Exploring Space, Exploring Earth

Paul Lowman, a NASA scientist for over 40 years, describes the impact of space flight on geology and geophysics. A foreword by Neil Armstrong emphasizes that the exploration of space has led us to a far deeper understanding of our own planet. Direct results from Earth-orbital missions include studies of Earth's gravity and magnetic fields. In contrast, the recognition of the economic and biological significance of impact craters on Earth is an indirect consequence of the study of the geology of other planets. The final chapter presents a new theory for the tectonic evolution of the Earth based on comparative planetology and the Gaia concept. Extensive illustrations, a glossary of technical terms, and a comprehensive bibliography provide geologists and geophysicists with a valuable summary of research. The book will also serve as a supplementary text for students of tectonics, remote sensing and planetary science.

PAUL LOWMAN has been involved in a wide range of space research programs at the Goddard Space Flight Center. In 1963–4 he took part in planning for the *Apollo* missions. He was Principal Investigator for Synoptic Terrain Photography on the *Mercury*, *Gemini*, and *Apollo* Earth-orbital missions, an experiment that laid the foundation for *Landsat*. Between 1965 and 1970 he taught lunar geology at the University of California, Catholic University of America, and the Air Force Institute of Technology. Dr Lowman was also involved with the *Mariner 9* Mars mission, the *Apollo* X-ray fluorescence experiment and *Apollo 11* and *12* sample analysis among others. His main research interest was and still is the origin of the continental crust, as approached through comparative planetology.

In 1974, Dr Lowman received the Lindsay Award from the Goddard Space Flight Center. He was elected a Fellow of the Geological Society of America in 1975, and of the Geological Society of Canada in 1988. Drawing on his dual career in terrestrial and lunar geology, he authored *Space Panorama* (1968), *Lunar Panorama* (1970), and *The Third Planet* (1972). He also contributed to *Mission to Earth* (1976), the first NASA compilation of *Landsat* pictures, edited by N. M. Short.

Exploring Space, Exploring Earth

New Understanding of the Earth from Space Research

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Foreword by Neil A. Armstrong

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To John A. O'Keefe
Founder of Space Geodesy

CONTENTS

FOREWORD

In the works of Homer, the Earth was portrayed as a circular disc floating on a vast sea and covered with a sky built from a hemispherical bowl. Critics soon noticed a flaw in this concept: the visible star field varied from place to place. From Greece, the Big Dipper was visible throughout its circle around the North Star, but southward along the Nile, it dipped below the horizon. Clearly, the surface of the Earth was somehow curved. Some thought the Earth was like the surface of a cylinder, curving to the north and south, but stretching in a straight line to the east and west. A student of Socrates, Parmenides, reasoned that the Earth must be a sphere, because any other shape would fall inward on itself. Plato also concluded that the Earth must be a sphere because a sphere was the most perfect shape for a solid body. Whether persuaded by the logic of Parmenides, or by loyalty to Plato, the Greeks came to accept a spherical Earth. A final argument, the most persuasive, was recorded by Aristotle. He noted that during an eclipse of the Moon, when the Earth's shadow fell on the surface of the Moon, the shadow was curved. The shape of the Earth would not be truly known, however, until the philosophers were replaced by the measurers.

In that category, one name stands above all others: Eratosthenes of Cyrene. To characterize him simply as a "measurer" would not do him justice; Eratosthenes was a Renaissance man long before the Renaissance. But we focus on his measuring. He determined the inclination of the ecliptic with an error of only one-half a degree. His most memorable measurement was the difference in latitude from Syene to Alexandria. By comparing the shadow lengths at noon on the summer solstice for the two locations, he calculated that they were separated by 7.5 degrees. Knowing the distance between the two cities, he calculated the circumference of the Earth to an accuracy of 99%. Eratosthenes further collected the observations of travelers, explorers, and sailors from throughout the known world –

a very small world by today's standards – and integrated that knowledge in his *Geographica*.

Understanding of the Earth grew slowly after this Golden Age. It was not until the invention of the caravel in the 15th century, and John Harrison's chronometer in the 18th century, that man's understanding of his planet began again to grow. With ships capable of long ocean voyages, precisely navigated in latitude and longitude, maps of the oceans, continents, and islands became increasingly comprehensive and reliable.

Despite this great increase in knowledge, our planet remained in many ways almost as mysterious as it had been in Homer's time. The forces causing volcanic eruptions, earthquakes, and hurricanes remained enigmatic. The interior of the Earth, the topography of the ocean floor, and the dynamic nature of the atmosphere, the ocean currents, and the global magnetic field eluded understanding well into the 20th century. Two world wars stimulated impressive improvements in instruments and methods.

The late 20th century also brought new caravels, ships that could sail the oceans of space. The fortuitous development of the liquid-fueled rocket and, at about the same time, the digital computer made flight through space a reality. Space was the new high ground, the place for a new perspective, from which the "measurers" could acquire information never before available. In just a few decades, knowledge of the Earth's secrets has increased beyond imagining.

Exploring Space, Exploring Earth describes this increase in knowledge of the solid earth – geology and geophysics. Paul Lowman is a geologist who has been involved in space research since 1959 at Goddard Space Flight Center, which has taken a leading part in space geodesy, remote sensing, lunar geology, and satellite meteorology and oceanography. He is thus one of the new "measurers" and summarizes their accomplishments since the launch of *Sputnik 1* in 1957. The book is dedicated to John O'Keefe, who in the tradition of Parmenides and Eratosthenes made a fundamental discovery about the shape of the Earth from the orbit of only the second American satellite launched, *Vanguard 1*, in 1959.

The 20th century brought remarkable changes in our understanding of the Earth, the Moon, and the universe. Let us hope that the present century is equally productive.

Neil A. Armstrong

PREFACE

Mine was the first generation in humanity's million-year history to have seen the Earth as a globe, hanging in the blackness of space.

When the spacecraft *Eagle* landed on Mare Tranquillitatis in 1969, there were still people alive who had seen the Wright brothers flying. A century of progress has permitted us to see almost the entire surface of the Earth, even the ocean floor thanks to satellite altimetry. It has also given us the first opportunity to compare the Earth with other planets, starting with the Moon (geologically a "planet").

My purpose in this book is to explore the impact of space flight on geology and its subsurface counterpart, geophysics, an impact largely unappreciated in the earth science community. We geologists tend to be conservative, perhaps more so than other scientists. One reason for this may be the nature of our subject: the solid earth, ideally the part of it we can see, feel, and hammer. Another may be the nature of our work, often involving field work in harsh and remote terrains. Whatever the cause, geologists are demonstrably conservative, which is basically why this book is needed.

Geology at the end of the 20th century had reached what appears to be a certain maturity, as I described in a 1996 review, whose abstract is reproduced here. It seems true that we really have settled some questions that in 1900 were not only unanswered but even unasked. The age of the Earth is no longer debated, except in the third significant figure. The mechanism responsible for most earthquakes is now well understood, to the point that seismologists can often tell us which fault slipped, in what direction, and by how much. The origin of granite, intensely controversial as late as 1960, is, in general, understood for most granites – caveats inserted because nature has fooled us before.

It was a magnificent century for science in general, and for the

Twelve Key 20th-Century Discoveries in the Geosciences

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ABSTRACT

This paper reviews 12 major discoveries in geology and geophysics during the 20th century, reasonably mature and discrete with respect to subject, time, or discoverer. The *Textbook of Geology* (Geikie, 1903) and *Understanding the Earth* (Brown and others, 1992) are used as benchmarks, supplemented by Yoder's 0007-1992 "Timetable of Petrology" (1993). The discovery of **the radioactive decay law** by Rutherford and Soddy was fundamental, bearing on the age of the Earth, internal energy, nature of the crust, and a quantitative geologic time scale. Discoveries of the **internal structure of the Earth,** investigated seismically, included definition of the core boundary (Gutenberg and Weichert), the inner core (Lehmann), the mantle/crust boundary (Mohorovic), the lithosphere, and the asthenosphere. **Deep structure of the continental crust,** revealed since 1975 by reflection profiling and study of exposed sections, has been found to be drastically different from previous concepts. **The magnetic reversal time scale** was developed by correlating reversed magnetization in terrestrial and marine rocks with radiometric and stratigraphic data, interpreted in light of sea-floor spreading. **Sea-floor spreading,** the key element of plate-tectonic theory, discovered by several independent lines of inquiry, has been directly confirmed by space-geodesy measurements of plate motion and intraplate rigidity in the Pacific Basin. **Elastic rebound,** the cause of shallow-focus earthquakes, was proposed after the 1906 California earthquake by Reid, using geodetic evidence; deep-focus events are still not understood. The **mechanism of overthrust faulting,** a major problem as late as the 1950s, was discovered by Hubbert and Rubey, who demonstrated that high fluid pressure could reduce normal stress to the point that gravity sliding would be effective. **X-ray diffraction** by the crystal lattice was discovered in 1912, and its applications revolutionized mineralogy, confirming solid solution and clarifying many crystallographic phenomena. The **origins of basaltic and granitic magmas,** completely unknown in 1900, were definitively explained for basalts by Bowen as partial melting of a peridotitic mantle, and for most granitic magmas as partial melting of crustal rocks by Tuttle and Bowen. Space exploration has revealed common patterns of **planetary differentiation,** including a first (or felsic) differentiation forming global primitive crusts, followed by a second (or basaltic) differentiation, including continued basaltic magmatism. Another major result of space exploration and related research has been discovery of the importance of **impact cratering**, proposed as being responsible for formation of continental nuclei, the first ocean basins, and many mass extinctions in the geologic record. The most important scientific achievement of the 20th century is suggested to be the discovery of **the DNA structure,** revealing not only the molecular basis for all life on Earth but a critical line of investigation, formation of RNA, for study of the origin of life.

Keywords: Extraterrestrial geology: geochemistry; geochronology; geology – general; geophysics – general; history of geology; history of science; mineralogy and crystallography; petrology – general; plate tectonics; reviews – articles; structural geology; volcanoes and volcanism.

Introduction

The 20th century opened with a surge of technological progress never equaled before or since. A mere two decades, from 1890 to 1910, saw the development of radio, aviation, electronics, the automobile industry, the steel-frame skyscraper, the Diesel engine, the steam turbine, and many other features of today's world existing, if at all, only in rudimentary form in 1890. In combination with the well known revolution in physics, these developments laid the infrastructure for a century of extraordinary scientific progress. The purpose of this review is to focus on advances in the solid-earth sciences, geology and geophysics, during the 20th century.

The approach will be to outline 12 discrete and reasonably mature discoveries of features or phenomena, and their consequences. Stress will be on the discoveries rather than on the people who made them, primarily to keep the paper within practical length. Two textbooks provide excellent benchmarks of progress since 1900: Geikie's (1903) *Textbook of Geology* and *Understanding the Earth* (Brown and others, 1992). Sullivan's (1991) *Continents in Motion*, though focussed on plate tectonics, is a well documented history of the earth sciences in general from the mid-19th century on. Yoder's (1993) "Timetable of Petrology" lists and documents specific developments from 0007 to 1992. Citations given will be largely of original sources.

solid-earth sciences. However, the "certain maturity" just described may be instead a certain stagnation, a feeling that the big problems in geology have now been solved. Most scientists will recognize this situation; it describes the prevailing view in physics around 1890.

I think that geology is on the verge of a major paradigm shift, to use the fashionable term, comparable to that in physics between 1895 and 1905. Geologists today subscribe almost unanimously to what W. K. Hamblin has called a "master plan," the theory of plate tectonics. The three essential mechanisms of plate tectonics – sea-floor spreading, subduction, and transform faulting – have in fact been confirmed by so many independent lines of evidence that we can consider them observed phenomena, at least in and around the ocean basins. Plate tectonic theory is called upon to explain, directly or indirectly, almost all aspects of terrestrial geology above the level of the crystal lattice. Even metamorphic petrology, in particular the new field of ultra-high pressure metamorphism, invokes phenomena such as continental collision to explain how rocks recrystallized 150 kilometers down are brought to the surface.

I think this is a mistake. We now know, from space exploration, that bodies essentially similar to the Earth in composition and structure have developed differentiated crusts, mountain belts, rift valleys, and volcanos without plate tectonics, in fact without plates. Furthermore, we now know, thanks partly to remote sensing from space, that the Earth's crust can not realistically be considered a mosaic of 12 discrete rigid plates. For these and other reasons, I disagree with certain aspects of plate tectonic theory, as will be explained in the text.

Is the Earth fundamentally unique? Most geologists think it is, and consider the discoveries of space exploration to be interesting but irrelevant to terrestrial geology. The basic objective of this book is to show the contrary: that **the exploration of space has also been the exploration of the Earth**, and that real understanding of its geology is just beginning now that we can see our own planet in almost its entirety, and can compare it with others.

Exploring Space, Exploring Earth is aimed primarily at geologists and geophysicists. However, it has been written to be understood even by readers without a single geology course. Such readers may in fact have the advantage of freedom from preconceived notions. Jargon is unavoidable, but has been kept to the minimum possible. Technical terms are explained either in context or in the glossary. Petrologic topics are presented without the use of phase diagrams, with one exception. The book is quantitative but non-mathematical, without a single equation. Readers who may be uneasy about this are invited to read the appropriate references, where they will find equations reaching to the horizon.

A serious word about mathematics: students should not be misled by the absence of equations in this book. Most of the topics covered here, in particular space geodesy and geomagnetism, involve enormous amounts of mathematical analysis and computer data handling. Any student considering a career in geophysics or geology in the 21st century must have a fundamental grasp of higher mathematics, such as algebra, calculus, and numerical analysis, and computer science (such as programming).

A minor stylistic point: the expressions "manned space flight" and "manned missions" will be used without apology in this book. Women have for years flown on space missions, manned warships, piloted eight-engined bombers. They no longer need condescending euphemisms.

A suggestion to the reader: geology is very much a visual science. If you have never had a geology course, I urge you to buy one of the many popular geology guides, get out of town, and *look* at your local geology. (If you live in San Francisco, you don't have to leave town.) Once you have learned even the most elementary facts about geology, you will be amazed at what you can see – and understand – in even a road cut. When you travel by air, especially over the western US, try to get a window seat (on the shady side: left going east, right going west), ignore the movie, and enjoy the panorama from 35,000 feet. The strangest planet in the solar system is our own; explore it yourself.

Space exploration begins on the ground. If you have never had an astronomy course, I suggest that you buy a $40 pair of binoculars (not a telescope), and *look* at the sky, in particular the Moon. Even 7×50 binoculars reveal a surprising amount of detail along the terminator, and may show the Galilean satellites of Jupiter, which were invisible until the invention of the telescope. Even without binoculars, simply learning your way around the night sky with a cardboard star finder will be fun. The constellations are a compass, a map, a clock, and a calendar; learn why.

Paul D. Lowman Jr.

ACKNOWLEDGEMENTS

This book summarizes the efforts of thousands of people, and the reference list is implicitly a partial acknowledgement of their contribution. I am particularly indebted to my colleagues at Goddard Space Flight Center, far too many after 41 years to name individually, with a few outstanding exceptions.

The first of these is the late John A. O'Keefe, without whom this book would never have been written. He and Robert Jastrow, in 1959 head of the Theoretical Division, took a chance on me when I was a graduate student on the "Korean G.I. Bill," with no academic credentials beyond a B.S. from a state university. I owe my career to them. However, beyond that, John O'Keefe was the founder of space geodesy, as the dedication indicates. The late Eugene Shoemaker also credited him with being "the godfather of astrogeology." He was instrumental in bringing the US Geological Survey into NASA programs in 1960, and helped draw up the first scientific plans for the *Apollo* landings. His tektite field work took him to North Africa, Australia, and many parts of North America. He also played a little-known but critical role in the *Landsat* program, by getting terrain photography onto the experiment list for the later *Mercury* flights, as documented in the remote sensing chapter. John O'Keefe was, in summary, one of the great figures of the heroic age of space exploration, ranking with Goddard, von Braun, Shoemaker, Van Allen, and von Karman. He died in September 2000, but I am gratified that he saw the manuscript of the book and its dedication well before his death.

I was originally invited to write this book in 1993 by Dr Catherine Flack, then with Cambridge University Press. I accepted the invitation at once, one reason being that Neil Armstrong and I had co-authored a paper "New Knowledge of the Earth from Space Exploration" in 1984, which Neil presented at the Royal Academy of Sciences in Morocco. We covered the same major topics presented in this book, now supplemented by 15 years of progress.

Exploring Space, Exploring Earth was written with the encouragement and support of the Goddard Space Flight Center management. However, I wish to specifically acknowledge the support of two Director's Discretionary Fund (DDF) grants. The first of these, from Tom Young in 1983, was for a lineament study by Nick Short and me on the Canadian Shield. It led to a successful *Shuttle* Imaging Radar experiment and gave me access to both the geology and the geologic community of Canada, a world leader in the field. The second DDF grant, from Joe Rothenberg in 1997, provided support for the Digital Tectonic Activity Map that opens the book.

In a long career I have had several branch chiefs, all of whom were friends as well as supervisors. I must specifically acknowledge the decision of the late Lou Walter, first chief of the Planetology Branch, to transfer me to the Geophysics Branch during a major reorganization in 1973. By forcing me to broaden my scientific scope, Lou helped lay the foundation for this book. My present branch chief, Herb Frey, has given me continual encouragement and support through the years the book has been in preparation. Herb's own scientific work on the tectonic effects of large impacts, and on crustal magnetism, cited in the text, has been important in my studies of crustal evolution.

I wish to thank the many Canadian geologists who have helped me, often by vigorous arguments, in particular Lorne Ayres, Hayden Butler, Ken Card, Tony Davidson, Mike Dence, Dave Graham, Jeff Harris, Paul Hoffman, Darrel Long, Wooil Moon, John Murray, John Percival, Walter Peredery, Don Rousell, Vern Singhroy, John Spray, Hank Williams, and Susan Yatabe. My wife, Karen, has accompanied me on many Canadian trips, making them much broader experiences by persuading me to look at something beside outcrops.

The late Eugene Shoemaker was both a friend and a continual inspiration as a pioneer in comparative planetology. His sudden death in a 1997 auto accident in the Australian outback was felt by thousands of geologists, as a personal and professional loss.

The Library of Congress Geography and Map Division has been an invaluable resource in writing this book. Ruth Freitag and Barbara Christy in particular have been generous with critical reviews, and in providing information for compilation of the tectonic activity maps. At Goddard Space Flight Center, the staff of the Homer E. Newell Library has been continually cooperative and helpful for many years.

Technical reviews of specific chapters have been provided by Barbara Christy, Steve Cohen, John O'Keefe, Mike Purucker, Tikku

Ravat, Dave Rubincam, Terry Sabaka, Pat Taylor, and Jacob Yates, to whom I am indebted.

An eminent French scientist, commenting on the value of the *International Space Station*, said, in 1998, that he was unaware of any scientific discovery made by an astronaut. Taking a narrow view, neither am I, but this book would not have been possible without the enormous accomplishments of the American manned space flight program.

Since 1962 I have worked frequently in Houston with the staff of Johnson Space Center, originally the Manned Spacecraft Center, and thank them collectively for their invaluable support in efforts ranging from terrain photography to analysis of lunar samples.

A specific acknowledgement, also collective, is to the astronauts of the *Mercury*, *Gemini*, *Apollo*, and *Skylab* programs for their outstanding accomplishments in hand-held terrain photography. It is not generally realized that the *Landsat* program was originally stimulated by the spectacular 70 mm color pictures they returned. I had the privilege of working with these men – the best of the best – and have tried to document their fundamental contributions in the remote sensing chapter and in the referenced article on the *Apollo* program.

This book is in a sense the final report on two radar experiments carried on the 41-G *Shuttle* mission of 1984, focussed on the origin of the Grenville and Nelson Fronts, east and west boundaries respectively of the Superior Province of the Canadian Shield. I thank the crew of the 41-G mission for their performance in overcoming in-flight problems, my co-investigators in the US and Canada for their contributions, and Dr R. E. Murphy for his support of the 41-G investigation.

The contribution of astronauts to space research, returning to the comment cited above, is not generally appreciated. The crew of HMS Beagle made no scientific discoveries. But their passenger did; he was Charles Darwin. My final acknowledgement is therefore to those whose day-to-day work laid the foundation for *Exploring Space, Exploring Earth*: astronauts, of course; deck hands on oceanographic expeditions; field geologists the world over; jug-hustlers in seismic reflection profiling; darkroom technicians; computer programmers; motor pool dispatchers; librarians; secretaries; and many more, too many to thank specifically. This is their book.

Paul D. Lowman Jr.