54

JAMES W. HEAD III*

The Moon and terrestrial planets: geology and geophysics

Before the Space Age, the study of the planets and their satellites was the domain of astronomers. Telescopic observations of planetary bodies focused on determining their size, position, orbit, density, average surface composition, and the physical state of their surface through photometric analysis. With few exceptions, geologists and geophysicists were occupied with the analysis of Earth, the very complex planet beneath their feet. But even in the latter part of the nineteenth century and the first half of the twentieth, a few geoscientists puzzled over the surface of the Moon, the nature of meteorites, and the geochemistry of the Solar System. G. K. Gilbert, Harold Urey, Ralph Baldwin, Gilbert Fielder, and Eugene Shoemaker each contributed to the foundation that was to become the basis for modern planetary geoscience (Stevenson 2000). Convergence between these disciplines began with the Space Age, and the ability to see the surfaces of other planetary bodies up close, to probe their interiors, and to analyze them from orbiters and flybys. More sophisticated and higher-resolution observations from spacecraft led to an understanding of the mineralogic makeup of their crusts through spectroscopic observations, and the distribution of their surface features through geological analysis of images taken at visible and radar wavelengths. Sophisticated tracking of spacecraft and direct deployment of instruments led to new insights into planetary geophysics. In the last half of the twentieth century, intense exploration of the Solar System changed planetary bodies from solely astronomical objects to geological and geophysical entities, and the picture that began to emerge was similar to that derived from the examination of any population of things: a tremendous diversity of characteristics, a handful of emerging themes, and a host of new questions.

How did planetary geologists and geophysicists approach these problems? Imagine observing a group of human beings. You might initially sort them by size and shape, and then distinguish them by various other physical attributes. But when the time came to understand the factors and processes that were responsible for these characteristics, you would need to look more closely, and to understand what was going on inside. Beneath the superficial variations in surface skin and in hair color and tone, what were the processes that were responsible for the activity of each of these organisms, its origin and its evolution? What internal structure and processes were responsible for its present state? How did the organism regulate its internal heat in the light of such extreme external variations? How did it give birth, how has it aged, and how will it die? Similar questions are key to understanding the birth and evolution of the array of terrestrial planetary bodies. As with humans, planets are complex systems in which most of the driving forces and regulating processes are hidden below the surface. Surface features can give clues as to how the interior works, but a detailed examination of the inside of these bodies is necessary before any real picture of the evolution of the planet as a whole can emerge. Of course, planets are not simple organisms that can be brought into the laboratory, studied, and dissected, allowing us to map out the anatomy of the interior and the role this plays in the evolution of its external features. Instead, indirect measurements are required, and indeed the surface features must be studied in detail if we are to infer the nature of the interior and how it may have changed with time.

* Brown University, Providence, RI, USA

James W. Head III, The Century of Space Science, 1295–1323

Thus, among the most fundamental areas of analysis are the nature of planetary surfaces, the processes and sequence of events implied by their geologic records, and the structure and state of their interiors and how they have evolved with time. One of the supreme achievements of the Space Age has been the links that have been forged between geology and geophysics to address these issues and to sketch out the story of planetary evolution.

What was the intellectual basis for this phase of planetary exploration? We had many questions about planetary interiors: What is their basic structure; are they homogeneous, an even mixture of planetary ingredients throughout their interior? If not, are they like a plum pudding, or layered, perhaps in several large layers, or like a torte, with multiple thin layers? And what are these layers made of? Are their compositions sorted by density, and if so, how does the increase in pressure with depth inside planets influence the changes in the state of these materials? When and why did this structure develop, and how does it change with time? Volcanic activity shows that planets are hotter in their interior than at the surface. Where does this heat come from, how is it distributed in the interior, and what are the processes by which the planet redistributes and gets rid of heat? And how has this changed with time, in the course of the planet's history? Once this type of knowledge is to hand, we can ask even more sophisticated questions: How do planets differ in their basic internal structure, and how does this determine their evolution? What role does size, and position in the solar nebula during planetary formation, play in the further evolution of the planets?

The approach to addressing these questions was neither intellectual nor systematic. Missions and experiments were undertaken or denied for a variety of reasons: national goals, national security, proximity to Earth, international competition, international cooperation, technological sophistication, financial constraints, politics, professional advocacy, personal advocacy, and scientific rationale. We explored the Moon before we analyzed the surfaces of Venus and Mercury. The Soviet Union sent many missions to Venus, while the United States sent only a few. After the crowning achievements of Apollo, most of the Moon's surface remained unstudied by spacecraft for over twenty years. The sequential exploration of the Solar System is a complex story of the historical interplay of these many factors, and has been told elsewhere (Stevenson 2000, Chapman 1988, Cruikshank 1983, Colin 1983, Vaniman *et al*. 1991, Kieffer *et al*. 1992, Snyder and Moroz 1992, Morrison 1999).

In this chapter we integrate these important historical steps into an overview of the geology and geophysics of terrestrial planetary bodies, as revealed by exploration of the Solar System in the last half of the twentieth century. We first briefly outline the basic processes that may have been involved in the formation and evolution of planetary interiors, and then look at the types of measurements and observations that might lead us to an understanding of their present and past states. Armed with the basic physical properties of the terrestrial or Earth-like planets (size, density, position in the Solar System), we turn to a brief description of the nature and ages of the surfaces of each terrestrial planetary body, and what is now known about their interiors. We start with the smallest, the Moon, and proceed upward in size, via Mercury, Mars, and Venus, to Earth. What were the major external (e.g., impact cratering) and internal (e.g., volcanism) processes that were responsible for their evolution, and when did most of this activity occur? What do we know about each planetary body's interior, and how does this relate to what we see on the surface? Once we have this basic information, we can explore some themes and processes that help to explain the observed characteristics, and address such questions as: What are the major factors that cause the differences in the interiors and geological histories of the planets? How much of a planet's history is predetermined by its starting conditions (its "genetic" makeup), and how much is determined by its later history (its "environment")? We conclude with several outstanding questions that need to be investigated in the exploration of the Earth and terrestrial planetary bodies in the twenty-first century.

THE NATURE OF PLANETARY INTERIORS AND GEOPHYSICAL PROCESSES

Present planetary interior structure can be viewed from two perspectives: that of internal compositional variations, usually configured in layers such as crust, mantle, and core; and that of variations in internal temperature and state, producing layers on Earth such as the lithosphere, the asthenosphere, and the outer molten and inner solid core. Internal compositional variations are produced by differentiation – that is, the segregation of materials of different composition from more primitive and homogeneous parent materials. Differentiation can be rapid and catastrophic, as in the case of core formation, a process in which denser iron-rich material sinks to the deepest interior. Because planets are hotter in their early history, core formation is thought to occur in the first few percent of a planet's history, and the amount of gravitational potential energy it releases is so high that surface melting is implied, at least for the larger planets. Differentiation can take place over increasingly longer periods of time as heat in the interior causes partial melting of the mantle and the ascent of the hotter, less dense melt products (magma) toward the surface to form crustal materials (intrusions, and extrusions such as volcanoes). Depending on the amount of energy involved, and the way it is distributed in the interior, melting and differentiation can be global (e.g., if the energy is from a high influx of globally distributed random impacts), or local to regional (e.g., in the case of mantle plumes producing circular hot spots, or a global system of linear cracks at mid-oceanic ridges). Variations in the relative proportions and timing of these factors can lead to major differences in the nature and age of the outer differentiated layer, the crust. Energy from early intense bombardment can produce a primary crust, later internal heating and melting can produce materials for a secondary crust, and reworking of these earlier crusts can yield tertiary crusts (Taylor 1989).

One of the most fundamental aspects of understanding planetary interiors comes from knowledge of heat. What are the sources of heat, how much of it does a planet have at any given time, what is its internal distribution, and how does a planet transfer and get rid of heat over time? These simple questions are the keys to understanding planetary evolution. How much heat derives from initial accretional energy, position relative to the Sun, electromagnetic heating, core formation and other density instabilities, large impacts, short and long-term radioactive decay of minerals, and tidal interactions? How is this heat distributed over time in what is known as a planet's thermal history? What is the rate of change of temperature as a function of depth, and how does this relate to the physical state of material (e.g., liquid, partially molten, solid)? What is the nature and stability of thermal boundary layers, the transitional layers separating materials with different temperatures? How is heat transferred through the course of the planet's evolution? What role does conduction play? How important is convection? How significant is advection – the direct transfer of heat by movement of molten material from the interior to the surface as in the volcanic flooding of a planetary surface? How does material behave under the tremendous temperatures and pressures typical of planetary interiors? What materials change phases (rearrange their internal structure), and how do they then behave? And how does all this add up? How do different planets lose heat as a function of time in what is known as their thermal evolution? Are there many paths or only a few? And what are the factors that determine this? And where are we going – if the planets are indeed evolving, where is the Earth heading?

Our present knowledge of the interior of most planets is based on their bulk density and on information obtained from measurements of surface geochemistry, moment of inertia, gravity, and present and fossil magnetic fields. Also, very significant are inferences made from geologic structure, topography, and geologic history, analogies with Earth, and assumptions about starting conditions. Deep drilling, and tectonic uplift and exposure of rocks from depth, provide some information about the upper few hundredths of a percent of the Earth's radius, and impact cratering can expose material from greater depths, perhaps even below the crust, on some planets. Detailed assessment of the interior of a planet requires surface seismic networks and heat flow probes, which have so far been emplaced only on the Earth and Moon.

INTERNAL STRUCTURE AND GEOLOGICAL HISTORY OF THE TERRESTRIAL PLANETARY BODIES

The Moon

The Moon, as our closest neighbor in space, was the first body to attract the attention of geologists studying other planetary surfaces. Eugene Shoemaker and his co-workers (Don Wilhelms, Jack McCauley, Baerbel Lucchitta, Elliot Morris, Farouk El Baz, and others) applied the basic principles of terrestrial stratigraphy to lunar surface features and geologic structures, and this enabled them to define geologic units and produce geologic maps, and thus to delineate the major surface processes and the sequence of events in lunar history. Similar mapping techniques have been applied to each successive planet explored over the last 25 years, and the collective maps (Carr *et al*. 1984, Head 1999) provide the basis for understanding the history of each planet and comparative planetary evolution. The will and determination of a handful of geoscientists in the USA (Harold Urey, James Arnold, Gerald Wasserburg, Robert Walker, Paul Gast, and George Wetherill and colleagues) and the Soviet Union (M. V. Keldysh, A. P. Vinogradov, Roald Sagdeev, Valery Barsukov, Mikhail Marov and colleagues) convinced their respective governments that international competition could also produce significant scientific results.

Pluto and Charon excepted, the Moon is the largest satellite, relative to its parent body, in the Solar System, and its mode of formation has captivated scientists for years. Current thinking is that the Moon formed very early in Solar System history when a Mars-sized object, one-half the diameter of the Earth, impacted the proto-Earth, ejecting crust and upper mantle material which re-accreted in Earth orbit to form the Moon (e.g., Hartmann and Davis 1975). Soon afterwards a global crust formed, under a bombardment that lasted for several hundred million years in which a massive influx of projectiles impacted the newly formed surface at several kilometers a second, producing impact craters of many sizes. This bombardment fragmented and fractured the upper few kilometers of the Moon's crust to form a thick soil layer (megaregolith) and produced interfingering global geologic units of ejecta representing the first few hundred million years of lunar history (e.g., Wilhelms 1987). This so-called late heavy bombardment ended about 3.8 billion years ago (Wasserburg *et al*. 1977), but not before the largest projectiles had excavated huge depressions (as large as 2,000 km in diameter) and spread ejecta over immense areas (Spudis 1993), producing the extremely

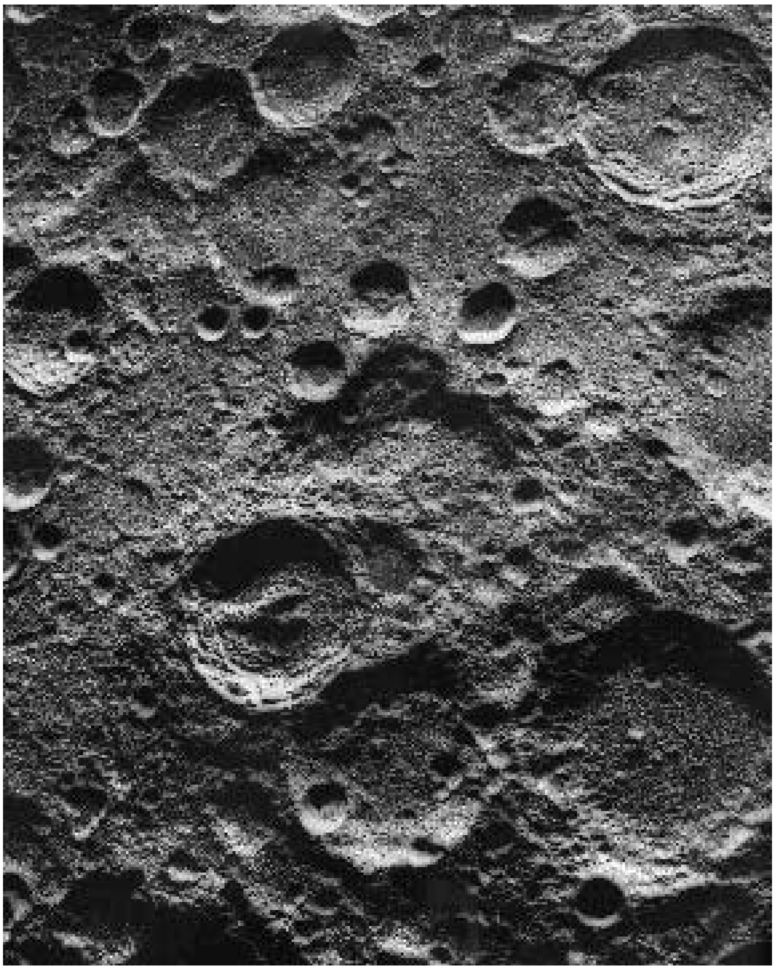

Figure 1 The heavily cratered lunar farside. The 75 km diameter King crater, with its lobster-claw-like central peaks, is the sharp-rimmed crater just to the lower left of the center. (NASA Apollo 16 image.)

rough surface topography typical of the lunar highlands that we see today (Figure 1). Data from the US missions Galileo, Clementine, and Lunar Prospector have provided a global view of the topography and mineralogy of the lunar crust (Spudis 1999), and have revealed details of a huge impact basin on the lunar farside that excavated to lower crustal and perhaps mantle depths (e.g., Pieters *et al*. 2000).

Volcanic flooding of the surface of the Moon became evident during the waning stages of the late heavy bombardment. By about 2.5–3.0 billion years ago, basaltic lavas had covered approximately 17% of the lunar surface, preferentially filling in the nearside, low-lying basin interiors to the lunar maria (Figure 2). Volcanic eruptions on the Moon were volumetrically significant, but far and few between, and occurred predominantly in the first half of its history, under a rapidly decreasing flux (e.g., Head and Wilson 1992). Tectonic activity on the Moon stands in stark contrast to that on our own planet. The limited array of lunar tectonic features occurs predominantly in and near the maria: linear rilles and graben, formed by crustal extension, were followed by sinuous (wrinkle) ridges formed by contraction (Solomon and Head 1980) (Figure 3). Virtually no major internally generated geologic activity for the last 2.5 billion years is manifested on the lunar surface. The Moon thus provides a picture of the first half of Solar System history (characterized by impact bombardment and early volcanism), and serves as a benchmark for the interpretation of the records preserved on other terrestrial planets. How do these features relate to the nature of the Lunar interior? Deployment of seismic instruments on the Moon and analysis of the results by Frank Press, Nafi Toksoz, Gary Latham, and others have helped to address this question.

Lunar samples collected by US Apollo and Soviet Luna missions (e.g., Papike *et al*. 1998), remote sensing, and surface seismic data show that the Moon has been internally differentiated into a crust, mantle, and possibly a small core (Figure 4). The feldspar-rich crust is thinner on the central nearside, about 55 km, but may reach thicknesses of 100 km

http://www.springer.com/978-0-7923-7196-0

The Century of Space Science
Bleeker, J.A.; Geiss, J.; Huber, M. (Eds.)
2001, XLIX, 1846 p., Hardcover
ISBN: 978-0-7923-7196-0