Origin and evolution of earth

Science, Geology

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Grand Research Questions in the Solid-Earth Sciences Board on Earth Sciences and Resources Division on Earth and Life Studies Copyright © National Academy of Sciences. All rights reserved. Origin and Evolution of Earth: Research Questions for a Changing Planet http://www. nap. edu/catalog/12161. html The NaTioNal academies Press 500 Fifth street, N. W. Washington, dc 20001 NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance. This study was supported by the National Science Foundation, Award No. EAR-0533650; National Aeronautics and Space Administration, Award No. NNH06CE15B, TO #104; U. S. Department of Energy, Award No. DE-FG02-05ER15664; and U. S. Department of Interior / U. S. Geological Survey, Award No. 05HQGR0138. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the organizations or agencies that provided support for the project. International Standard Book Number-13: 978-0-309-11717-3 (Book) International Standard Book Number-10: 0-309-11717-3 (Book) International Standard Book Number-13: 978-0-309-11718-0 (PDF) International Standard Book Number-10: 0-309-11718-6 (PDF) Library of Congress Catalog Number: 2008929776 Additional copies of this report are available from the National Academies Press, 500 Fifth Street, N. W., Lockbox 285, Washington, DC 20055; (800) 624-6242 or (202) 334-3313 (in the Washington metropolitan area); Internet, http://www. nap. edu. Cover: Selection of scales and disciplines relevant to Earth science. Top: Artist's conception of an emerging solar system around the star Beta Pictoris. Courtesy of Lynette R. Cook and the National Aeronautics and Space Administration. Bottom right: Outcrop of Neoproterozoic (750-800 million years old) platform carbonates (left) and subjacent interbedded carbonaceous shales and stromatolitic carbonates (right) exposed by receding glacier, northeastern Spitsbergen. Courtesy of Andrew Knoll, Harvard University. Bottom middle: A spherical-global view (orthographic projection) of the western hemisphere 105 million years ago. Courtesy of Ronald Blakey, Northern Arizona University. Bottom left: Ground motion intensities for a simulated magnitude 7. 7 earthquake on the San Andreas Fault in the Los Angeles area. Visualization courtesy of Amit Chourasia and Steve Cutchin, San Diego Supercomputer Center, University of California, San Diego, based on data provided by Kim Olsen and colleagues, Southern California Earthquake Center. Back: Repeated images of the crystal structure of stishovite, a mantle mineral that can store water in Earth's interior. Courtesy of Lars Stixrude, University of Michigan. Copyright 2008 by the National Academy of Sciences. All rights reserved. Copyright © National Academy of Sciences. All rights reserved. Origin and Evolution of Earth: Research Questions for a Changing Planet http://www. nap. edu/catalog/12161. html The National academy of sciences is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Ralph J. Cicerone is president of the National Academy of Sciences. 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Origin and Evolution of Earth: Research Questions for a Changing Planet http://www. nap. edu/catalog/12161. html Preface O ver the past four decades, Earth scientists have made great strides in understanding our planet's workings and history. We understand as never before how plate tectonics shapes our planet's surface, how life can be sustained over billions of years, and how geological, biological, atmospheric, and oceanic processes interact to produce climate–and climatic change. Yet at the most basic level, this progress has served principally to lay bare more fundamental questions about Earth. Expanding knowledge is generating new questions, while innovative technologies and new partnerships with other sciences provide new paths toward answers. The Committee on Grand Research Questions in the Solid-Earth Sciences was established at the request of the U. S. Department of Energy, National Aeronautics and Space Administration, National Science Foundation, and U. S. Geological Survey to frame some of the great intellectual challenges inherent in the study of Earth and other planets. Although many reports have identified research priorities in Earth science, few have cast them as compelling, fundamental science questions. Such " big picture" questions may require decades to answer and research support from many agencies and organizations. The answers to these questions could profoundly affect our understanding of the planet on which we live. The committee began by drafting " strawman" questions and publishing them for comment in Eos, Transactions of the American Geophysical Union (Linn, 2006), on the National Academies website, and in electronic newsletters of the American Geological Institute ii and the Association of Women Geoscientists. Written input was also gathered from colleagues. The committee met four times to gather input, discuss community feedback, and write its report. A small committee cannot hope to have all the expertise needed to cover the broad range of topics discussed in this report. Consequently, the committee solicited essays from colleagues. Of particular note were the essays provided by Greg Beroza, Katharine Cashman, and Kevin Zahnle. Other colleagues who devoted many hours helping the committee sort through ideas include Alan Anderson, Richard Bambach, Katherine Freeman, James Kasting, Barbara Romanowicz, Sean Solomon, and Mary Lou Zoback. The committee is deeply appreciative of their contributions. The committee also thanks the many other individuals who provided input or feedback on the questions: Richard Allen, Paul Barton, Steven Benner, David Bercovici, Robert Berner, Robert Blair, Jr., Gudmundur Bodvarsson, Alan Boss, Gabriel Bowen, Susan Brantley, Douglas Burbank, Frank Burke, Kenneth Caldeira, Richard Carlson, John Chambers, Frederick Colwell, Kevin Crowley, Gedeon Dagan, Andrew Davis, William Dickinson, William Dietrich, David Diodato, Bruce Doe, Robert Dott, Jr., Benjamin Edwards, Peter Eichhubl, Michael Ellis, W. Gary Ernst, Douglas Erwin, Rodney Ewing, Fredrick Frey, Arthur Goldstein, Linda Gundersen, David Halpern, Wayne Hamilton, T. Mark Harrison, John Hayes, James Head, Michael Hochella, Jr., Vance Holliday, Richard Iverson, A. Hope Jahren, Raymond Jeanloz, Gerald Joyce, Joseph Kirschvink, John LaBrecque, Thorne Lay, Antonio Lazcano, Copyright © National Academy of Sciences. All rights reserved. Origin and Evolution of Earth: Research Questions for a Changing Planet http://www. nap. edu/catalog/12161. html iii PREFACE Cin-Ty Lee, William Leeman, Jonathan Lunine, Ernest Majer, Michael Manga, Anthony

Mannucci, William McDonough, Dan McKenzie, Marcia McNutt, H. Jay Melosh, Peter Molnar, Isabel Montanez, Alexandra Navrotsky, Shlomo Neuman, Gary Olhoeft, Carolyn Olson, Peter Olson, Minoru Ozima, Nazario Pavoni, Donald Porcelli, Jonathan Price, Steven Pride, George Redden, Paul Renne, Robin Reichlin, Mark Richards, Daniel Schrag, Norman Sleep, D. Kip Solomon, Gerilyn Soreghan, Frank Spear, Gary Sposito, Steven Stanley, Ross Stein, Robert Stern, David Stevenson, Lynn Sykes, Jack Szostak, Thomas Tharp, Leon Thomsen, Oliver Tschauner, Terry Tullis, Greg Valentine, Richard Von Herzen, Joseph Wang, James Whitcomb, Raymond Willemann, M. Gordon Wolman, Nicholas Woodward, Eva Zanzerkia, Xiaobing Zhou, and Herman Zimmerman. Donald J. DePaolo, Chair Copyright © National Academy of Sciences. All rights reserved. Origin and Evolution of Earth: Research Questions for a Changing Planet http://www. nap. edu/catalog/12161. html Acknowledgment of Reviewers T his report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council’s Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their participation in the review of this report: Douglas Erwin, Smithsonian Institution Jonathan Fink, Arizona State University Jeffrey Freymueller, University of Alaska Russel Hemley, Carnegie

Institution of Washington Thomas Jordan, University of Southern California Louise Kellogg, University of California, Davis Rosamond Kinzler, American Museum of Natural History Jay Melosh, University of Arizona Franklin Orr, Stanford University Norman Sleep, Stanford University Steven Stanley, University of Hawaii David Stevenson, California Institute of Technology Robert van der Hilst, Massachusetts Institute of Technology Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations nor did they see the final draft of the report before its release. The review of this report was overseen by Marcia McNutt, Monterey Bay Aquarium Research Institute. Appointed by the National Research Council, she was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution. ix Copyright © National Academy of Sciences. All rights reserved. Origin and Evolution of Earth: Research Questions for a Changing Planet http://www. nap. edu/catalog/12161. html Copyright © National Academy of Sciences. All rights reserved. Origin and Evolution of Earth: Research Questions for a Changing Planet http://www. nap. edu/catalog/12161. html Contents SUMMARY 1 ORIGINS Question 1: How did Earth and other planets form? 7 Question 2: What happened during Earth’s “ dark age" (the first 500 million years)? 18 Question 3: How did life begin? 27 EARTH’S INTERIOR Question 4: How does Earth’s interior work, and how does it affect the surface? 35 Question 5: Why does Earth have plate

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200 years later–after it was established that matter was made of atoms, that atoms had nuclei, and that some of those nuclei were unstable to radioactive decay–was it possible to establish the scale of geological time. The first accurate measurement of Earth's age, 4. 55 billion years, made in the mid-1950s (Patterson, 1956), was a major step in establishing a timescale for Earth, for life, and for the Universe. Until the 1960s, geological science was built almost entirely on the study of rocks and landforms on the continents; little was known about the seafloor. The grand research questions of the early 20th century were heavily influenced by this continent-centric view, as well as by a focus on mineral and water resources and discoveries in paleontology. There were grand questions about how volcanoes, mountain ranges, and sedimentary basins were created; why mineral deposits and petroleum deposits formed where and when they did; how fast mountains were built and eroded away; why fossils first became abundant only 500 million years ago; and what caused ice ages and earthquakes. An additional tantalizing question was why the Atlantic coastlines of South America and Africa looked like they were pieces of a puzzle that might once have been joined together. This seemingly unconnected set of grand questions of the mid-20th century were largely organized and linked by the advent of plate tectonics theory. In just half a decade, between 1963 and 1968, spurred largely by the first observations of the magnetism and depth of the seafloor, a grand picture of the dynamic behavior of the planet emerged. It was deduced that Earth's surface consists of a dozen or so irregular, stiff plates that move a few centimeters per year and that the boundaries of these plates are the locations of earthquakes, volcanoes, and mountain ranges.

The plate movements are connected to a planetwide system of solid-state convection deep within Earth, an idea that was inconceivable to most geologists a decade before. The plate tectonics model, including its corollaries of mantle convection, seafloor spreading, and continental drift, not only explained the pattern of earthquakes, volcanoes, and mountain ranges but also eventually provided possible mechanisms to create the continents and seafloor, to gradually shift Earth's climate over geological time, and to influence the course of biological evolution. Toward the end of this watershed period of the 1960s, the United States landed the first astronauts Copyright © National Academy of Sciences. All rights reserved. Origin and Evolution of Earth: Research Questions for a Changing Planet http://www. nap. edu/catalog/12161. html ORIGIN AND EVOLUTION OF EARTH on the Moon, who brought back rock samples that provided a glimpse of another planetary body much different from Earth. This new perspective ushered in the modern era where Earth is viewed as a planet and its constitution, history, and character are compared to those of other planets. In 1980 another breakthrough came from evidence that Earth was struck by a large meteoroid 65 million years ago and that the impact probably caused the extinction of dinosaurs and many of the other living things on the planet at the time (Alvarez et al., 1980). Within a few years it became evident that some meteorites found on Earth came from Mars (Bogard and Johnson, 1983). These two developments underscored the idea, which had begun with studies of impact craters on Earth and the Moon, that Earth must be viewed in its astronomical context; for example, life could be terminated by uninvited extraterrestrial objects or imported from other Solar System planets! Over the past 20 years the transformation of Earth science has continued. Major advances in technology that allow Earth to be observed much better at both large and small scales, continuing planetary exploration, and advanced computing have all contributed. We can now see into minerals and discern individual atoms, measure the properties of rocks at the immense pressures and temperatures inside Earth, watch continents drift and mountains grow in real time, and understand how organisms evolve and interact with Earth based on their DNA. We have also been able to extract new information from meteorites that tells us about how planets form and even about how the interiors of stars work. Armed with new tools, Earth science is turning to the deeper fundamental questions–the origin of Earth; the origin of life; the structure and dynamics of planets; the connections between life, climate, and Earth's interior; and what the Earth may hold for humankind in the future. SCOPE AND PURPOSE OF THIS REPORT At the request of the U. S. Department of Energy, the National Science Foundation, the U. S. Geological Survey, and the National Aeronautics and Space Administration, the National Academies established a committee to propose and explore grand Earth science questions being pursued today. The charge to the com- mittee, given below, provided unusual freedom in the selection of topics, without regard to agency-specific issues, such as mission relevance and implementation. The committee will formulate a short list of grand research questions driving progress in the solid-Earth sciences. The research questions will cover a variety of spatial scales and temporal scales, from subatomic to planetary and from the past (billions of years) to the present and beyond. The questions will be written in a clear, compelling way and will be supported by text and figures that summarize progress to date and outline future challenges. This report will not discuss implementation issues (e. g., facilities, recommendations aimed at specific agencies) or disciplinary interests. Our response to this charge has been to attempt to capture the scope and aspirations of what might best be referred to as geological and planetary science, which is another way of saying solid-Earth science. Research in this area draws on nearly every scientific discipline. However, research questions that are mainly the domain of other subdisciplines of Earth science–such as ocean, atmospheric, or space science–are discussed to the extent they are linked to solid-Earth science. The committee began by developing criteria for what constitutes a “ grand" question. Our definition of grand questions was partly determined by the small number requested in the charge, which led us to aim for 7 to 10 questions, and partly by a desire for the questions to meet at least two of the following criteria: - it transcends the boundaries of a narrow subfield of geological and planetary science; - it deals with eternal issues, such as the origins of Earth and life; - it is connected with phenomena that have significant impact on human well-being. Our ultimate objective was to capture in this series of questions the essential scientific issues that constitute the frontier of Earth science at the start of the 21st century. It is our hope that these questions and our descriptions of them are as compelling as we believe the science to be and that this short report is useful to those who would like to understand more about where Earth science stands, how it got there, and where it might be headed. We have attempted to make the text accessible to managers of scientific programs, graduate students, and colleagues in sister disciplines who have Copyright © National Academy of Sciences. All rights reserved. Origin and Evolution of Earth: Research Questions for a Changing Planet http://www. nap. edu/catalog/12161. html SUMMARY the technical or scientific background needed to comprehend what is discussed. Our most difficult problem in selecting the grand questions was to distill from a large number of topics and questions the “ most worthy" candidates. To do so the committee canvassed the broad geological community and deliberated in meetings and telephone conferences. After arriving at 10 grand questions, the committee set about writing, as well as soliciting written contributions from other scientists. Some of our questions present truly awesome challenges and may not be fully understood for decades, if ever. Others seem more tractable, and significant progress may be made in a matter of years. Overall, we have included most of what the committee regards as the important issues and also most of what was suggested by the respondents to our canvassing effort. There was, in fact, a fair degree of consensus about what constitutes a grand question and which ones should be included here. GRAND RESEARCH QUESTIONS FOR THE 21ST CENTURY Although we started by simply identifying the overarching questions we believe to be driving modern Earth science, we found that these questions can be grouped into four broad themes. These themes constitute the four chapters of the report, and within each chapter are descriptions of the grand questions. Chapter 1 deals with origins–the origin of Earth and other Solar System planets, Earth’s earliest history, and the origin of life. Chapter 2 treats the workings of Earth’s interior and its surface manifestations and includes a question on material properties and their fundamental role in Earth processes. Chapter 3 addresses the habitability of the surface environment–climate and climate change and Earth—life interactions. Chapter 4 focuses on geologica10 hazards and Earth resources–earthquakes and volcanoes and modern environmental issues associated with water and other fluids in and on Earth. The following is a summary of the 10 grand research questions identified by the committee: 1. how did earth and other planets form? The Solar System, with its tantalizing geometric patterns and its wide variety of planets and moons, presents intriguing questions that become more nuanced as we make new observations from spacecraft and more exacting measurements on meteorites. While it is generally agreed that the Sun and planets all coalesced out of the same nebular cloud, it is still not known how Earth obtained its particular chemical composition, at least not in enough detail to understand its subsequent evolution or why the other planets ended up so different from ours and from each other. Earth, for example, has retained a life-giving inventory of volatile substances, including water, but Earth is far different from every other planet in this regard. Advanced computing capabilities are enabling development of more credible models of the early Solar System, but further measurements of other Solar System bodies and extrasolar planets and objects appear to be the primary pathway to furthering our understanding of the origin of Earth and the Solar System. 2. What happened during earth’s “ dark age" (the first 500 million years)? It is now believed that in the later stages of Earth’s formation, a Mars-sized planet collided with it, displacing a huge cloud of debris that became our Moon. This collision added so much heat to Earth that the entire planet melted. Little is known about how this magma soup differentiated into the core, mantle, and lithosphere of today or how Earth developed its atmosphere and oceans. The so-called Hadean Eon is a critical link in our understanding of planetary evolution, but we have little information about it because there are almost no rocks of this age preserved on Earth. Clues about this time period are accumulating, however, as we learn more about meteorites and other planets and extract new information from ancient crystals of zircon on Earth. 3. how did life begin? The origin of life is one of the most intriguing, difficult, and enduring questions in science. Because life in the Solar System arose billions of years ago, some of the most fundamental questions about its origin are geological. Our knowledge of the materials from which life originated, and where, when, and in what form it first appeared, stems from geological investigations of rocks and minerals that represent the only remaining evidence. When life first arose, the conditions at Earth's surface may have been much different than today's, and one critical challenge is to de- Copyright © National Academy of Sciences. All rights reserved. Origin and Evolution of Earth: Research Questions for a Changing Planet http://www. nap. edu/catalog/12161. html ORIGIN AND EVOLUTION OF EARTH velop an accurate picture of the physical environments and the chemical building blocks available to early life. The quest to establish the origin of life is inherently multidisciplinary, spanning organic chemistry, molecular biology, astronomy, and planetary science, as well as geology and geochemistry. There is growing interest in studying Mars, where there is a sedimentary record of early planetary history that predates the oldest Earth rocks and other star systems where planets have been detected. 4. how does earth's interior work, and how does it affect the surface? As planets age, they gradually cool, and this causes them to move through stages where their internal processes, their atmospheres, and their surface processes are gradually changing. The primary means by which heat is moved from the interior to the surface is planetwide solid-state and liquid convection. Although we know that the mantle and core are in constant convective motion, we can neither precisely describe these motions today nor calculate with confidence how they were different in the past. Core convection produces Earth’s magnetic field, which may have had an important influence on surface conditions. Mantle convection is the cause of volcanism, seafloor generation, and mountain building, and materials like water and carbon are constantly exchanged between Earth’s surface and its deep interior. Consequently, without detailed knowledge of Earth’s internal processes we cannot deduce what Earth’s surface environment was like in the past or predict what it will be in the future. 5. Why does earth have plate tectonics and continents? The questions regarding plate tectonics now have less to do with the soundness of the theory than with why Earth has plate tectonics in the first place and how closely it is related to other unique aspects of Earth–the abundant water, the existence of continents and oceans, and the existence of life. We do not know whether it is possible to have one aspect without the others or how they are interdependent. The existence and persistence of continental crust present problems as fundamental as those of plate tectonics. Continental crust makes the planet habitable by nonmarine life, and weathering of its surface plays a role in regulating Earth’s climate. But we still do not know when continents first formed, how they are preserved for billions of years, or exactly how they evolved to be what they are like today. New data and observations indicate that climate and erosion play a fundamental role in building and shaping mountain ranges and thus are fundamental to the formation as well as the destruction of continental crust. 6. how are earth processes controlled by material properties? Deciphering the secrets of the rock record on Earth and other planets begins with the understanding of large-scale geological processes. The keys to understanding these processes are the basic physics and chemistry of planetary materials. The high pressures and temperatures of Earth's interior, the enormous size of Earth and its structures, the long expanse of geological time, and the vast diversity of materials and properties all present special challenges. These challenges are being met with new research tools based on synchrotron radiation, new measurements and simulation capabilities for large domains and heterogeneous materials, and quantum mechanics-based calculations of material properties under extreme conditions. New research areas are developing around the study of natural nanoparticles and the mediation of chemical processes by microorganisms. 7. What causes climate to change–and how much can it change? Global climate conditions have been favorable and stable for the past 10, 000 years, but we also know from geological evidence that momentous changes in climate can occur in periods as short as decades or centuries. Yet despite the numerous factors that can change climate, from the slowly changing luminosity of the Sun to the building of new mountain ranges and changes in atmospheric composition, Earth's surface temperature seems to have remained within relatively narrow limits for most of the past 4 billion years. How does it remain well regulated in the long run, even though it can change so abruptly? Recent discoveries have highlighted periods of Earth history when the climate was extremely cold, was extremely hot, or changed especially quickly. Understanding these special conditions may lead to new insights about Earth's climate, as will new geochemical observa- Copyright © National Academy of Sciences. All rights reserved. Origin and Evolution of Earth: Research Questions for a Changing Planet http://www. nap. edu/catalog/12161. html SUMMARY tions made on ancient sedimentary rocks and improved models for the climate system that will eventually enable us to predict the magnitude and consequences of climate changes. 8. how has life shaped earth–and how has earth shaped life? Earth scientists have a tendency to view Earth's geological evolution as a fundamentally inorganic process. Life scientists, in the same spirit, tend to regard the evolution of life as a fundamentally biological issue. Yet the development of life has clearly been influenced by the conditions of Earth's surface, while Earth's surface has been influenced by the activities of life forms. The atmosphere would not contain oxygen if it were not for life, and the presence of oxygen has enabled other types of life to evolve. We know that geological events and meteoroid impacts have caused massive extinctions in the past and influenced the course of evolution. But the exact ties between geology and evolution are still elusive. On the modern Earth we are interested in the role of life in geological processes like weathering and erosion. And we seek to understand how life may have manifested itself and left traces preserved in the geological records of other planets. 9. can earthquakes, volcanic eruptions, and their consequences be predicted? Thanks largely to sensitive new instrumentation and better understanding of causes, geologists are moving toward predictive capabilities for volcanic eruptions. For earthquakes, progress has been made in long-term forecasts, but we may never be able to predict the exact time and place an earthquake will strike. Continuing challenges are to deepen our understanding of how fault ruptures start and stop, to improve our simulations of how much shaking can be expected near large earthquakes, and to increase the warning time once a dangerous earthquake begins. Studies of volcanic activity have entered a new era as a result of real-time seismic, geodetic, and electromagnetic probes of active subsurface processes. But it remains a challenge to integrate such real-time data with field studies of volcanoes and laboratory studies of volcanic materials. The ultimate objective is to develop a clear picture of the movement of magma, from its sources in the upper mantle to Earth's crust, where it is temporarily stored, and ultimately to the surface where it erupts. 10. how do fluid flow and transport affect the human environment? Good management of natural resources and the environment requires knowledge of the behavior of fluids, both below ground and at the surface. The major scientific objectives are to understand how fluids flow, how they transport materials and heat, and how they interact with and modify their surroundings. New experimental tools and field measurement techniques, plus airborne and spaceborne measurements, are offering an unprecedented view of processes that affect both the surface and the subsurface. But we still have difficulty determining how subsurface fluids are distributed in heterogeneous rock and soil formations, how fast they flow, how effectively they transport dissolved and suspended materials, and how they are affected by chemical and thermal exchange with the host formations. Much better models of streamflow and associated erosion and transport are needed if we are to accurately assess how human impacts and climate change affect landscape evolution and how these effects can be managed to sustain ecosystems and important watershed characteristics. The ultimate objective–to produce mathematical models that can predict the performance of natural systems far into the future–is still out of reach but critical to making informed decisions about the future of the land and resources that support us. Copyright © National Academy of Sciences. All rights reserved. Origin and Evolution of Earth: Research Questions for a Changing Planet http://www. nap. edu/catalog/12161. html Copyright © National Academy of Sciences. All rights reserved. Origin and Evolution of Earth: Research Questions for a Changing Planet http://www. nap. edu/catalog/12161. html 1 Origins T he modern study of Earth is ultimately rooted in humankind’s desire to understand its origins. Although it was once assumed that intelligent life was unique to Earth, we have now gained an appreciation that even though it may not be unique, the existence of advanced life on planets may well be uncommon. None of the other planets of the Solar System are presently suitable for the complex life forms that exist on Earth, and we have yet to identify other stars that have planets much like Earth. Although the odds are good that there is other life in our galaxy, this inference has not been confirmed. Considering the apparent rarity of Earth-like life, it is natural to want to understand what went into making Earth suitable for life and how life arose. Pursuing these questions leads us to fundamental issues about how stars and planets form and evolve and to questions about how the modern Earth works, from the innermost core to the atmosphere, oceans, and land surface. This chapter presents three questions related specifically to origins–one regarding the origin of Earth and other planets and one regarding the origin of life. These two questions are separated by a third that deals with Earth's earliest history: the 500 million to 700 million years between the time of the origin of the Solar System and the oldest significant rock record preserved on Earth. During this early, still poorly understood, stage of Earth's development, tremendous changes must have taken place, accompanied by myriad catastrophic events, all leading ultimately to a setting in which life could develop and eventually thrive. QUESTION 1: HOW DID EARTH AND OTHER PLANETS FORM? One of the most challenging and relevant questions about Earth's formation is why our planet is the only one in the Solar System with abundant liquid water at its surface and abundant carbon in forms that can be used to make organic matter. This question is part of a broader set: why the inner planets are rocky and the outer planets are gaseous; how the growth and orbital evolution of the outer planets influenced the inner Solar System; why all of the largest planets are so different from one another; and how typical our Solar System is within the Milky Way galaxy. Although these questions are longstanding, the answers are only now emerging from new insights provided by astronomy, isotopic chemistry, Solar System exploration, and advanced computing. And although we know in general how to make a planet like Earth–starting with some stardust and allowing gravity, radiation, and thermodynamics to do their parts–our answers often serve only to refine our questions. For example, the details of Earth's chemical composition–such as how much of the heatproducing elements uranium, thorium, and potassium it contains; how much oxygen and carbon it contains; and how it came to have its particular allotment of noble gases and other minor constituents–turn out to be critical to models of Earth's geological processes and, ultimately, to understanding why Earth has remained suitable for life over most of its history. Copyright © National Academy of Sciences. All rights reserved. Origin and Evolution of Earth: Research Questions for a Changing Planet http://www. nap. edu/catalog/12161. html ORIGIN AND EVOLUTION OF EARTH how do Planets Form around stars? We do not know how unique or unusual the Solar System is, but observations of other planetary systems are providing new ideas for how planets form and evolve. Astronomical observations of star-forming regions and young stars, together with hydrodynamic models of star formation, support the conclusion that stars–including the Sun–form by the gravitational collapse of a molecular cloud core composed of materials manufactured and reprocessed in many earlier generations of stars. Because the typical molecular cloud is rotating at the time of collapse, the developing star is surrounded by a rotating disk of gas and dust. Most disks around young stars, as viewed through telescopes, are approximately 99 percent gas and 1 percent dust, but even that small proportion of dust makes the disks opaque at visible wavelengths (Figures 1. 1 and 1. 2). Gas-giant planets, such as Jupiter and Saturn in our system, are believed to form in such circumstellar disks, but direct astronomical observations of planets forming have not yet been made. Observations of planets around other nearby stars with masses similar to the Sun indicate that planet formation is a common outcome of star formation, but no star has yet been observed with a system of planets that looks anything like the Solar System. Over 200 extrasolar planets have been discovered by several indirect techniques (e. g., radial velocity of the host star, stellar transit, and microlensing) (Butler et al., 2006;). Multiple planets are known to orbit some two dozen stars. The vast majority of these FIGURE 1. 1 Hubble Space Telescope images of four protoplanetary disks around young stars in the Orion nebula, located 1, 500 light-years from the Sun. The red glow in the center of each disk is a newly formed star approximately 1 million years old. The stars range in mass from 0. 3 to 1. 5 solar masses. Each image is of a region about 2. 6 Ã— 1011 km (400 AU) across and is a composite of three images taken in 1995 with Hubble's Wide Field and Planetary Camera 2 (WFPC2), through narrow-band filters that admit the light of emission lines of ionized oxygen (represented by blue), hydrogen (green), and nitrogen (red). SOURCE: Mark McCaughrean, Max Planck Institute for Astronomy; C. Robert O'Dell, Rice University; and the National Aeronautics and Space Administration, . FIGURE 1. 2 Hubble Space Telescope WFPC2 image of Herbig-Haro 30, a prototype of a young (approximately 1million-year-old) star surrounded by a thin, dark disk and emitting powerful bipolar jets of gas. The disk extends about 6 Ã— 1010 km from left to right in the image, dividing the edge-on nebula in two. The central star is hidden from direct view, but its light reflects off the upper and lower surfaces of the flared disk to produce the pair of reddish nebulae. The gas jets, shown in green, are driven by accretion. SOURCE: Chris Burrows, Space Telescope Science Institute; John Krist, Space Telescope Science Institute; Kare Stapelfeldt, Jet Propulsion Laboratory; and colleagues; the WFPC2 Science Team; and the National Aeronautics and Space

Administration, . Copyright © National Academy of Sciences. All rights reserved. Origin and Evolution of Earth: Research Questions for a Changing Planet http://www. nap. edu/catalog/12161. html ORIGINS 215 Planets 0. 8 Orbital Eccentricity Msin i < 15 M JUP 0. 6 0. 4 0. 2 0. 0 0. 1 Earth for why they form so close to the star (Butler et al., 2006). These hot Jupiters are thought to be telling us that large planets can drift inward toward their star as they form. Models also suggest that planets can under some circumstances drift away from the star, so the ultimate location of the planets may have little to do with where they originally formed. Extrasolar planets more than a few tenths of an AU distant from their host star often have quite eccentric orbits, which contrasts with the Solar System where all of the planets except Mercury have nearly circular orbits. how did the solar system Planets Form? The Solar System is composed of radically different types of planets. The outer planets (Jupiter, Saturn, Uranus, and Neptune) are distinguished from the inner planets by their large size and low density. The outer planets are the primary products of the planet formation process and comprise almost all of the mass held in the planetary system. They are also the types of planet that are most easily recognized orbiting other stars. The inner planets (Mercury, Venus, Earth, and Mars) are composed mostly of rock and metal, with only minor amounts of gaseous material. There are " standard models" for the formation of both types of planets, but they have serious deficiencies and large uncertainties. According to the standard model for outer-planet formation, the formation of giant planets starts with condensation and coalescence of rocky and icy material to form objects several times as massive as Earth. These solid bodies then attract and accumulate gas from the circumstellar disk (Pollack et al., 1996). The two largest outer planets, Jupiter and Saturn, seem to fit this model reasonably well, as they consist primarily of hydrogen and helium in roughly solar proportions, but they also include several Earth masses of heavier elements in greater than solar proportions, probably residing in a dense central core. Uranus and Neptune, however, have much lower abundances of hydrogen and helium than Jupiter and Saturn and have densities and atmospheric compositions consistent with a significant component of outer Solar System ices. An alternative to the standard model is that the rock and ice balls are not needed to induce the formation of gas-giant planets; they can form directly from the gas and dust in the disk, which can collapse under 1. 0 Semimajor Axis (AU) Figure 1. 3. eps FIGURE 1. 3 Summary of known extrasolar planets sorted by distance from host star and orbital eccentricity. All of the planets in the Solar System have eccentricities of 0. 2 or less. SOURCE: Courtesy of Geoffrey Marcy, University of California, Berkeley. Used with permission. planets are thought to be gas giants on the basis of their masses and densities. Presumably, more gas giants are observed because they are large, and large planets are much easier to detect, leaving open the question of how many terrestrial planets remain hidden from Earth in distant planetary systems. A few “ super-Earths, " with masses of several to 10 Earth masses, may be terrestrial planets, but no measurements of the radius or density of these objects has confirmed this. Gas-giant planets appear to be more likely with stars that have proportions of heavier elements (heavier than H, He, and Li) as high as the Sun (Fischer and Valenti, 2005), suggesting that heavy-element concentrations in the circumstellar disk influence the rate or efficiency of planet formation. Measurements of the masses, orbital distances, and orbital eccentricities (Figure 1. 3) of extrasolar planets provide clues about processes that may help determine what the final planetary system looks like. A particularly interesting class of planets, that of gas-giant planets in orbits extremely close to (less than 0. 1 AU)1 their host stars–sometimes called " hot Jupiters"–are significant because models have been unable to account astronomical unit, or AU, is a unit of length nearly equal to the semimajor axis of Earth's orbit around the Sun, or about 150 million km. 1The Copyright © National Academy of Sciences. All rights reserved. Origin and Evolution of Earth: Research Questions for a Changing Planet http://www. nap. edu/catalog/12161. html 0 ORIGIN AND EVOLUTION OF EARTH its own gravity like miniversions of the Sun (Boss, 2002). In this model the excess abundances of heavy elements in Jupiter and Saturn would have been acquired later by capture of smaller rocky and icy bodies. This model, however, does not account well for the compositions of Uranus and Neptune, which do not have very much gas. Other important questions about the outer planets are when they formed and the extent to which they may have drifted inward or outward from the Sun during and after formation. Where the outer planets were and when is important for understanding how the inner planets formed. The primary difference between the inner and outer planets (rock versus gas and ice) is thought to reflect the temperature gradient in the solar nebula. Temperatures were relatively high (> 1000 K) near the developing Sun, dropping steadily with distance. Near the Sun, mainly silicates and metal would have condensed from the gas (so-called refractory materials), whereas beyond the asteroid belt, temperatures were low enough for ices (i. e., water, methane, ammonia) containing more volatile elements to have condensed, as well as solid silicates. It was once thought that as the nebula cooled, solids formed in a simple unidirectional process of condensation. We now know that solids typically were remelted, reevaporated, and recondensed repeatedly as materials were circulated through different temperature regimes and variously affected by nebular shock waves and collisions between solid objects. Important details of the temperatures of the solar nebula, however, are still uncertain, including such significant issues as peak temperatures, how long they were maintained, and how temperature varied with distance from the Sun and from the midplane of the disk. Defining these conditions is an important part of understanding how the chemical compositions of the planets and meteorites came to be. The standard model for the formation of the inner planets is somewhat more complicated than the model for outer-planet formation and is based largely on theory and anchored in information from meteorites and observations of disks around other stars (Chambers, 2003). The model strives to explain how a dispersed molecular cloud with a small amount of dust could evolve into solid planets with virtually no intervening gas and how the original mix of chemical elements in the molecular cloud was modified during that evolution. Significant unknowns are how long the process took, how solid materials were able to coagulate into progressively larger bodies, and how and when the residual gas was dissipated. The time for centimetersized solid objects to form at Earth's distance from the Sun, according to the standard model, might have been as short as 10, 000 years. These small solid objects were highly mobile, pulled

Sun-ward large distances by the Sun's gravity as a result of drag from the still-present H-He gas. Submeter-sized objects were also strongly affected by turbulence in the gas. A particular deficiency of the standard model is its inability to describe the formation of kilometer-sized bodies from smaller fragments. The current best guess is that the dust grains aggregated slowly at first, and growth accelerated along with object size as small objects were embedded into larger ones (Weidenschilling, 1997). The aggregation behavior of objects greater than a kilometer in size is better understood: they are less affected by the presence of gas than are smaller pieces, and their subsequent evolution is governed by mutual gravitational attractions. Growth of still larger bodies, or planetesimals, from these kilometer-sized pieces should have been more rapid, especially at first. Gravitational interactions gave the largest planetesimals nearly circular and coplanar orbits–the most favorable conditions for sweeping up smaller objects. This led to runaway growth and formation of Moon- to Marssized planetary embryos. Growth would have slowed when the supply of small planetesimals was depleted and the embryos evolved onto inclined, elliptical orbits. Dynamical simulations based on statistical methods and specialized computer codes are finding that a number of closely spaced planetary embryos are likely to have formed about 100, 000 years after planetesimals appeared in large numbers (e. g., Chambers, 2003). The later stages of planet formation took much longer, involved progressively fewer objects, and hence are less predictable (Figure 1. 4). The main phase of terrestrial planet formation probably took a few tens of millions of years (Chambers, 2004). The final stages were marked by the occasional collision and merger of planetary embryos, which continued until the orbits of the resulting planets separated sufficiently to be protected from additional major collisions. Although there are four terrestrial planets, models suggest that the number could easily have been three Copyright © National Academy of Sciences. All rights reserved. Origin and Evolution of Earth: Research Questions for a Changing Planet http://www. nap. edu/catalog/12161. html ORIGINS Simulation 1 2 3 4 FIGURE 1. 4 Results of four representative numerical simulations of the final stage of accretion of the terrestrial planets. The segments in each pie show the fraction of material originating from the four regions of the solar nebula shown by the shades of gray, and the size of the pie is proportional to the volume of each planet. In each simulation the largest planet has a size similar to Earth's, but there can be either two or three other planets, and the sizes vary. The planets typically receive material from all four zones, with preference for the zones closest to their final orbit location. SOURCE: Chambers (2004). Copyright 2004 by Elsevier Science and Technology Journals. Reprinted with permission. or five, and they would have been at different disFigure 1. 4. eps tances from the Sun (Figure 1. 4). Tidal interactions with nebular gas may have caused early-formed inner planets to migrate inward substantially while they were forming, and several planets may have been lost into the Sun before the gas dispersed (McNeil et al., 2005). The fact that there are no rocky planets beyond Mars is likely a consequence of the presence of the giant planets, particularly Jupiter. The large mass and strong gravitational pull of Jupiter probably prevented the formation of additional rocky planets in the region now occupied by the asteroid belt by disrupting the orbits of bodies in that region before they could form a large planet. Jupiter and Saturn also sent objects from the asteroid belt either out of the Solar System or spiraling into the inner-planet region where they became parts of the planets forming there or fell into the Sun. The asteroids represent the 0. 01 percent of material that survived this process. What do meteorites say about the origin of earth? Earth has undergone so much geological change that we find little evidence in rocks about its origin or even its early development (Question 2). Many meteorites, on the other hand, were not affected by the high-temperature processing that occurs in planetary interiors. They are fragments of, or soil samples from, miniplanets that formed in what is now the asteroid belt just as the Solar System was starting out. Thus, they preserve significant clues about the state of the Solar System when the planets were forming (Figure 1. 5). For this reason, studies of meteorites play a major role in helping us understand Earth's origin. One gift of meteorites is to reveal the age of the Solar System. Precise radiometric dating of hightemperature inclusions within meteorites shows that the first solid objects in our home system formed 4, 567 million years ago (see Box 1. 1). We also know that shortly thereafter planetesimals of rock and metal formed and developed iron-rich cores and rocky crusts (see Question 2). Some meteorites are chemically like the Sun (for elements other than H, He, Li, C, N, O, and noble gases), and some of these same meteorites contain tiny mineral grains of dust that survived from earlier generations of stars (see Box 1. 2). Other meteorites are parts of small planetary bodies that experienced early volcanism and that were later broken up by collisions. Beyond these clues, meteorites fall short of providing all the information needed to understand Earth, partly because most of them formed far from the Sun (the main asteroid belt is between Mars and Jupiter), and the relationship between meteorites and planets is not fully understood. The systematic collection of well-preserved samples from Antarctica has greatly expanded the number of meteorites available for study and has yielded rarities such as meteorites from Mars and the Moon. Beyond what they tell us about Earth, meteorites Copyright © National Academy of Sciences. All rights reserved. Origin and Evolution of Earth: Research Questions for a Changing Planet http://www. nap. edu/catalog/12161. html ORIGIN AND EVOLUTION OF EARTH FIGURE 1. 5 The Allende meteorite, a carbonaceous chondrite, is a mixture of CAIs (calcium-, aluminum-rich inclusions; larger irregularly shaped light-colored objects) and chondrules (round light-colored objects) in a dark-colored matrix of minerals and compounds. The CAIs and chondrules are a high-temperature component that formed and were in some cases reprocessed at temperatures above 1000°C. SOURCE: Hawaii Institute of Geophysics and Planetology. Used with permission. provide a benchmark for understanding the composition of the Sun and even the Universe as a whole. Most of the visible mass of the Universe, and almost all stars, is composed primarily of hydrogen and helium made during the Big Bang. The rest of the elements–the “ heavier" ones with more protons and neutrons in their nuclei–were produced by nucleosynthesis, or thermonuclear reactions within stars. Most nucleosynthesis happens in big stars. These massive stars last only about 10 million to 20 million years before they explode as supernovae. The new elements they make, before and during the explosion, are thrown back into space where they are later recycled into new stars. In the approximately 10 billion years between the origin of the Universe and the origin of the Solar System, hundreds of generations of massive stars have exploded, and over this long period about 1 percent (by weight) of the original H and He has been converted to heavier elements. Meteorites give us the most detailed information about the abundances of these heavier elements. Meteorites tell us still more about the formation of the Solar System out of the nebular disk. The abundance of heavy elements in the Sun is known moderately well from spectroscopic data. The planets, however, formed from the nebular disk, so it is important to know whether the disk had the same composition as the Sun, and whether it was homogeneous or varied significantly in composition, perhaps with radial distance from the proto-Sun. The standard model for the composition of the solar nebula is based on studies of a class of meteorites called chondrites (Figure 1. 5). Chondrites, the commonest type of meteorites, are stony bodies formed from the accretion of dust and small grains that were present in the early Solar System. They are often used as reference points for chemicals present in the original solar nebula. The most primitive of these objects–those least altered by heat and pressure–are carbonaceous chondrites, whose chemical compositions match that of the Sun for most elements. The relative amounts of elements and their isotopes can be measured much more precisely on meteoritic materials than by solar spectroscopy, so chondritic meteorites play a special role in helping to understand both Earth and nucleosynthesis in our galaxy. Because chondritic elemental abundances look similar to those of the Sun, the disk likely had about the same composition as the Sun. What is the chemical composition of earth? The most critical question related to the formation of Earth is why the planet has its particular chemical makeup. Although we know quite a lot about this issue, a key unanswered question is the origin of Earth's water. Earth, like other objects forming near the Sun, is thought to have formed mainly as a relatively hightemperature partial condensate from a gas of solar composition. The uncondensed gas containing water, carbon, and other volatile elements was swept away by the early solar wind or by ultraviolet radiation pressure. Much of the volatile elements that might have been incorporated into the early Earth is thought to have been lost during the intense heating of the Hadean Eon (Question 2). It has been suggested that the giant pl