THE
DYNAMIC
PLANET

THE DYNAMIC PLANET

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PREFACE

Twenty years ago, I wrote a brief elementary text on rocks and minerals entitled *Earth Materials;* it was one of a group of short volumes aimed at the advanced college freshman and *Scientific American* audience. Although I was pleased with "Earth Mat," my contribution appeared to have been presented at too high a level to be very effective in an introductory earth science course, yet insufficiently detailed to provide a reasonably complete mineralogy-petrology text for earth science majors. Because it was written prior to the commencement of exploration of the solar system, as well as the full blooming of plate tectonic concepts—both of which have subsequently revolutionized our understanding of the origin and diversity of earth materials—it seems high time to present a next-generation approach. Similar to the earlier effort, familiarity with high school–level chemistry is assumed. Just in case it is needed, the periodic table of the elements is reprinted at the back of the book.

Although patterned after the original in the mineral and rock sections, the present book represents a considerable departure from the treatment in "Earth Mat." The title, *The Dynamic Planet,* alludes to the inexorable constructional forces internal to the planet that couple with degradational processes at the surface. Together, they produce a unique life-giving habitat within the inner solar system. Sections dealing with the Earth's place in the solar system, and sections dealing with its internal structure, have been added and expanded, respectively; new chapters deal with Alfred Wegener, continental drift and plate tectonics, with energy and mineral resources, with geologic hazards and the Circumpacific "Ring of Fire," and with the origin and evolution of the Earth's crust. Many terms are defined in the text, where they constitute the subject under consideration. Other, more tangential expressions are identified parenthetically. A glossary has been added after chapter 7 for further reference if the terminology becomes confusing.

Considerably reduced and revised are the chapters describing minerals and rocks, and mercifully eliminated is the chapter that introduced classical thermodynamics and phase equilibria. The latter subject rightfully belongs in a modern mineralogy-petrology text, but this is not what I have written. Nor have I put together an all-encompassing, modern earth science text; several excellent elementary books already exist. Instead, I have attempted to show how the exciting developments in space exploration and, especially, global tectonics are impacting the solid earth sciences. Far from a comprehensive, beginning geology text, *The Dynamic Planet,"* pitched at a higher level as it is, contains what I regard as some of the central, provocative, and transformative, themes in this ever-expanding discipline.

ACKNOWLEDGMENTS

I would like to thank several people at UCLA: Harriet Arnoff, who typed and retyped the manuscript, Jean Sells, who drafted many of the illustrations, and my faculty associates Mark D. Barton and Wayne A. Dollase, who helpfully reviewed portions of it. Half a dozen different elementary classes at UCLA were subjected to the presentation which was evolved into this book: for their anguished but constructive feedback I am also very grateful.

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CONTENTS

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STRUCTURE OF THE EARTH AND ITS DYNAMIC CHARACTER

As a function of their orbital distances from the Sun, the planets in our solar system exhibit systematic and progressive variations in their chemical constitution and surface appearance. Spatial relationships of the nine planets, as well as those of a typical comet (a wandering "dirty snowball") and of the asteroid belt (meteorite swarm), are shown in figure 1.1. Table 1.1 presents additional solar system information in more quantitative fashion. The innermost planet, Mercury, is metal-rich; the next three, Venus, Earth, and Mars, fundamentally stony, with the outer planets representing progressively more gassy giants and, finally, proportionately more icy, condensed bodies. The Oort cloud, at the outer gravitational limit of our solar system, is the ill-defined home of icy condensates, or comets.

The reason for these contrasts in planetary composition is not known with absolute certainty, but appears to be related mainly to distance from the Sun. Condensation of the solar nebula 4.5–4.6 billion years ago (see chapter 7) might have led to initial differences in the composition of the planets during their growth stages, reflecting chemical heterogeneities in the primordial dust cloud. On the other hand, the solar wind (energy radiating from the Sun) undoubtedly has exerted a strong influence over the distribution of the more volatile elements in the planets; those bodies closer to the Sun each contain high proportions of normally solid (refractory) elements of low volatility whereas, proceeding away from the Sun, the condensed masses become progressively enriched in low-condensation and low-melting temperature (gassy) elements. Very probably, this thermal gradient (temperature gradient), encompassing the Sun and its environment has been largely responsible for the compositional contrasts of the planets.

In fact, each planet is unique in its external aspect and internal nature. The Earth is the middle member of the three stony planets. These terrestrial-like bodies, and our earthly satellite, the Moon, exhibit different surficial features principally because of the contrasting degrees to which their outermost rinds have been reworked. This subject will be taken up again in chapter 7, but suffice it to note here that the interiors of all the planets are hotter than their surfaces because of internal (primordial, radioactive, self-compressive, and kinetically generated) heat. The most efficient mechanism for removal of large quantities of buried heat is by material circulation, or overturn, within the planet, with cooling (energy loss) taking place at the surface. Larger masses contain more heat, and—possessing larger mass/surface ratios—rid themselves of thermal energy more slowly; hence they remain hot and internally turbulent for a longer period of time.

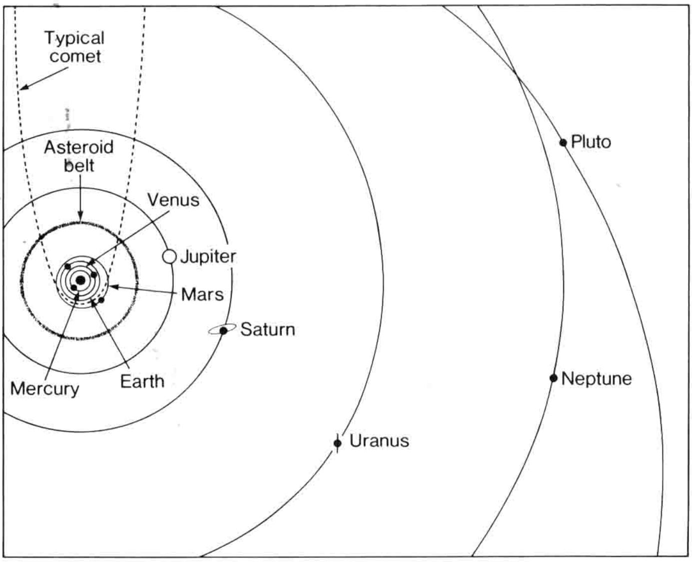

FIGURE 1.1. Orbits of the nine planets in the solar system, as well as that of a tyical comet in Sun-approaching orbit, and of the asteroid belt, properly scaled (after Hartman 1983, figure 2.1). Some planetary satellites, such as the Earth's Moon, the four Galilean satellites of Jupiter, Saturn's Titan, Neptune's Triton, and the largest asteroids are bigger than, or approach the sizes of Pluto and Mercury, the smallest planets. Pluto has an elliptical orbit, and, while generally farther from the Sun, crosses the orbit of the eighth planet, Neptune.

TABLE 1.1. Distances from the Sun, Diameters, and Types of Planets in the Solar System

	Distance from Sun in AU[a]	*Diameter of Planet in km*	*Planetary Type*
Mercury	0.4	4,878	iron
Venus	0.7	12,104	stony
Earth	1.0	12,756	stony
Moon	1.0	3,476	stony
Mars	1.5	6,796	stony
Asteroids	~2.8	small	stony
Jupiter	5.2	142,796	gassy
Saturn	9.5	120,660	gassy
Uranus	19.2	50,800	gassy/icy
Neptune	30.0	48,600	icy
Pluto	39.4	2,400–3,800	icy
(Oort Cloud)	100–50,000	small	icy

[a] One astronomical unit (AU) is the distance between the Earth and Sun, about 149,600,000 km.

Assuming that meteorite populations are (and were) relatively uniformly distributed throughout our portion of the solar system, crater density on a planet provides a relative measure of the extent of internally fueled surface reworking: the more numerous the impact craters, the slower the bodily circulation and consequent surficial reworking by mass flow within the planet. Intensely pockmarked planets are nearly dead, or at least are less active internally than those lacking an abundance of such topographic phenomena. Thus, if we compare the relative sizes (and consequent heat contents) of the Moon, Mercury, Mars, Venus, and the Earth with their external features, it is apparent that most of our planet's surface has formed during the very recent geologic past, whereas the Moon, Mercury, and Mars became almost totally inactive several billion years ago. Venus is far less well known because of its dense, obscuring CO_2 cloud cover, but radar imagery has provided enough topographic control to conclude tentatively that surface activity—hence internal circulation—probably ceased there more than a billion years ago. These relationships are illustrated diagrammatically in figure 1.2.

Thus, although possessing chemical characteristics similar to its sunward, hotter sister Venus, as well as its outer, colder brother Mars, the Earth is markedly different from these neighboring siblings. This is understandable given the relative sizes and internal heat budgets discussed above. But it is also a consequence of the position of our planet relative to the radiant solar flux (solar wind). Solid, liquid and gaseous H_2O are stable at and near the Earth's surface. Venus' proximity to the

Sun is responsible for its higher surface temperatures and lack of liquid H_2O oceans. Mars, in contrast, is so distant from the Sun that, on its surface, H_2O frost is presently confined to seasonal polar caps (which actually consist mostly of dry ice—solid CO_2). We need only to glance at photos taken from spacecrafts (e.g., compare figures 1.3, 1.4 and 1.5) to recognize that, in comparison to the dense, torrid, carbon dioxide–enshrouded Venus, and the arid, frigid, nearly atmosphereless Mars, the Earth's outer envelope consists of a particularly hospitable and dynamic

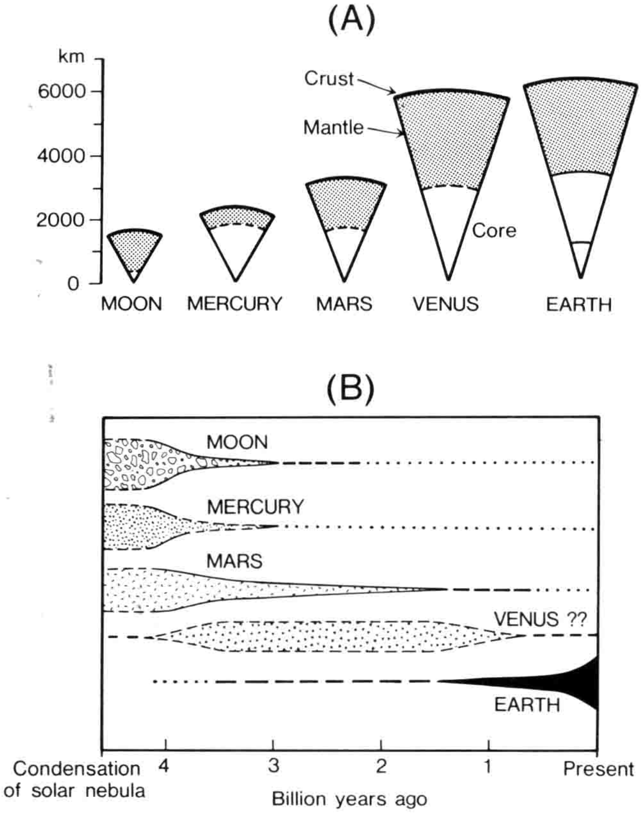

FIGURE 1.2. Relative (A) sizes and gross structures of the inner, terrestrial planets, and of the Moon, and (B) inferred surface reworking of these bodies due to volcanism, erosion, deposition, and meteorite bombardment (modified after Head and Solomon 1981, figures 3 and 12). The increasing surety of time of surface feature production is shown by dotted, dashed, and solid lines, respectively. The vertical axis in (B) is a spatial separation parameter that has no particular significance.

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interplay among atmosphere (gassy sphere), hydrosphere (watery sphere), and variegated surface of the solid planet. We have much to love about planet Earth.

Firmly on the ground, we may suspect that, contrary to popular belief, mountains and rivers of our terrestrial landscape are not the immutable, permanent features they seem to be. The forces of erosion (wind, running water, glaciation, and down-slope mass movement), acting over the millennia are reducing topographic prominences to more subdued outlines. Rivers, flowing in their ever-shifting courses, carry solid debris and other, dissolved materials supplied by the agents of erosion toward an ultimate rendezvous with the sea. There, the entrained particles spread laterally and settle, and dissolve constituents eventually precipitate out. Over the billions of years of geologic time since the formation of the Earth (see chapter 7), these processes must have planed off the continents many times over, and deposited vast quantities of sediment in the ocean basins.

Why, then, isn't the Earth a nearly featureless plain at or beneath sea level? Experience tells us that this is not at all the case; graphic proof is demonstrated by a map of the Earth's surface, such as illustrated in figure 1.6. We will pose this question again, and find a fuller explanation in chapter 2. Apparently, constructional forces within the Earth, driven by the slow but inexorable motions of deeply buried solid

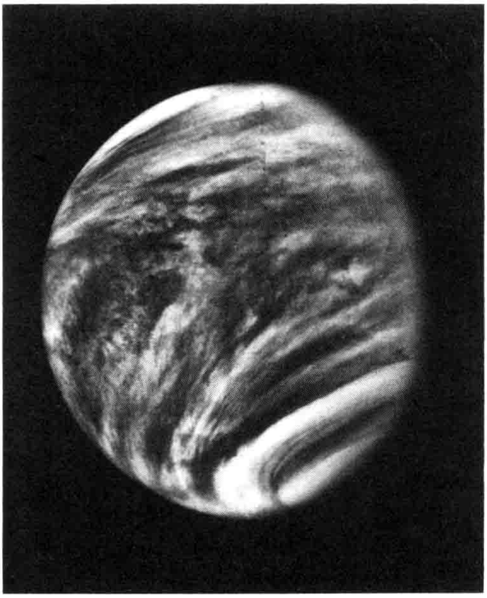


FIGURE 1.3. Mariner 10 photo of Venus from a distance of 720,000 kilometers (NASA photo).

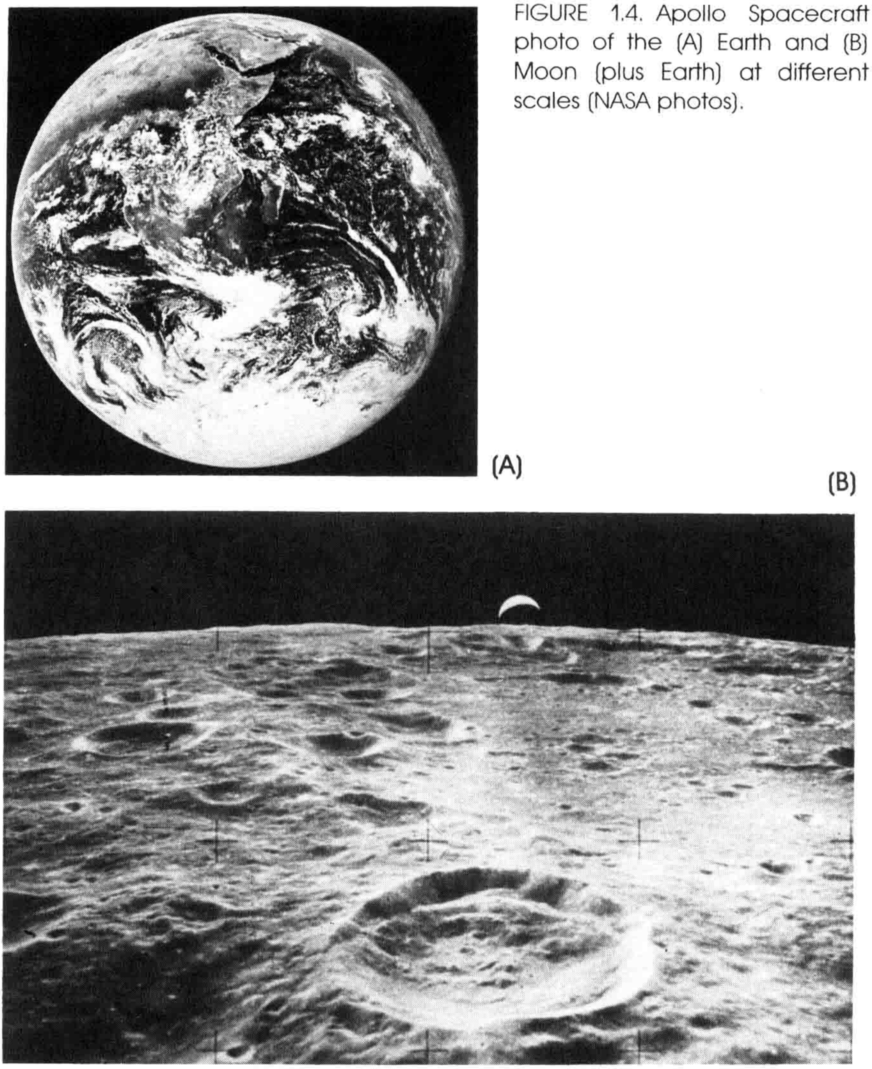


FIGURE 1.4. Apollo Spacecraft photo of the (A) Earth and (B) Moon (plus Earth) at different scales (NASA photos).

but plastic rock, have swept the ocean basins nearly free of sediments and have resulted in upheaval of rocky sections of the Earth's crust. These internal terrestrial processes thus oppose the surface degradation visible to us all, for clearly we still have mountain belts, just as evidently existed in the ancient geologic past.

To develop an appreciation for the processes at work today, and by inference, those that operated during the distant past, we turn to a

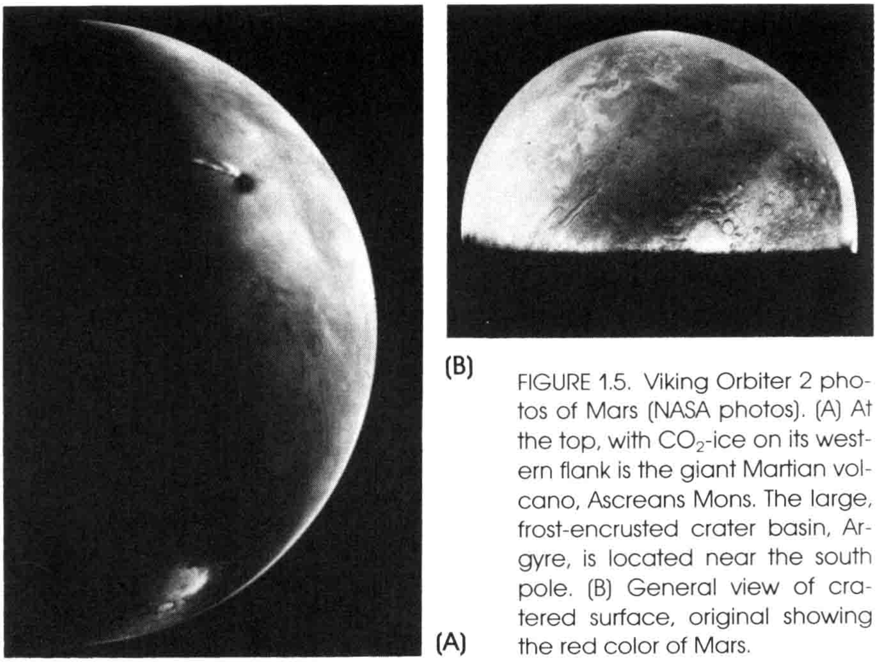


FIGURE 1.5. Viking Orbiter 2 photos of Mars (NASA photos). (A) At the top, with CO_2-ice on its western flank is the giant Martian volcano, Ascreans Mons. The large, frost-encrusted crater basin, Argyre, is located near the south pole. (B) General view of cratered surface, original showing the red color of Mars.

consideration of the internal structure of the Earth. Our planet's constitution is a reflection of its original accretionary growth history and subsequent evolution. Such changes over time may largely be attributed to the escape of heat from the deep interior, as will be discussed in chapter 7. But what is the present, generalized structure of the planet? The Earth consists of a series of nested shells, or layers, of contrasting physical and chemical properties. First, the overall structural relationships will be described; then the kinds of evidence employed by earth scientists to deduce the nature of these shells will be presented.

The metric system will be used throughout this volume. As an aid for those steeped in the archaic English measurement system, a few of the more common conversions are presented in table 1.2. To help with the chemistry, the periodic table of the elements is printed at the back of the book.

GROSS INTERNAL CONSTITUTION OF THE EARTH

Diagrammatic sketches, representing a sector from the atmosphere to the center of the Earth are shown in figure 1.7. The Earth is sur-

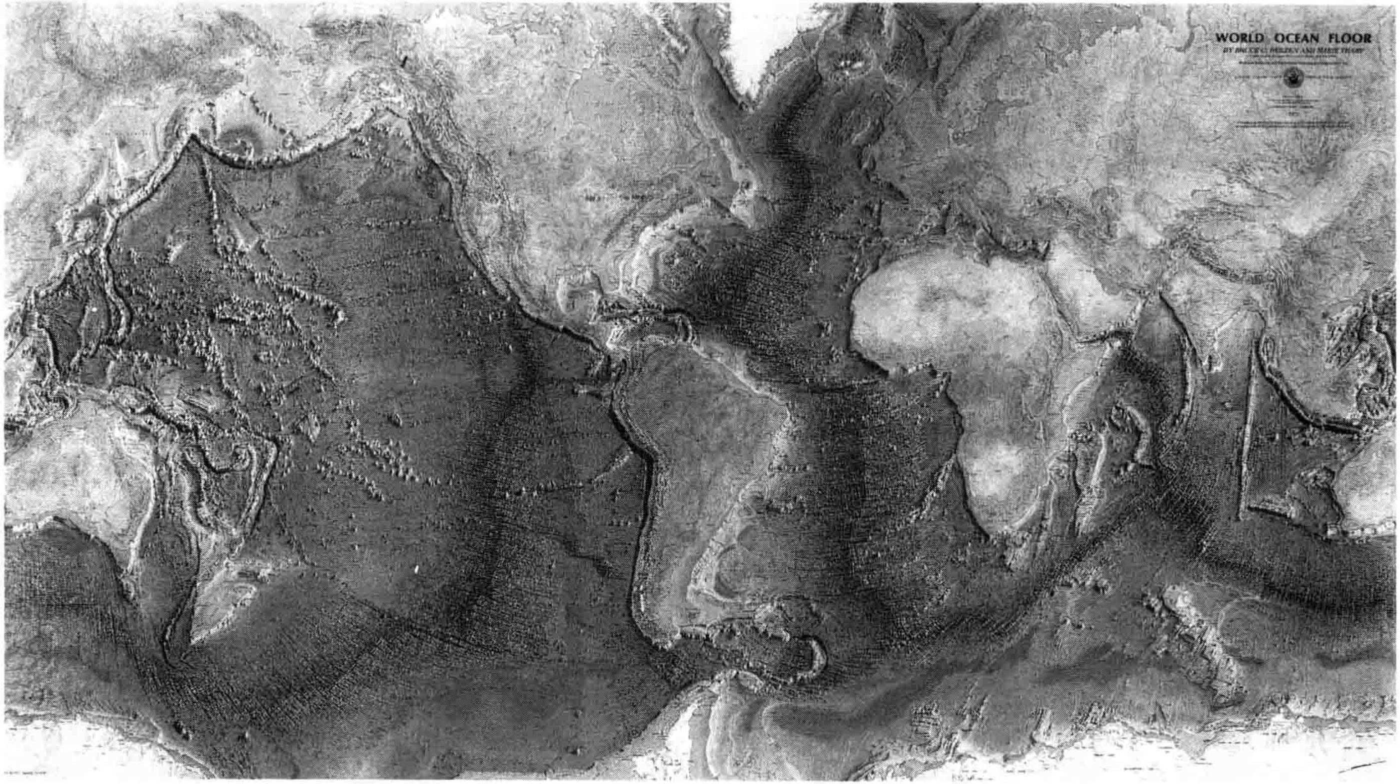


FIGURE 1.6. Relief map of the surface of the solid Earth (Heezen and Tharp 1977). Note that our planet is divided into two major physiographic provinces—continents and ocean basins. The latter are full "to the brim" with seawater, and in fact overly so, for the continental shelves are portions of the high-standing continents and islands that are slightly below sea level.

TABLE 1.2. Selected Conversion Factors

Metric		*English*	
1 bar	= 0.9869 atmosphere	1 atmosphere	= 14.696 pounds/square inch
	= 10^5 pascals		= 1.0133 bars
	= 100 kilopascals		
1 kilobar	= 1,000 bars		
	= 100 megapascals		
1 megabar	= 10^6 bars		
	= 100 gigapascals		
Temperature in degrees Celsius (T_C)	= $5/9(T_F - 32)$	Temperature in degrees Fahrenheit (T_F)	= $9/5T_C + 32$
Temperature in degrees Kelvin (T_K)	= $T_C - 273.16$		
1 centimeter	= 0.3937 inch	1 inch	= 2.540 centimeters
			= 25.40 millimeters
1 angstrom (Å)	= 10^{-8} centimeter	1 foot	= 0.3048 meter

rounded by a gaseous layer consisting chiefly of nitrogen and oxygen (N_2 makes up about 79 percent, O_2 about 20 percent of the atmosphere, with CO_2 and other, rarer gas species constituting the remainder); the atmosphere is densest at sea level, and becomes progressively rarified with elevation. No sharp break with outer space exists, but the gas molecules are so widely dispersed above about twenty kilometers that we may regard this elevation as the effective limit of the earth-enveloping atmosphere. The ocean basins make up about two-thirds of the surface of the solid Earth, and are great depressions lying about five kilometers below sea level. The continents and islands, together constituting about one-third of the solid Earth's surface, rise above sea level only a few hundred meters on the average. Because seawater more than fills the ocean basins, the hydrosphere laps onto the margins of the continents and islands (see, for instance Hudson's Bay; the Grand Banks, and the East China Sea); these are the so-called continental shelves. Thus, the Earth's surface consists mainly of ocean water, making up slightly more than 70 percent of the exposed area; land, some of which is lake- or ice-covered, constitutes the remaining 30 percent.

The surficial distinction between continents and ocean basins seen in figure 1.6 reflects an underlying structural and chemical difference clarified in figure 1.7B. The outer rind of the solid Earth, called the crust, is of two distinctly different types, continental and oceanic. Continental crust, enriched in silica, alkalies, volatiles, and radioactive elements, is characterized by light-colored granitic and allied rocks (see chapter 4

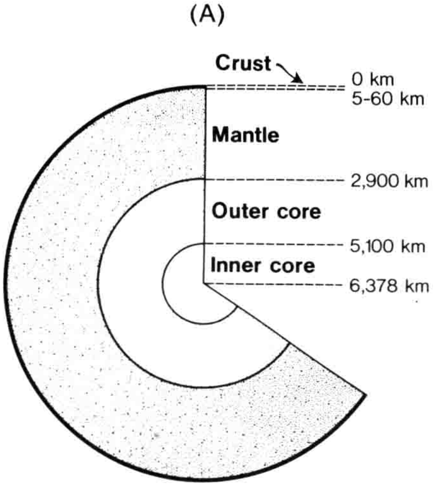
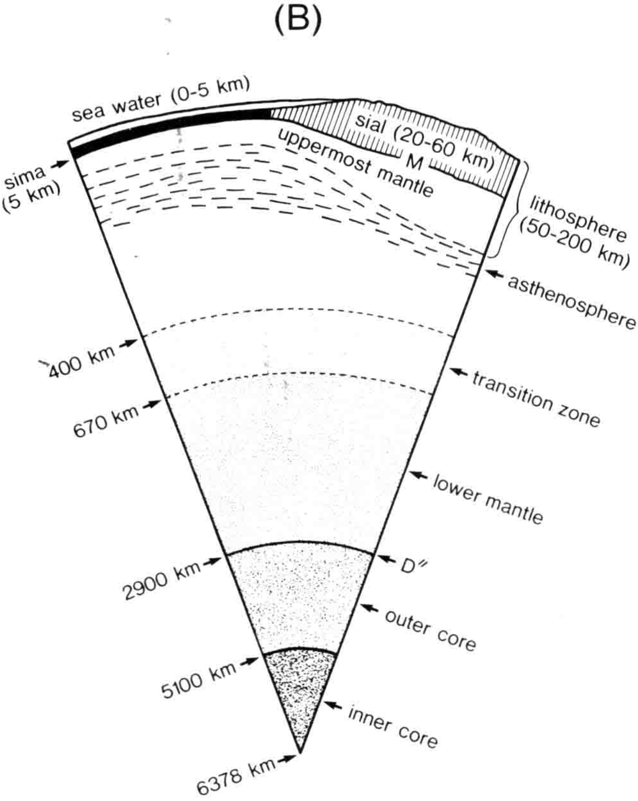


FIGURE 1.7. Schematic section through the Earth. The overall structure, properly scaled, is illustrated in (A). Details of the crust and mantle are shown schematically (not to scale!) in (B). The Mohorovicic discontinuity is abbreviated M, the narrow zone at the core-mantle discontinuity as D″.



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