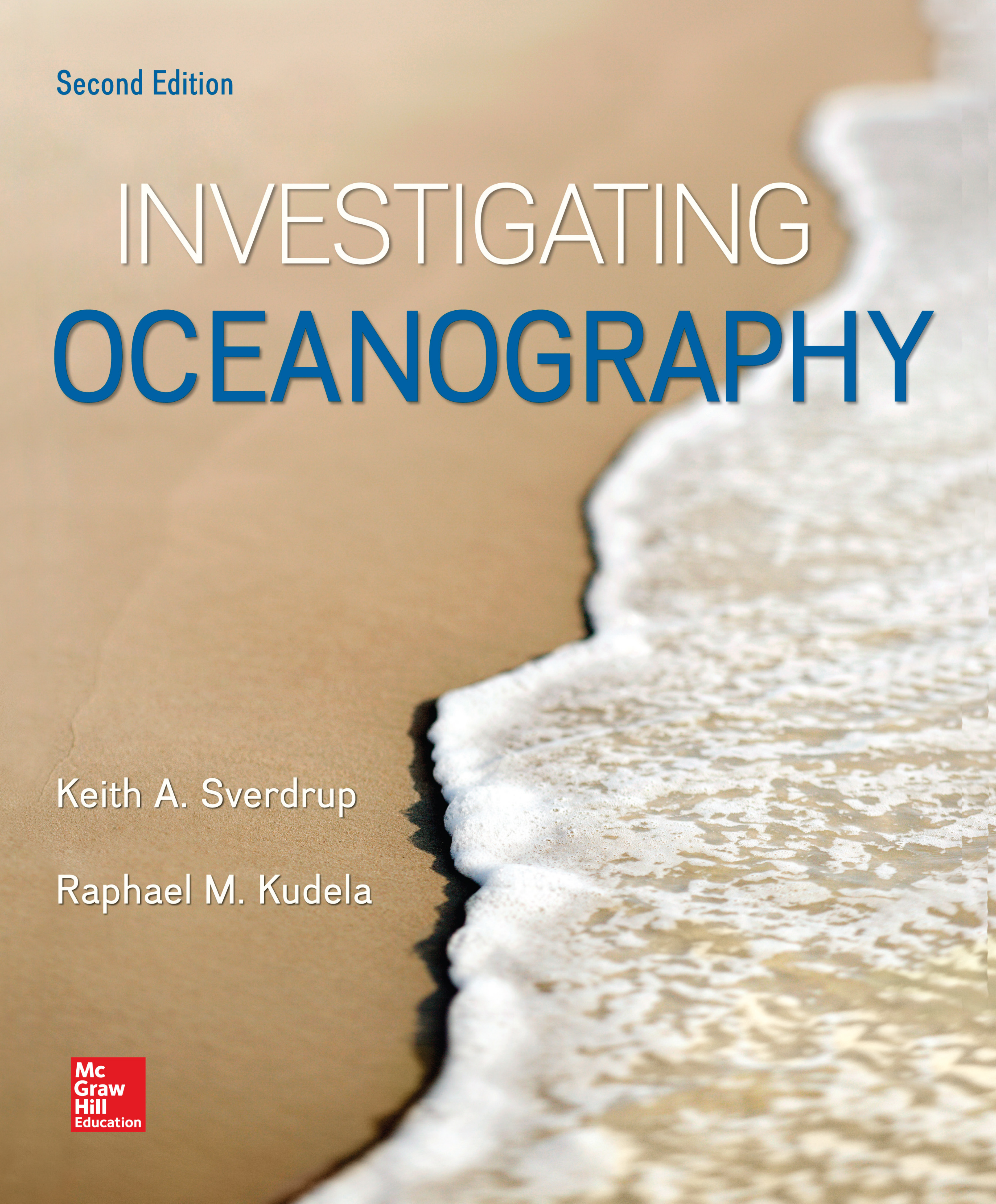


Second Edition

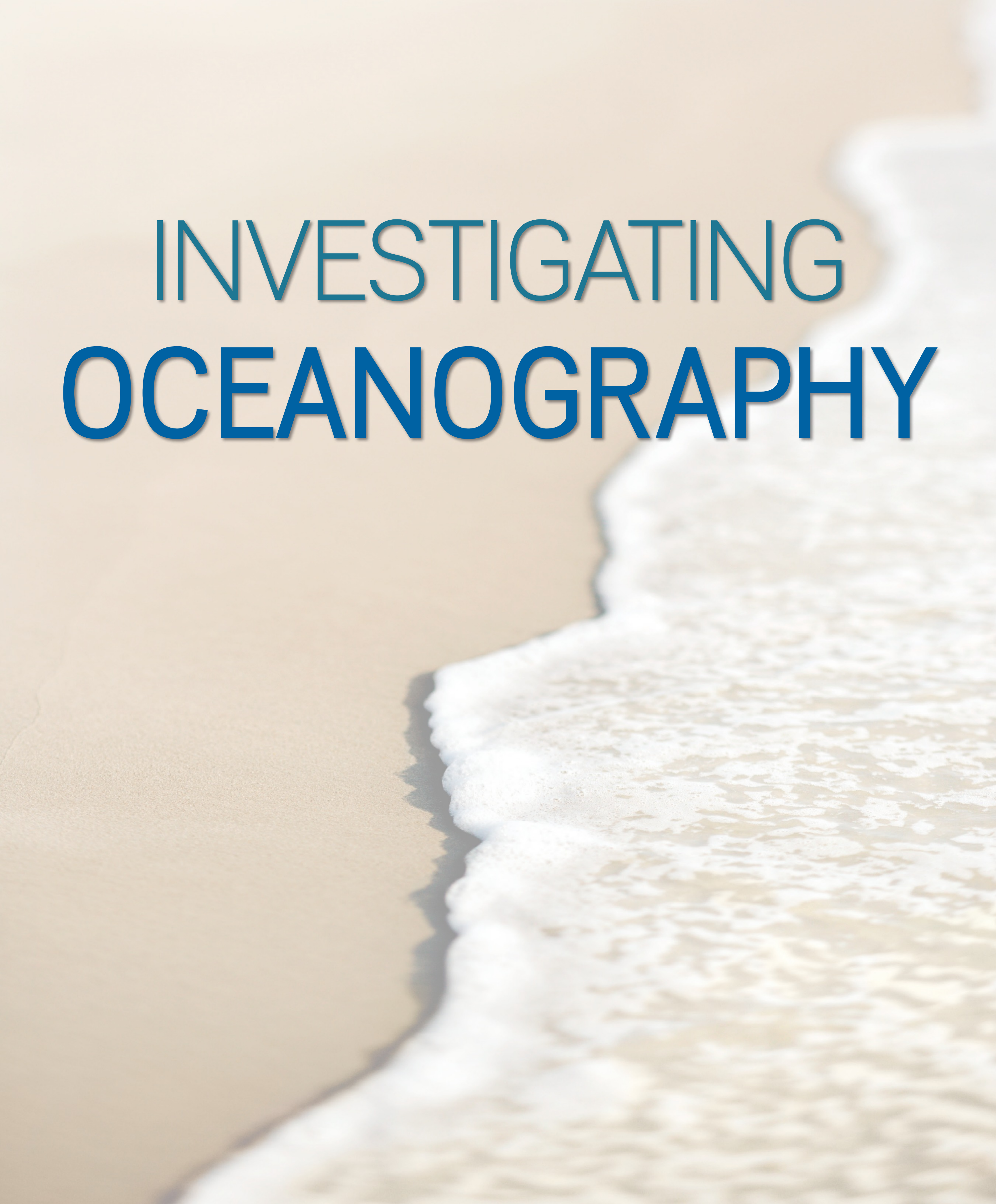
INVESTIGATING OCEANOGRAPHY

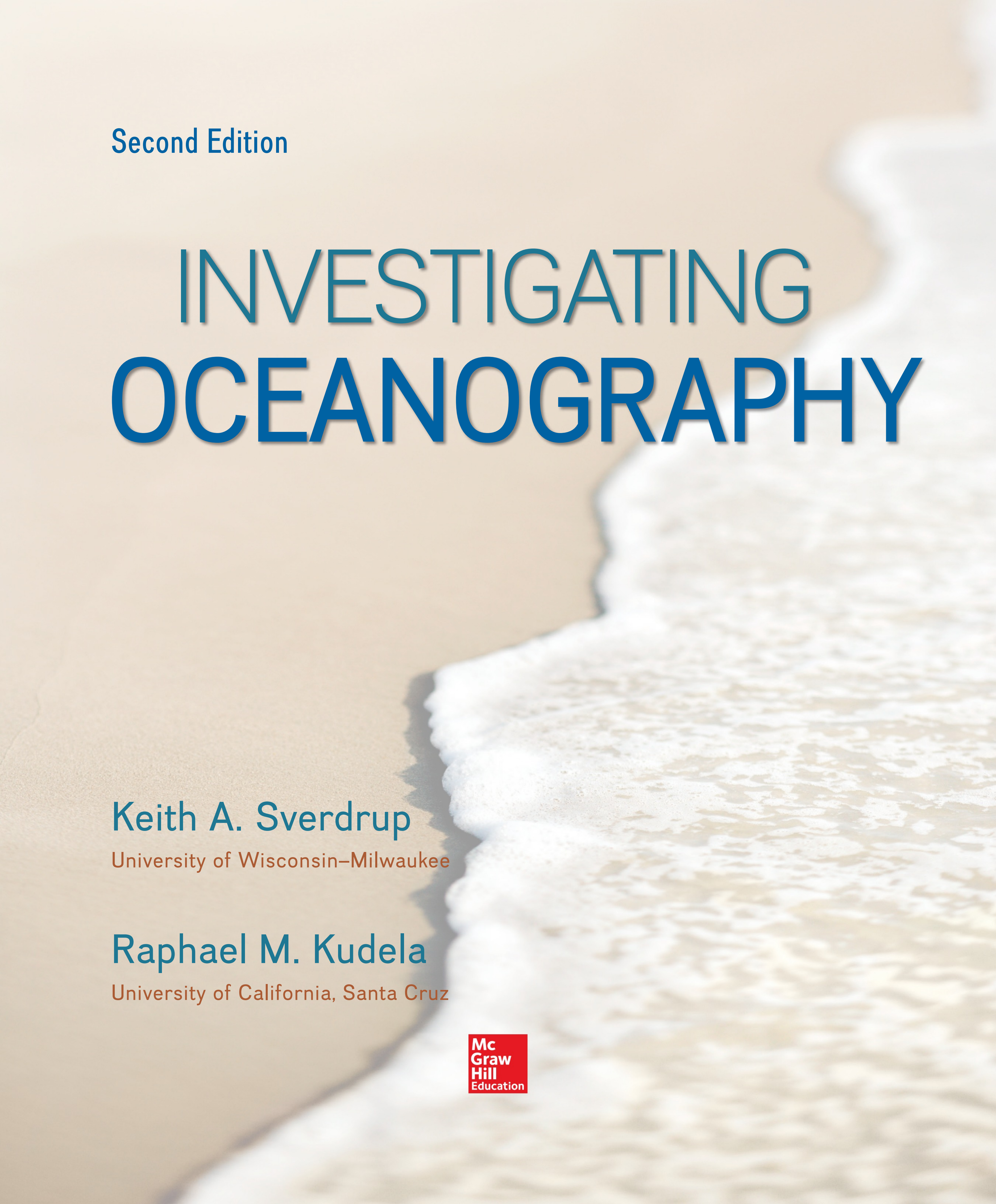
Keith A. Sverdrup

Raphael M. Kudela

Mc Graw Hill Education

INVESTIGATING OCEANOGRAPHY





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Raphael M. Kudela
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Dedicated to

Barbara Sverdrup Stone and
Stephanie Fouse

and

Robert, Eleanor, and Sarah Kudela

About the Authors

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Keith received his BS in Geophysics from the University of Minnesota and his PhD in Earth Science, with a dissertation on seismotectonics in the Pacific Ocean basin from the Scripps Institution of Oceanography at the University of California-San Diego. Keith has participated in a number of oceanographic research cruises throughout the Pacific Ocean including the far Western Pacific, from Guam to the Philippines and Taiwan; the South Central Pacific in regions of French Polynesia including the Society Islands, the Line Islands and the Marquesas; and in the Eastern Pacific off the coast of Mexico.

Keith has been active in oceanography education throughout his career, serving on committees of the American Geophysical Union (AGU), the American Institute of Physics (AIP), and the Geological Society of America (GSA). He was a member of AGU's Education and Human Resources Committee for twelve years (chairing it for four years), and also chaired AGU's Excellence in Geophysical Education Award Committee, the Editorial Advisory Committee for the journal *Earth in Space*, and the Sullivan Award Committee for excellence in science journalism. Keith served as a member of AIP's Physics Education Committee for six years.

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Raphael teaches at both the undergraduate and graduate levels, including participation in the NASA Student Airborne Research Program.

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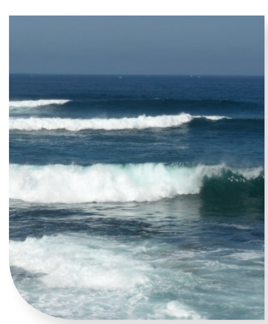

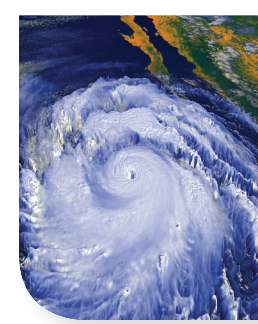

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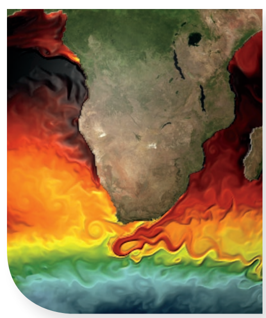

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Preface

What's New In This Edition?

New pedagogical features include revised/new figures and photographs that provide improved graphic illustration of ideas and issues. New Diving In boxes authored by experts in their fields have been added to provide additional detailed information about exciting and cutting edge issues in ocean sciences. Data and concepts are updated throughout the text, including the addition of critical terms to the glossary and a review of the appendices. This edition is closely tied to online resources in **Connect,** which support studying and learning for students as well as teaching and grading for instructors. Resources on **Connect** include figures, animations, movie clips, data analysis exercises, online quizzes, and course management software.

Specific Changes to Chapters

- **Prologue** Discussion of the early migration of people from Asia into the Pacific and Indian Ocean basins has been revised to reflect the latest evidence from anthropology and archaeology. A revised figure illustrating this has been added.
- **Chapter 1** The "Origin of the Oceans" Diving In box has been revised by discussing new evidence that Earth may have formed as a wet planet with liquid surface water from the very beginning of its history. The time boundaries on the geologic timescale in Table 1.2 are completely revised.
- **Chapter 3** Several figures have been replaced with new images that improve illustration of concepts. A new Diving In box has been added describing a deep submersible exploration of the Mariana Trench.
- **Chapter 5** Discussion of carbon dioxide cycle has been revised and the figure of major carbon dioxide pathways has been extensively updated. In addition, the figures of the Keeling curve have been updated.
- **Chapter 6** Discussion of the Antarctic ozone hole and its associated figures have been revised and updated. The data provided in the figure related to the Multivariate ENSO index have been updated. A new Diving In box focusing on climatically induced changes in tidewater glaciers in the Arctic has been added.
- **Chapter 8** New images are used to illustrate different types of breaking waves and rip currents.
- **Chapter 10** A new Diving In box discussing longshore sediment transport has been added. Many images of primary and secondary coasts have been replaced.
- **Chapter 12** The role of biological organisms in biogeochemical cycling in the ocean has been expanded by adding details on nitrogen fixation and mineral ballasting.
- **Chapter 13** Several photos of marine organisms have been replaced with improved and updated images. The most recent data on whale populations have been included in the tables.
- **Chapter 14** Additional details highlighting the importance of benthic microalgae and meiofauna have been included.
- **Chapter 15** Statistics on the impact of humans on the marine environment, including new information about the projected contribution of plastics to pollution, have been updated. Several images were updated to provide better examples of the chapter material.
- **Chapter 16** Data from the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report, released in 2014, have been included. A new Diving In box highlighting extreme events such as Superstorm Sandy was added.
- **Glossary** New critical terms used in the text have been added.

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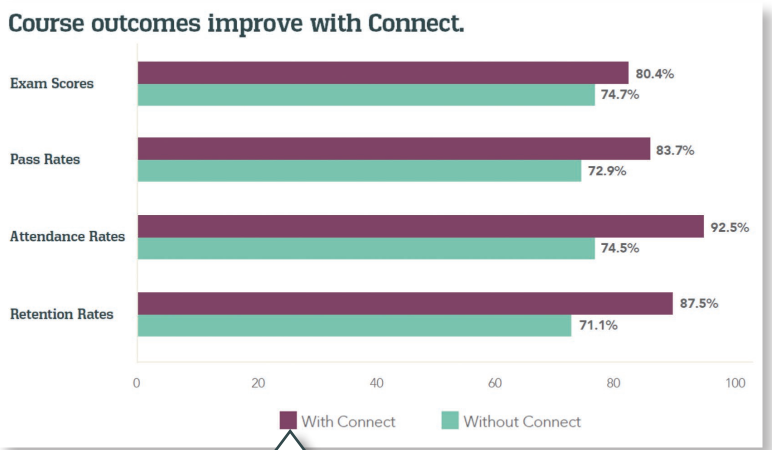

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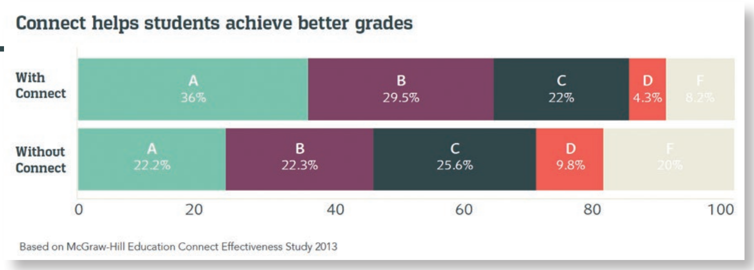

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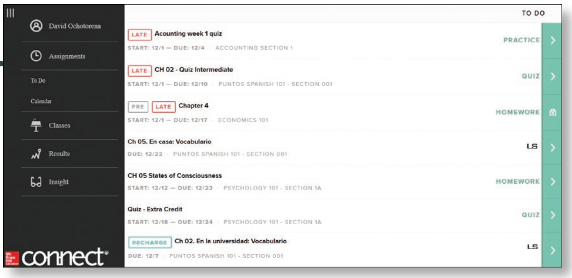

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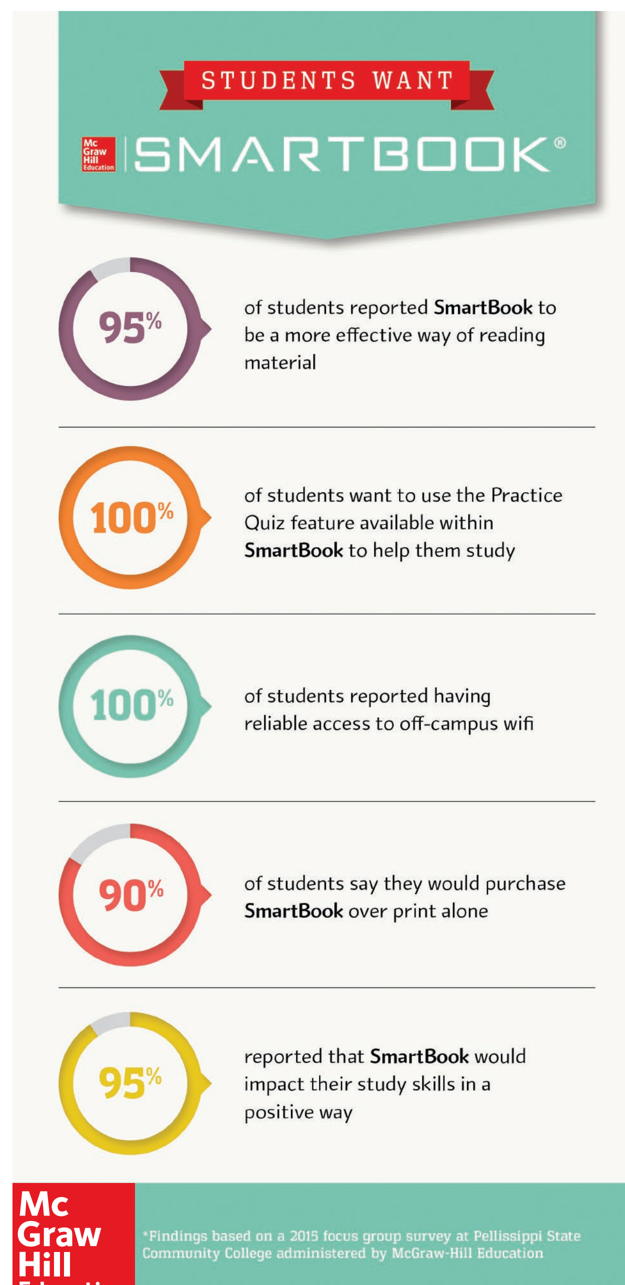


PROLOGUE

The History of Oceanography

Learning Outcomes

After studying the information in this chapter students should be able to:

1. *discuss* the interaction of early civilizations with the oceans,
2. *sketch* the major seafaring routes of the great voyages of discovery in the fifteenth and sixteenth centuries, James Cook's voyages of discovery, and the scientific voyages of Charles Darwin and the *Challenger* expedition,
3. *list* the major discoveries of the *Challenger* expedition,
4. *compare* and *contrast* the methods of making scientific measurements in the nineteenth and twentieth centuries,
5. *describe* the difference in both the quantity of oceanographic data and the density of that data available to oceanographers now compared to the nineteenth century.

PROLOGUE OUTLINE

A sextant and marine charts. The sextant is an early navigational aid first constructed by John Bird in 1759.

Oceanography is a broad field in which many sciences are focused on the common goal of understanding the oceans. Geology, geography, geophysics, physics, chemistry, geochemistry, mathematics, meteorology, botany, and zoology have all played roles in expanding our knowledge of the oceans. Oceanography is often broken down into a number of subdisciplines.

Geological oceanography includes the study of Earth at the sea's edge and below its surface, and the history of the processes that form the ocean basins. Physical oceanography investigates the causes and characteristics of water movements such as waves, currents, and tides and how they affect the marine environment. It also includes studies of the transmission of energy such as sound, light, and heat in seawater. Marine meteorology (the 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 the water, its processes, and its interactions. Biological oceanography concerns marine organisms and the relationship between these organisms and the environment in the oceans. Ocean engineering is the discipline that designs and plans equipment and installations for use at sea.

The study of the oceans was promoted by intellectual and social forces as well as by our needs for marine resources, trade and commerce, and national security. Oceanography started slowly and informally; it began to develop as a modern science in the mid-1800s and has grown dramatically, even explosively, in the last few decades. Our progress toward the goal of understanding the oceans has been uneven and progress has frequently changed direction. The interests and needs of nations as well as the scholarly curiosity of scientists have controlled the ways we study the oceans, the methods we use to study them, and the priority we give to certain areas of study. To gain perspective on the current state of knowledge about the oceans, we need to know something about the events and incentives that guided people's previous investigations of the oceans.

P.1 The Early Times

People have been gathering information about the oceans for millennia, accumulating bits and pieces of knowledge and 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. During the Paleolithic period, humans developed the barbed spear, or harpoon, and the gorge. The gorge was a double-pointed stick inserted into a bait and attached to a string. At the beginning of the Neolithic period, the bone fishhook was developed and later the net. By 5000 B.C., copper fishhooks were in use.

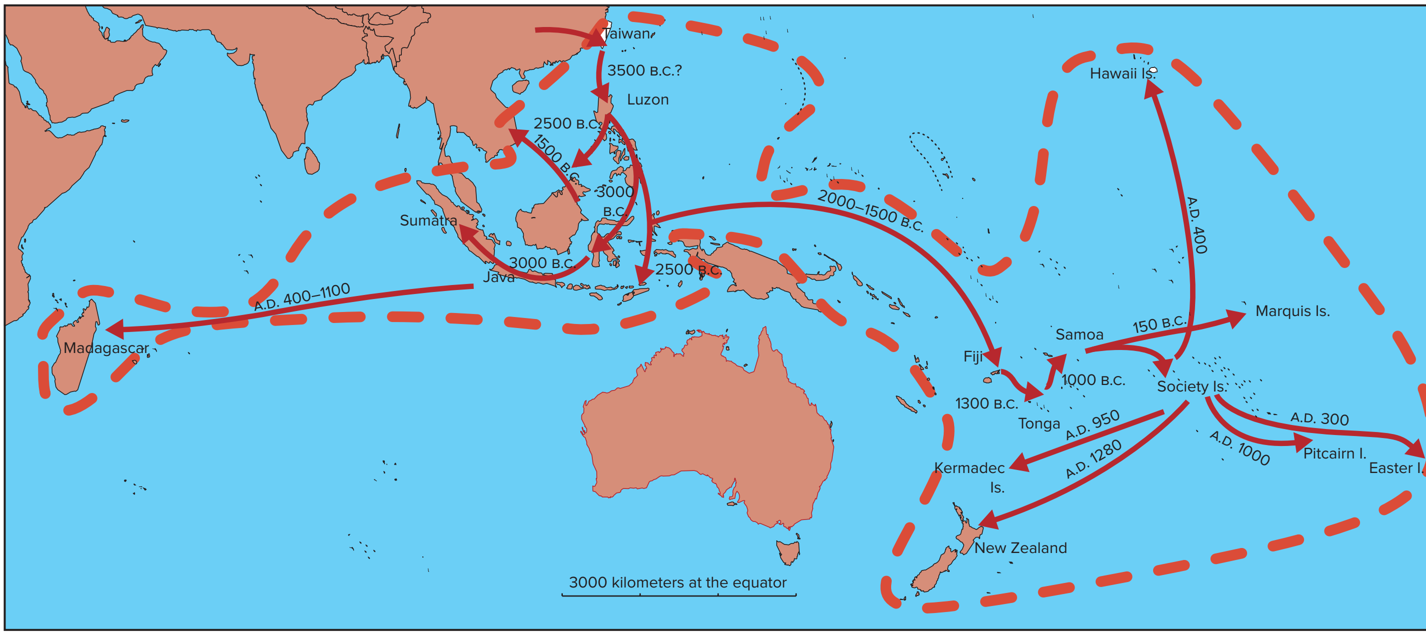
The remains of shells and other refuse, in piles known as kitchen middens, have been found at the sites of ancient shore settlements. These remains show that our early ancestors gathered shellfish, and fish bones found in some middens suggest that they also used rafts or some type of boat for offshore fishing. The artifacts that have been found probably give us only an idea of the minimum extent of ancient shore settlements. Drawings on ancient temple walls show fishnets; on the tomb of the Egyptian Pharaoh Ti, Fifth Dynasty (5000 years ago), is a drawing of the poisonous pufferfish with a hieroglyphic description and warning. As long ago as 1200 B.C. or earlier, dried fish were traded in the Persian Gulf; in the Mediterranean, the ancient Greeks caught, preserved, and traded fish, while the Phoenicians founded fishing settlements, such as "the fisher's town" Sidon, that grew into important trading ports.

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 to 146 B.C., were well-known as excellent sailors and navigators. While their land was fertile it was also densely populated, so they were compelled to engage in trade 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 that 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.

Evidence from anthropology and archaeology suggests that the people who first explored and populated the Pacific and Indian Ocean Basins migrated from Asia to the island of Taiwan and then to the main island of Luzon in the north Philippines sometime between 4500–2500 B.C. (fig. P.1*a*). These people are known as the Austronesians. Over the next 1000 years they moved progressively south through the rest of the Philippines and the nearby islands of the Celebes Sea, Borneo, and Indonesia. This was relatively easy because of the comparatively short distances between islands in the far southwestern Pacific region. The Austronesians would travel west into the Indian Ocean basin and east further into the Pacific Ocean basin. Those who traveled west reached present day Sulawesi, Java, and Sumatra around



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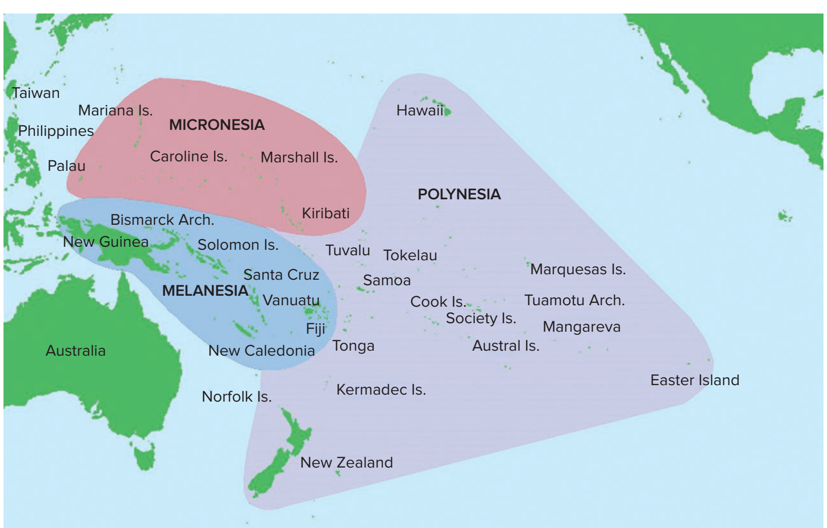


(b)

Figure P.1 (a) The migration of people across the Indian and Pacific Ocean basins. Specific dates are estimates from current research but may change with further study. The pale dashed red border shows the maximum extent of known Austronesian migration. Austronesians migrated from Asia into the far western Pacific by 2500 B.C. They then moved west into the Indian Ocean and east into the Pacific Ocean. (b) The regions of Melanesia and Micronesia in the Pacific Ocean were populated between 2000–1500 B.C. Polynesia was populated by 1000 B.C., and the Polynesians later extended their voyages throughout a triangular-shaped region bounded by Easter Island to the east, the Hawaiian Islands to the north, and New Zealand to the south.

3000 B.C. and later, sometime between A.D. 400–1100, Madagascar (fig. P.1*a*). The Austronesians who traveled east populated the islands of Melanesia and Micronesia (fig. P.1*b*) between 2000–1500 B.C. They then continued east and began populating the islands of Polynesia by 1000 B.C., leading to the development of the distinctive Polynesian culture. Polynesians embarked on more extensive voyages, where the distances between islands grew from tens of kilometers in the western Pacific to thousands of kilometers in the cases of voyages to the Hawaiian Islands and Easter Island. There is some uncertainty about when they settled specific regions. It is thought they reached and colonized Easter Island around A.D. 300, the Hawaiian Islands by about A.D. 400, and arrived in New Zealand around A.D. 1280. By the early thirteenth century, Polynesians had colonized every habitable island in a triangular region roughly twice the size of the United States, bound by Hawaii to the north, New Zealand to the southwest, and Easter Island to the east (fig. P.1*b*).

A basic component of navigation throughout the Pacific was the careful observation and recording of where prominent stars rise and set on the horizon. Observed near the equator, the stars appear to rotate from east to west 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" by dividing the horizon into thirty-two segments where their known stars rose and set. These directions form a compass and provide a reference for recording information about the direction of winds, currents, waves, and the relative positions of islands, shoals, and reefs (fig. P.2). The Polynesians also navigated by making close observations of waves and cloud formations. Observations of birds and distinctive smells of land such as flowers and wood smoke alerted them to possible landfalls. Once islands were 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. P.3).

Figure P.2 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 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.

Figure P.3 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.

As early as 1500 B.C., Middle Eastern peoples of many different ethnic groups and regions were exploring the Indian Ocean. In the seventh century A.D., they were unified under Islam and controlled 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 A.D. in the Arabian Sea.)

The Greeks called the Mediterranean "Thalassa" and believed that it was encompassed by land, which in turn was surrounded by the endlessly circling river Oceanus. In 325 B.C., Alexander the Great reached the deserts of the Mekran Coast, now a part of Pakistan. He sent his fleet down the coast in an apparent effort to probe the mystery of Oceanus. He and his troops had expected to find a dark, fearsome sea of whirlpools and water spouts inhabited by monsters and demons; they did find tides that were unknown to them in the Mediterranean Sea. Pytheas (350–300 B.C.), a navigator, geographer, astronomer, and contemporary of Alexander, made one of the earliest recorded voyages from the Mediterranean to England. From there, he sailed north to Scotland, Norway, and Germany. He recognized a relationship between the tides and the Moon, and made early attempts at determining latitude and longitude. These early sailors did not investigate the oceans; for them, the oceans were only a dangerous road, a pathway from here to there, a situation that continued for hundreds of years. However, the information they accumulated slowly built into a body of lore to which sailors and voyagers added each year.

While the Greeks traded and warred throughout the Mediterranean, they observed the sea and asked questions. Aristotle (384–322 B.C.) believed that the oceans 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. 276–195 B.C.) of Alexandria, Egypt, invented the study of geography as well as a system of latitude and longitude. He was the first person to calculate the tilt of Earth's axis. One of his greatest achievements was his calculation of Earth's circumference; he accomplished this without ever leaving Egypt (fig. P.4). Eratosthenes knew that at local noon on the summer solstice, the Sun would be directly overhead in the city of Syene, located on the Tropic of Cancer at 23½°N. On that day and at that time, the Sun's rays would shine down into a well in the city and illuminate the bottom of the well. At the same time and day, the Sun's rays would cast a shadow behind a pole in his home city of Alexandria due north of Syene. By measuring the height of the pole and the length of the shadow, Eratosthenes could calculate the angle away from perpendicular of the Sun's elevation in Alexandria, which he determined to be about 7.2°, or roughly 1/50 of a circle. Assuming that the distance between the Sun and Earth is so large that all of the Sun's rays of light are parallel to each other when they reach Earth, Eratosthenes could say that the angle between Syene and Alexandria was also about 7.2°, or roughly 1/50 of a circle. Repeated surveys of the distance between Syene and Alexandria yielded a distance of 5000 stadia, so Eratosthenes concluded that Earth's circumference was 252,000 stadia. The length of an Egyptian stadion was 157.5 m, so Eratosthene's estimate of Earth's circumference was 39,690 km (24,662 mi), an error of only about 1% compared to today's accepted average value of about 40,030 km (24,873 mi). Posidonius (c. 135–50 B.C.) reportedly measured an

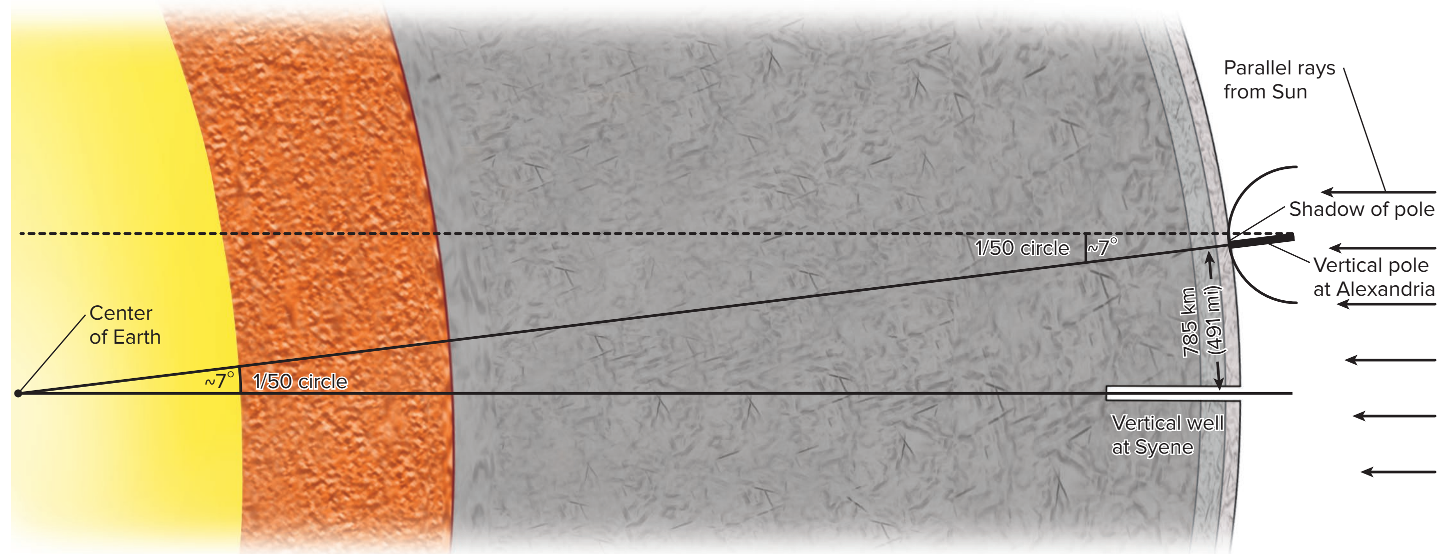


Figure P.4 Eratosthenes used geometry to calculate Earth's circumference. By careful measurement, he was able to estimate Earth's circumference to within about 1% of today's value. (The diagram is not drawn to scale.)

ocean depth of about 1800 m (6000 ft) near the island of Sardinia, according to the Greek geographer Strabo (c. 63 B.C.–A.D. 21). Pliny the Elder (c. A.D. 23–79) related the phases of the Moon to the tides and reported on the currents moving through the Strait of Gibraltar. Claudius Ptolemy (c. A.D. ~85–161) 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. His atlas listed more than 8000 places by latitude and longitude, but his work contained a major flaw. He had accepted a value of 29,000 km (18,000 mi) for Earth's circumference. This value was much too small and led Columbus, more than 1000 years later, to believe that he had reached the eastern shore of Asia when he landed in the Americas.

QUICK REVIEW

1. Name the subfields of oceanography.
2. What did early sailors use for guidance during long ocean voyages?
3. What kind of "compass" did the Polynesians use for navigation?
4. How long ago was Earth's circumference first calculated and how was it done?
5. How did Ptolemy's atlas contribute to a greater understanding of world geography, and how did it produce confusion?

P.2 The Middle Ages

After Ptolemy, intellectual activity and scientific thought declined in Europe for about 1000 years. However, shipbuilding improved during this period; vessels became more seaworthy and easier to sail, so sailors could make longer 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. P.5). 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 985–86, 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.

To the south, in the region of the Mediterranean after the fall of the Roman Empire, Arab scholars preserved Greek and Roman knowledge and continued to build on it. The Arabic writer El-Mas'údé (d. 956) gives the first description of the reversal of the currents due to the seasonal monsoon winds. Using this knowledge of winds and currents, Arab sailors established regular trade routes across the Indian Ocean. In the 1100s, 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, knowledge of navigation increased. Harbor-finding 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.

Although tides were not understood, the Venerable Bede (673–735) illustrated his account of the tides with data from the British coast. His calculations were followed in the tidal observations collected by the British Abbot Wallingford of Saint Alban's Monastery in about 1200. His tide table, titled "Flod at London

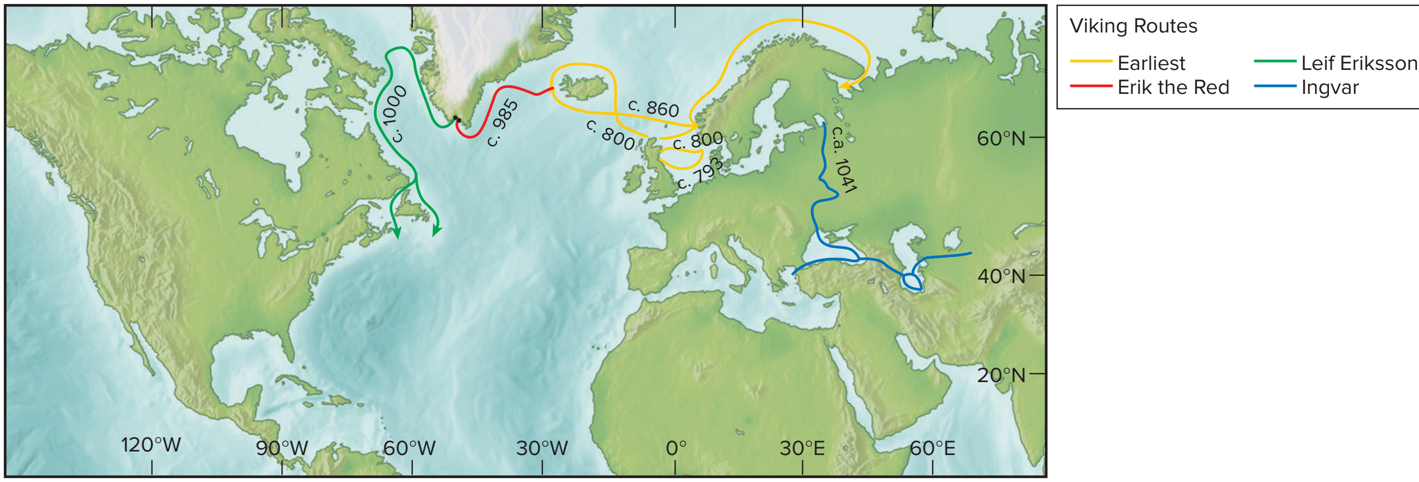


Figure P.5 Major routes of the Vikings to the British Isles, to Asia, and across the Atlantic to Iceland, Greenland, and North America.

Brigge," documented the times of high water. Sailors made use of Bede's calculations until the seventeenth century.

As scholarship was reestablished in Europe, Arabic translations of early Greek studies were translated into Latin and thus became available to European scholars. The study of tides continued to absorb the medieval scientists, who were also interested in the saltiness of the sea. 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.

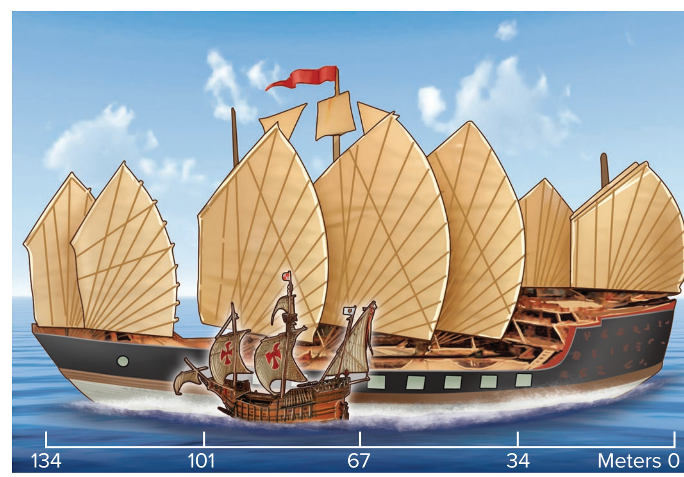
QUICK REVIEW

1. What advances occurred during the Middle Ages that allowed longer ocean voyages?
2. During the tenth century, which oceans were explored and by which cultures?
3. Where did the Vikings establish a large colony in the North Atlantic?

P.3 Voyages of Discovery

From 1405 to 1433, the great Chinese admiral Zheng He conducted seven epic voyages in the western Pacific Ocean and across the Indian Ocean as far as Africa. Zheng He's fleet consisted of over 300 ships. The fleet is believed to have included as many as sixty-two "treasure ships" thought to have been as much as 130 m (426 ft) long and 52 m (170 ft) wide; this was ten times the size of the ships used for the European voyages of discovery during this period of time (fig. P.6). The purpose of these voyages remains a matter of debate among scholars. Suggested reasons include the establishment of trade routes, diplomacy with other governments, and military defense. 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 400 years 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



(a)

(b)

Figure P.6 (a) Admiral Zheng He's "treasure ships" were over 130 m long. In comparison, Christopher Columbus's flagship, the *Santa Maria*, is estimated to have been about 18 m long. (b) Zheng He's probable route from China along the coast of the Indian Ocean to Africa.

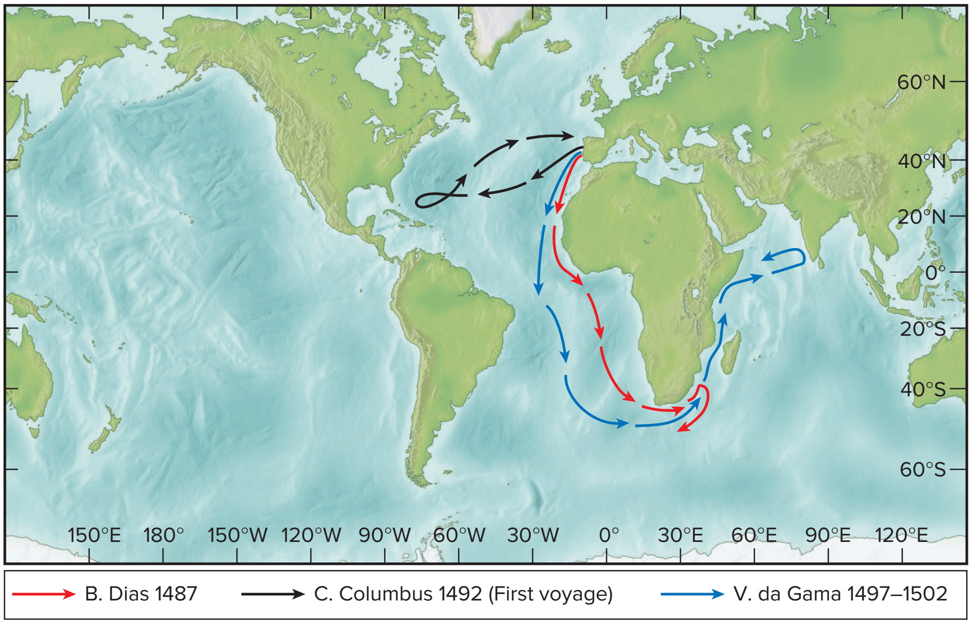


Figure P.7 The routes of Bartholomeu Dias and Vasco da Gama around the Cape of Good Hope and Christopher Columbus's first voyage.

individual most responsible for the great age of European discovery was Prince Henry the Navigator (1394–1460) of Portugal. In 1419, his father, King John, made him governor of Portugal's southernmost coasts. Prince Henry was keenly interested in sailing and commerce, and studied navigation and mapmaking. He established a naval observatory for the teaching of navigation, astronomy, and cartography about 1450. From 1419 until his death in 1460, Prince Henry sent expedition after expedition south along the west coast of Africa to secure trade routes and establish colonies. These expeditions moved slowly due to the mariners' belief that waters at the equator were at the boiling point and that sea monsters would engulf ships. It wasn't until twenty-seven years after Prince Henry's death that Bartholomeu Dias (1450?–1500) braved these "dangers" and rounded the Cape of Good Hope in 1487 in the first of the great voyages of discovery (fig. P.7). Dias had sailed in search of new and faster routes to the spices and silks of the East.

Portugal's slow progress along the west coast of Africa in search for a route to the east finally came to fruition with Vasco da Gama (1469–1524) (fig. P.7). In 1497, he followed Bartholomeu Dias's 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 fourteen heavily armed ships and defeated the Arab fleet. By 1511, the Portuguese controlled 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, in fact, he had reached the New World (fig. P.7).

Italian navigator Amerigo Vespucci (1454–1512) made several voyages to the New World (1499–1504) for Spain and Portugal, exploring nearly 10,000 km (6000 mi) of South American coastline. He accepted South America as a new continent not part of Asia, and in 1507, German cartographer Martin Waldseemüller applied the name "America" to the continent in Vespucci's honor. Vasco Núñez de Balboa (1475–1519) crossed the Isthmus of Panama and found the Pacific Ocean in 1513, and in the same year, Juan Ponce de León (1460?–1521) discovered Florida and the Florida Current. All claimed the new lands they found for their home countries. Although these men had sailed for fame and 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 eighteen of the original crew. This was the first circumnavigation of Earth (fig. P.8). 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 the circumference of Earth. It is said that Magellan tried to test the mid-ocean depth of the Pacific with a hand line, but this idea seems to come from a nineteenth-century German oceanographer; writings from Magellan's time do not support this story.

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 North America. Sir Martin Frobisher (1535?–94) made three voyages in 1576, 1577, and 1578, and Henry Hudson (d. 1611) made four voyages (1607, 1608, 1609, and 1610), dying with his son when set adrift in Hudson Bay by his mutinous crew. The Northwest Passage continued to beckon, and in 1615 and 1616, William Baffin (1584–1622) made two unsuccessful attempts.

While European countries were setting up colonies and claiming new lands, Francis Drake (1540–96) set out in 1577 with 165 crewmen and five ships to show the English flag around the world (fig. P.8). He was forced to abandon two of his ships off the coast of South America. He was separated from the other two