The Surface of Mars

Our knowledge of Mars has grown enormously over the last decade as a result of the Mars Global Surveyor, Mars Odyssey, Mars Express, and the two Mars Rover missions. This book is a systematic summary of what we have learnt about the geological evolution of Mars as a result of these missions, and builds on the themes of the author's previous book on this topic.

The surface of Mars has many geological features that have recognizable counterparts on Earth. Many are huge in comparison to those on Earth, including volcanoes, canyons and river channels that are ten times larger than their terrestrial equivalents. The book describes the diverse Martian surface features and summarizes current ideas as to how, when, and under what conditions they formed. It explores how Earth and Mars differ and why the two planets evolved so differently. While the author's main focus is on geology, he also discusses possible implications of the geological history for the origin and survival of indigenous Martian life.

Up-to-date and richly illustrated with over two hundred figures, the book will be a principal reference for researchers and students in planetary science. The comprehensive list of references will also assist readers in pursuing further information on the subject.

MICHAEL CARR is a Geologist Emeritus at the U.S. Geological Survey, and has over 40 years' experience of planetary science research. In the early 1970s Dr. Carr was a member of the Mariner 9 team and leader of the Viking Orbiter Imaging team. He was co-investigator on the Mars Global Surveyor, the Mars Exploration Rovers, and the High Resolution Stereo Camera on Mars Express. He is a Fellow of the Geological Society of America, the American Geophysical Union, and the American Association for the Advancement of Science, and was awarded the 1994 National Air and Space Museum Lifetime Achievement Award for his work on Mars. He is also the author of *The Surface of Mars* (1981) and *Water on Mars* (1996).

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Preface

This book summarizes our knowledge of the morphology of the martian surface and speculates on how the surface evolved to its present state. During the last three decades our knowledge of Mars has increased dramatically. A succession of orbiting spacecraft (Table I) have observed the planet at ever-increasing resolution, rovers have traversed the surface, analyzing and scrutinizing rocks along the way, and ever more sophisticated techniques are being used to analyze increasing numbers of martian meteorites. The planet has had a complicated history. The aim of the book is to summarize our understanding of the nature and sequence of the processes that led to the present configuration of the surface. While the book is intended for the serious student or researcher, technical jargon is avoided to the extent that it is possible without compromising precision. It is hoped that the book will be readable to informed non-Mars specialists as well as those active in the field. Sufficient documentation is provided to enable the reader to dig more deeply wherever he or she wishes. Heavy reliance is placed on imaging data. Other evidence is referred to where available, but at the present time, imaging is by far the most comprehensive global data set that we have in terms of areal coverage and resolution range.

Exploration of Mars has captured world-wide interest. Mars is an alien planet yet not so alien as to be incomprehensible. The landscape is foreign yet we can still recognize familiar features such as volcanoes and river channels. We can transport ourselves through our surrogate rovers to a surface both strange and familiar and readily imagine some future explorers following in their paths. While past speculations about martian civilization may now seem absurd, the possibility that Mars may at one time have hosted some form of life remains plausible. It remains the strongest scientific driver of the Mars Exploration program. The life

Table I. *Mars missions*

Mariner 4	US	11/28/1964	Flew by 7/15/1965; first S/C images
Mariner 6	US	2/24/1969	Flew by 7/31/1969; imaging and other data
Mariner 7	US	3/27/1969	Flew by 8/5/1969; imaging and other data
Mars 2	USSR	5/19/1971	Crash landed; no surface data
Mars 3	USSR	5/28/1971	Crash landed; no surface data
Mariner 8	US	5/8/1971	Fell into Atlantic Ocean
Mariner 9	US	5/30/1971	Into orbit 11/3/1971; mapped planet
Mars 4	USSR	7/21/1973	Failed to achieve Mars orbit
Mars 5	USSR	7/25/1973	Into orbit 2/12/1975; imaging and other data
Mars 6	USSR	8/5/1973	Crash landed
Mars 7	USSR	8/9/1973	Flew by Mars
Viking 1	US	8/20/1975	Landed on surface 7/20/1976; orbiter mapping
Viking 2	US	9/9/1975	Landed on surface 9/3/1976; orbiter mapping
Phobos 1	USSR	7/7/1988	Lost 9/2/1988
Phobos 2	USSR	7/12/1988	Mars and Phobos remote sensing
Mars Observer	US	9/22/1992	Failed Mars orbit insertion
Pathfinder	US	12/4/1996	Landed 7/4/1997; lander and rover
Global Surveyor	US	11/7/1996	Into orbit 9/11/1997; imaging and other data
Odyssey	US	4/7/2001	Into orbit 10/24/2001: imaging, remote sensing
Spirit Rover	US	6/10/2003	Landed in Gusev 1/3/2004
Opportunity Rover	US	7/7/2003	Landed in Meridiani 1/24/2004
Mars Express	Europe	6/2/2003	In orbit 12/25/2003; imaging, remote sensing
Reconnaissance Orbiter	US	8/12/2005	In orbit 3/10/2006; imaging, remote sensing

theme is constantly in the background throughout the book. Impacts have implications for survival of any early life, and may have resulted in cross-fertilization of Mars and Earth. Large floods may have temporarily affected global climates and provided temporary refuges in the resulting lakes and seas. Volcanic activity may have created hydrothermal systems in which life could thrive. Conditions on early Mars may have been very similar to those on early Earth, at a time when life had already taken hold. Thus, while the book is not explicitly about life, almost every chapter has implications for the topic.

The book is intended as a replacement for an earlier book (Carr, 1981) that summarized our understanding of the planet as it was shortly after completion of the Viking missions. This book is different from the original in several ways. The field was much less mature when the first book was written. I was able to read most of the literature and examine most of the imaging data. Neither of these tasks is possible any longer. Approximately 500 papers are published on Mars each year and the number is increasing. One can no more write a book about Mars and reference all the relevant papers, than one can about the Earth. Similarly, the book has been written without seeing most of the available imaging.

Over 200,000 images have been taken just with the Mars Orbiter Camera on Mars Global Surveyor, and a comparable amount of imaging data has been acquired by THEMIS on Mars Odyssey, the High Resolution Stereo Camera on Mars Express, and the Mars rovers. In addition to the imaging there are vast amounts of other remote sensing data, as well as analytical data from the surface and from meteorites. Clearly, summarizing all this data has involved a great deal of simplification.

The book is a snapshot of a moving picture. Following Viking there was almost a twenty-year drought during which barely any data was returned from the planet. But since the landing of Mars Pathfinder in 1996 and the insertion of Mars Global Surveyor into orbit in 1997, we have been receiving a steady stream. Along with the new data have come new ideas as to how the planet has evolved. The pace of change is rapid because our knowledge of the planet is still rudimentary and the data flux is high. It could be argued that the time is inopportune for a summary because of the rate of change. But change will continue. After two decades, new interpretations of the Viking data were still forthcoming. It will likely also take decades to digest the data currently being returned. I hope that there will never be a time when the field stabilizes and a good time to write a summary arrives.

The book was written in 2005 and 2006. I had just retired after having participated in almost every mission to Mars since the late 1960s, including several months of Mars Exploration Rovers (MER) operations at Jet Propulsion Laboratory (JPL). The book has benefited significantly from the continuous informal science discussions that are part of participating in missions. The Mars Rover end-of-day discussions, when the scientists would gather and exchange ideas about any topic that had intrigued them, were particularly stimulating. The Mars Orbiter Laser Altimeter (MOLA) team on Mars Global Surveyor held regular meetings on different science topics that were always fun. Of course, the book has benefited mostly from the engineers who have built and operated the spacecraft that have flown all the science instruments to Mars in recent years. Without sound engineering there is no science. The engineers do most of the hard work acquiring the data. The scientists have the fun of interpreting it all.

Two people deserve special mention for the help they provided. Phil Christensen, of Arizona State University, the THEMIS Principal Investigator, offered to make mosaics of areas of interest for illustrations. Some of the most spectacular images in the book are these THEMIS mosaics. Jim Head of Brown University is also a major contributor to the book. Jim has unusually broad expertise in planetary science, and is possibly the most prolific author in the field of planetary geology. He agreed to review all the chapters as they were written and provided numerous insightful comments that added greatly to the accuracy and comprehensiveness of the final product. Above all he provided encouragement to keep at it.

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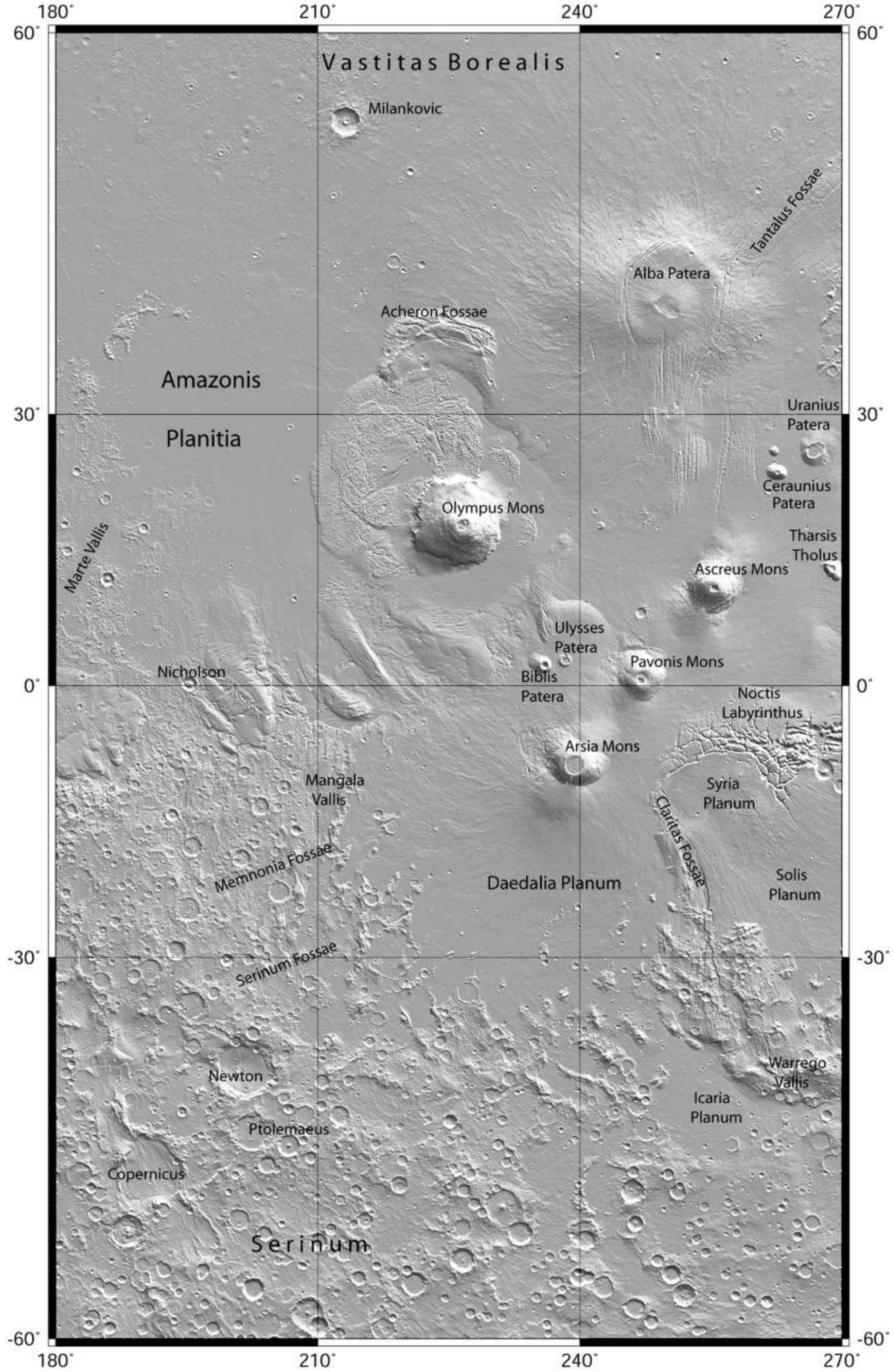
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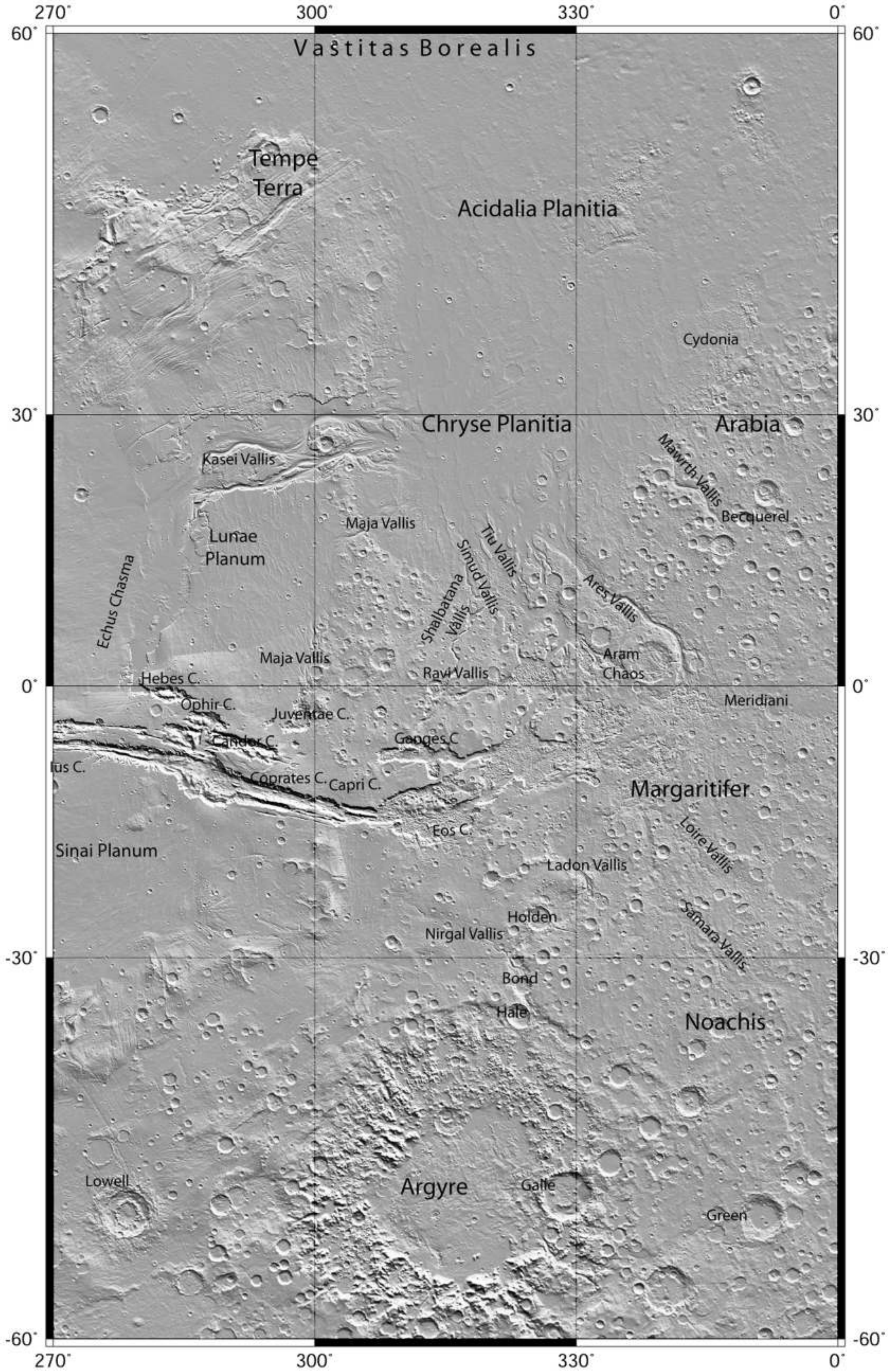
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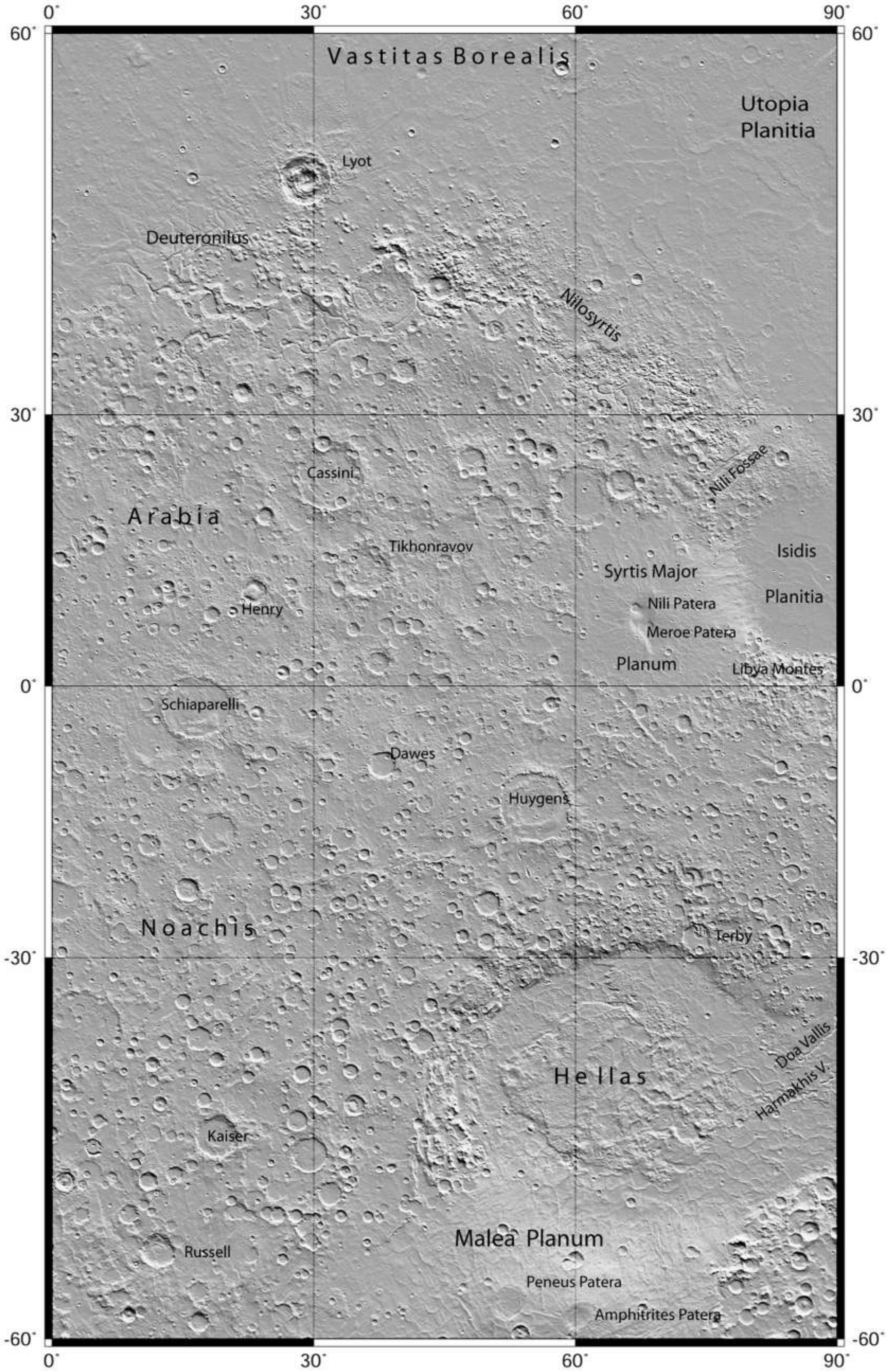
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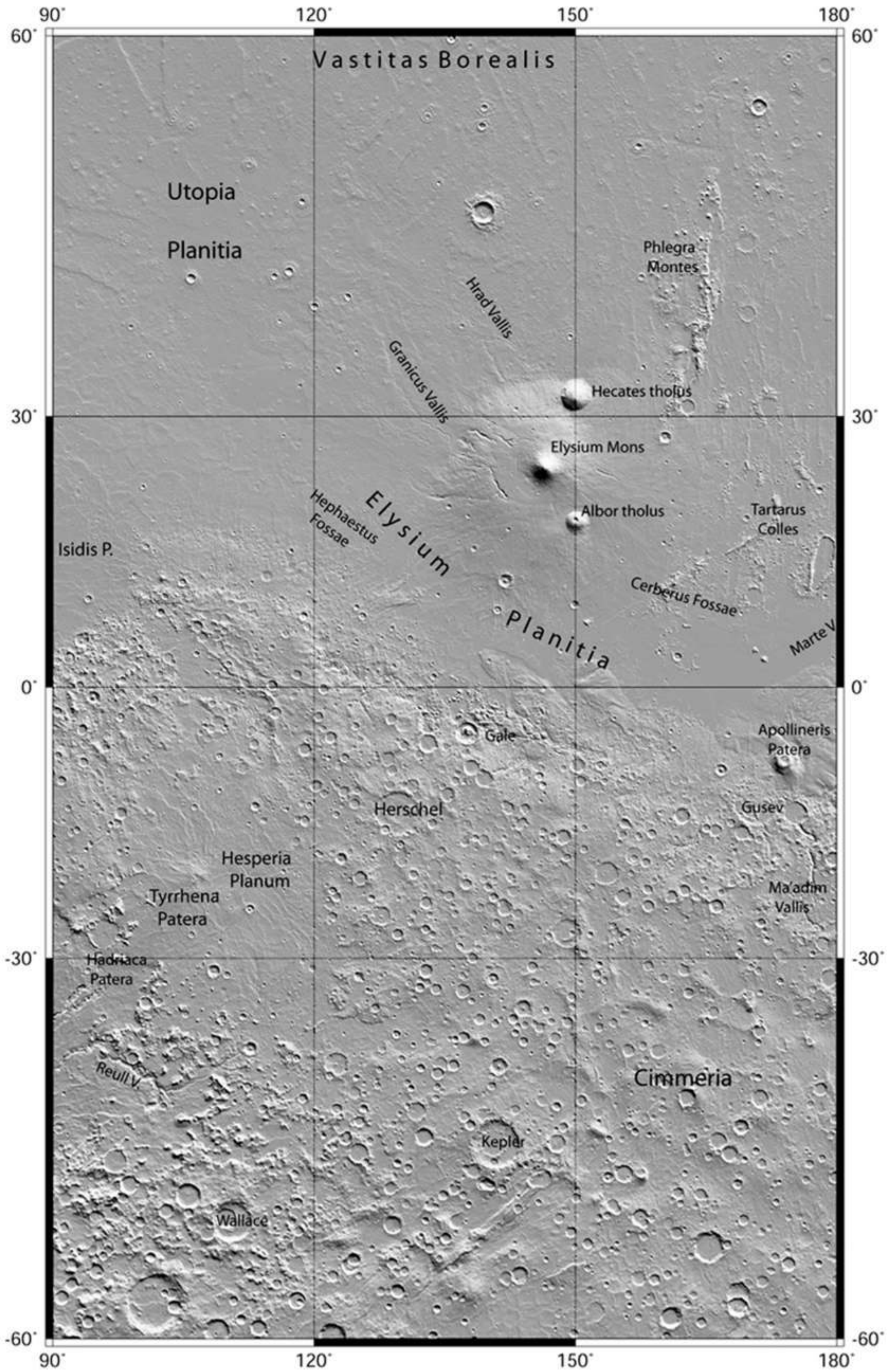
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