

## REPORT

## MARTIAN GEOLOGY

## Exposed subsurface ice sheets in the Martian mid-latitudes

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Thick deposits cover broad regions of the Martian mid-latitudes with a smooth mantle; erosion in these regions creates scarps that expose the internal structure of the mantle. We investigated eight of these locations and found that they expose deposits of water ice that can be >100 meters thick, extending downward from depths as shallow as 1 to 2 meters below the surface. The scarps are actively retreating because of sublimation of the exposed water ice. The ice deposits likely originated as snowfall during Mars' high-obliquity periods and have now compacted into massive, fractured, and layered ice. We expect the vertical structure of Martian ice-rich deposits to preserve a record of ice deposition and past climate.

One-third of the Martian surface contains shallow ground ice. This ice is a critical target for science and exploration: it affects modern geomorphology, is expected to preserve a record of climate history, influences the planet's habitability, and may be a potential resource for future exploration. The extent of Martian ground ice and the depth to the ice table have been predicted in theory (1–3) and have been tested both in situ (4) and from orbital observations (5–17). However, the vertical structure of subsurface ice remains poorly known, including its layering, thickness, and purity, which record its emplacement and subsequent modification processes. Information about the structure, depth, and purity of shallow ice is also required to plan possible in situ resource utilization (ISRU) on future missions (18).

Early theoretical predictions suggested that Martian subsurface ice would be ice-cemented ground (19). Orbital neutron-spectrometer data have revealed ice contents greater than the likely pore space volume in the upper few centimeters of the ice table in many locations (5–7). Shallow ice (<1 to 2 m) exposed by fresh impacts remains distinct for months or years, also indicating a low rock or dust content, although possibly modified by the impact process (8, 20, 21). The Phoenix lander on the northern plains uncovered both ice-cemented regolith and deposits of pure (>99 vol-

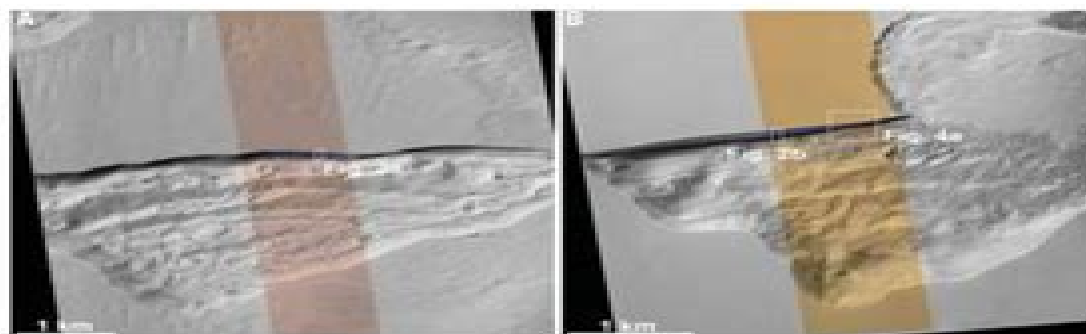
ume %) ice (4, 24) at a few centimeters depth. The ice at that site likely extends to 9 to 66 m depth on the basis of shallow radar reflections (25), but geomorphic interpretations suggest that ice-cemented ground is dominant there (26). However, ice-loss landforms indicate that several regions on Mars have high ice volume fractions extending through substantial subsurface depths (27, 28), and radar echo power data have suggested high ice contents beneath areas of the northern plains (8). Subsurface radar reflections indicate the presence of debris-covered glaciers (29, 30) as well as buried regional ice sheets in the Utopia and Arcadia Planitia regions that are up to 120 m thick and nearly pure ice (22, 23). Because the radar did not resolve the top of the ice, it is likely to be within ~20 m of the surface, the limit of the radar instrument's ability to iden-

tify shallow signals (25). The smaller-scale structure of the ice sheets and rocky cover are unresolved with current radar data. It remains unknown whether the ice within a few meters of the surface has the same origin and age as the deeper ice because the upper ice is most readily modified and best coupled to the recent climate.

We describe observations of the vertical structure of ground ice using the Mars Reconnaissance Orbiter (MRO). The observations target eight locations that have steep, pole-facing scarps created by erosion (Figs. 1 and 2 and figs. S1 to S3) in images from the High-Resolution Imaging Science Experiment (HRISSE); seven are located in the southern hemisphere, and the eighth location is a cluster of scarps in Milanković Crater in the north (table S1). Each of the scarps is relatively blue (compared with surrounding terrain) in enhanced-color HRISSE images, and three locations have water-ice signatures in mid-summer spectral data (Fig. 3 and figs. S4 and S5) taken by MRO's Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) (23). CRISM spectra show an H<sub>2</sub>O ice absorption feature at 1- $\mu$ m wavelength (fig. S6), which can be masked by as little as 1% soil (24). Tens of micrometers of dust are needed to make an opaque cover (24), so the dust content is low and/or wind removes dust.

Several lines of evidence indicate that the scarps are exposures of subsurface ice rather than persistent seasonal frost. First, they remain distinct from the surrounding terrain in color in all HRISSE images, including many observations acquired long after seasonal frost has sublimated from steep pole-facing slopes at higher latitudes. Second, Mars Odyssey Thermal Emission Imaging System (THEMIS) observations indicate late-afternoon scarp temperatures above the likely atmospheric frost point (23). Last, nearby pits lack relatively blue material that would be expected for topographically controlled frost (fig. S7).

The units hosting the scarps drap the terrain, with some meter-scale boulders on the surface



**Fig. 1. Pits with scarps exposing ice.** (A and B) Scarps 1 and 2. Both (A) and (B) show HRISSE red-filter data merged with the center color strip (23) in early-summer observations. Parallel ridges indicate retreat of scarps (fig. S3). North is up and light is from the left in all figures.

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# Exposed Subsurface Ice Sheets In The Martian Mid Latitudes

**JR Anderson**



### **Exposed Subsurface Ice Sheets In The Martian Mid Latitudes:**

*Mars Geological Enigmas* Richard Soare, Susan Conway, Jean-Pierre Williams, Dorothy Oehler, 2021-05-23 *Mars Geological Enigmas* From the Late Noachian Epoch to the Present Day presents outstanding questions on the geology of Mars and divergent viewpoints based on varying interpretations and analyses The result is a robust and comprehensive discussion that provides opportunities for planetary scientists to develop their own opinions and ways forward Each theme opens with an introduction that includes background on the topic and lays out questions to be addressed Alternate perspectives are covered for each topic including methods observations analyses and in depth discussion of the conclusions Chapters within each theme reference each other to facilitate comparison and deeper understanding of divergent opinions Offers a transchronological view of the geological history of Mars addressing thematic questions from a broad temporal perspective Discusses outstanding questions on Mars from diverging perspectives Includes key questions and answers as well as a look ahead to which puzzles remain to be solved

**Mars On Earth: A Study Of The Qaidam Basin** Long Xiao, 2021-01-04 Mars has been extensively photographed by cameras and compositionally detected by spectrometers onboard orbiters on a global scale and explored in situ by landers and rovers at both local and outcrop scales in different locations The results have proved that the Martian surface is rich in Earth like geomorphologies and the study of terrestrial analogs to Mars has been listed as one of the highest priorities of Martian science With increasing new discoveries by in situ explorations Mars exploration has begun to enter the era of focusing on detailed analyses at regional to outcrop levels rather than global mapping Analog studies are playing a crucial role in this transition making this book which introduces the methodology and provides cases for readers essentially important Dozens of sites on Earth have been listed as analog targets for comparative study with the geomorphology geology geochemistry environment and habitability of Mars However due to the diversity of landforms and forming mechanisms and the long history of Mars no single analog site on Earth can be fully compared to Mars Nonetheless the Qaidam Basin has been listed as an unique Mars analog site for studying the red planet s geomorphology geology and environmental changes particularly regarding the evolution of paleolakes on Mars This kind of setting has always been listed as a top priority for the search of life on Mars This book contains first hand information and on site images obtained by the work s contributing authors and is an essential read for anyone interested in Martian geomorphology and its evolution processes and history

**The Book of Mars** Stuart Clark, 2022-11-10 From myth to Musk astrology to astronomy Dr Stuart Clark selects the very best writing about the Red Planet From its very first sighting Mars has been a source of fascination for humanity Named for the Roman god of war this red planet has been explored more than any other beyond Earth and continues to occupy a distinctive place in our imagination It s an environment that may even foster life In *The Book of Mars* Dr Stuart Clark selects one hundred pieces of writing about the planet It is a collection that brings together fact and fiction dreams and fears centuries of observation and more recent feats of interstellar exploration

From classic writers of science fiction Stanley G Weinbaum Arthur C Clarke H G Wells Ray Bradbury Pamela Sargent Roger Zelazny to distinguished experts in astronomy astrobiology and aerospace engineering from Hugo and Nebula Award winning authors Kim Stanley Robinson Mary Robinette Kowal to trail blazing journalists and science communicators from Andy Weir's *The Martian* to Elon Musk's SpaceX programme *The Book of Mars* is an extraordinary overview both of the Red Planet and of the way scientific investigation diffuses into culture

*Astrobiology* Akihiko Yamagishi, Takeshi Kakegawa, Tomohiro Usui, 2019-02-27 This book provides concise and cutting edge reviews in astrobiology a young and still emerging multidisciplinary field of science that addresses the fundamental questions of how life originated and diversified on Earth whether life exists beyond Earth and what is the future for life on Earth Readers will find coverage of the latest understanding of a wide range of fascinating topics including for example solar system formation the origins of life the history of Earth as revealed by geology the evolution of intelligence on Earth the implications of genome data insights from extremophile research and the possible existence of life on other planets within and beyond the solar system Each chapter contains a brief summary of the current status of the topic under discussion sufficient references to enable more detailed study and descriptions of recent findings and forthcoming missions or anticipated research Written by leading experts in astronomy planetary science geoscience chemistry biology and physics this insightful and thought provoking book will appeal to all students and scientists who are interested in life and space

*Advances in Extraterrestrial Drilling: Yoseph Bar-Cohen, Kris Zacny, 2020-12-23* *Advances in Extraterrestrial Drilling* Ground Ice and Underwater includes the latest advances that have been made in recent years in developing drilling and excavation mechanisms for extraterrestrial bodies The chapters cover drill types drilling techniques and their advantages and associated issues rock coring including acquisition damage control caching and transport and data interpretation as well as unconsolidated soil drilling and borehole stability This book includes a description of the basic science of the drilling process associated processes of breaking and penetrating various media the required hardware and the process of excavation and analysis of the sampled media Covers the most recent advances in extraterrestrial drilling Discusses drilling in the broadest range of media including ground ice underwater and planetary surfaces from shallow to very deep Provides a comprehensive description of key drilling techniques and the efforts to develop unified approach to assessing the required tools for given drilling requirements Discusses how environment affects drilling and approaches to addressing the effects and current challenges of drilling and excavation on other planets Examines novel drilling and excavation approaches Dr Yoseph Bar Cohen is the Supervisor of the Electroactive Technologies Group <http://ndeaa.jpl.nasa.gov> and a Senior Research Scientist at the Jet Propulsion Lab Caltech Pasadena CA His research is focused on electro mechanics including planetary sample handling mechanisms novel actuators that are driven by materials such as piezoelectric and EAP also known as artificial muscles and biomimetics Dr Kris Zacny is a Senior Scientist and Vice President of Exploration Systems at Honeybee Robotics Altadena CA His expertise includes space

mining sample handling soil and rock mechanics extraterrestrial drilling and In Situ Resource Utilization ISRU

**Integrative Human Biochemistry** Andrea T. Da Poian, Miguel A. R. B. Castanho, 2021-01-04 This book covers in detail the mechanisms for how energy is managed in the human body The basic principles that elucidate the reactivity and physical interactions of matter are addressed and quantified with simple approaches Three dimensional representations of molecules are presented throughout the book so molecules can be viewed as unique entities in their shape and function The book is focused on the molecular mechanisms of cellular processes in the context of human physiological situations such as fasting feeding and physical exercise in which metabolic regulation is highlighted Furthermore the book uses key historical experiments that opened up new concepts in biochemistry to further illustrate how the human body functions at molecular level helping students to appreciate how scientific knowledge emerges New to this edition 30 challenging practical case studies 2 3 at the end of each chapter based on movies novels biographies documentaries paintings and other cultural and artistic creations far beyond canonic academic exercises A set of challenging questions and problems in the end of each case study to further engage students with the applications of medical biochemistry Insights into the answers to the challenging questions to help steer teaching learning interactions key to productive lectures PBL problem based learning or traditional tutorials or e learning approaches Advance praise for the second edition The Challenging Cases are compelling both from a scientific viewpoint and for the perspective they provide on the history of medicine David M Jameson University of Hawaii Using case studies to reinforce the biochemistry lessons is extremely effective as well as entertaining Joseph P Albanesi UT Southwestern Medical Center Advance Praise for the first edition This textbook provides a modern and integrative perspective of human biochemistry and will be a faithful companion to health science students following curricula in which this discipline is addressed This textbook will be a most useful tool for the teaching community Joan Guinovart Former director of the Institute for Research in Biomedicine Barcelona Spain and former president of the International Union of Biochemistry and Molecular Biology IUBMB *Ices in the Solar-System* Richard Soare, Jean-Pierre Williams, Caitlin Ahrens, Frances Butcher, Mohamed Ramy El-Maarry, 2023-11-20 *Ices in the Solar System* A Volatile Driven Journey from the Inner Solar System to its Far Reaches details the evolution of ice on planetary bodies within the Solar System including terrestrial planets and the Moon Ceres and other dwarf planets or volatile asteroids icy Galilean and Saturnian satellites Triton and disparate Uranian moons and Pluto other Kuyper belt objects and comets The book provides a view of different ice types throughout the Solar System i e H<sub>2</sub>O CO<sub>2</sub> CH<sub>4</sub> etc that characterize icy processes on disparate bodies Ice and icy processes at micro through macro scales are discussed The book geographically spans the major planetary bodies of the Solar System covering surface and subsurface geologies geophysics and geochemistry of ices to answer questions such as the nature and extent of water ice and different frozen volatile species how do ices give us clues to interiors and oceans and more Draws a pan solar system view of various ice species Identifies and addresses outstanding and sometimes puzzling

questions about these ices Describes the dynamic relationships between these ices and the geological history of the planets moons and smaller bodies where they occur Studies these relationships using multiple analytical scales and techniques

An Astrobiology Strategy for the Search for Life in the Universe National Academies of Sciences, Engineering, and Medicine, Division on Engineering and Physical Sciences, Space Studies Board, Committee on Astrobiology Science Strategy for the Search for Life in the Universe, 2019-03-20 Astrobiology is the study of the origin evolution distribution and future of life in the universe It is an inherently interdisciplinary field that encompasses astronomy biology geology heliophysics and planetary science including complementary laboratory activities and field studies conducted in a wide range of terrestrial environments Combining inherent scientific interest and public appeal the search for life in the solar system and beyond provides a scientific rationale for many current and future activities carried out by the National Aeronautics and Space Administration NASA and other national and international agencies and organizations Requested by NASA this study offers a science strategy for astrobiology that outlines key scientific questions identifies the most promising research in the field and indicates the extent to which the mission priorities in existing decadal surveys address the search for life s origin evolution distribution and future in the universe This report makes recommendations for advancing the research obtaining the measurements and realizing NASA s goal to search for signs of life in the universe

**The Space Age Generation** William Sheehan, Klaus R. Brasch, 2024-03-05 In 1957 Sputnik launched toward the stars President Kennedy then announced that the United States would send men to the Moon and then return them to Earth These pivotal moments sparked an unequalled bound forward in human innovation and scientific exploration At the heart of this momentous time were the men and women working behind the scenes Scientists historians and astronomers share their memories and contributions from this unparalleled era in essays told in their own words They are the remarkable generation who witnessed and contributed to some of space science s most stunning achievements Here they have recorded their memories their childhood inspirations their challenges failures and triumphs for future generations A unique and authoritative record of a momentous period in human history The Space Age Generation highlights the golden age of space exploration and the people who made it happen Contributors Leo Aerts Alexander Basilevsky Klaus Brasch Clark R Chapman Dale P Cruikshank William K Hartmann William Leatherbarrow Baerbel Koesters Lucchitta Yvonne Pendleton Peter H Schultz William Sheehan Paolo Tanga Charles A Wood

**Mars** Stephen James O'Meara, 2020-06-15 Mars is a small world with a big reputation This mysterious singular planet with volcanoes that dwarf Mount Everest a canyon system that would stretch fully across the United States and curious landscapes that perhaps once harbored water has fascinated us for centuries In the most up to date account available of the elusive Red Planet Stephen James O'Meara follows our longstanding love affair with this unique celestial body from the musings of humanity s first stargazers to the imaginings of science fiction writers radio broadcasters and filmmakers to the latest images and discoveries from the Curiosity rover The book also reviews plans for piloted missions to Mars and what it

will take for those missions to succeed 01-01-2022, 0000000 0000 00000 0000000 Visions into Voyages for Planetary Science in the Decade 2013-2022 National Academies of Sciences, Engineering, and Medicine, Division on Engineering and Physical Sciences, Space Studies Board, Committee on the Review of Progress Toward Implementing the Decadal Survey Vision and Voyages for Planetary Sciences, 2018-12-30 In spring 2011 the National Academies of Sciences Engineering and Medicine produced a report outlining the next decade in planetary sciences That report titled Vision and Voyages for Planetary Science in the Decade 2013 2022 and popularly referred to as the decadal survey has provided high level prioritization and guidance for NASA s Planetary Science Division Other considerations such as budget realities congressional language in authorization and appropriations bills administration requirements and cross division and cross directorate requirements notably in retiring risk or providing needed information for the human program are also necessary inputs to how NASA develops its planetary science program In 2016 NASA asked the National Academies to undertake a study assessing NASA s progress at meeting the objectives of the decadal survey After the study was underway Congress passed the National Aeronautics and Space Administration Transition Authorization Act of 2017 which called for NASA to engage the National Academies in a review of NASA s Mars Exploration Program NASA and the Academies agreed to incorporate that review into the midterm study That study has produced this report which serves as a midterm assessment and provides guidance on achieving the goals in the remaining years covered by the decadal survey as well as preparing for the next decadal survey currently scheduled to begin in 2020 *Advances in Terrestrial and Extraterrestrial Drilling:* Yoseph Bar-Cohen, Kris Zacny, 2021-08-26 This two volume set includes the latest principles behind the processes of drilling and excavation on Earth and other planets It covers the categories of drills the history of drilling and excavation various drilling techniques and associated issues rock coring acquisition damage control caching and transport restoration of in situ conditions and data interpretation as well as unconsolidated soil drilling and borehole stability It describes the drilling process from basic science and associated process of breaking and penetrating various media and the required hardware and the process of excavation and analysis of the sampled media Mars and the Earthlings: A Realistic View on Mars Exploration and Settlement Cyprien Verseux, Muriel Gargaud, Kirsi Lehto, Michel Viso, 2025-01-17 In an era of public Mars fascination this book offers an objective presentation of the challenges of crewed Mars missions and discusses scenarios of Mars settlements under scientific technical social economic ethical and political aspects With the aim to make the reader comprehend what is plausible and what is at stake the book tries to clarify misconceptions and half truths spreading rapidly in the public The authors argue that approximations and misinformation should be countered for two main reasons First to avoid missing out on the benefits that Mars exploration may bring including major scientific discoveries and an inspiring federative human endeavor Second to remediate dangerous delusions such as the idea that humanity could be transferred there should the Earth become inhabitable in the near term In preparation for this book a group of European world renowned

scientists from fields as diverse as astronomy planetology geology biology philosophy or economics as well as astronauts and science fiction writers was gathered to discuss Mars missions ranging from near term robotic missions all the way to large scale settlements and even the feasibility of terraforming For each they draw arguments from their domains of expertise to discuss what is feasible and what is desirable The result provides researchers with an objective review of the field policy makers with a reference to make informed decisions and the general public with a tool to form educated opinions **Space Robotics** Xiu Tian Yan,Gianfranco Visentin,2024-12-11 This book presents the latest research findings from leading space robotic researchers around the world together with contributions from leading space systems industrialists on the practical aspects of research and development in space robotics The book also considers future challenges and trends to provide a look ahead for space robotics The European Commission set up the Space Robotic Technologies Strategic Research Cluster SRC in its flagship funding programme Horizon 2020 with the goal of enabling major advances in strategic key points of Space Robotics Technologies in order to improve European competitiveness Space robotics have advanced rapidly in recent years as reflected in recent successful space exploration missions like NASA s successful landing and operation of the Curiosity rover on Mars and the European Space Agency s equally successful landing of its Philae probe on comet 67P Churyumov Gerasimenko These advances have inspired many young graduates and undergraduates to study space robotics

**Life in Extreme Environments** Guido di Prisco,Howell G. M. Edwards,Josef Elster,Ad H. L. Huiskes,2020-10-15 A diverse account of how life exists in extreme environments and these systems susceptibility and resilience to climate change

**The Value of Science in Space Exploration** James S. J. Schwartz,2020 In The Value of Science in Space Exploration James S J Schwartz provides a thoughtful and rigorous defense of the view that space exploration activities should focus primarily on science and that the knowledge and understanding we will gain from expanded space science activities will benefit humanity more over the next century than any attempts to settle Mars or mine asteroids **Planetary Astrobiology**

Victoria Meadows,Giada Arney,Britney Schmidt,David J. Des Marais,2020-07-07 Are we alone in the universe How did life arise on our planet How do we search for life beyond Earth These profound questions excite and intrigue broad cross sections of science and society Answering these questions is the province of the emerging strongly interdisciplinary field of astrobiology Life is inextricably tied to the formation chemistry and evolution of its host world and multidisciplinary studies of solar system worlds can provide key insights into processes that govern planetary habitability informing the search for life in our solar system and beyond Planetary Astrobiology brings together current knowledge across astronomy biology geology physics chemistry and related fields and considers the synergies between studies of solar systems and exoplanets to identify the path needed to advance the exploration of these profound questions Planetary Astrobiology represents the combined efforts of more than seventy five international experts consolidated into twenty chapters and provides an accessible interdisciplinary gateway for new students and seasoned researchers who wish to learn more about this expanding field



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The Human Cosmos Jo Marchant,2020-09-03 For most of human history we have had a close relationship with the stars Once they shaped our religious beliefs power structures scientific advances and even our biology But over the last few centuries we have separated ourselves from the universe that surrounds us And it comes at a cost The Human Cosmos is a tour of this history from the Hall of the Bulls in Lascaux to Tahitian sailors navigating by the stars from medieval monks grappling with the nature of time to Einstein realising that space and time are the same It shows we need to rediscover the universe we inhabit its effect on our health and its potential for inspiration and revelation **The Atmosphere and**

**Climate of Mars** Robert M. Haberle,R. Todd Clancy,François Forget,Michael D. Smith,Richard W. Zurek,2017-06-29 This volume reviews all aspects of Mars atmospheric science from the surface to space and from now and into the past

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