M. GRANT GROSS

OCEANOGRAPHY

FIFTH · EDITION

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Preface

Oceanography is the scientific study of the sea. During the century since its beginnings in the round-the-world voyage of the Challenger Expedition (1872–1876), study of the ocean has changed the way we view and use the ocean. More importantly, oceanography has changed the way we view the entire earth. Some of the most significant contributions of oceanography have occurred since the first edition of this book appeared in 1967. This fifth edition reflects current developments in the field; other major changes, even now underway, will likewise be reflected in future editions.

This edition retains the focus of previous editions. It builds on high-school-level mathematics (algebra) and general science backgrounds. The book is intended for use in a one-quarter course or for a one-semester course with supplemental materials. The book could also be a supplemental text in related subjects, such as marine geology or marine biology.

While retaining much of the information from the fourth edition, this text also explains new discoveries in oceanography. Some topics (especially the chapters on water and sea salt) have been reorganized and condensed. The chapter on marine organisms has been expanded to discuss marine ecosystems and particularly interesting organisms—marine mammals and seabirds.

Features that assist students in studying and reviewing the subject matter have been expanded. The Supplementary Readings (articles and books) and Questions have been revised and enlarged. A new section—Key Terms and Concepts—has been added to help students identify particularly significant materials.

There are many new illustrations, especially photographs. Revision of most of the original artwork to clarify key points has stemmed primarily from comments of users of previous editions.

Contents

1 Earth—The Water Planet

Earth is the water planet. Since the crust solidified more than 4 billion years ago, water has been extracted from the earth's interior by volcanic action to collect in ocean basins (Figure 1.1). Nearly 71% of the earth's surface is overlain by ocean waters, averaging 3730 m (12,200 ft) deep. At any instant only a small fraction of the earth's water is present in the atmosphere, retained on the land in lakes, or locked in glaciers and ice caps. Nearly all the water remains in the ocean where it has a profound effect on our lives.

Most people live within a few hundred kilometers of the sea. For all of us, the ocean provides recreation and food, receives wastes, and serves as a global highway. Even to those living far inland, its influence on daily life is great because the ocean supplies water necessary for life. It stores and then releases much of the solar energy that powers earth's atmospheric circulation, causing our weather. By contrasting the large daily temperature changes in a desert with the more even temperatures of coastal areas, we can see the importance of the ocean's role as a climatic buffer.

In short, ours is a water-conditioned existence. By studying the ocean, we learn about a controlling feature of our life. With better understanding we may someday be able to predict changes in the oceanic circulation and in climate. Equally important, we must learn enough about the ocean to permit us to use it more fully for transport or waste disposal, without destroying its use as a food source or recreational area.

1.1 AGE AND ORIGIN OF THE OCEAN

The ocean is an ancient feature of the earth's surface, and through time the records of its origins have been obscured. Both ocean basins and continents were formed by the processes discussed in Chapter 2. Due to a gradual release of water at the earth's surface through volcanic action, water originally bound in interior rocks has accumulated at the earth's surface, beginning nearly 4 billion years ago (Figure 1.2). Some ancient rocks—approximately 3.8 billion years old—contain waterworn pebbles and

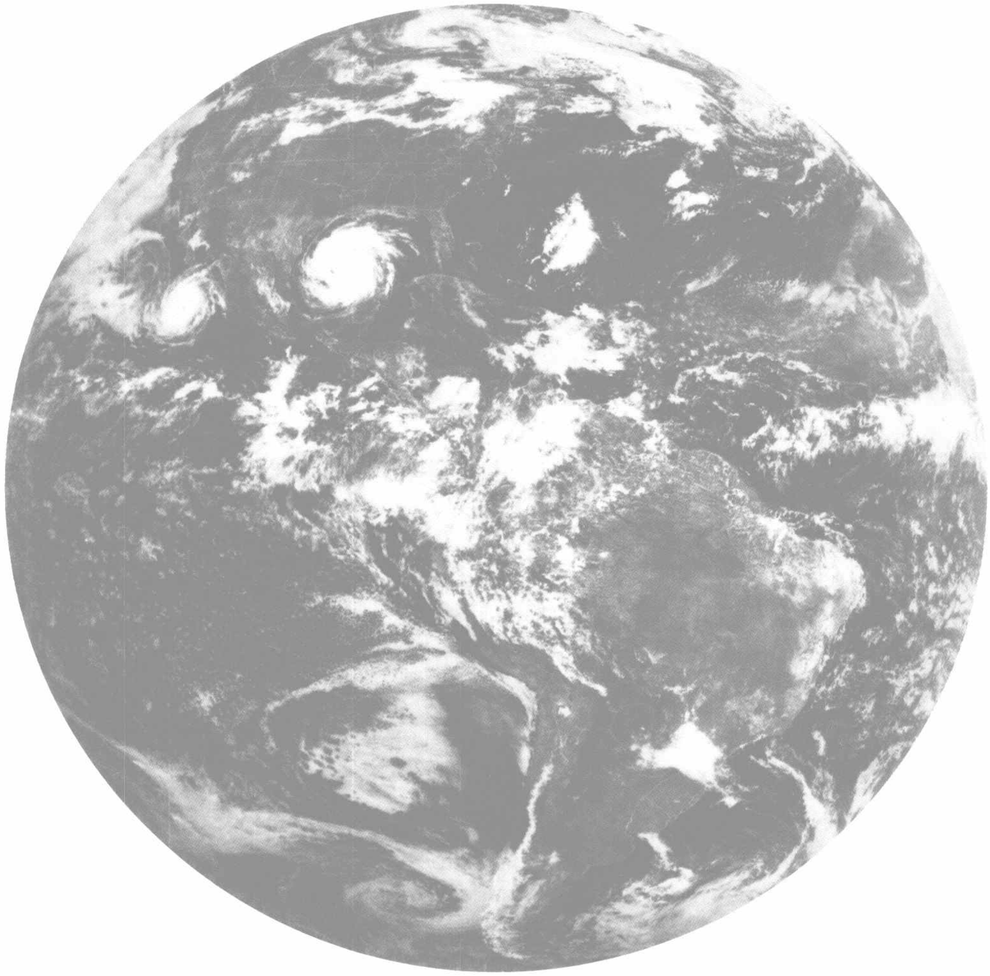


FIGURE 1.1 Earth as seen on August 8, 1980, from a satellite permanently located 22,000 miles above South America. North America is left center. The white areas are clouds; spiral ones are hurricanes. Hurricane Allen—one of the largest of the century—is in the Gulf of Mexico. Hurricane Isis is on the Pacific coast of Mexico. (Photograph courtesy of NASA)

other features that suggest that they were deposited in water. Some of these ancient rocks (3.4 billion years old) contain primitive one-celled bacterialike organisms, visible with electron microscopes. Photosynthesis of primitive aquatic plants released oxygen about 2 billion years ago, vital to the later development of complex animal life on earth.

We know little about changes in seawater composition through time. It appears that the composition of sea salt has changed little. Oxygen has probably become more abundant in the atmosphere, and consequently in the ocean, due to **photosynthesis**, which is the formation of new plant material using energy from sunlight and carbon dioxide plus water.

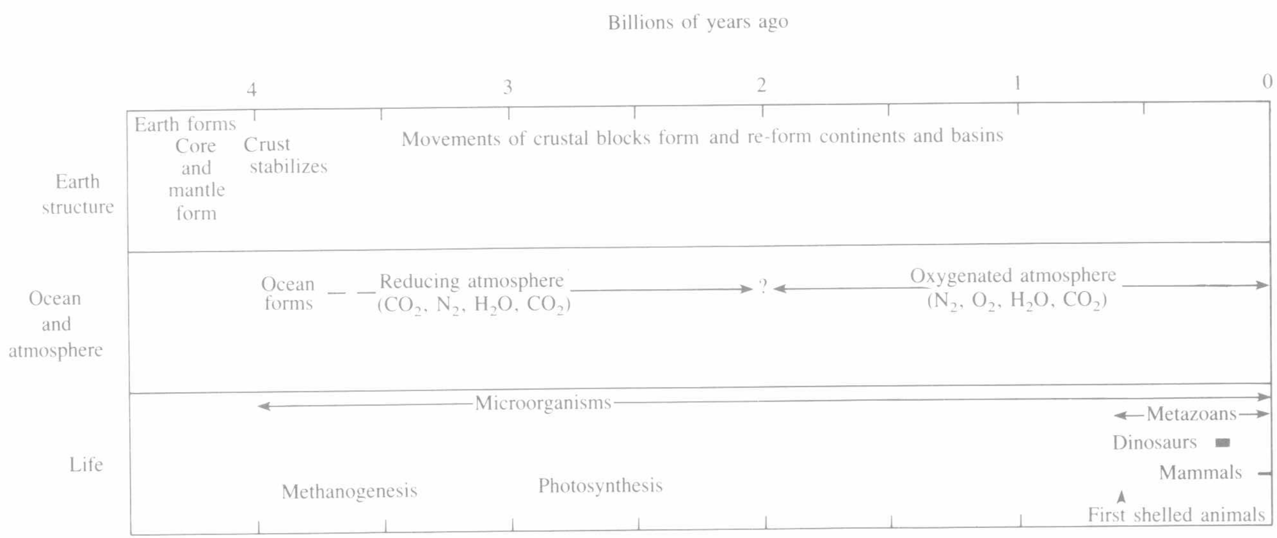


FIGURE 1.2 Schematic representation of earth history showing the development of the ocean, atmosphere, and life.

1.2 PERMANENCE OF OCEAN BASINS

Although the ocean is an ancient feature of the earth, **shorelines**—boundaries between land and water—continually change, although very slowly. *Shorelines change location as continents rise and fall or as the sea surface rises or falls relative to a stable continent.* Slow movements of continents have occurred repeatedly during earth's history and continue today. Elevated ancient beaches along the California coast and submerged Greek and Roman temples around the Mediterranean demonstrate such movements and their effects on shorelines.

Changes in the amount of seawater in the ocean also alter the sea level. For example, large and relatively sudden changes in sea level accompany the growth or disappearance of large ice sheets on land, called **glaciers**. Water stored in these continent-sized glaciers comes from the ocean. Consequently, sea level falls when glaciers form and rises when they melt (Figure 1.3).

Over the past 3 million years the earth has experienced many glacial advances and retreats. About 20,000 years ago, large areas of the northern continents were ice-covered, and the sea stood about 130 m (430 ft) below its present level (Figure 1.3). Much of the shallow, submerged edge of continents was then dry land. For example, Asia and North America were connected by land, which is now covered by shallow seas. Early humans migrated across this area from Asia to populate North and South America. Mammoths, extinct elephant-like animals, grazed on the submerged Atlantic continental margin of North America, and rivers flowed through large valleys on these now submerged lands.

When the continental glaciers melted, sea level rose (Figure 1.3), flooding river valleys. On glacier-carved, mountainous coasts, picturesque, steep-sided inlets called **fjords** were formed. If all the water remaining in the present Antarctic and Greenland ice sheets were returned to the ocean, sea level would rise about 50 m (160 ft), flooding large portions of low-lying coastal plains and many coastal cities—up to the twentieth floor in downtown New York City.

Even slower changes in shorelines occur as continents and ocean basins slowly move, driven by forces deep in the earth. This process, called plate tectonics, is discussed in Chapter 2.

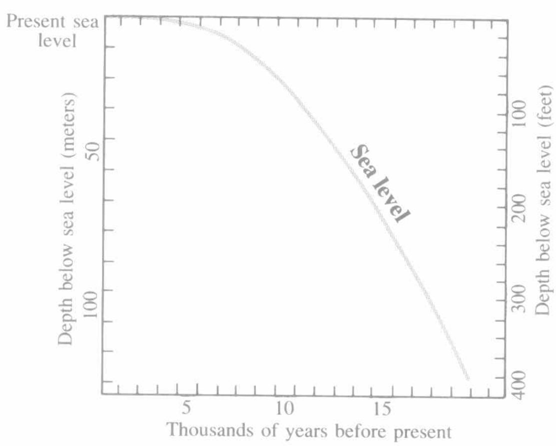


FIGURE 1.3 Change in sea level during the past 20,000 years caused by the melting and retreat of continental glaciers during the latest phase of the Ice Age.

1.3 DISTRIBUTION OF LAND AND WATER

Of the earth's surface (510 million km^2, or 197 million mi^2), the ocean covers 361 million km^2 (139 million mi^2), or 70.8%. Although the average depth of the ocean is 3.73 km (2.32 statute miles), it is insignificant (1/1700) compared to the earth's radius. Excluding water retained in pores of sedimentary rocks, the ocean contains 97% of our planet's free water (Table 1.1).

Ocean basins and continents are unevenly distributed over the earth's surface (Figure 1.4). The continental blocks generally have an oceanic area opposite it on the other side of the earth. Most land (67%) lies in the Northern Hemisphere. If the Northern Hemisphere is the land hemisphere, the Southern Hemisphere is mainly water. Not only does ocean cover 81% of the earth's surface between latitudes 40° and 65°S, but there is also almost no land to impede the atmospheric or oceanic circulation. In the Southern Hemisphere's "Roaring Forties" (around 40°S latitude) the ocean dominates. Viewed from space looking down on the South Pole (see frontispiece), *the world ocean is a broad band surrounding Antarctica with three northward-projecting gulfs.*

There is only one interconnected ocean, but for convenience oceanographers divide it into three parts: the Atlantic (including the Arctic Sea), the Indian, and the Pacific oceans (Figure 1.4). Where natural boundaries are absent, north-south lines separate the oceans. We separate the Pacific and Indian oceans by a line running southward through Indonesia and then from Australia to Antarctica along 150°E, approximately through the island of Tasmania. The islands north of Australia form a natural boundary between the Pacific and Indian oceans. Northward, the shallow Bering Strait is a partial barrier to ocean currents, as it separates the Pacific Ocean and Arctic Sea. A line between Cape Horn (the southern tip of South America) and Antarctica, at approximately longitude 60°W, divides the Pacific and Atlantic oceans.

The **Pacific Ocean**, largest of the three ocean basins, is nearly as large as the Indian and Atlantic oceans combined. It contains slightly more than half the water in the world ocean. The Pacific is the deepest ocean (average depth 3940 m, or 12,900 ft) because it includes few shallow marginal seas. It also contains many trenches, the deepest areas in the oceans; some are nearly 11,000 m (36,000 ft) deep. These trench areas of active volcanoes and frequent earthquakes form the Pacific "Rim of Fire," a region of active mountain building.

TABLE 1.1 Mass and Distribution of the Hydrosphere

	Mass (10^{15} tons)	Relative Abundance (%)
Seawater	1410	86.5
Lakes, rivers	0.5	0.03
Continental ice	22	1.3
Water vapor in atmosphere	0.013	0.001
Water in sediments and sedimentary rocks	200	12.2
Totals	1632	100

SOURCE: A. Poldervaart, "Chemistry of the Earth's Crust," Geological Society of America Special Paper 62 (1955), p. 121. Used by permission.

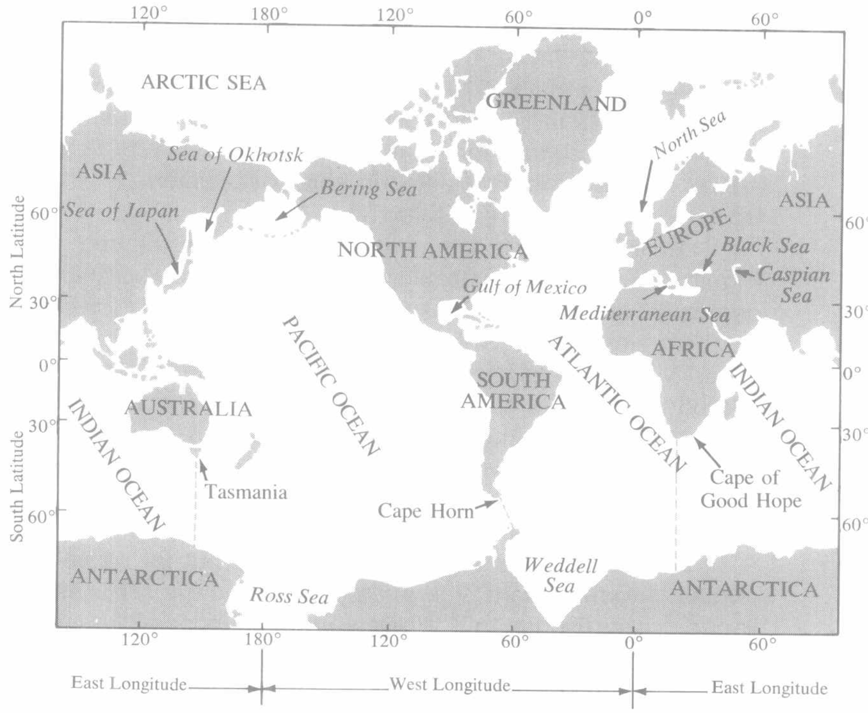


FIGURE 1.4 Continents and ocean basins, showing the boundaries of the major ocean basins.

Relatively few rivers discharge into the Pacific Oean. In fact, the surface area of the Pacific is ten times greater than that of the land drained by the streams flowing into it (Table 1.2). Thus the Pacific is less affected by continents than are the other ocean basins. Conditions in the Pacific Ocean—especially the Southern Hemisphere—most nearly resemble what we should expect on a completely water-covered earth.

TABLE 1.2 Areas and Depths of the Major Ocean Basins

Ocean Area	Water Area*		Land Area Drained†		Ratio of Water to Land	Average Depth	
	(10^6 km^2)	(10^6 mi^2)	(10^6 km^2)	(10^6 mi^2)		(km)	(mi)
Pacific	180	69.5	18	6.95	10	3.94	2.44
Atlantic	107	41.3	67	25.8	1.6	3.31	2.06
Indian	74	28.6	17	6.57	4.3	3.84	2.38
World Ocean	361	139	102	39.4	3.6	3.73	2.32

SOURCE; H. W. Menard and S. M. Smith, "Hypsometry of Ocean Basin Provinces," *Journal of Geophysical Research* 71 (1966): 4305; and J. Lyman, "Chemical Considerations," *Conference on Physical and Chemical Properties of Sea Water,* Publication 600 (Washington, D.C.: National Academy of Sciences—National Research Council, 1959), p. 89.

*Includes adjacent seas, Arctic, Mediterranean, and Black seas included in the Atlantic Ocean.

†Excludes Antarctica and continental areas with no exterior drainage.

The **Atlantic Ocean** is a relatively narrow, twisted body of water, bounded by roughly parallel continental margins. Including the Arctic Sea, the Atlantic Ocean has the greatest north-south extent; it connects the northern and southern polar regions (Figure 1.4). Because of its many shallow adjacent seas (Caribbean, Mediterranean, Baltic, Gulf of Mexico, and the Arctic Sea) and broad continental shelves, the Atlantic is the shallowest of the three oceans—its average depth is 3310 m (10,850 ft). Many rivers, including the world's two largest, the Amazon and the Congo, discharge into the Atlantic. The Atlantic's surface area is only 1.6 times the area drained by rivers flowing into it. This abundance of river discharge is noticeable in the lowered salt content in surface waters of partially enclosed seas, such as the Arctic Sea.

The Atlantic Ocean has few islands. The West Indies in the North Atlantic and the South Sandwich Islands of the South Atlantic are volcanic islands; other islands (Iceland, the Azores, St. Paul's Rocks, and Tristan da Cunha) are part of the Mid-Atlantic Ridge, a gigantic mid-ocean mountain range.

We separate the Indian and Atlantic oceans by a north-south line between the Cape of Good Hope (the southern tip of Africa) and Antarctica along longitude 20°E. The **Indian Ocean** extends only a short distance across the equator into the Northern Hemisphere; its northern limit lies at roughly 25°N. It has few islands or adjacent seas. The average depth of the Indian Ocean (3840 m, or 12,600 ft) is intermediate between the Atlantic and Pacific ocean averages. The surface area is 4.3 times as large as the area drained by streams discharging into it, such as the great Ganges and the Brahmaputra rivers, which flow from the Himalaya Mountains into the northern Indian Ocean.

The Northern Indian ocean varies radically during the year, as winds change direction seasonally. During the northeast monsoons of winter (in the Northern Hemisphere), the ocean surface currents are distinctly different from those during the southwest monsoons of summer. Some currents reverse direction seasonally.

Island groups, such as the Japanese Islands or the Aleutians, or land barriers, like the Kamchatka Peninsula, isolate parts of the coastal ocean, forming **seas**. Most of these seas have distinctive features because of (1) restricted communication with the open ocean, (2) the influence of the adjacent continent, such as dry cold winds, and (3) usually excess precipitation and river discharge.

Largest of the partially isolated (marginal) seas, the **Arctic Sea** forms a nearly isolated northern extension of the Atlantic Ocean (see frontispiece). Including this northern part, which extends across the pole down to the shallow Bering Strait at 66°N, the Atlantic Ocean extends to about 70°S, halfway around the earth in a north-south direction. The Arctic Sea waters are diluted by discharges of several large rivers, such as the Lena and Yenisei rivers of Asia. These and other rivers keep Arctic surface waters substantially less salty than the adjacent North Atlantic Ocean. Sea ice covers approximately 70% of the Arctic Sea throughout the year. During the Northern winter, nearly all the Arctic is covered by sea ice.

Next in size are the **Caribbean Sea–Gulf of Mexico** between North and South America and the **Mediterranean Sea** between Europe and Africa. Both lie near 30°N in the warm subtropical climate belt and include the earth's great deserts. Each is characterized by excess **evaporation**. (That is, more water is removed by evaporation than comes in from river discharge or precipitation.) Even the Mississippi River flowing into the northern Gulf of Mexico does not contribute enough fresh water to compensate for excess evaporation. Consequently, surface waters of both these seas are characterized by higher salt contents than the rest of the ocean.

The **Black Sea** is connected to the Mediterranean by the Bosporus, a narrow channel with a mean width of 700 m (slightly less than half a mile) and a minimum depth of approximately 40 m (130 ft). Such a restricted channel does not permit free communication with the Mediterranean Sea. At times in the past this tenuous connection with the world ocean has been completely severed. The **Caspian Sea**, to the east of the Black Sea, was also once connected with the world ocean. Subsequent movements of Africa and Asia and changes in sea level have eliminated its connection.

1.4 GENERAL CHARACTERISTICS OF THE OCEAN

General features of the ocean have been known for decades. *The ocean basins are interconnected, so processes acting in the most remote basin eventually affect all the ocean.* For example, the warm, arid climate around the Mediterranean Sea causes marked evaporation and hence makes the surface waters saltier than the adjacent Atlantic. Warm, salty water from the Mediterranean enters the Atlantic Ocean along the bottom of the Strait of Gibraltar and can be detected about 1.5 km (1 mi) below the surface over a large part of the Atlantic before losing its identity by mixing with waters above and below. This injection of saline waters makes the North Atlantic waters the saltiest in the world ocean.

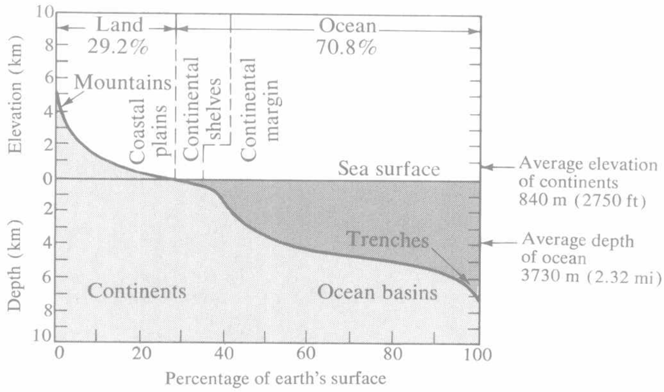
We assume that the deep waters of the world ocean are changing very slowly, if at all, with time. This so-called **steady state assumption** permits oceanographers to use data taken as much as 100 years ago to study deep-ocean processes. The importance of this assumption is evident when one considers the enormous area of the ocean and the difficulty of getting simultaneous data. An important recent advance in ocean sciences is the ability to detect slight changes in temperature or salinity of deep ocean waters.

Because of the ocean's great age and slow rate of change, seawater is generally well mixed. Bottom water in the deep ocean returns to the surface in 500 to 1000 years, and the oceans have apparently existed for 4 billion years. Thus ocean waters must have been mixed several million times. Because of this thorough mixing, the relative abundance of individual sea salts are nearly identical, regardless of where the samples are collected. The apparently uniform chemical composition of the ocean arises from its long history and from our restricted vantage point, covering about 100 years for a feature that has existed at least 40 million times as long.

1.5 ELEVATIONS, DEPRESSIONS, AND CRUSTAL STRUCTURE

Mountains higher than 6000 m (19,700 ft) are rare (Figure 1.5). So are parts of the ocean floor deeper than 6000 m. These extreme heights or depths constitute less than 1% of the earth's surface. We also find that average ocean depth is 3730 m (12,200 ft) and that average land elevation is approximately 850 m (2790 ft). The average level of the earth's crust is 2430 m (8000 ft) below sea level. In other words, *if we leveled the continents and filled the ocean basins with the debris, the earth would be covered uniformly by water about 1.5 mi deep.*

FIGURE 1.5 Hypsometric curve showing the percentage of the earth's surface above any given depth or elevation. [After H. U. Sverdrup, M. W. Johnson, and R. H. Fleming. *The Oceans: Their Physics, Chemistry, and General Biology.* (Englewood Cliffs, N.J.: Prentice-Hall, Inc., 1942), p. 19]



Elevations and depths on the earth's crust have two dominant levels. One, averaging around 300 m (980 ft) above sea level, is the continental surface. The other, between 4000 and 5000 m (13,000 and 16,000 ft) below sea level, is deep-ocean bottom.

These two levels are the result of fundamental differences in composition between the crust forming continents and ocean basins. *Continents are made of granitic rocks (rich in silica and aluminum) with densities (mass per unit volume) of about 2.8 g/cm^3. The oceanic crust consists of basaltic rocks (rich in iron and magnesium) with an average density of about 3.0 g/cm^3. The earth's crusts float as rigid blocks on the underlying nearly liquid mantle, with an average density of about 4.5 g/cm^3.* Continents float higher than the ocean basins because granitic rocks are less dense than basaltic rocks.

The ocean floor at depths less than 2000 m (6500 ft) generally exhibits continental-type structures. At depths greater than 4000 m (13,000 ft), it usually has a thin basaltic oceanic-type crust, quite unlike that of the continents.

1.6 TECHNIQUES FOR OCEAN STUDIES

Large ship-mounted (Figure 1.6) expeditions have long been the hallmark of ocean studies, but that is changing rapidly. Until about 1950, large oceanographic expeditions were usually mounted by a single country, as in the case of the *Challenger* (Great Britain) and *Meteor* (Germany) expeditions. But the enormous areas involved and the increasing need for more detailed observations taken at nearly the same time led to international expeditions and long-term research. Studies of the ocean and its effect on the atmosphere increasingly require international efforts using many types of "platforms." Satellites are now major contributors to such studies and promise to become even more important in the future (Figure 1.7).

In the 1950s, study of ocean basins accelerated because of the availability of detailed maps of ocean areas previously uncharted. The results of those investigations have led to a new concept of the earth's crust, known as plate tectonics or seafloor spreading, discussed in Chapter 2. Answering questions of earth history requires samples of sediment deposits and rock from the ocean bottom well beyond the capabilities of normal oceanographic ships. Special ships now drill in the deep waters

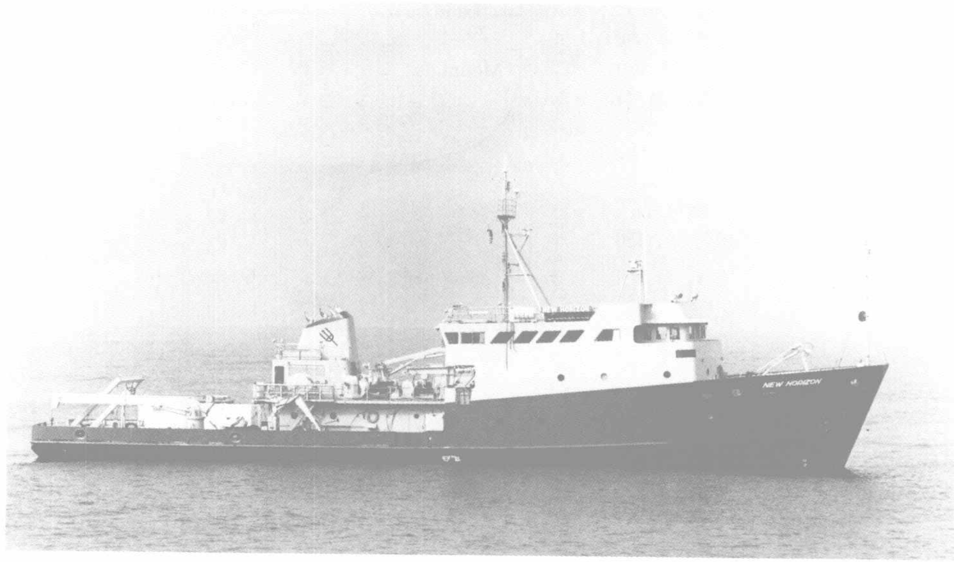


FIGURE 1.6 The research vessel *New Horizon*, operated by the Scripps Institution of Oceanography, supports research by oceanographers in all disciplines. (Photograph courtesy of Scripps Institution of Oceanography, University of California, San Diego)

FIGURE 1.7 SEASAT-A was launched in 1978 to measure ocean conditions from an altitude of 800 km (500 mi). The satellite circled the earth 14 times daily, returning every 3 days to each part of the ocean. Data from the sensors on this satellite provided the first data on global ocean conditions for 100 days. (Drawing courtesy of NASA)