Cambridge University Press
978-1-107-03629-1 — The Atlas of Mars
Kenneth S. Coles, Kenneth L. Tanaka, Philip R. Christensen
Excerpt
More Information

CHAPTER 1

Introduction

Mars is the fourth planet from the Sun and the outermost of the rocky, terrestrial planets that make up the inner solar system. Mars is the second smallest planet; only Mercury is smaller. Surface gravity on Mars is 3.71 m s^{-2}, which is 37.6% that of the Earth. The present atmospheric pressure is low (~0.6 kPa) relative to Earth's (101 kPa), and the atmosphere is mostly carbon dioxide (95%). The obliquity of Mars (tilt of the axis of rotation relative to the plane of orbit) is presently 25 degrees and may have varied by tens of degrees over the past tens of millions of years and longer (Laskar *et al.*, 2004).

The rotational period (sidereal) of Mars is slightly longer than that of Earth, at 24 hours 37 minutes, while the Martian solar day (sol) is 24 hours 40 minutes. The orbit of Mars is more elliptical (eccentricity = 0.093) than that of Earth (0.017), so the seasons vary in length with northern spring being the longest. The sidereal period is 687 days (670 Martian sols), while the synodic period relative to Earth, and the interval between oppositions of Mars, averages 780 days. The progress of the seasons is commonly given by L_s, which is the orbital longitude, or angle in degrees at the Sun measured from the northern hemisphere spring equinox to the position of Mars. Thus, L_s = 90° is the summer solstice in the northern hemisphere and the winter solstice in the south (Carr, 2006 gives additional detail on the motion of Mars).

Organization of atlas; map scale and projections

The chapters following this one give the reader a short summary of the history of spacecraft exploration of Mars (Chapter 2), global views of datasets (Chapter 3), the geography of Mars (Chapter 4), and the geology of Mars (Chapter 5).

The heart of the atlas considers the geography and geology found in each of 30 maps. We follow the Mars Chart (MC) system of quadrangle[1] maps that were first created for the Mariner 9 images in the early 1970s. These maps cover Mars in 30 sheets, originally at a nominal scale of 1:5,000,000, though published maps vary from this scale when matching along map boundaries is a priority (Batson *et al.*, 1979). We have instead maintained a consistent numerical scale of 1:10,000,000, using Mercator projection scaled at the equator for sheets at 0–30° latitude, in Lambert conformal projection for the sheets covering 30–65° latitude scaled on standard parallels of 36.15° and 59.47°, and polar stereographic scaled at 90° latitude for the two polar sheets covering 65–90° latitude.

Each sheet is first presented in a pair of facing maps. The first is in color to show elevations in the MOLA (Mars Orbiter Laser Altimeter) dataset with a minimum of annotation beyond a latitude and longitude graticule every 10 degrees. The map margins indicate the numbers of adjacent map sheets. The second map shows the surface using the THEMIS (Thermal Emission Imaging System) daytime infrared dataset, with named

[1] We follow a common usage in geology, where the term *quadrangle* denotes any map sheet, even those not having four corners.

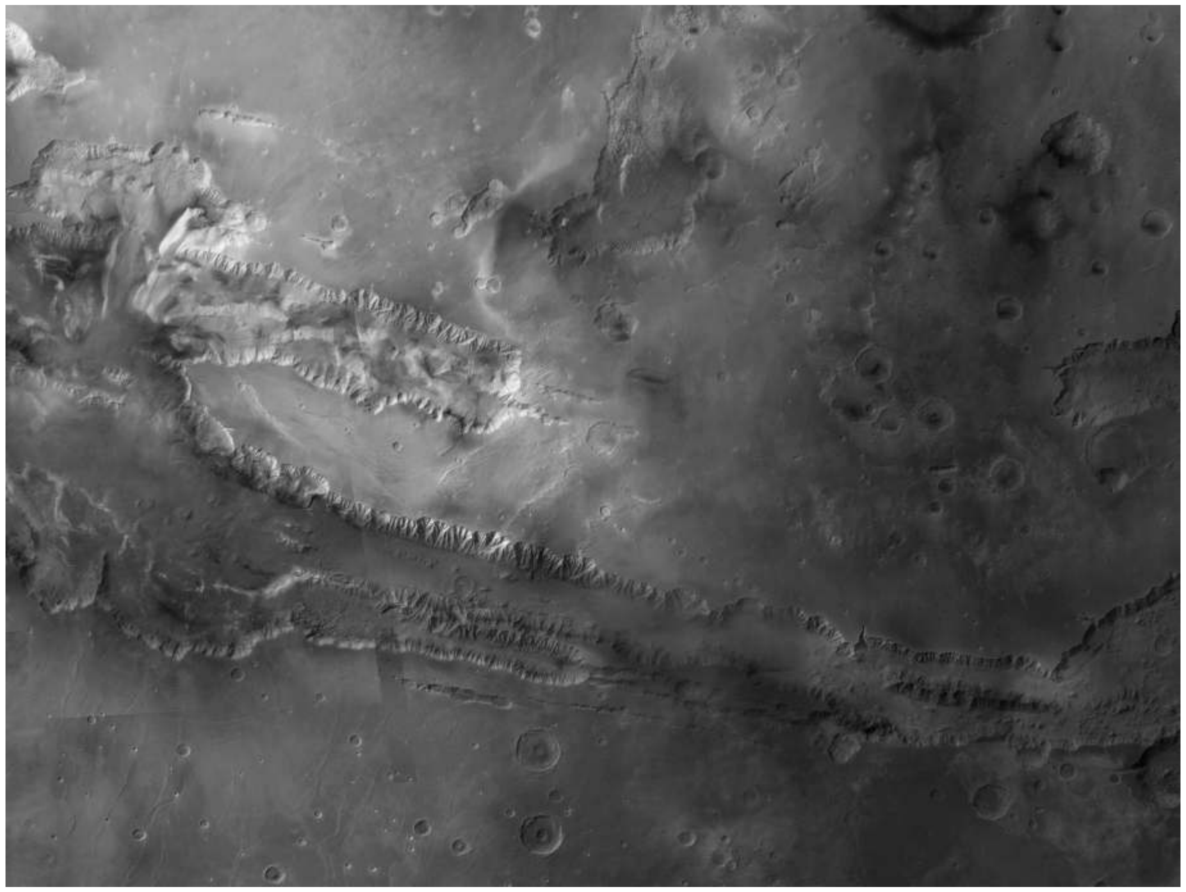


FIGURE 1.1 Mosaic of images from the Mars Orbiter Camera (MOC-WA) view taken through a red filter. The view shows the northeastern portion of Valles Marineris and adjacent plana (NASA/JPL-Caltech/MSSS).

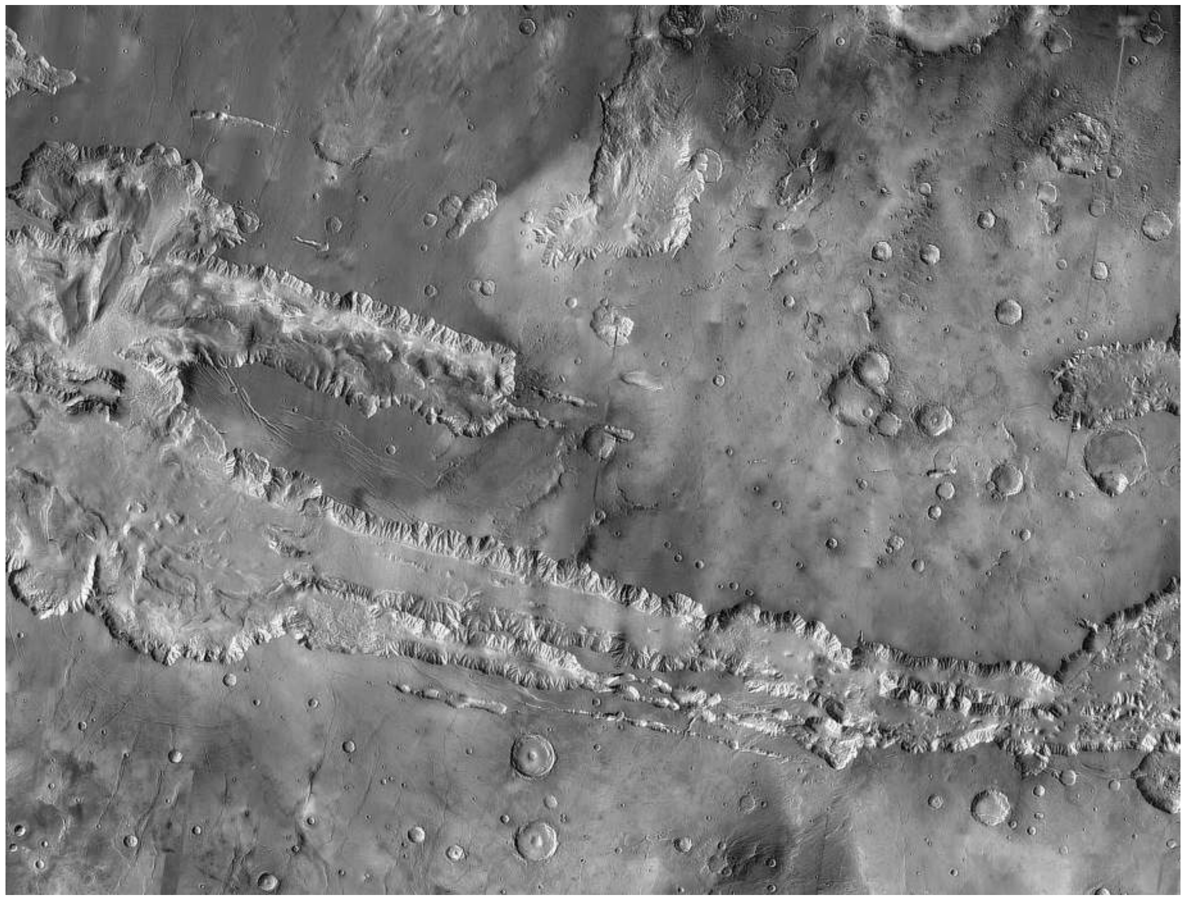


FIGURE 1.2 The same region as Figure 1.1 is shown in a mosaic of THEMIS daytime infrared images. A thermal infrared image is bright where the surface is warmest. The warm regions in an infrared image are those that either retain heat or are dark and absorb more sunlight. This correspondence between warm in THEMIS and dark in the visible is strikingly evident in Figure 1.1. While daytime infrared images from THEMIS, which we use extensively in this atlas, cover all of Mars and have great detail, this comparison is a reminder that visible and infrared images show different properties of the Martian surface (NASA/JPL-Caltech/Arizona State University).

features (Figures 1.1 and 1.2 show how infrared and visible images of Mars differ). For the sake of clarity, we generally omit names of minor features, where crowded, and of craters smaller than 20 km in diameter on the maps, though they are included in the Gazetteer in plain (non-bold) font. Albedo features (defined solely by amount of reflected light) are not included on the maps or in the Gazetteer. The location map and other images (except where noted) showing elevation derived from MOLA data in this atlas use the “rainbow” color scheme of the first MOLA release (Smith *et al.*, 1999).

The third page of each map sheet includes summaries of the geography and geology. Also shown is a color MOLA topography index map with boxes locating the images featured in one or more following pages. The geology (generalized from Tanaka *et al.*, 2014) is shown at 1:20,000,000 scale as well. The image location map uses the elevation color scheme of the first, overview, map, while a brief legend for the geologic map is shown (the full list of units is given in the Appendix). The accompanying images and text for each map describe prominent, unique, or enigmatic features with the intention of covering each important feature type and process at least once among the 30 map sheets. Some of the images are well-known classics while others were chosen by searching all those available that cover a given area.

Throughout this work we aimed to strike a balance between listing every possible reference to published scientific work and omitting references entirely. The goal is a small but representative list of sources to enable the reader to learn more. While we cannot include all of the thousands of Mars publications that come out each year or all the explanations put forth to explain what we see, or don’t see, on Mars, we acknowledge this work and commend it to the reader who wishes to seek it out.

The atlas concludes with an Appendix, which lists the units of the various geologic maps, unit conversions, and Latin descriptors, a brief Glossary of Terms, as well as a Gazetteer, which gives basic data about named features and lists the map(s) where they are shown.

Creation of THEMIS base maps

Each quadrangle of a previous THEMIS daytime infrared global mosaic (Hill *et al.*, 2014), which was composed of THEMIS band 9 (12.57 μm) images, was visually reevaluated, image by image. Images that reduced the quality of the overall mosaic were removed and replaced by higher-quality images as follows (Hill and Christensen, 2016).

1. Images with poor geometry, where large offsets with adjacent images were evident (due to extrapolations over gaps in spacecraft position and pointing telemetry, etc.), were removed and replaced by images with better geometry data. The previous THEMIS global mosaics, as well as this one, do not attempt to tie images to ground points, though offsets are usually small relative to the 100 m/pixel resolution of the mosaic.
2. Images with significant noise resulting from low surface temperatures, atmospheric effects, etc. have been replaced by higher-quality images where possible.
3. Small gaps due to line dropouts in various images were filled with the highest-quality images available.
4. Coverage was extended poleward of 87.3 degrees north and south latitude, the limit of the Mars Odyssey orbit, with images taken off-nadir.

Coordinates on Mars

Latitude and longitude

Coordinates for Mars exist in two different systems: planetographic latitude with longitude increasing to the west, and planetocentric latitude with longitude increasing to the east. The definition of latitude also differs, being either the angle between the equatorial plane and a vector directed at the point of interest measured at the center of mass of Mars (planetocentric), or the angle between a vector perpendicular to a (non-spherical) reference surface at the point of interest and the equatorial plane (planetographic; Planetary Data System, 2009). Both systems are approved for use on Mars by the International Astronomical Union (IAU) (Seidelmann *et al.*, 2002).

Planetographic latitude with west longitude was the system used for most maps and publications prior to 2002. Planetocentric latitude with east longitude has been adopted for use by the USGS and other organizations for use in making more recent Mars maps and imagery (Duxbury *et al.*, 2002). The maps and descriptions in this atlas follow this recent practice and use planetocentric coordinates. Converting longitude between the systems requires only simple arithmetic, but the latitude conversion is more complex. The nomenclature maps at the USGS Gazetteer of Planetary Nomenclature website (https://planetarynames.wr.usgs.gov/) show both coordinate systems for conversion between them.

Elevation and datum definition

Elevations on Mars are derived from MOLA measurements of radius relative to the center of mass of the planet. An equipotential surface derived from these measurements is chosen to match the mean equatorial radius at the equator (3396 km) and extended to other latitudes (Smith *et al.*, 1999; 2001). This surface incorporates the effects of the local gravity field and the rotational flattening of the planet; the surface is commonly referred to as “datum” in this atlas. This serves as a reference for positive and negative elevations on Mars much as mean sea level (which is also an equipotential surface) does on Earth. Chapter 4 discusses the surface elevation of Mars in terms of regional geography.

Geographic nomenclature

Planetary nomenclature, like terrestrial nomenclature, is used to uniquely identify a feature on the surface of a planet or satellite so that the feature can be easily located, described, and discussed. Names are intended to be descriptive rather than imply a specific origin. The USGS Gazetteer of Planetary Nomenclature (the basis for names in this atlas, https://planetarynames.wr.usgs.gov/) contains detailed information about all names of topographic and albedo features on planets and satellites (and some planetary ring and ring-gap systems) that the IAU has named and approved from its founding in 1919 through to the present time.

Note on Latin terms

Feature names on Mars are commonly given in Latin form. Terms for types of features (descriptors) are listed in the Appendix of this atlas. While the naming and spelling is systematized, in our experience the pronunciation of feature names (as for Latin in general) within the scientific community is not. We have not attempted to reconcile these variations; one attempt to provide guidance is that of Hargitai and Kereszturi (2010).

Image resolution – how much detail do we see?

Spacecraft images of Mars, which now number over two million, consist of picture elements, or pixels, recorded and returned to Earth in digital form. Each pixel represents an area (typically a square) with a uniform level of gray or color. When pixels are displayed as an image, features about four pixels across are the smallest that can be resolved. For images we report the size shown by one pixel. For example, an image with a pixel size of 6 m would reveal features down to about 24 m in size. Although we do not display the finest detail in printed versions of all images, the available resolution may be useful information for readers wishing to consult the original images. In general descriptions of spacecraft instruments, the term resolution in this atlas serves as a synonym for pixel size.

An example from Earth illustrates the effect of smaller pixel size on the resolution of features. Figure 1.3 shows a portion of the Earth's surface with 4-km pixels. While ridges and valleys are evident, little other detail is seen.

Compare this to Figure 1.4, where the increase in resolution is five-fold, to 800 m per pixel. It is easier to recognize that the view includes one of the most spectacular valleys on Earth. The Grand Canyon might not be recognized on the first, coarser image if it were the only information from another planetary body.

A number of cameras have produced the images of Mars used in this atlas; the names and common abbreviations for each are given in Chapter 2 (see Table 2.1, which gives typical pixel sizes and the amount of Mars covered). In image captions where applicable we give coordinates, dimensions of the area shown, and the north direction.

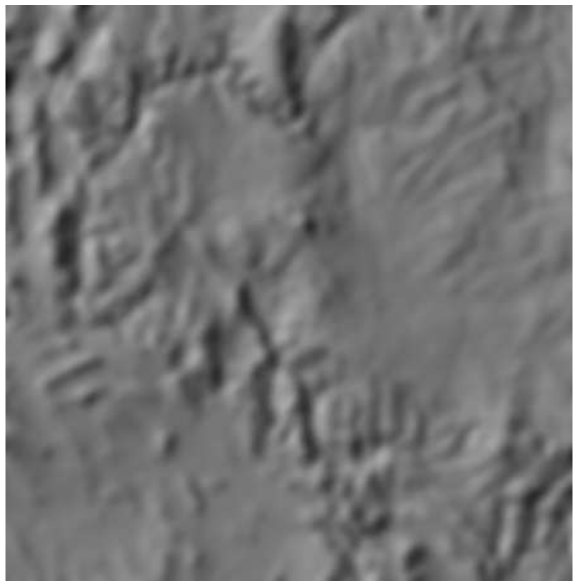


FIGURE 1.3 A portion of Earth's surface depicted using a digital elevation model (DEM), artificially illuminated from the west (blurred to the equivalent of 4-km pixels, view about 450 km by 450 km, north at top, DEM from US Geological Survey).

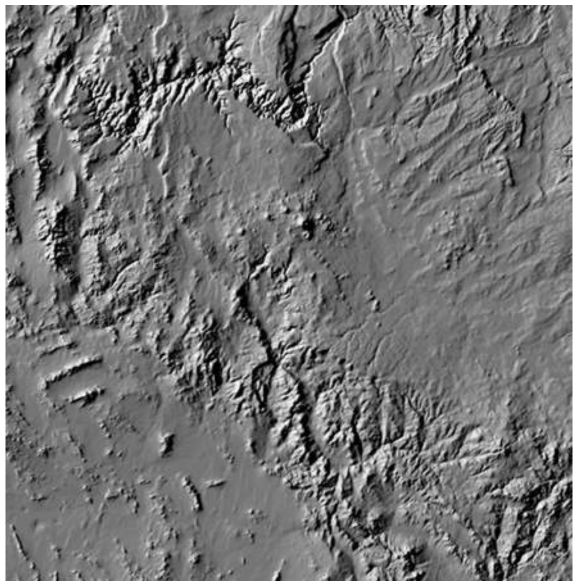


FIGURE 1.4 The same area and dataset as Figure 1.3, shown using 800-m pixels, i.e. five times better resolution. The view shows part of Arizona in the southwest USA, extending from the Grand Canyon in the north to Phoenix in the south.

Cambridge University Press
978-1-107-03629-1 — The Atlas of Mars
Kenneth S. Coles, Kenneth L. Tanaka, Philip R. Christensen
Excerpt
More Information

CHAPTER 2

History of Exploration of Mars

Mars has attracted study ever since its motions were first apparent to ancient skywatchers. Summaries of early observations and ideas are listed in, e.g., Collins, 1971; Hartmann and Raper, 1974; Moore, 1977; Kieffer *et al.*, 1992a; Martin *et al.*, 1992; Sheehan, 1996; Morton, 2002. Hubbard (2011) gives an interesting example of the planning of Mars missions.

Pre-spacecraft studies

Although Mars is Earth's second closest planetary neighbor (after Venus), the detail in telescopic observations since Galileo's, in 1609, has been limited by the small size of Mars and the effects of Earth's atmosphere (Slipher, 1962; Kieffer *et al.*, 1992a; Martin *et al.*, 1992).

Schiaparelli and Lowell: The "canals"

Reports of "canali" (Italian for channels; commonly "canals" in English), especially by Schiaparelli in Italy (starting in 1877) and Lowell in the USA, starting in the 1890s, influenced ideas about Mars for nearly a century (Figures 2.1a and 2.1b; Hartmann and Raper, 1974; Kieffer *et al.*, 1992a). Despite a number of claims by these and other visual observers (Sheehan, 1996), no convincing photographic evidence was presented, and eventually spacecraft found no traces of canals. The canals or channels

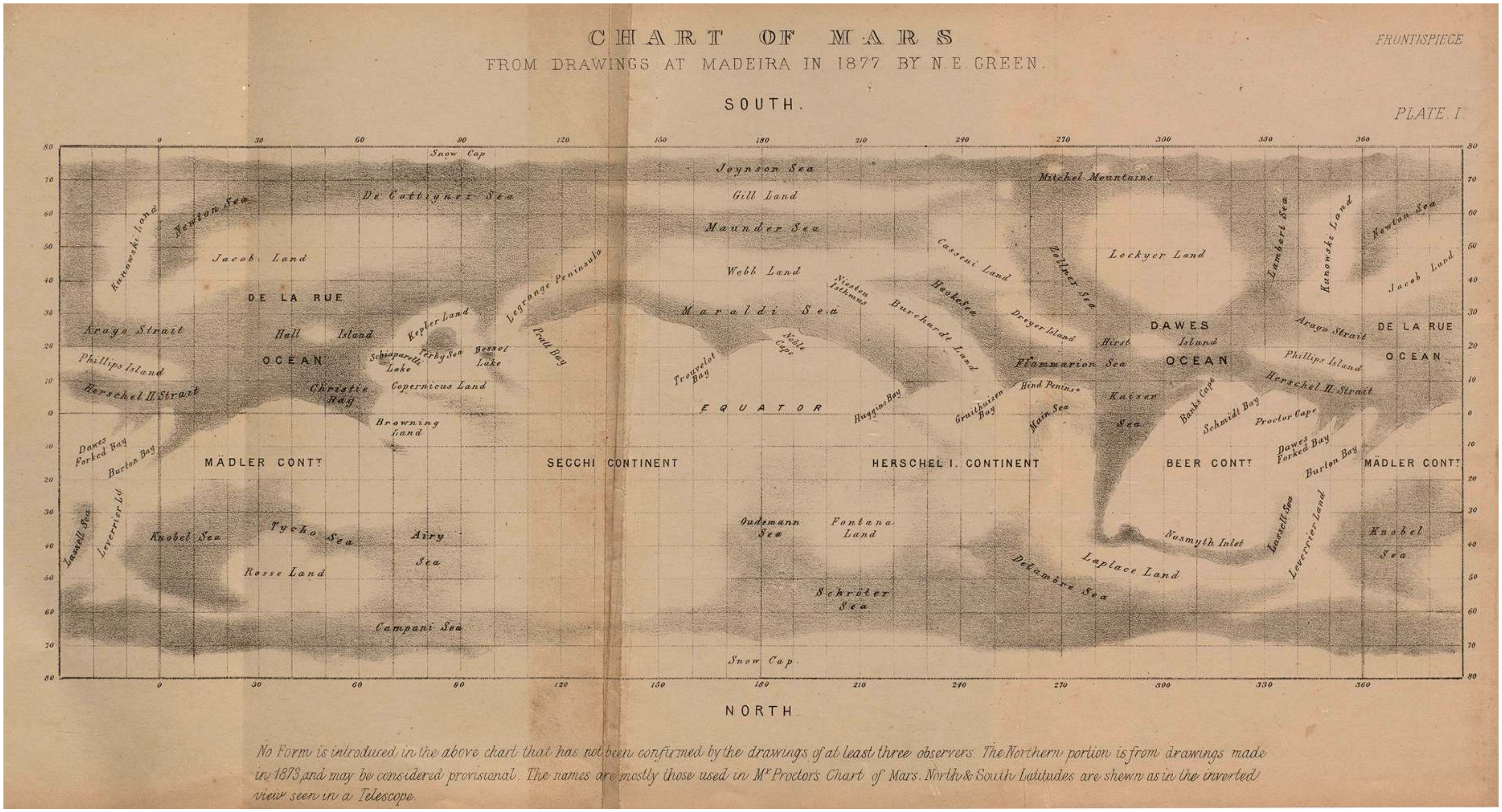


FIGURE 2.1 (a) Map of Mars markings ("albedo"), by English amateur astronomer and artist Nathaniel Green in 1877. While the names used by Green did not persist in the later work of others, he was rather careful about the limits of observation and doubted the so-called canals (map as reproduced in Ledger, E., 1882, *The Sun, Its Planets and Their Satellites*: London, courtesy H. Hargitai/T. Lindemann).

Cambridge University Press
978-1-107-03629-1 — The Atlas of Mars
Kenneth S. Coles, Kenneth L. Tanaka, Philip R. Christensen
Excerpt
More Information

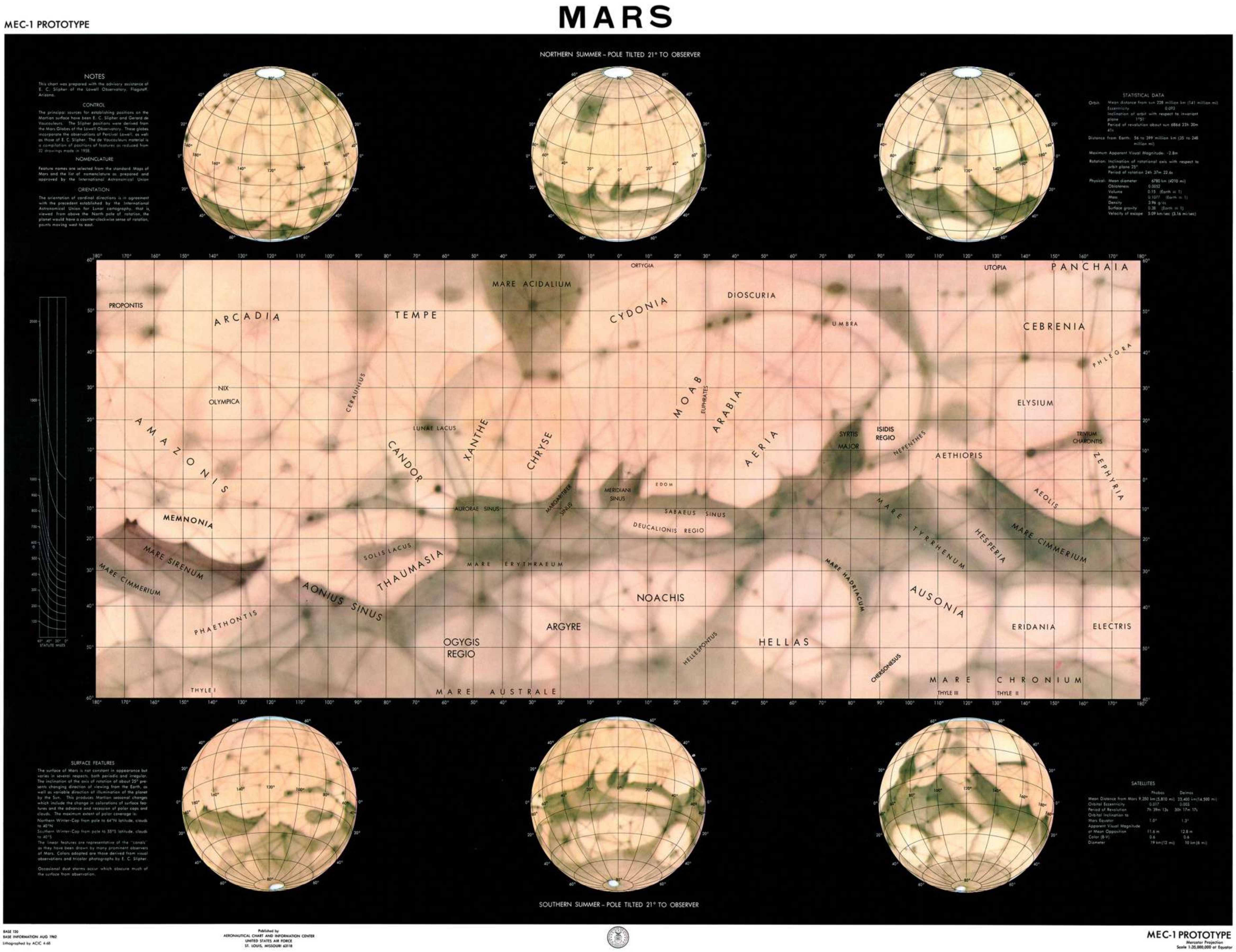


FIGURE 2.1 (b) Map of Mars albedo prepared by the US Air Force Aeronautical Chart and Information Center in 1962, primarily from the maps of E. C. Slipher at Lowell Observatory. Note the fine, canal-like features (courtesy of Lunar and Planetary Institute).

evidently were an imagined perception rather than a real feature.

Telescopic observation

Studies of Mars from telescopes on Earth are insufficient to discern the planet's geologic nature, but they do yield information about dust storms in the atmosphere and seasonal changes in the polar caps. Albedo markings (areas of light and dark; see Figure 3.1 in Chapter 3) are readily apparent and change over time, though the consistency of seasonal patterns in these changes is a matter of debate (Hartmann and Raper, 1974; Martin *et al.*, 1992). By the time of the first spacecraft missions, maps of Mars emphasized these major markings (Figures 2.1a and 2.1b; Martin *et al.*, 1992; Morton, 2002).

TABLE 2.1 Spacecraft imaging of Mars used in this Atlas

Mission	Per cent of Mars covered	Brightness levels	Pixel size at close encounter/periapsis	Spectral bands	Lines × samples
Mariner 4 (1965)	1	64	1.25 km	One (two color filters)	200 × 200
Mariner 6/7 (1969)	100[a] 10[b,c] <1[b,d]	256	4–43 km[a] 1 km[b,c] 100 m[b,d]	One (three color filters)[c] One[d]	704 × 945
Mariner 9 (1971–72)	100[c] 1–2[d]	512	500 m[c] 50 m[d]	One (eight color or polarizing filters)[c] One[d]	700 × 832
Viking 1/2 Orbiters (1976–80)	100 <1	128	150–300 m 8 m	One (six color filters)	1,056 × 1,182
Mars Global Surveyor – MOC (1997–2006)	100[c] 5[d]	256	240 m[c] 1.5–12 m[d]	Two[c] One[d]	var. × 3,456[a] var. × 2,048[b]
Mars Odyssey – THEMIS (2002–)	65 100	256	18 m (visible) 100 m (infrared)	Five visible Ten infrared	1,024 × 1,024 (visible) 240 × 320 (infrared)
Mars Express – HRSC (2004–)	95 (at mean pixel size of 18 m)	256	10–20 m	Four spectral bands, three bands for three dimensional images	var. × 5,184
Mars Reconnaissance Orbiter – HiRISE (2006–)	~3	16,000	0.3 m	Three	var. × 20,264 (red) var. × 4,048 (green and infrared)
Mars Reconnaissance Orbiter – CTX (2006–)	>99	4096	6 m	One	var. × 5,064

For Mariner 6/7, Mariner 9, Mars Global Surveyor, MOC: a = far encounter, b = near encounter, c = wide-angle camera, d = narrow-angle camera . "Brightness levels" gives the number of shades of gray coded in the image. "Lines" gives the number of rows of (generally square) pixels in an image, while "samples" is the number of pixels in a line. The number of lines varies for some instruments. Sources: Bell *et al.*, 2013; Carr and Evans, 1980; Christensen *et al.*, 2004; Collins, 1971; Gwinner *et al.*, 2015; Jaumann *et al.*, 2007; Leighton *et al.*, 1965; 1969; Levinthal *et al.*, 1973; Malin *et al.*, 1991; Masursky *et al.*, 1970; Masursky, 1973; NASA, 1967; 1969; 1974; 2017; Snyder and Moroz, 1992; Spitzer, 1980; Tanaka *et al.*, 1992; also mission information from HiRISE, HRSC, MSSS, NSSDC.

First Mars spacecraft

A large number of robotic spacecraft have been launched toward Mars. Orbiters and landers and results from them that are noteworthy in the mapping and geologic study of the planet are summarized here. Progress in the coverage and resolution of imaging is summarized in Table 2.1 and illustrated in Figures 2.2 and 2.3. For views from surface landers and rovers see Chapters 4 and 5.

Mariner 4 and Mariner 6/7

The first evidence of the nature of the Martian surface came from observations by the Mariner 4 spacecraft, in 1965. Images covering about 1 percent of Mars at pixel size near 1 km showed a heavily cratered surface similar to the ancient highland terrain on the Moon (Figure 2.2a; Leighton *et al.*, 1965). Mariner 6 and 7, a pair of flyby spacecraft in 1969, imaged 10 percent of Mars at a resolution similar to Mariner 4 and gave a similar impression of the surface. A few images did show featureless plains, regions termed "chaotic" (imaged by a later mission in Figure 2.3a), and the south polar cap (Leighton *et al.*, 1969; NASA, 1969; Collins, 1971; Snyder and Moroz, 1992).

Mariner 9

The greatest single advance in knowledge of Mars was due to the Mariner 9 mission of 1971–72. This spacecraft, the first to orbit another planet, made images of the entire surface that resolved features of 2–3 km over the course of one Earth year (NASA, 1974; Jaumann *et al.*, 2007). It also observed the gravity field and character of, and variations in, the atmosphere (Snyder and Moroz, 1992). Among the many discoveries were Moon-like cratered highlands, immense volcanoes, the enormous Valles Marineris canyon system, numerous channels and branching valley networks, suggesting erosion by a moving fluid such as water, evidence of dust transport by wind, and layered deposits near the polar caps. Mariner 9 spurred a revolution in thinking about the geology of Mars (Hartmann and Raper, 1974; NASA, 1974; Hartmann, 2003) and set the stage for the planned landings of the ambitious Viking program.

Soviet spacecraft

Among a number of attempted Soviet missions to Mars are several noteworthy achievements. The lander vehicle of the Mars 3 mission apparently landed successfully on the surface in December 1971, and broadcast radio signals for less than a minute before falling silent. The companion orbiter spacecraft returned a number of images, as did the Mars 4 flyby and Mars 5 orbiter (both in 1974; Perminov, 1999; Mitchell, 2004). Phobos 2 entered Mars orbit (in 1989) and returned a number of images and other observations of Mars and of Phobos, but contact was lost before a planned close approach to Phobos (Sagdeev and Zakharov, 1989).

Viking 1 and 2

The Viking 1 and 2 spacecraft, two orbiters and two landers, arrived at Mars in 1976. Both

Cambridge University Press
978-1-107-03629-1 — The Atlas of Mars
Kenneth S. Coles, Kenneth L. Tanaka, Philip R. Christensen
Excerpt
More Information

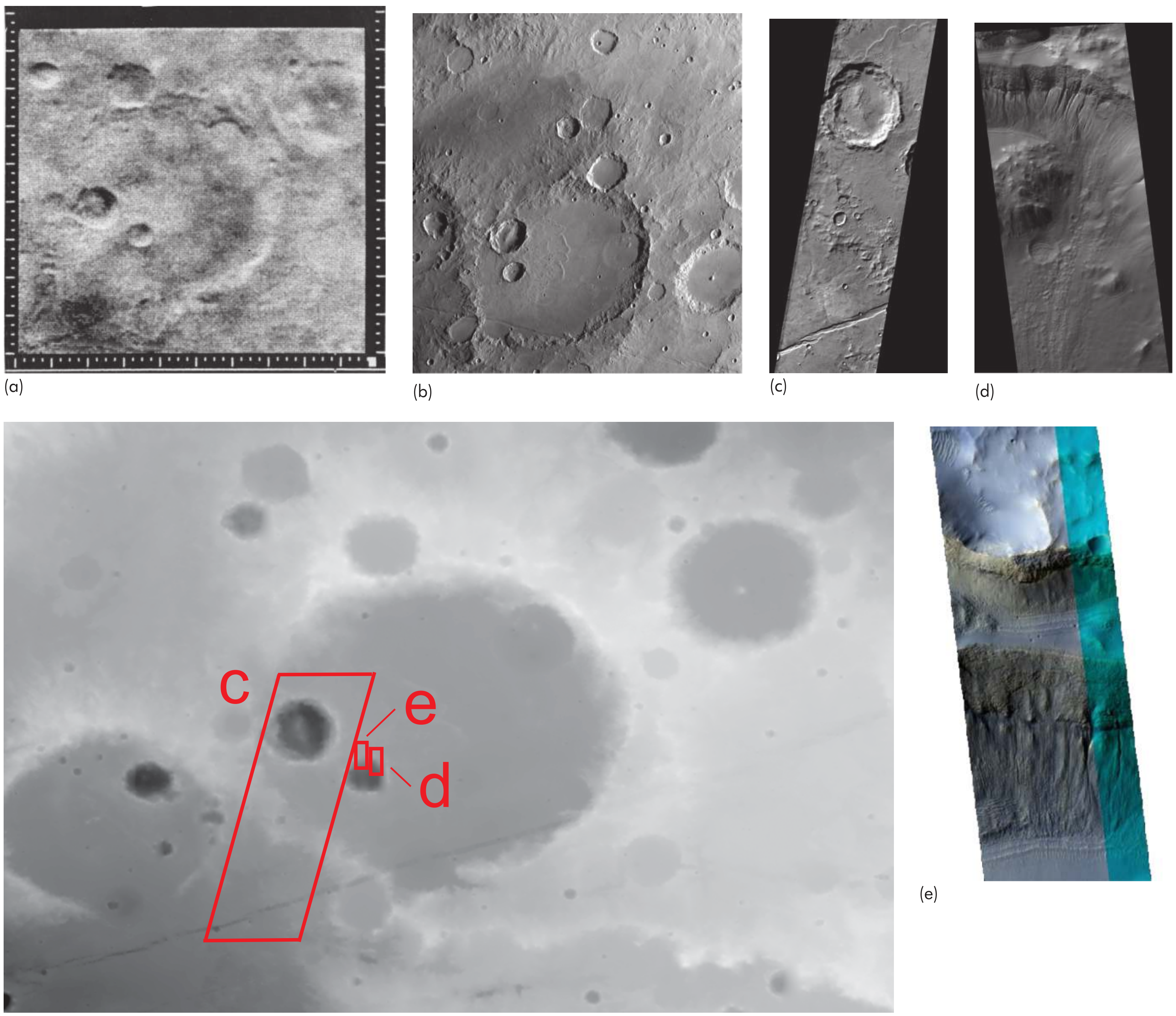
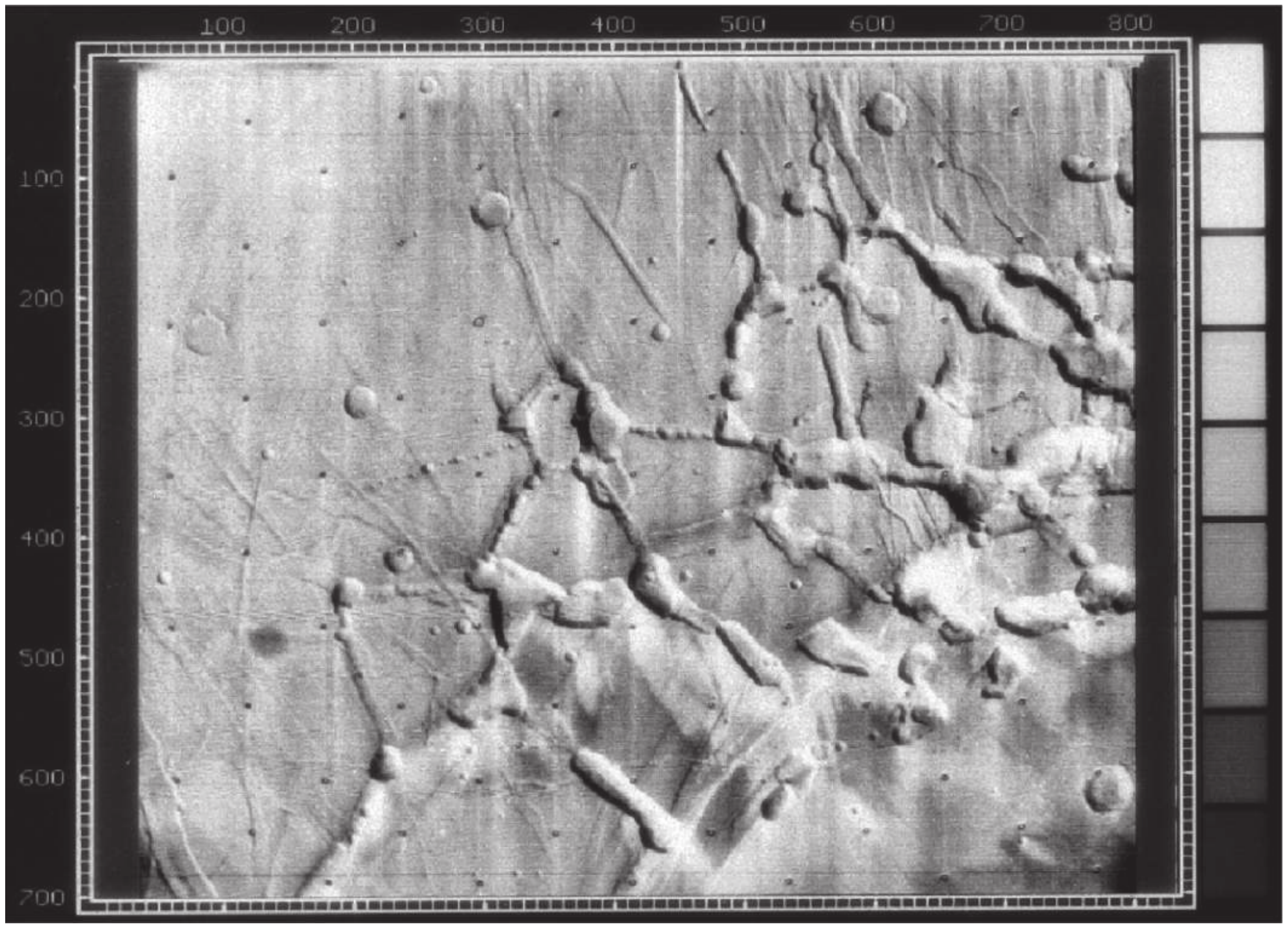
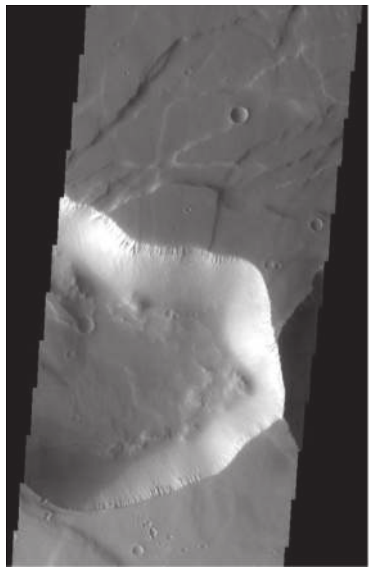


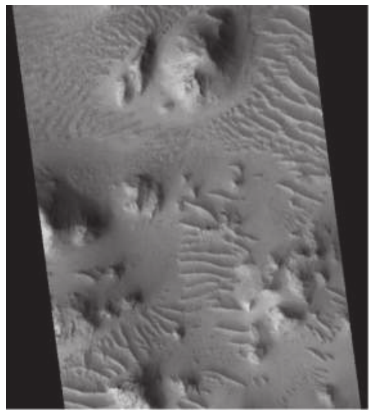
FIGURE 2.2 Mariner crater (151 km in diameter, at 34.68° S, 195.76° E) named for the Mariner 4 spacecraft that first imaged it, in 1965. (a) Mariner 4 frame 11 (pixel size about 1.2 km, NASA/JPL-Caltech). (b) Viking orbiter 1 (image 635A72, red filter, pixel size about 300 m) showing detail in craters and the ejecta around two younger craters inside Mariner crater (NASA/JPL-Caltech). (c) THEMIS infrared daytime image of the larger interior crater and a fracture of the Sirenum Fossae (image I34775002, pixel size about 100 m, NASA/JPL-Caltech/Arizona State University). (d) and (e) Two views of the north rim of the smaller of the two interior craters (d: MOC-NA image E02/00757, pixel size 6 m, view about 3 km across, NASA/JPL-Caltech/MSSS; e: HiRISE color image PSP_002317_1445, 25 cm/pixel, view about 1 km across, NASA/JPL-Caltech/University of Arizona). Locations of images in Figures 2.2c–e shown over MOLA grayscale elevation at lower left.



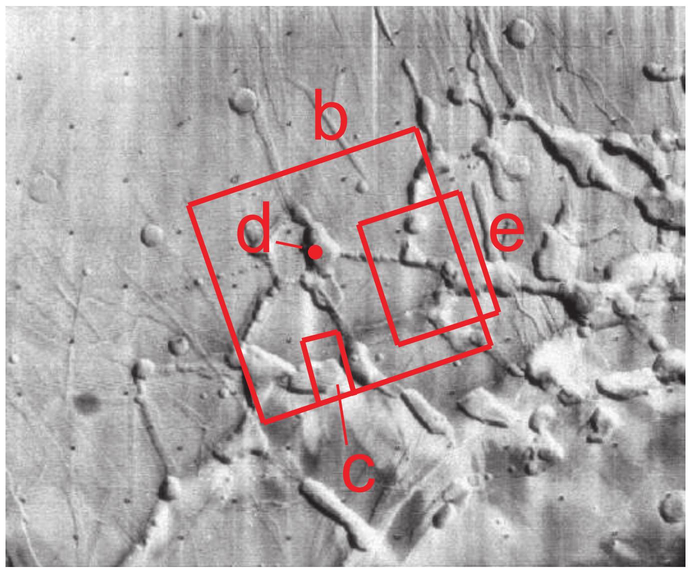
(a)

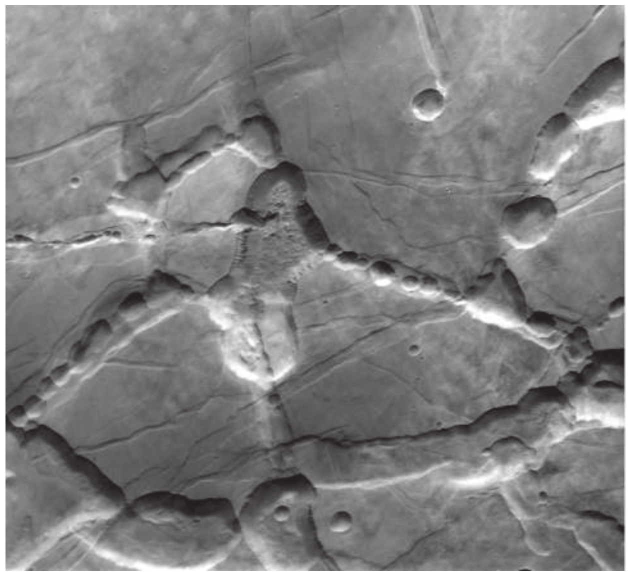


(c)

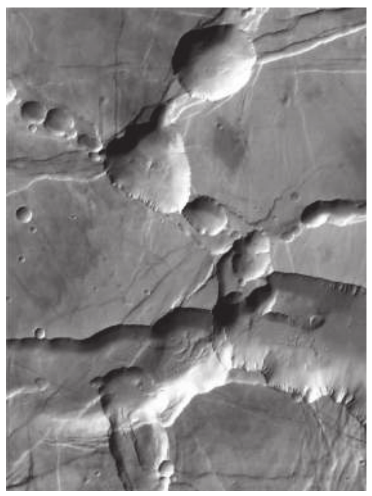


(d)





(b)



(e)

FIGURE 2.3 Noctis Labyrinthus, a system of intersecting fracture valleys (at 5.25° S, 255° E) near the center of the Tharsis uplift. (a) Mariner 9 image (MRVS 4187–45, pixel size about 0.5 km, view 400 km across). (b) Viking 1 Orbiter image, showing the area in the center of the Mariner 9 image (image 049A26, pixel size about 120 m, view 160 km across, images in Figures 2.3a and 2.3b both NASA/JPL-Caltech). (c) THEMIS visible image (V06633001, pixel size about 35 m, view 18 km wide, NASA/JPL-Caltech/Arizona State University). (d) Detail in floor of collapsed region (MOC-NA image M09/06504, pixel size 3 m, view 1.5 km wide), showing hills and dunes (NASA/JPL-Caltech/MSSS). (e) HRSC image H3210_0000_ND4 (12.5 m/pixel, 55 km by 70 km, ESA/DLR/FU-Berlin). Locations of images in Figures 2.3b–e are shown over the Mariner 9 image at lower left.

landings were successful and gave the first detailed information from the surface (see Chapter 4). Experiments that were designed for the purpose of detecting living organisms on Mars returned negative results. The orbiters returned images and other measurements for 4 years and mapped the entire planet over all Martian seasons at a pixel size of several hundred meters, and selected areas at tens of meters, ten to one hundred times better resolution than Mariner 9 (Carr and Evans, 1980; Spitzer, 1980; Snyder and Moroz, 1992). Two decades passed after Viking before another spacecraft successfully reached Mars; during this time, maps of the entire planet and numerous geologic studies came out of the Viking data.

Missions since 1996

The most recent phase of Mars exploration, since the late 1990s, has led to a significant increase in the types, spatial resolution, and amount of data returned both from Mars orbit and on the surface (for summaries of results see e.g., Carr, 2006; Barlow, 2008; Bell, 2008; Jaumann *et al.*, 2015; Haberle *et al.*, 2017).

Mars Pathfinder landed in the vast, ancient flood plain known as Chryse Planitia in 1997, hosting the first arrival of a rover, named Sojourner, to the planet. The landing included the use of a heat shield for aerobraking through the atmosphere, followed by deployment of a parachute and then airbags to cushion the lander's impact with the surface. Once safely landed, the rover was guided off a landing platform. Cameras and other instruments on both the platform and rover were able to survey rocks and soil surrounding the platform, as well as the landscape farther afield and the surrounding atmosphere. The spacecraft operated successfully for almost 3 months, returning thousands of images, chemical measurements of rocks and soils, and data on the weather and atmospheric dust.

The **Mars Global Surveyor** was active in Mars orbit between 1997 and 2006. It measured the magnetic and gravity fields, mapped surface mineral composition, monitored the atmosphere, and made a detailed map of elevation ("Mars Orbiter Laser Altimeter [MOLA] topography," used as base for index and overview maps in this atlas). The Mars Orbiter Camera (MOC) returned over 240,000 images. These included daily global coverage in the visible range at 7.5 km pixel size, and coverage in visible/near infrared wavelengths of 5.45 percent of Mars at 12 m, and 0.5 percent showing details as small as a few meters (Malin *et al.*, 2010). The MOC included a narrow-angle (MOC-NA) and two wide-angle (MOC-WA) cameras, one with a red filter and the other with a blue filter.

Mars Odyssey has orbited Mars since 2001, while sensing gamma rays and neutrons to study the composition of the surface and search for water, measuring space radiation, and operating a visible/infrared camera, the Thermal Emission Imaging System (THEMIS). THEMIS yields 18-m pixels in five visible bands and 100-m pixels in ten infrared bands (Christensen *et al.*, 2004).

The **Mars Express** orbiter mission (ESA, arrived at Mars in 2003 and began imaging in 2004) carries a host of experiments to study minerals on the surface, to search for water ice beneath the surface using radar, to study the atmosphere and interactions with the solar wind, and to image the surface in color and near-infrared with pixels as fine as 2 m using a super resolution channel (High Resolution Stereo Camera, HRSC; Jaumann *et al.*, 2007).

NASA's ambitious, second-generation **Mars Exploration Rover** (MER) mission landed two rovers on opposite sides of the planet in 2004. These rovers, which were better equipped for scientific investigations and were larger than Sojourner, landed with the same techniques, and were able to operate independently from their landing platforms. The Spirit rover (MER-A) investigated the floor of and ancient hills within Gusev crater, before failing to respond in 2011, after traversing more than 7.7 km. Meanwhile, the Opportunity rover (MER-B) landed on the highland plain known as Meridiani Planum and was able to document rock strata in a series of impact crater walls, as well as other geologic and atmospheric features and dynamics. At the time that contact was lost (2018), Opportunity had logged more than 45 km of travel, and had explored the rim of Endeavour crater.

The **Mars Reconnaissance Orbiter**, since 2006, has looked for the history of water in the planet, including in the subsurface, the atmosphere, and in minerals, and has studied layered deposits and possible ancient shorelines. The instruments include shallow radar (SHARAD) and a 50-cm telescope with a visible/near-infrared camera (High Resolution Imaging Science Experiment; HiRISE), which has a resolution near 1 m (30-cm pixels; McEwen *et al.*, 2007a). The Context Camera (CTX, 6-m pixels) provides a wider view of the region imaged by HiRISE).

The **Phoenix** mission was the first successful lander in a polar region, arriving in 2008. For 5 months it investigated the presence of water ice and minerals in the arctic soil, using a robotic arm to scoop samples for analysis. Instruments included a heating unit to drive off volatiles for analysis by a mass spectrometer and a chemical analyzer that tested soil pH and minerals. Cameras characterized the landscape at the landing site, and a weather station recorded conditions in the northern spring and summer (Smith *et al.*, 2009).

The latest rover mission, **Mars Science Laboratory** (MSL), Curiosity, arrived on Mars in 2012 in the floor of Gale crater, which hosts a 5-km-high mound known as Aeolis Mons (or, informally, Mount Sharp). The Curiosity rover can be characterized as a mobile laboratory given its sophisticated capabilities to detect and measure compositional information, both remotely and with on-board equipment. As of the time of this writing (2018), Curiosity had investigated water- and wind-formed strata and landforms near its landing site and had begun ascending Mount Sharp. Here, a host of experiments are planned with the objective of reconstructing the geologic history and potential habitability of the paleo-environments in which the strata were lain down.

The **Mars Atmosphere and Volatile Evolution** (MAVEN) mission arrived in 2014 to study the history of Mars climate through the interactions of the Mars atmosphere with space, including how the solar wind may have stripped away much of the gas and water in the once-thick atmosphere. MAVEN's orbit takes it through the uppermost atmosphere, where the instruments study gas composition, behavior, and solar-wind interactions, while imaging of the atmosphere in the ultraviolet occurs in higher parts of the elliptical orbit.

The **Mars Orbiter Mission or Mangalyaan** (Indian Space Research Organisation, ISRO; it arrived at Mars in 2014) is a technology demonstration mission with instruments to measure hydrogen/deuterium, methane, and other gases, a thermal infrared imaging spectrometer, and a visible camera.

The first **ExoMars Trace Gas Orbiter and Schiaparelli Mission** (ESA) arrived at Mars in late 2016. The orbiter has several instruments to measure methane and other trace gases of possible biologic significance, as well as the Colour and Stereo Surface Imaging System (CaSSIS), to identify and study the location of any trace gas sources on the Mars surface. The unsuccessful Schiaparelli lander was intended to test entry, descent, and landing technology in preparation for a future rover mission, for which the orbiter will serve as the communications relay.

The **Interior Exploration using Seismic Investigations, Geodesy and Heat Transport** (**InSight**) mission will employ geophysical methods to study the deep interior of Mars. InSight landed on Elysium Planitia (MC-15) in December 2018. Instruments will measure seismic waves traveling through Mars, heat flow from the subsurface, and careful tracking of the site from Earth to establish the effect of interior structure on the rotation of Mars. Among a number of other robotic missions to Mars planned by several nations is the NASA **Mars 2020** rover mission, with a planned landing in Jezero crater (see MC-13). The rover is based on the Curiosity design and will cache drill-core samples for possible return to Earth by a future mission.

Cambridge University Press
978-1-107-03629-1 — The Atlas of Mars
Kenneth S. Coles, Kenneth L. Tanaka, Philip R. Christensen
Excerpt
More Information

CHAPTER 3

Global Character of Mars

The global views presented here in Figures 3.1 to 3.14 convey properties of the surface (albedo, elevation, dust cover, relative abundance of various minerals), near-surface region (ice, thermal inertia), and interior (local gravity, crustal thickness, magnetic field). The maps are in simple cylindrical projection, using planetocentric coordinates where possible. Some datasets are only available in other views and are reproduced as they were made available.

Albedo

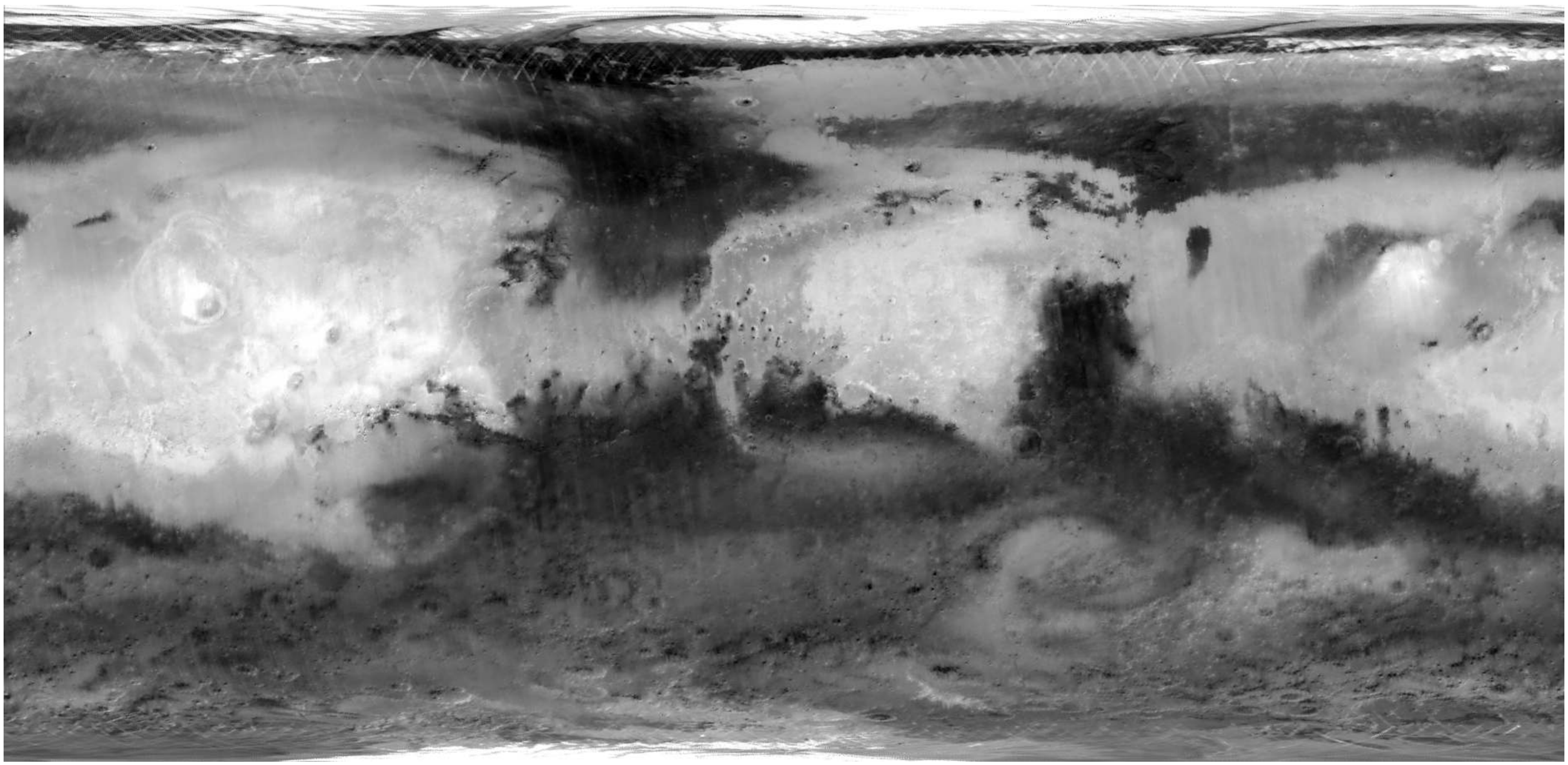


FIGURE 3.1 Albedo denotes the light or dark appearance of different parts of the surface, originally as seen by telescope. The albedo of Mars shows seasonal variations, possibly due to movement of windblown dust and changes in ice deposits. Albedo features do not appear exactly the same after each seasonal cycle, giving rise to longer-term, permanent changes. Data, here plotted over MOLA shaded relief, are from the Thermal Emission Spectrometer (TES, on Mars Global Surveyor; Christensen *et al.*, 2001; 7.5 km/pixel, simple cylindrical projection, planetocentric).

