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Fundamentals of OCEANOGRAPHY Fifth Edition

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Higher Education

FUNDAMENTALS OF OCEANOGRAPHY, FIFTH EDITION

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We shall not cease from exploration And the end of all our exploring Will be to arrive where we started And know the place for the first time. Through the unknown, remembered gate When the last of earth left to discover Is that which was the beginning; At the source of the longest river The voice of a hidden waterfall . . . Not known, because not looked for, But heard, half heard, in the stillness Between two waves of the sea.

T.S. Eliot From "Little Gidding," The Four Quartets

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Preface

Fundamentals of Oceanography is intended for professors and students who need a more basic oceanography text to better serve less intensive college oceanography courses, courses tailored for nonscience majors interested in learning more about the fascinating, and often mysterious, marine world that covers 71% of Earth's surface and yet is more poorly mapped than the surface of the Moon. This fifth edition is an extensive revision in response to the suggestions and ideas of instructors as well as advances in the ocean sciences. Our goal in this edition is to provide students with up-to-date information, and to make each chapter as clear and readable as possible without sacrificing scientific accuracy. This fifth edition continues to emphasize principles, processes, and properties of the oceans.

Because oceanography embraces immense amounts of geological, physical, chemical, biological, and engineering information related to the marine environment, and because of the interdependency among these subject areas, the choice of topics to be included in a fundamentals text presents a complex challenge. We have endeavored to choose those topics that best illustrate basic processes and at the same time answer students' questions about the oceans while encouraging their interest. We invite instructors to change the sequence of material to best fit their own presentations and to elaborate on subjects as desired.

Eleven *Items of Interest* are included in this edition to cover issues that are not addressed directly in the text. In chapter 2 new sections have been added discussing the origin of the oceans and evidence for extraterrestrial oceans in our solar system. The discussion of plate tectonics and plate boundaries in chapter 3 has been extensively revised, and a number of new figures have been added. In chapter 5 the section on carbon dioxide as a buffer has been rewritten and expanded. The discussion of El Niño-Southern Oscillation in chapter 6 has been completely revised, and new figures have been added to further illustrate it. Chapter 7 updates information about the National Energy Laboratory in Hawaii and The Great Sneaker Spill. Waves and Tides (chapter 8) has been reviewed and revised with special emphasis placed on wave sorting, tidal forces, and energy from tidal currents. Environmental issues in chapter 9 have also been updated. All primary production values in chapter 10 are new, and new information on ice worms and the Lost City vent field has been included. Chapter 11 has been extensively rewritten: information on bacteria and red tides has been updated, and a section on viruses has been added; also all fisheries data have been amended from the last available FAO reports. Chapter 12 contains new information on tropical coral reefs and deep water coral reefs; benthic harvests are extracted from the latest available FAO data. Short essays on the responsibilities of a chief scientist and ship's Captain in planning and executing a successful oceanographic expedition have been included in the middle of the text (following chapter six).

Fundamentals of Oceanography continues to present students with numerous aids to facilitate their study of oceanography. Each chapter opens with learning objectives, and review questions are presented as self-checks for the student at the end of each section. Throughout this text, information is presented in table form to help the student organize, summarize, and compare. Chapters end with a concise summary to aid in review, a list of key terms, critical thinking questions to encourage reflection about chapter topics, suggested readings to explore subjects in more detail, and Internet references related to topics of discussion. Internet reference symbols have also been added to figure captions in the text where appropriate. Three appendices are included: (1) methods of deriving latitude and longitude, (2) taxonomic classifications of plankton, nekton, and benthos, and (3) scientific notation and units. All quantities in the text are given in both metric and traditional units.

Instructor Supplements

McGraw-Hill offers a variety of supplements to assist instructors with both preparation and classroom presentation.

The Digital Content Manager CD-ROM set is a multimedia collection that offers a wide selection of photos, figures, and tables from the text, as well as additional photos, animations, and 34 videos from Scripps Institution of Oceanography. The Digital Content Manager CD allows instructors to utilize these assets in multiple formats to create customized classroom presentations, dynamic course website content, or attractive printed support materials. The digital resources on this crossplatform 2 CD-ROM set are grouped within easy-to-use folders and organized by chapter. The Digital Content Manager CD set is a shared tool with Sverdrup/Duxbury/Duxbury: An Introduction to the World's Oceans, 8th edition, and the correlation guide to this Fundamentals of Oceanography, 5th edition text can be found within the Online Learning Center at www.mhhe.com/sverdrup5. The Scripps video segments included on the Digital Content Manager CD are also available to instructors on videocassette.

A text-specific Online Learning Center, which can be found at www.mhhe.com/sverdrup5, provides resources for both students and instructors. The password-protected Online Learning Center contains the Instructor's Manual, which includes answers to the Study Questions and Study Problems from the text, and PowerPoint Lecture Outlines for each chapter.

The Instructor's Testing and Resource CD is a cross-platform tool that contains questions specific to each chapter to help instructors generate tests, and also contains an Instructor's Manual

which includes the Answers to Critical Thinking Questions from the text, as well as Internet Exercises for each chapter. A set of overhead transparencies provides 100 figures from the text in full color. These ancillaries are available to instructors through their McGraw-Hill sales representative.

The Classroom Performance System (CPS) brings interactivity into the classroom. CPS is a student response system using wireless connectivity. It gives instructors the ability to create their own questions and receive immediate feedback from each student in the class. CPS is a great tool for engaging students in lecture and assessing student comprehension of discussion topics. For more information on CPS, contact your Mc-Graw-Hill Sales Representative, or the McGraw-Hill Customer Service Department at 1-800-338-3987.

For instructors wishing to incorporate hands-on oceanography exercises into their course, McGraw-Hill offers an exceptional workbook entitled "Investigating the Ocean" by R. Leckie and R. Yuretich of University of Massachusetts-Amherst. Additional earth science supplements offered by McGraw-Hill appropriate for this course include the "Journey Through Geology" CD-ROM by the Smithsonian Institution and a geoscience videotape library. Contact your McGraw-Hill sales representative for details on these products.

Student Supplements

The Internet makes oceanographic information and data available to researchers and it also provides images and information in many forms to instructors and students. Public agencies and museums, universities and research laboratories, satellites and oceanographic projects, interest groups and individuals all over the planet provide information that can be publicly accessed. The text-specific Online Learning Center (OLC) website, which can be found at www.mhhe.com/sverdrup5, provides chaptersorted links to many websites that contain information pertinent to each chapter's content. In addition, web links are provided within the OLC for further information on many figures and boxed readings within each chapter. Wherever you see the web link icon web hink in your textbook, you will find associated web links for the indicated figure or boxed reading on the OLC. The OLC also hosts a complete Student Study Guide, chapter quizzing, interactive key term flashcards, animations, and Internet exercises to help with chapter study.

Acknowledgments

We acknowledge that this book is a product of many experiences in the field, at sea, and in the classroom. We extend our thanks to many friends and colleagues who have graciously answered our questions, helped us with current information, and provided access to their photo files. We particularly thank:

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University of Texas-Dallas

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Departure of the USS Constitution, "Old Ironsides," after 116 years in dock, July 1997, Boston, MA.



Chapter

History of Oceanography

LEARNING OBJECTIVES

After reading this chapter, you should be able to

- Understand the diversity of the sciences collected to form "oceanograph
- Understand the development of oceanography as a science.
- Follow the development of ocean knowledge from early voyages of exploration and discovery.
- Understand the significance of navigation in describing the oceans and making accurate maps of their extent and boundaries.
- Recognize the contributions of early U.S. oceanography to the developme of marine commerce.
- Understand the role of early scientific voyages in the investigation of the world's oceans.
- Recognize the role of U.S. agencies in developing oceanography before a after World War II.
- Recognize the relationship between technology, international cooperation and the development of recent large-scale oceanographic programs.
- Discuss the programs being planned for the future.

Chapter Outline

- 1.1 The Early Times
- 1.2 The Middle Ages
- 1.3 Voyages of Discovery
- 1.4 The Importance of Charts and Navigational Information
- 1.5 Ocean Science Begins
- **1.6** The *Challenger* Expedition
- 1.7 Exploratory Science

Marine Archaeology & Maritime History—Item of Interest

- 1.8 Oceanography in the Twentieth Century
- 1.9 Oceanography of the Recent Past, Present, and the Future

Summary

Critical Thinking

Suggested Readings

Online Learning Center

ceanography is a broad field in which many sciences focus on the common goal of understanding the oceans. Geology, geography, geophysics, physics, chemistry, geochemistry, mathematics, meteorology, botany, and zoology all play roles in expanding our knowledge of the oceans. Geological oceanography includes the study of Earth at the sea's edge and below its surface and the history of the processes that formed the ocean basins. Physical oceanography investigates the causes and characteristics of water movement such as waves, currents, and tides and how they affect the marine environment. It also studies the transmission of energy such as sound, light, and heat in seawater. Marine meteorology (the

oceans. Ocean engineering is the discipline of designing and planning equipment and installations for use at sea.

Our progress toward the goal of understanding the oceans has been uneven, and it has frequently changed direction. The interests and needs of nations as well as the intellectual curiosity of scientists have controlled the rate at which we study the oceans, the methods we use to study them, and the priority we give to certain areas of study. To gain some perspective on the current state of knowledge about the oceans, we need to know something of the events and incentives that guided previous in-

study of heat transfer, water cycles, and air-sea interactions) is

often included in the discipline of physical oceanography.

Chemical oceanography studies the composition and history of

seawater, its processes, and its interactions. Biological oceanog-

raphy concerns itself with the marine organisms and the rela-

tionship between these organisms and the environment in the

1.1 The Early Times

vestigations of the oceans.

People have been gathering information about the oceans for millennia, passing it on by word of mouth. Curious individuals must have acquired their first ideas of the oceans from wandering the seashore, wading in the shallows, and gathering food from the ocean's edges. As early humans moved slowly away from their inland centers of development, they took advantage of the sea's food sources when they first explored and later settled along the ocean shore. The remains of shells and other refuse found at the sites of ancient shore settlements show that our early ancestors gathered shellfish, and certain fish bones

suggest that they also began to use rafts or some type of boat for offshore fishing. Some scientists think that many more artifacts have been lost or scattered as a result of rising sea level. It is very likely that the artifacts that have been found only give us an idea of the minimum extent of ancient shore settlements.

Early information about the oceans was mainly collected by explorers and traders. These voyages left little in the way of recorded information. Using descriptions passed down from one voyager to another, early sailors piloted their way from one landmark to another, sailing close to shore and often bringing their boats up onto the beach each night.

Some historians believe that seagoing ships of all kinds are derived from early Egyptian vessels. The first recorded voyage by sea was led by Pharaoh Snefru about 3200 B.C. In 2750 B.C. Hannu led the earliest documented exploring expedition from Egypt to the southern edge of the Arabian Peninsula and the Red Sea.

The Phoenicians, who lived in present-day Lebanon from about 1200 B.C. to 146 B.C., were well known as excellent sailors and navigators. While their land was fertile it was densely populated so they were compelled to engage in trade with others to acquire many of the goods they needed. They accomplished this by establishing land routes to the East and marine routes to the West. The Phoenicians were the only nation in the region at that time who had a navy. They traded throughout the Mediterranean Sea with the inhabitants of North Africa, Italy, Greece, France, and Spain. They also ventured out of the Mediterranean Sea to travel north along the coast of Europe to the British Isles and south to circumnavigate Africa in about 590 B.C. In 1999 the wreckage of two Phoenician cargo vessels circa 750 B.C. was explored using remotely operated vehicles (ROVs) that could dive to the wreckage and send back live video images of the ships. The ships were discovered about 48 km (30 mi) off the coast of Israel at depths of 300 to 900 m (roughly 1000-3000 ft).

Extensive migration throughout the Southwestern Pacific may have begun by 2500 B.C. These early voyages were relatively easy because of the comparatively short distance between islands in the far Southwestern Pacific region. By 1500 B.C. the Polynesians had begun more extensive voyages to the east where the distance between islands grew from tens of miles at the edge of the western Pacific to thousands of miles in the case

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of voyages to the Hawaiian Islands. They successfully reached and colonized the Hawaiian Islands sometime between A.D. 450 and 600. By the eighth century A.D., they had colonized every habitable island in a triangular region roughly twice the size of the United States bound by Hawaii on the north, New Zealand in the southwest, and Easter Island to the east.

A basic component of navigation throughout the Pacific was the careful observation and recording of where prominent stars rise and set along the horizon. Observed near the equator, the stars appear to rotate from east to west around Earth on a north-south axis. Some rise and set farther to the north and some farther to the south, and they do so at different times. Navigators created a "star structure," dividing the horizon into 32 points where the stars for which the points are named rise and set. These points form a compass that provides a reference for recording information about the direction of winds, currents, waves, and the relative positions of islands, shoals, and reefs (fig. 1.1). The Polynesians also navigated by making close observations of waves and cloud formations. Observations of birds and the distinctive smells of land such as flowers and wood smoke alerted them to possible landfalls. Once islands had been discovered, their locations relative to one another and to the regular patterns of sea swell and waves bent around islands could be recorded with stick charts constructed of bamboo and shells (fig. 1.2).

As early as 1500 B.C. Arabs of many different ethnic groups and regions were exploring the Indian Ocean. In the seventh century A.D. they were unified under Islam and began to control the

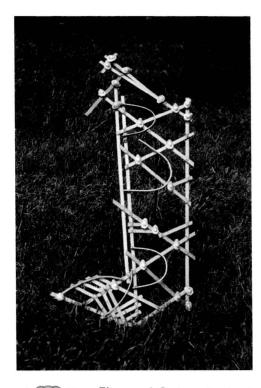
trade routes to India and China and consequently the commerce in silk, spices, and other valuable goods (this monopoly wasn't broken until Vasco da Gama defeated the Arab fleet in 1502).

These early sailors did not investigate the oceans; for them the sea was only a dangerous road, a pathway from here to there. This situation continued for hundreds of years. However, the information that they accumulated became a body of lore to which sailors and voyagers added from year to year.

While the Greeks traded and warred throughout the Mediterranean, they observed and also asked themselves questions about the sea. Aristotle (384–322 B.C.) believed that the ocean occupied the deepest parts of Earth's surface; he knew that the Sun evaporated water from the sea surface, which condensed and returned as rain. He also began to catalog marine organisms. The brilliant Eratosthenes (c. 265–194 B.C.) of Alexandria, Egypt, mapped his known world and calculated Earth's circumference to be about 40,250 kilometers (km) or 25,000 miles (mi) (today's measurement is 40,067 km or 24,881 mi). Posidonius (c. 135-50 B.C.) reportedly measured an ocean depth to about 1800 meters (6000 ft) near the island of Sardinia, according to the Greek geographer Strabo (c. 63 B.C.-c. A.D. 21). Pliny the Elder (A.D. 23-79) related the phases of the Moon to the tides and reported on the currents moving through the Strait of Gibraltar. Ptolemy, in A.D. 127-151,



web Ink Figure 1.1 On Satawal Island master navigator Mau Piailug teaches navigation to his son and grandson with the help of a star compass. The compass consists of an outer ring of stones, each representing a star or a constellation when it rises or sets on the horizon, and an inner ring of pieces of palm leaf representing the swells which travel from set directions and which together with the stars help the navigator find his way over the sea. In the center of the ring, the palm leaves serve as a model outrigger canoe.



web hink Figure 1.2 A navigational chart (rebillib) of the Marshall Islands. Sticks represent a series of regular wave patterns (swells). Curved sticks show waves bent by the shorelines of individual islands. Islands are represented by shells.

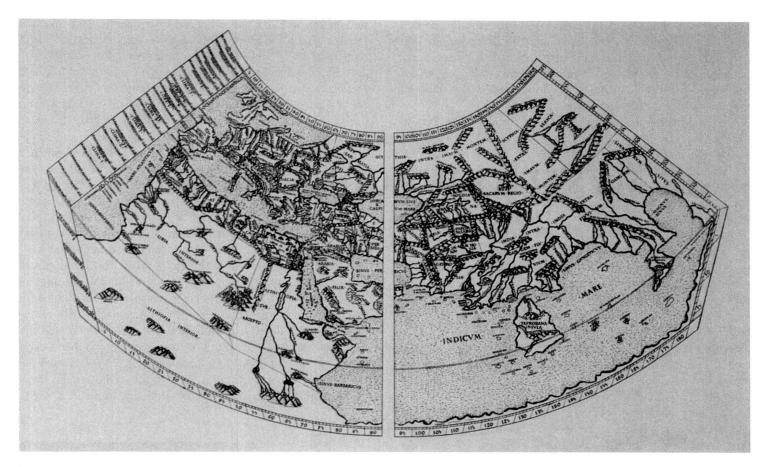


Figure 1.3 A chart from an Italian fifteenth-century edition of Ptolemy's Geographia.

produced the first world atlas and established world boundaries: to the north the British Isles, northern Europe, and the unknown lands of Asia; to the south an unknown land, "Terra Australis Incognita," including Ethiopia, Libya, and the Indian Sea; to the east China; and to the west the great Western Ocean reaching around Earth to China on the other side (fig. 1.3). His atlas listed more than 8000 places by latitude and longitude, but his work contained a major error: he had accepted a value of 29,000 km (18,000 mi) for Earth's circumference. This shortened Earth distances and allowed Columbus, more than a thousand years later, to believe that he had reached the eastern shore of Asia when he landed in the Americas.

Name the subfields of oceanography.

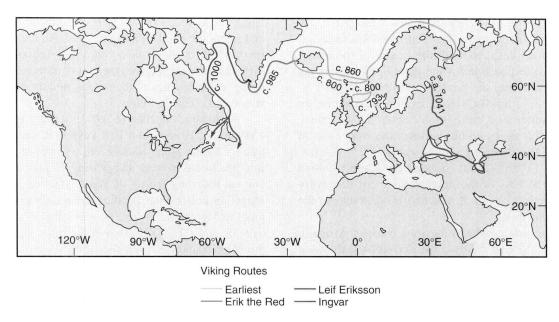
What did early sailors use for guidance during long ocean voyages?

What kind of "compass" did the Polynesians use for navigation?

How long ago was Earth's circumference first calculated? How did Ptolemy's atlas contribute to a greater understanding of world geography, and how did it produce confusion?

1.2 The Middle Ages

After Ptolemy, intellectual activity and scientific thought declined in Europe for about one thousand years. However, shipbuilding improved during this period; vessels became more seaworthy and easier to sail allowing sailors to extend their voyages. The Vikings (Norse for *piracy*) were highly accomplished seamen who engaged in extensive exploration, trade, and colonization for nearly three centuries from about 793 to 1066 (fig. 1.4). During this time they journeyed inland on rivers through Europe and western Asia, traveling as far as the Black and Caspian Seas. The Vikings are probably best known for their voyages across the North Atlantic Ocean. They sailed to Iceland in 871 where as many as 12,000 immigrants eventually settled. Erik Thorvaldsson (known as Erik the Red) sailed west from Iceland in 982 and discovered Greenland. He lived there for three years before returning to Iceland to recruit more settlers. Icelander Bjarni Herjolfsson, on his way to Greenland to join the colonists in 985-6, was blown off course, sailed south of Greenland, and is believed to have come within sight of Newfoundland before turning back and reaching Greenland. Leif Eriksson, son of Erik the Red, sailed west from Greenland in 1002 and reached North America roughly 500 years before Columbus.



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Figure 1.4 Major routes of the Vikings to the British Isles, to Asia, and across the Atlantic to Iceland, Greenland, and North America.

To the south, in the Mediterranean region after the fall of the Roman Empire, the Arabs preserved the knowledge of the Greeks and the Romans, on which they continued to build. The Arabic writer El-Mas'údé (d. 956) gave the first description of the reversal of the ocean currents due to the seasonal monsoon winds. Using this knowledge of winds and currents, the Arabs established regular trade routes across the Indian Ocean. In the 1200s large Chinese junks with crews of 200 to 300 sailed the same routes (between China and the Persian Gulf) as the Arab dhows.

During the Middle Ages, while scholarship about the sea remained static, the knowledge of navigation increased. Harborfinding charts, or *portolanos*, appeared. These charts carried a distance scale and noted hazards to navigation, but they did not have latitude or longitude. With the introduction of the magnetic compass to Europe from Asia in the thirteenth century, compass directions were added. One example, a Dutch navigational chart from Johannes van Keulen's *Great New and Improved Sea-Atlas or Water-World* of 1682–84, is shown in figure 1.5.

As scholarship was reestablished in Europe, Arabic translations of early Greek studies were translated into Latin, which made them again available to northern European scholars. By the 1300s, Europeans had established successful trade routes, including some partial ocean crossings. An appreciation of the importance of navigational techniques grew as trade routes were extended.

What advances occurred during the Middle Ages that allowed longer ocean voyages?

During the tenth century, which oceans were explored and by what people?

Where did the Vikings establish a large colony in the North Atlantic?

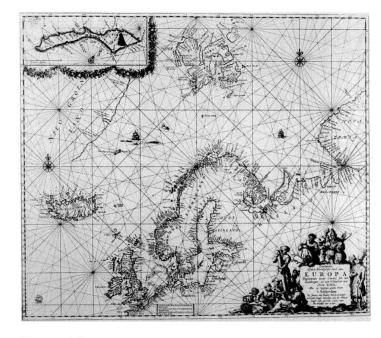


Figure 1.5 A navigational chart of northern Europe from Johannes van Keulen's *Sea-Atlas* of 1682–84.

1.3 Voyages of Discovery

Early in the fifteenth century the Chinese organized seven voyages to explore the Pacific and Indian Oceans. More than 300 ships, one more than 122 m (400 ft) long, participated in these ventures to extend Chinese influence and demonstrate the power of the Ming dynasty. The voyages ended in 1433 when their explorations led the Chinese to believe that other societies had little to offer, and the government of China withdrew within its borders beginning a 400-year period of isolation.

In Europe the desire for riches from new lands persuaded wealthy individuals, often representing their countries, to underwrite the costs of long voyages to all the oceans of the world. The individual most responsible for the great age of European discovery was Prince Henry the Navigator (1394–1460) of Portugal. He established a naval observatory for the teaching of navigation, astronomy, and cartography about 1450. Prince Henry sent expedition after expedition down the west coast of Africa to secure trade routes and to establish colonies. Bartholomeu Dias (1450?–1500) rounded the Cape of Good Hope in 1487 in the first of the great voyages of discovery (fig. 1.6). Dias sailed in search of new and faster routes to the spices and silks of the East.

Portugal's slow progress down the west coast of Africa in search for a route to the east finally came to fruition with Vasco da Gama (1469–1524). In 1498 he followed Bartholomeu Dias' route to the Cape of Good Hope and then continued beyond along the eastern coast of the African continent. He successfully mapped a route to India but was challenged along the way by Arab ships. In 1502, da Gama returned with a flotilla of 14 heavily armed ships and defeated the Arab fleet. By 1511, the Portuguese mastered the spice routes and had access to the Spice Islands. In 1513, Portuguese trade extended to China and Japan.

Christopher Columbus (1451–1506) made four voyages across the Atlantic Ocean in an effort to find a new route to the East Indies by traveling west rather than east. By relying on inaccurate estimates of Earth's size he badly underestimated the distances involved and believed he had found islands off the coast of Asia when he reached the New World. The Italian navigator Amerigo Vespucci (1454–1512) made several voyages to the New World (1499–1504) for Spain and Portugal; he accepted South America as a new continent, not part of Asia. In 1507, the German cartographer Martin Waldseemüller applied the name "America" to the continent in Vespucci's honor. Vasco

Nuñez de Balboa (1475–1519) crossed the Isthmus of Panama and found the Pacific Ocean in 1513. All claimed the new lands they found for their home countries. Although they had sailed for riches, not knowledge, they more accurately documented the extent and properties of the oceans, and the news of their travels stimulated others to follow.

Ferdinand Magellan (1480–1521) left Spain in September, 1519 with 270 men and five vessels in search of a westward passage to the Spice Islands. The expedition lost two ships before finally discovering and passing through the Strait of Magellan and rounding the tip of South America in November 1520. Magellan crossed the Pacific Ocean and arrived in the Philippines in March 1521 where he was killed in a battle with the natives on April 27, 1521. Two of his ships sailed on and reached the Spice Islands in November 1521 where they loaded valuable spices for a return home. In an attempt to guarantee that at least one ship made it back to Spain the two ships parted ways. The Victoria continued sailing west and successfully crossed the Indian Ocean, rounded Africa's Cape of Good Hope, and arrived back in Spain on September 6, 1522 with 18 of the original crew. This was the first circumnavigation of Earth (fig. 1.7). Magellan's skill as a navigator makes his voyage probably the most outstanding single contribution to the early charting of the oceans. In addition, during the voyage he established the length of a degree of latitude and measured Earth's circumference.

By the latter half of the sixteenth century, adventure, curiosity, and hopes of finding a trading shortcut to China spurred efforts to find a sea passage around the north side of North America. Sir Martin Frobisher (1535?–94) made three voyages in the 1570s, and Henry Hudson (d. 1611) made four voyages between 1607 and 1610, dying with his son when set adrift in Hudson Bay by his mutinous crew. The Northwest Passage continued to beckon, and William Baffin (1584–1622) made two attempts in 1615 and 1616.

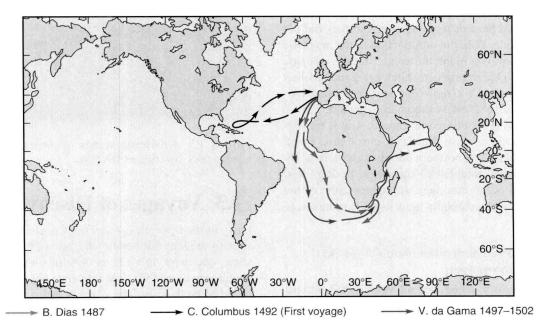




Figure 1.6 The routes of Bartholomeu Dias and Vasco da Gama around the Cape of Good Hope and Christopher Columbus's