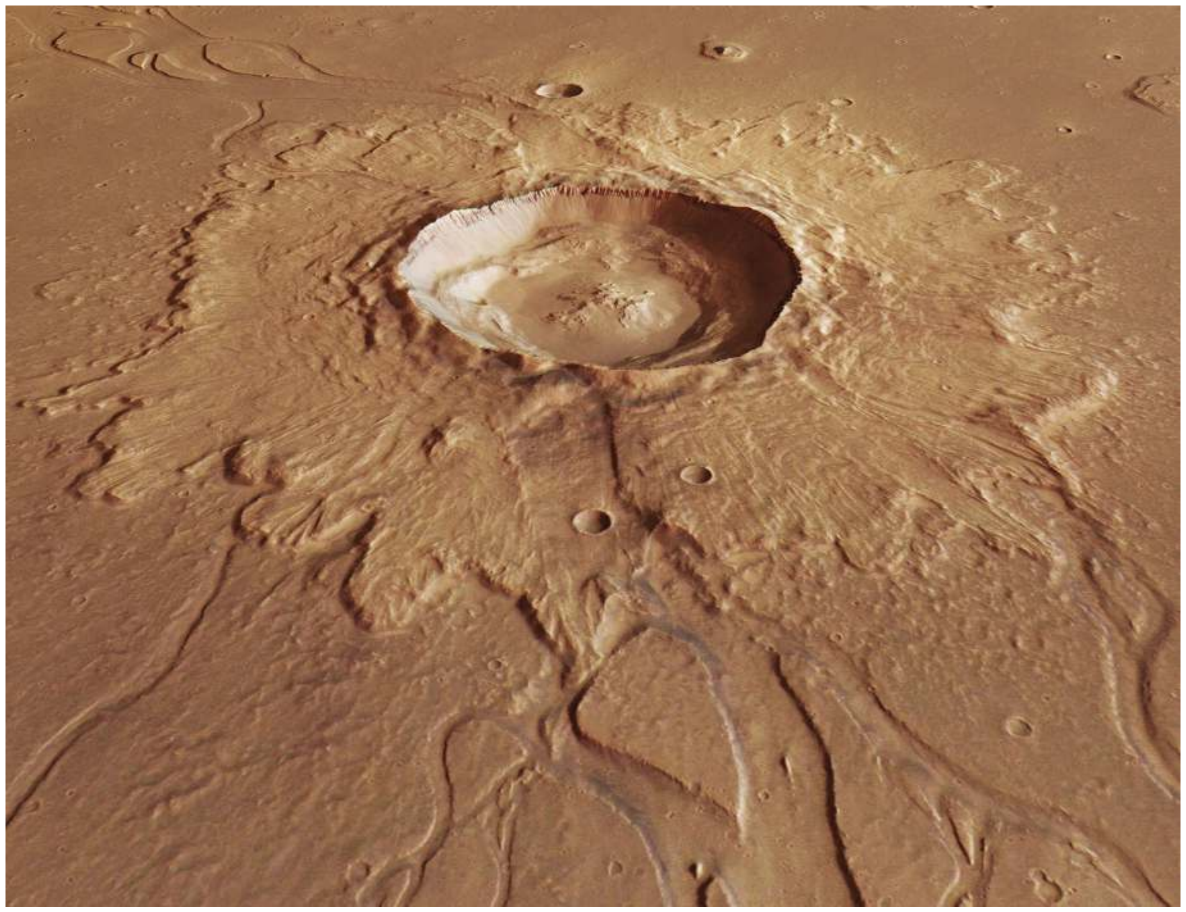


The Atlas of Mars

Mapping Its Geography and Geology

Planetary scientist and educator Ken Coles has teamed up with Ken Tanaka from the United States Geological Survey's Astrogeology team and Phil Christensen, Principal Investigator of the Mars Odyssey orbiter's THEMIS science team, to produce this all-purpose reference atlas, *The Atlas of Mars*. Each of the 30 standard charts includes: a full-page color topographic map at 1:10,000,000 scale, a THEMIS daytime infrared map at the same scale with features labeled, a simplified geologic map of the corresponding area, and a section describing prominent features of interest. The *Atlas* is rounded out with extensive material on Mars' global characteristics, regional geography and geology, a Glossary of Terms, and an indexed Gazetteer of up-to-date Martian feature names and nomenclature. This is an essential guide for a broad readership of academics, students, amateur astronomers, and space enthusiasts, replacing the NASA atlas from the 1970s.

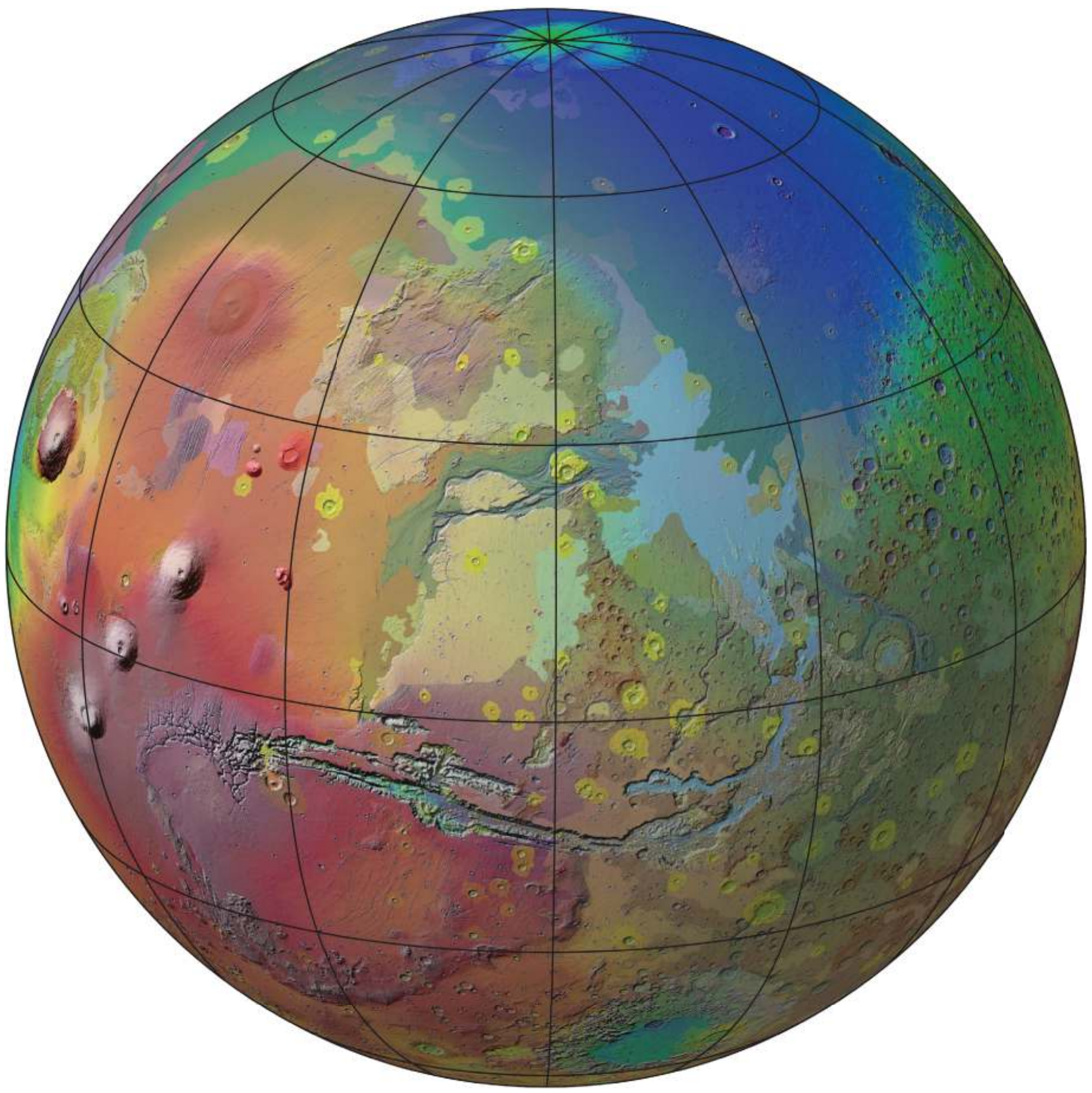
Kenneth S. Coles is Associate Professor and Planetarium Director at Indiana University of Pennsylvania. An award winning teacher, he has dedicated his career to sharing planetary science and geology discoveries with university students, schoolchildren, and the public.

Kenneth L. Tanaka is a Geologist retired from the US Geological Survey Astrogeology Science Center in Flagstaff, Arizona. He has 35 years of experience in the geologic mapping of Mars, informing NASA's exploration missions, and has received the US Department of Interior's Distinguished Service Award.

Philip R. Christensen is Regents' Professor of Planetary Geoscience at Arizona State University. He is the Principal Investigator for the Mars Odyssey THEMIS instrument and has received the Geological Society of America's G. K. Gilbert Award, NASA's Exceptional Scientific Achievement Medal, and NASA's Public Service Medal.

Half title image caption: An impact crater, about 15 km across, shows ejecta emplaced by fluidized flow during the impact. The crater overlies channels of Hebrus Valles. While Hebrus may appear to have been caused by the impact, streamlined islands within channels on both sides of the crater record flow in the same direction, consistent with channel origin prior to the impact. The view is toward the south in Utopia Planitia at 20° N, 126° E (see map MC-14 in this atlas; HRSC orbit 5122, 16 m/pixel, ESA/DLR/FU-Berlin).

Title image caption: The western hemisphere of Mars shown in two datasets. The Mars Orbiter Laser Altimeter (MOLA) representation in the lower left and upper right portions of the globe shows elevation (by color) and topographic relief (by artificial illumination from upper left; see Figure 3.2b in Chapter 3 for a more detailed explanation). Colored units from the Geologic Map of Mars are merged with the MOLA relief view and displayed in a swath from upper left to lower right (further explanation accompanies Figures 5.1a–d in Chapter 5). The enormous Olympus Mons and the three aligned Tharsis Montes are immense shields that dominate the Tharsis volcanic region to the west (largely red). Heavily cratered terrain lies to the east, including the Argyre impact basin (the blue-green area at bottom). The extensive Valles Marineris canyon system, just below and left of center, forms part of the Thaumasia plateau's northern edge. Emanating to the north and east of Valles Marineris are broad outflow channels that cut through lava plains and cratered terrain. The channels extend into the northern lowlands (blue region), wherein the Viking 1 and Mars Pathfinder spacecraft landed. At top, the north polar ice cap, Planum Boreum, rises above the surrounding lowlands. (View centered at 20° N, 300° E; grid spacing 30 degrees.)



The Atlas of Mars

Mapping Its Geography and Geology

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Preface

The decade that followed the arrival of the Viking landers and orbiters on Mars in 1976 saw the release of a global atlas (Batson *et al.*, 1979),[1] a new global geologic map (Scott and Tanaka, 1986; Greeley and Guest, 1987; Tanaka and Scott, 1987), and even a digital image of the entire surface (the Mars Digital Image Model, or MDIM). Kieffer *et al.* (1992b) summarized the major conclusions of this work. The stage was set for a series of spacecraft missions to Mars that began in the 1990s and continues today. Every one of the realizations about Mars in the pages that follow is a discovery in progress. They continue even as we write. Since the information we present will undoubtedly continue to grow and change rapidly, why this atlas now?

This book comes about as a result of a confluence of new information and understanding about Mars. The global imagery is more detailed than in the past, and a small percentage of the surface can be studied at the level of individual boulders and gullies. Mapping from new data has greatly improved our knowledge of the geology of the entire planet compared to the last synthesis, a generation ago. The relative dating of units and events, particularly by crater counting, is also more refined. Sensors that gather infrared and radar data now tell us the composition and mineralogy of the surface and the structure beneath the surface, not seen in visible light. Details of subsurface water ice have emerged, not only in polar regions but all over Mars. Observations on the surface by increasingly sophisticated landers and rovers have confirmed some ideas and discounted others.

Some aspects of Mars exploration have been covered in detail elsewhere:

- Collections of great pictures (many published, with more issued each year);
- Histories (in detail) of pre-space age ideas about Mars (e.g. Sheehan, 1996);
- Histories of the robotic exploration of Mars (e.g. Morton, 2002; Hubbard, 2011; Stooke, 2012, 2016);
- Detailed analyses of findings by individual landers (e.g. Mishkin, 2003; Squyres, 2005) or orbiting instruments (e.g. Beyer *et al.*, 2012);
- Arguments for (or against) Mars exploration (e.g. Zubrin, 2011);
- The geology of Mars, presented in the framework of geologic time (in the book by Hartmann, 2003, which we commend to the reader); and
- The atmosphere and climate of Mars (Haberle *et al.*, 2017).

Our focus here is a synoptic view of geology: how geology controls or influences some typical landforms, how the environment has changed over the history of Mars, and current debates and outstanding questions in Mars research. In sum, this overview of what we know and what we don't know will suggest what is important to study next on the red planet.

While some of this will be of use to active Mars researchers, we particularly hope to reach other readers: scientists from other fields, interested non-scientists, and persons who wonder what all the missions to Mars have told us. It is an astonishing assortment of facts, ideas, and most of all entire new questions and mysteries to motivate further work. But then, why should the study of the fourth planet differ from any other field of human inquiry?

Acknowledgments

Staff at the justly renowned US Geological Survey (USGS) Astrogeology Science Center gave input and suggestions from the first ideas for this atlas through to the final drafts. While we couldn't incorporate every idea they gave us, we appreciate their willingness to share ideas and point us to useful images and other resources: Jen Blue, Colin Dundas, Ken Herkenhof, Chris Isbell, Randy Kirk, Baerbel Lucchita, Moses Milazzo, David Portree, Larry Soderbloom, and Tim Titus. Also at the USGS, Rose Hayward checked the nomenclature maps and Gazetteer for completeness and Chris Okubo reviewed the entire manuscript.

Images were generously created or provided for our use by Vic Baker, Donald Barker, Serina Diniega, Henrik Hargitai, Rose Hayward, Jack Holt, Eric Peterson, Than Putzig, and Alexis Rodriguez. Additional valuable ideas came from Nick Deardorff, Robert Jacobsen, Gregory Michael, and Thomas Platz. The many researchers who have been studying Mars for over half a century and building and operating robotic missions have both inspired this work and made much of it possible. Many of their ideas remain useful and have held up well under prolonged study. We would like to acknowledge the staff (past and present) who have collected and processed images and data of Mars, as well as those who have made them very accessible and useful, at the USGS, NSSDC (NASA), JPL-Caltech, THEMIS (Arizona State University), HiRISE (University of Arizona), HRSC (Freie Universität Berlin), and MSSS, along with others listed in the credits for each image. The collections, staff, and facilities of the US Geological Survey Library, the Indiana University of Pennsylvania Libraries, and the Logansport-Cass County Public Library were essential to the research for this atlas.

A key figure throughout this effort has been Vince Higgs at Cambridge University Press. He first proposed that this work be based on the new geologic map of Mars, and he and his staff patiently and professionally shepherded us through the entire process, in spite of how lengthy it became. We are sure we speak for all the contributing authors as we offer gratitude to the teachers who trained us, the colleagues and students who work with us, and the loved ones who support us as we worked in a focused way on a time-consuming but gratifying project.

We dedicate this book to Ron Greeley (1939–2011), who pioneered the application of geologic and cartographic mapping in planetary science. Ron helped bring rigorous mapping standards to planetary geology, and he inspired a generation of scientists to apply geologic principles and techniques to study the planets and moons in our solar system.

K. S. C.
K. L. T.
P. R. C.

[1] A revision of the 1979 atlas is listed in one online bibliography as having been assigned the designation NASA Special Publication SP-506. Neither the authors nor the archivist at the US Geological Survey Astrogeology office can find any evidence that such a revision was ever completed or published.

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Abbreviations

CNES (*Centre National d'Études Spatiales*) National Centre for Space Studies, space agency of France
CNRS (*Centre National de la Recherche Scientifique*) National Centre for Scientific Research, France
CRISM Compact Reconnaissance Imaging Spectrometer for Mars, on MRO
CTX Context Camera, on MRO
DEM Digital elevation model
DLR (*Deutsches Zentrum für Luft- und Raumfahrt*) German Aerospace Center, space agency of Germany
ESA European Space Agency
ExoMars Exobiology on Mars, series of ESA missions (as of this writing, the first mission is the Trace Gas Orbiter [TGO] mission)
GSFC Goddard Space Flight Center of NASA
GRS Gamma Ray Spectrometer, on MO.
HiRISE High Resolution Imaging Science Experiment, on MRO
HRSC High Resolution Stereo Camera, on ESA Mars Express orbiter
IAS (*Institut d'Astrophysique Spatiale*), Institute of Space Astrophysics, France
ISRO Indian Space Research Organisation, the national space agency of India
JHUAPL Johns Hopkins University Applied Physics Laboratory
JPL Jet Propulsion Laboratory, operated for NASA by the California Institute of Technology (Caltech)
MAVEN Mars Atmosphere and Volatile Evolution, NASA orbiter
MC Mars Chart, system of 30 maps, originally at 1 to 5 million scale, created for Mars in the early 1970s
MDIM Mars Digital Image Model, an image mosaic of the Mars surface derived from Viking orbiter imagery
MER Mars Exploration Rover, NASA twin missions A and B, also known as Spirit and Opportunity, respectively
MGS Mars Global Surveyor, NASA orbiter
MO Mars Odyssey, NASA orbiter
MOC Mars Orbiter Camera, on MGS
MOLA Mars Orbiter Laser Altimeter, on MGS
MRO Mars Reconnaissance Orbiter, NASA mission
MSL Mars Science Laboratory, also known as Curiosity, a NASA surface rover
MSSS Malin Space Science Systems, involved in the engineering and/or operation of MOC, CTX, and THEMIS-visible, among others
NASA National Aeronautics and Space Administration, space agency of the USA
NSSDC National Space Science Data Center, data archive for NASA
OMEGA (*Observatoire pour la Minéralogie, l'Eau, les Glaces et l'Activité*) Visible and Infrared Mineralogical Mapping Spectrometer, on ESA Mars Express orbiter
SHARAD Shallow Radar, on MRO
TES Thermal Emission Spectrometer, on MGS
THEMIS Thermal Emission Imaging System, on MO
USGS United States Geological Survey

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How to Use this Atlas

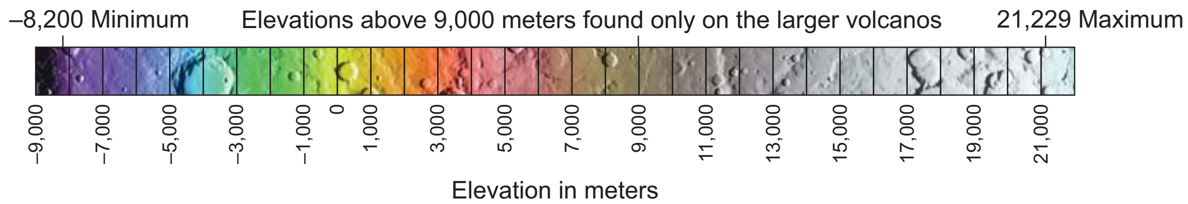
Global maps of Mars are found in Chapter 2 (maps predating exploration by spacecraft), Chapter 3 (showing various properties or abundances, see also Figures 15.E and 23.B), Chapter 4 (regional geographic features in Figures 4.1 and 4.2), and Chapter 5 (geology, Figures 5.1 through 5.6, 5.9, and 5.11). **Thirty map sheets** showing physiography, geology, and feature names follow Chapter 5, as shown in the accompanying index map below.

Elevation on many of the maps is depicted by the colors shown here.

The names and correlation of the **geologic map units** used on the geologic maps are summarized in the Appendix, while Chapter 5 describes the units in more detail.

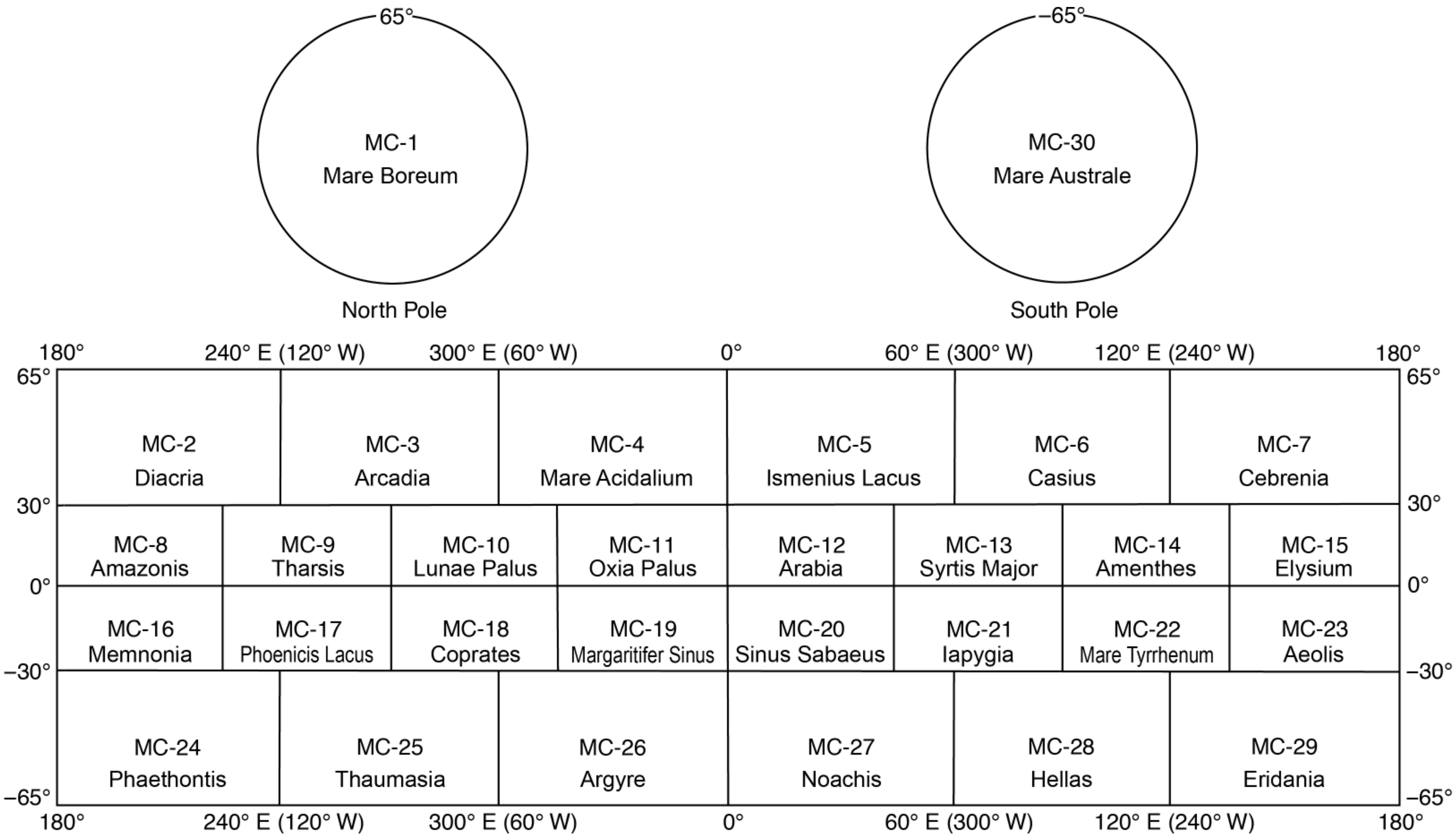
The **figures** in the first five chapters are denoted by chapter number, figure number in that chapter and, where needed, a lower-case letter indicating the figure part. For example, Figure 3.1 and Figures 3.2a and 3.2b are the first three figures in Chapter 3.

In the map sheets the figures are denoted by Map Chart (MC) number and an upper case letter; sometimes a number follows the upper case letter. Thus Figure 3.A accompanies MC-3, Arcadia, and Figures 8.A1–8.A5 accompany MC-8, Amazonis.



To find features

- By known name: turn to the Gazetteer, or for informal names see the Index.
- By feature type: use the Index to find examples (see the Glossary of Terms for definitions).
- By geologic period: use Figure 5.9 together with the index map of Mars Charts below to locate maps showing units of a particular age.
- By region: use the index map of Mars Charts below with Figures 4.1 and 4.2 to find the appropriate numbered map(s).



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Sources of Images

Individual images from particular instruments or provided by colleagues are credited in captions. Some images (particularly using the MOLA dataset) were created by the authors for this work. Details for all these sources are also given below. The web page for this atlas, www.cambridge.org/atlasofmars, includes links to some of the most useful sites that give access to these and other images of Mars.

CRISM (Compact Reconnaissance Imaging Spectrometer for Mars): NASA/JPL-Caltech/Johns Hopkins University Applied Physics Laboratory

CTX (Context Camera): NASA/JPL-Caltech/Malin Space Science Systems (see Malin *et al*., 2007; Bell *et al*., 2013)

HiRISE (High Resolution Imaging Science Experiment): NASA/JPL-Caltech/University of Arizona (see McEwen *et al*., 2007a)

HRSC (High Resolution Stereo Camera): European Space Agency/Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)/Freie Universität Berlin (Free University of Berlin; see Jaumann *et al*., 2007; 2015; Gwinner *et al*., 2016)

MDIM (Mars Digital Image Model) derived from Viking Orbiter imagery, Version 2.1 from NASA Ames Research Center/USGS

MOC (Mars Orbiter Camera): NASA/JPL-Caltech/Malin Space Science Systems (see Malin *et al*., 1991)

MOLA (Mars Orbiter Laser Altimeter): Except where otherwise noted, images were created using the MOLA color and/or MOLA hillshade datasets from NASA/JPL-Caltech/Goddard Space Flight Center (see Smith *et al*., 2001)

OMEGA (Observatoire pour la Minéralogie, l'Eau, les Glaces et l'Activité): ESA/Centre National d'Études Spatiales/Centre National de la Recherche Scientifique/Institut d'Astrophysique Spatiale/Université Paris-Sud, Orsay (see Ody *et al*., 2012)

SHARAD (Shallow Radar): NASA/JPL-Caltech/Sapienza University of Rome/Southwest Research Institute

TES (Thermal Emission Spectrometer): NASA/JPL-Caltech/Arizona State University (see Christensen *et al*., 2001)

THEMIS (Thermal Emission Imaging System): NASA/JPL-Caltech/Arizona State University (see Christensen *et al*., 2004)

