain an overprint of contour lines on a mosaic, relief, or albedo base.

In some instances, the same map compilation is published at different scales and in slightly different formats. For example, the Venus map compiled on format C will be reduced in scale and published at 1:25 000 000 on format B, and as a single sheet at 1:50 000 000 on format A. Similarly, it may be desirable to combine existing 1:2 000 000 Mars mosaics and publish them at reduced scale in the 1:5 000 000 Mars quadrangle format. Since no new compilation is involved, the cost of these extra versions is negligible.

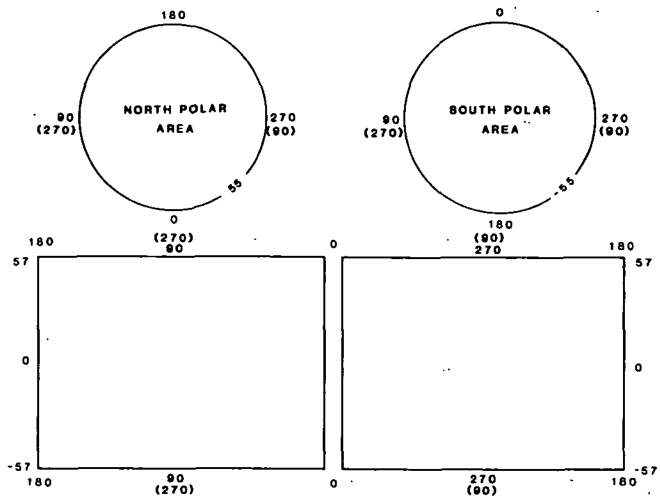


FORMAT A

Map Format A

Format A is used to map entire planets on a single sheet. The use of similar scales facilitates intercomparison of landforms and other features appearing in the maps, but is not always feasible because of the wide range in sizes of planets being mapped. The format is therefore used at scales ranging from 1:2 000 000 to 1:50 000 000 for planetwide maps, and is subdivided into formats B and C for the larger planets to allow mapping of planets at the same scale.

SCALE	BODY	DATA SOURCE	STATUS	TOPO	MOSAIC	RELIEF	ALBEDO	COMPOSITE	TOTAL
1:50M	Venus	Pioneer	**PUB**					1	1
			IPR			1		1	2
		VRM	PLAN	2		2		2	6
1:25M	Mars	Mariner 9	**PUB**			2	2	1	5
		MCGO	FUT	1					1
		MCGO + Viking	FUT					1	1
	Io	Voyager	**PUB**				1		1
		Galileo	FUT				1		1
	Europa	Voyager	**PUB**				1		1
		Galileo	FUT				1		1
	Ganymede	Voyager	**PUB**				1		1
		Voyager	PLAN			1	1		2
		Galileo	FUT				1		1
	Callisto	Voyager	**PUB**				1		1
		Voyager	PLAN			1	1		2
		Galileo	FUT				1		1
	Triton	Voyager	FUT				1		1
1:15M	Mercury	Mariner 10	**PUB**			1	1		2
	Io	Voyager	**IPR**				1		1
			PLAN			1			1
		Galileo	PLAN		2	1	1		4
	Europa	Voyager	**IPR**				1		1
			PLAN			1			1
1:10M	Tethys	Voyager	**PUB**				2		2
	Dione	Voyager	**PUB**				2		2
	Rhea	Voyager	**PUB**				2		2
			PLAN			1	1		2
	Iapetus	Voyager	**PUB**				1		1
			PLAN			1	1		2
	Ariel	Voyager	PLAN			1	2		3
1:5M	Tethys	Voyager	PLAN			1	1		2
	Dione	Voyager	PLAN			1	1		2
1:2M	Mimas	Voyager	**PUB**				2		2
			PLAN			1	1		2
	Enceladus	Voyager	**PUB**			1	1		2
			PLAN				1		1
	Miranda	Voyager	PLAN			1	2		3

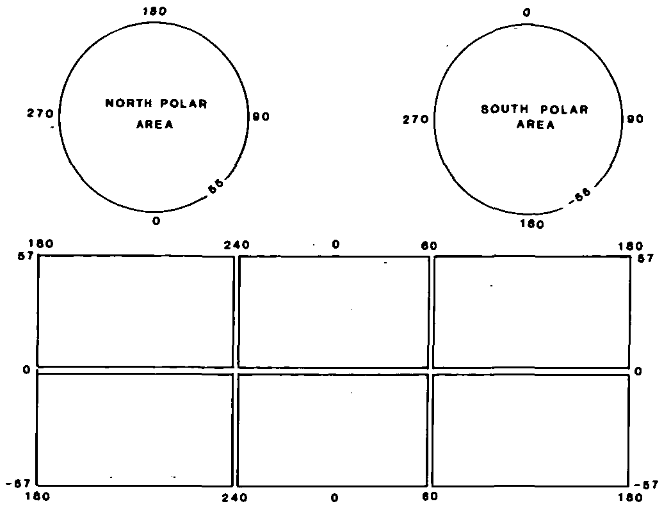


FORMAT B

Map Format B

A subdivision of format A.

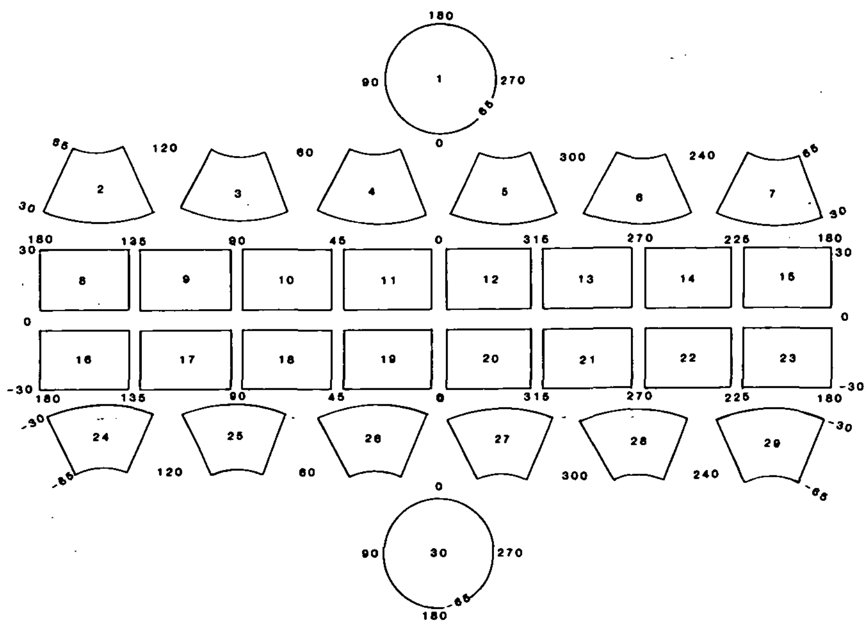
SCALE	BODY	DATA SOURCE	STATUS	TOPO	MOSAIC	RELIEF	ALBEDO	COMPOSITE	TOTAL
1:25M	Venus	VRM	PLAN	6		6		6	18
1:15M	Mars	Viking	**PUB**			3			3
			IPR	3			2	3	8
		MGCO+ Viking	FUT	3				3	6
	Ganymede	Voyager	PLAN			3	3		6
		Galileo	FUT		3	3	3		9
	Callisto	Voyager	PLAN			3	3		6
		Galileo	FUT		3	3	3		9
	Triton	Voyager	PLAN		3	3	3		9
1:5M	Rhea	Voyager	PLAN		2	2	2		6
	Ariel	Voyager	PLAN		2	2	2		6



Map Format C

A subdivision of format A, to allow synoptic mapping of Venus at 1:15 000 000.

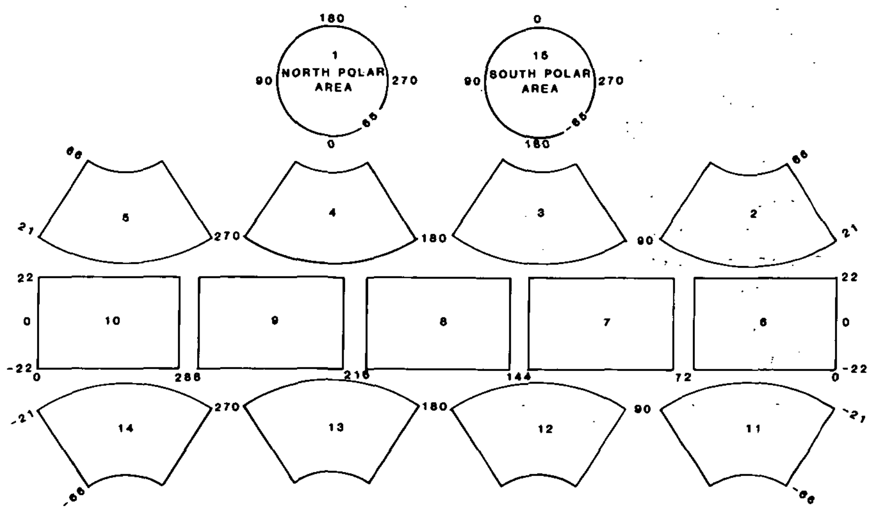
SCALE	BODY	DATA SOURCE	STATUS	TOPO	MOSAIC	RELIEF	ALBEDO	COMPOSITE	TOTAL
1:15M	Venus	VRM	PLAN	8		8		8	24



Map Format D

The Mars 1:5 000 000 mapping format. The planets and larger satellites have been subdivided into quadrangles for mapping at the 1:5 000 000 scale (formats D, E, F, and G). Equatorial regions are mapped on Mercator projections, intermediate latitudes on Lambert conformal conic projections, and polar regions on polar stereographic projections. These projections are conformal; that is, small features retain their correct shapes regardless of their locations on the map. Scale factors are selected so that map scales are the same at join lines between Mercator and Lambert projections and between Lambert and polar projections. Maps in the same latitude zone can be joined by mosaicking to make single, large sheets.

SCALE	BODY	DATA SOURCE	STATUS	TOPO	MOSAIC	RELIEF	ALBEDO	COMPOSITE	TOTAL
1:5M	Mars	Mariner 9	**PUB**			30		14	44
		Viking	**PUB**			14			14
		Viking	**IPR**			4			4
		Viking	PLAN			12			12
		Viking	FUT		30			30	60
		MGCO+ Viking	FUT	30				30	60

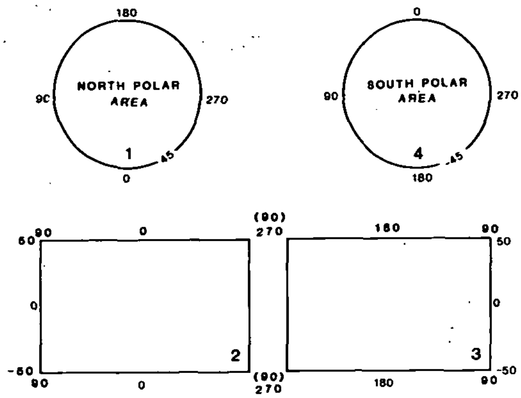


FORMAT E

Map Format E

The 1:5 000 000 mapping format for Mercury-sized planets and satellites.

SCALE	BODY	DATA SOURCE	STATUS	TOPO	MOSAIC	RELIEF	ALBEDO	COMPOSITE	TOTAL
1:5M	Mercury	Mariner 10	**PUB**			9			9
	Ganymede	Voyager	**IPR**				8		8
		Voyager	PLAN				7		7
		Galileo	PLAN		15	15	15		45
	Callisto	Voyager	PLAN				15		15
		Galileo	PLAN		15	15	15		45
	Triton	Voyager	PLAN		15	15	15		45

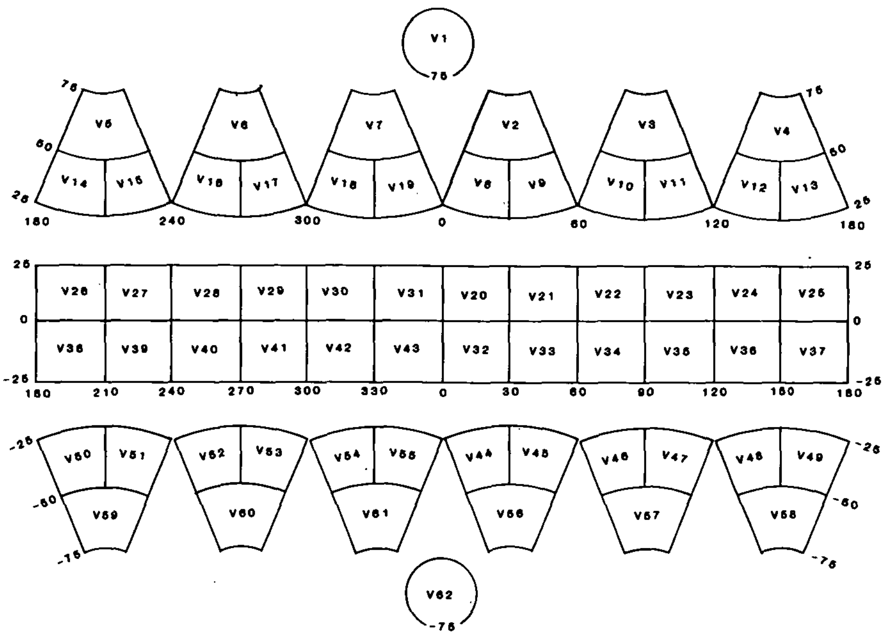


FORMAT F

Map Format F

The lunar size range does not lend itself to convenient subdivision of this kind at 1:5 000 000. Format F was originally designed for mapping the Moon and is now being used to map Io and Europa as well.

SCALE	BODY	DATA SOURCE	STATUS	TOPO	MOSAIC	RELIEF	ALBEDO	COMPOSITE	TOTAL
1:5M	Moon	LO+ Apollo	**PUB**			2	5		7
		LO+ Apollo	PLAN			1	1		2
	Io	Voyager	**IPR**				3		3
		Galileo	PLAN			4	4		8
		Galileo	FUT		8				8
	Europa	Voyager	**IPR**				2		2
		Galileo	PLAN			4	4		8
		Galileo	FUT						

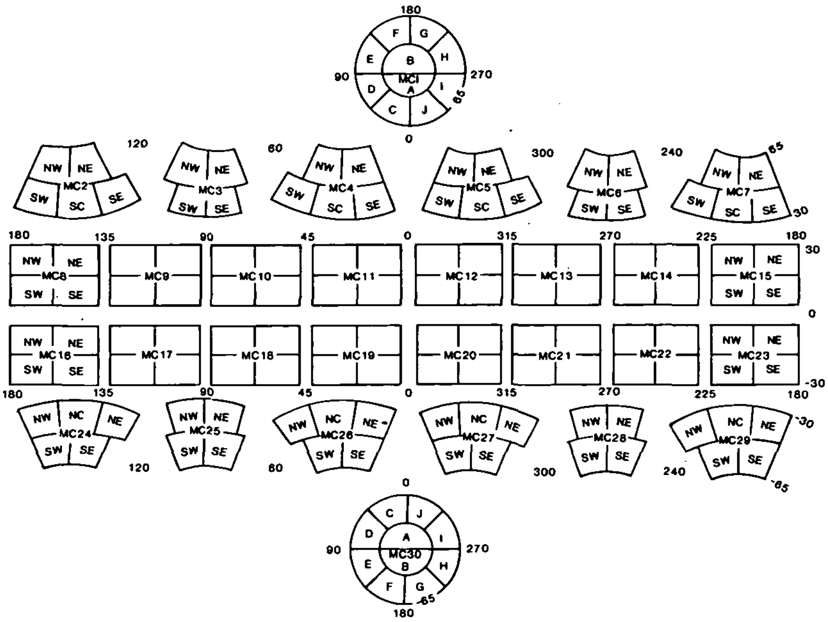


FORMAT G

Map Format G

The format for mapping Venus at 1:5 000 000.

SCALE	BODY	DATA SOURCE	STATUS	TOPO	MOSAIC	RELIEF	ALBEDO	COMPOSITE	TOTAL
1:5M	Venus	VRM	PLAN	62	62	62		62	248

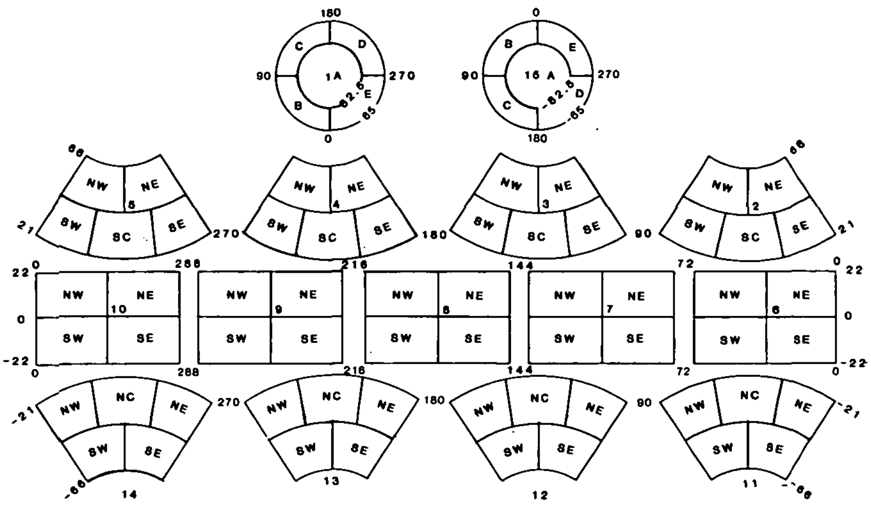


FORMAT H

Map Format H

Viking image quality and scientific requirements dictate mapping scales larger than 1:5 000 000 for Mars. The 1:2 000 000 series subdivides the Mars 1:5 000 000 quadrangles to permit more detailed mapping at the larger scale. The same projections are used for both series; only the scales and longitude boundaries of the quadrangles have been changed, so that 1:2 000 000 quadrangles can be joined by mosaicking into sheets geometrically similar to, but larger than, the 1:5 000 000 quadrangles.

SCALE	BODY	DATA SOURCE	STATUS	TOPO	MOSAIC	RELIEF	ALBEDO	COMPOSITE	TOTAL
1:2M	Mars	Viking	**PUB**		107	2			109
			IPR		47				47
			PLAN	80				80	160
		MGCO+ Viking	FUT	140				140	280

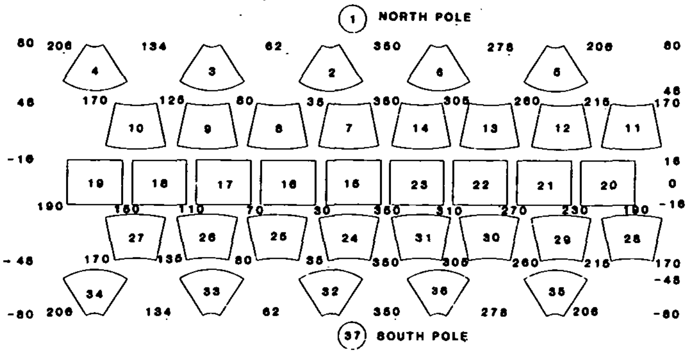


FORMAT J

Map Format J

Similarly, format E has been subdivided into format J to permit mapping Mercury, Ganymede, Callisto, and Triton at 1:2 000 000, when and if data become available that justify mapping at that scale. A similar subdivision of the 1:5 000 000 quadrangle of Venus may eventually be required.

SCALE	BODY	DATA SOURCE	STATUS	TOPO	MOSAIC	RELIEF	ALBEDO	COMPOSITE	TOTAL
1:2M	Ganymede	Galileo	PLAN		70				70
	Callisto	Galileo	PLAN		70				70
	Ganymede	Galileo	FUT			70	70		140
	Callisto	Galileo	FUT			70	70		140
	Triton	Voyager	FUT		TBD	TBD	TBD		TBD

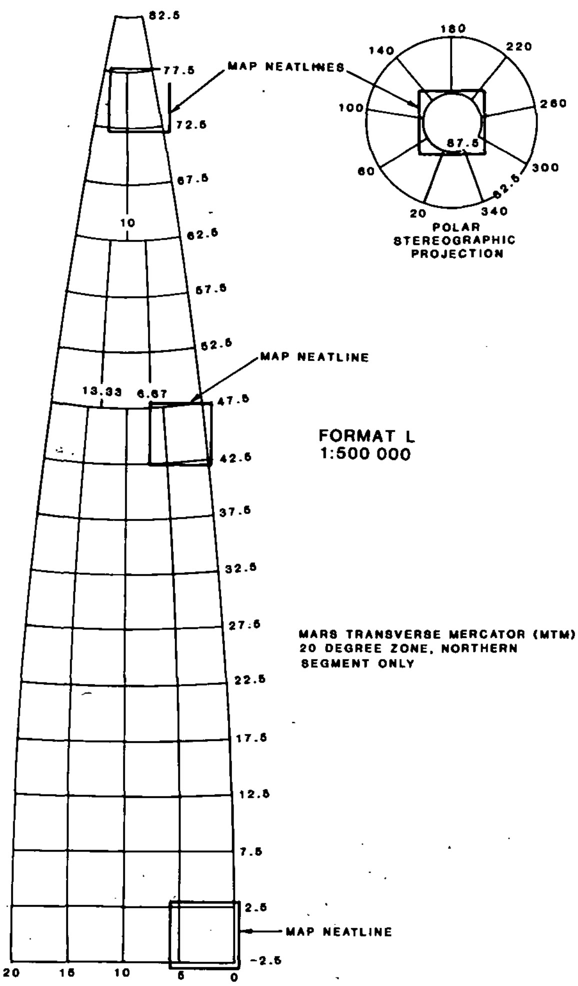


FORMAT K

Map Format K

Format K was designed for mapping the Moon, Io, and Europa at 1:2 000 000. Mapping the Moon at 1:2 000 000 could proceed with data now in hand should scientific need dictate. The Galileo mission is expected to return data adequate for mapping large parts of Io and Europa at that scale. Format K is an expansion of the format used for the lunar 1:1 000 000 format; the projection geometry is such that existing lunar 1:1 000 000 quadrangles can be mosaicked exactly to fit enlargements of the 1:2 000 000 quadrangles. This necessitates the use of two Lambert conformal conic zones, which have different curvatures along their join parallels (48° north and south).

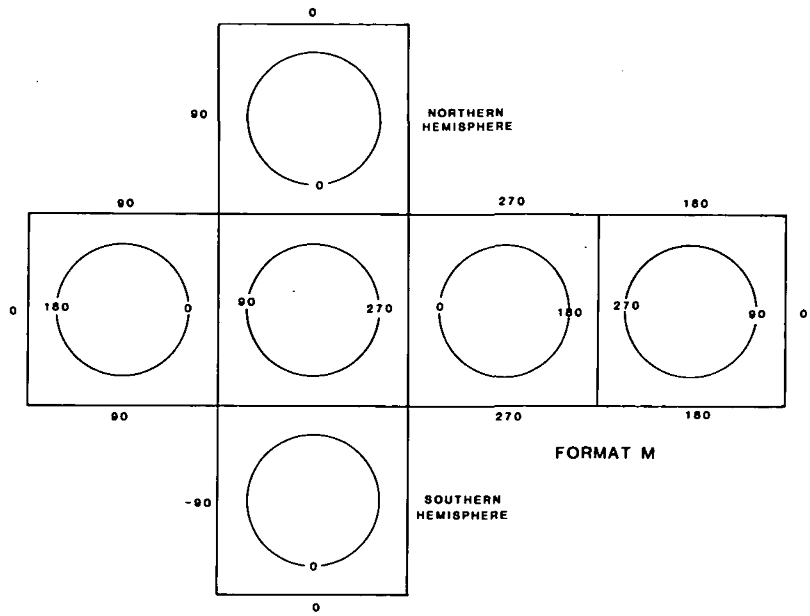
SCALE	BODY	DATA SOURCE	STATUS	TOPO	MOSAIC	RELIEF	ALBEDO	COMPOSITE	TOTAL
1:2M	Moon	LO + Apollo							
	Io	Galileo	PLAN		37				37
	Io	Galileo	FUT			37	37		74
	Europa	Galileo	PLAN		37				37
		Galileo	FUT			37	37		74



Map Format L

Viking returned thousands of images that resolve landforms with dimensions of 100 meters and smaller. These images contain unique evidence of poorly understood surface processes, the study of which requires appropriate scale mapping. The Mars Transverse Mercator (MTM) system was designed to support these studies. The series consists of transverse Mercator projections in zones 20° longitude by 75° latitude, containing 112 quadrangles each. The scale is 1:504 000 at the central meridian of each projection zone and 1:496 000 on the extreme edge. Stereographic projections are used for the polar regions. The MTM system provides a systematic framework for making maps in support of topical high-resolution studies. There is no plan to compile more than a small percentage of the nearly 2000 sheets in the series.

SCALE	BODY	DATA SOURCE	STATUS	TOPO	MOSAIC	RELIEF	ALBEDO	COMPOSITE	TOTAL
1:500K	Mars	Viking	IPR		36				36
			PLAN	50	250			50	350
		MGCO+ Viking	FUT	250				250	500



Map Format M

Reasonable characterizations of entire planets on single pages of books, journals, or magazines pose unique cartographic problems. The significant properties of most landforms do not show at that scale and must be exaggerated slightly, whereas the least significant must be subdued to avoid confusing clutter. Format M was designed for those types of small-scale maps. Scales used depend on the size of the planet to allow meaningful display of any hemisphere of any planet within page boundaries ranging from approximately 100 to 400 mm. Lambert's azimuthal equal area projections are used in this format for the spherical or spheroidal planets. This projection has the advantage that any closed figure (a circle or square, for example) of given dimensions covers exactly the same number of square kilometers on the planet, no matter where it is placed on the map. Shapes of features are not preserved. Craters appear as ellipses at the edge of the map and as circles in the center, but this apparent foreshortening is not nearly as pronounced as on an orthographic projection.

Reasonably high-resolution images are available for several small, irregular satellites like Phobos. Their shapes do not lend themselves to portrayal on conventional map projections. Some system for cartographic treatment of these objects will become increasingly relevant as planetary exploration expands to include asteroids and comet nuclei. Format M, utilizing orthographic projections, is a partial answer to the problem. Three-dimensional image projection techniques can be used to normalize spacecraft images with random perspectives to one or more orthogonal views of Phobos, Diemos, Amalthea, and Hyperion.

SCALE	BODY	DATA SOURCE	STATUS	TOPO	MOSAIC	RELIEF	ALBEDO	COMPOSITE	TOTAL
Miscel-laneous	All	existing maps	IPR				14		14
	Phobos	Viking	FUT		1		1	1	3
	Diemos	Viking	FUT		1		1	1	3
	Amalthea	Voyager	FUT		1		1	1	3
	Hyperion	Voyager	FUT		1		1	1	3

Miscellaneous Formats

(not illustrated)

A variety of maps, particularly of the Moon and Mars, were produced prior to the development of a full range of consistent, systematic formats for special mapping. For example, a series of maps was made at 1:5 000 000 of multiring basins on the terrestrial planets, and of the Chryse hydrographic basin on Mars. The oblique stereographic projection was used for these maps. Others include special purpose high-resolution maps on Mars, most of which could now be accommodated by either format H or format L. It is likely that future data return will dictate the design of a large-scale map series for Venus and other bodies. Since this has not yet been done, potential mapping of this kind is included in the following table.

SCALE	BODY	DATA SOURCE	STATUS	TOPO	MOSAIC	RELIEF	ALBEDO	COMPOSITE	TOTAL
1:10M	Mercury	Mariner 10	PUB		1				1
	Moon	existing maps	PUB				2		2
1:5M	Moon	LO, Zond	PUB			1			1
	Mars	Viking	PUB			2			2
	Mercury	Mariner 10	PUB			1			1
1:5M	Venus	VRM	FUT	20	20	20		20	80
	Moon	Telescope, LO, Apollo	PUB		478	54	20	273	825
	Mars	Mariner 9 Viking	PUB		5	6	1	7	19
	Io	Voyager	PUB		3				3
	Galileo Satellites	Galileo	FUT		12	12	12		36
	Triton	Voyager	FUT		4	4	4		12

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