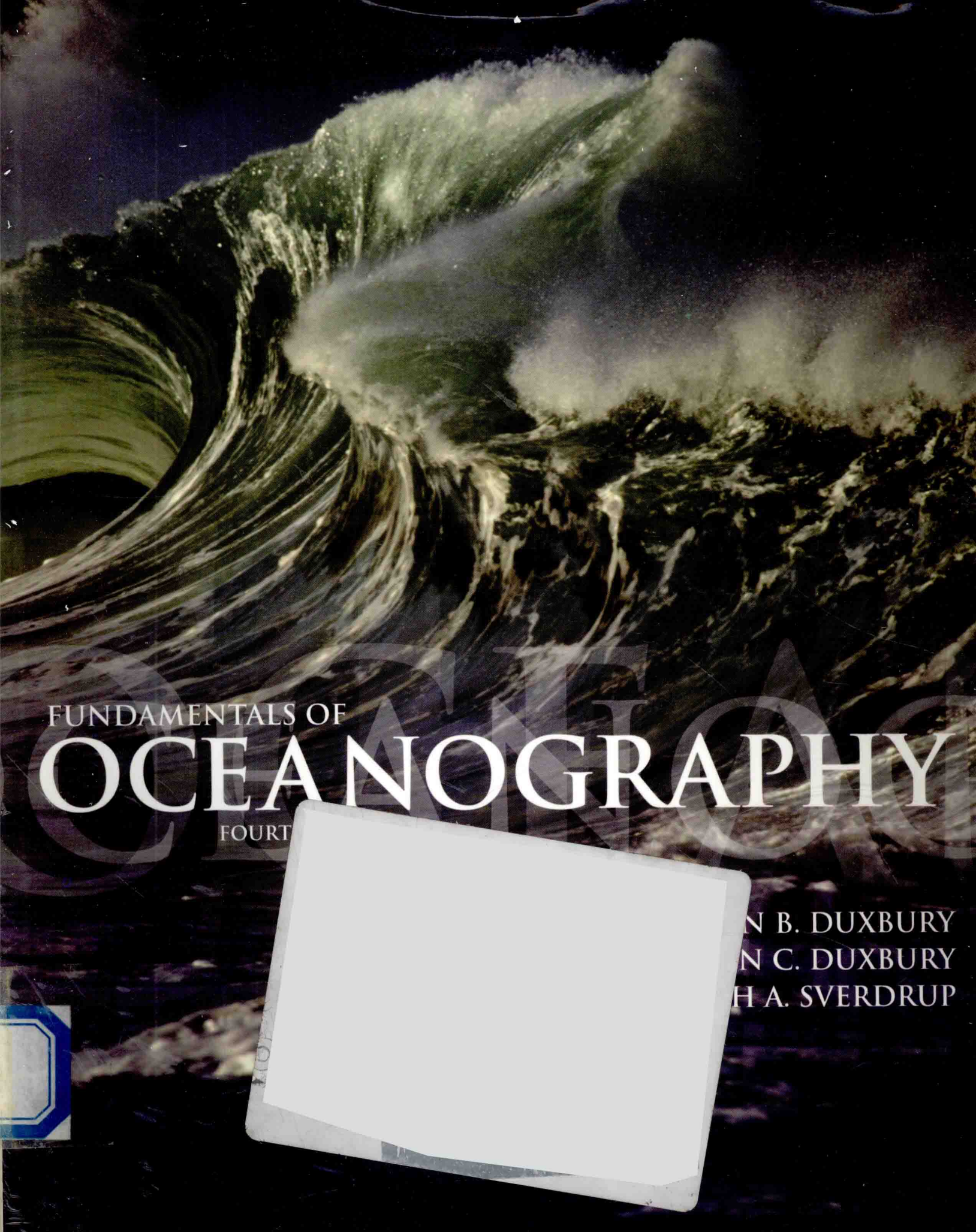

FUNDAMENTALS OF OCEANOGRAPHY

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FUNDAMENTALS OF OCEANOGRAPHY

FOURTH EDITION

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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 the Earth's surface and yet is more poorly mapped than the surface of the Moon. This fourth 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 fourth 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.

Six new *Items of Interest* have been added to this edition for a total of twelve topics designed to cover issues that are not addressed directly in the text. The new topics include the recovery of black smokers from the seafloor, the use of sound to measure ocean temperature, tsunami warning systems, national marine sanctuaries, whale falls, and biodiversity in the oceans. The discussion of plate tectonics and plate boundaries in chapter 3 has been extensively revised. In chapter 4 the material concerning marine sediments has been reorganized to emphasize sediment classification and characteristics. New measurement techniques and new instruments used by oceanographers are discussed and illustrated in chapter 7. The environmental problems presented by "dead zones" and the toxic *Pfiesteria* organism are new to chapter 9, and chapter 10 has a new section on extremophiles, microorganisms that live under conditions of extreme temperature. Chapter 12 provides new data on the world's coral reefs, and all fisheries catch data has been updated in chapters 11 and 12. 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.

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, critical thinking questions to encourage reflection about chapter topics, suggested readings to explore subjects in more detail, and internet references related to topics of discusssion. Internet references 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.

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:

Marcia McNutt
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We also wish to extend a special thanks to the instructors who used and reviewed the first three editions of this text and to those who contributed to the development of this fourth edition.

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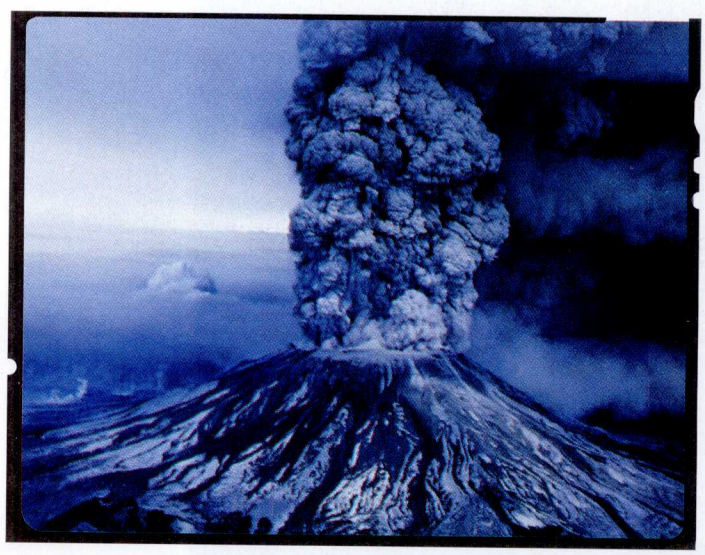
Finally, we express our sincere gratitude to McGraw-Hill and the outstanding staff members working with us to bring you this textbook.

contents



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

chapter four

The Sea Floor

chapter five

Water

chapter six

The Atmosphere and the Oceans

chapter seven

Circulation Patterns and Ocean Currents

chapter eight

Waves and Tides

chapter nine

Coasts, Estuaries, and Environmental Issues

chapter ten

Oceanic Environment and Production

chapter eleven

Life in the Water

chapter twelve

Life on the Sea Floor

chapter one

History of Oceanography

By the seventeenth century significantly improved charts and navigation instruments were available to mariners.

Learning Objectives

After reading this chapter, you should be able to

- Understand the diversity of the sciences collected to form "oceanography."
- 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 development 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 and 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.

History of Oceanography

Oceanography 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 the Earth at the sea's edge and below its surface and the history of the processes that formed the ocean basins. Physical oceanography investigates how and why the oceans move; marine meteorology, the study of heat transfer, water cycles, and air-sea interactions, is often included in this discipline. Chemical oceanography studies the composition and history of seawater, its processes, and its interactions. Biological oceanography concerns itself with the marine organisms and the relationship between these organisms and the environment of 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 investigations of the oceans.

The Early Times 1.1

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.

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 miles) 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 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 the 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 the 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 the circumference of the Earth 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, 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

Figure 1.1

A traditional navigator from the Caroline Islands instructing others in the use of a "star structure" showing the relative points on the horizon where key stars rise and set.

More Information: www.museum.upenn.edu/Navigation/Misc/contents.html

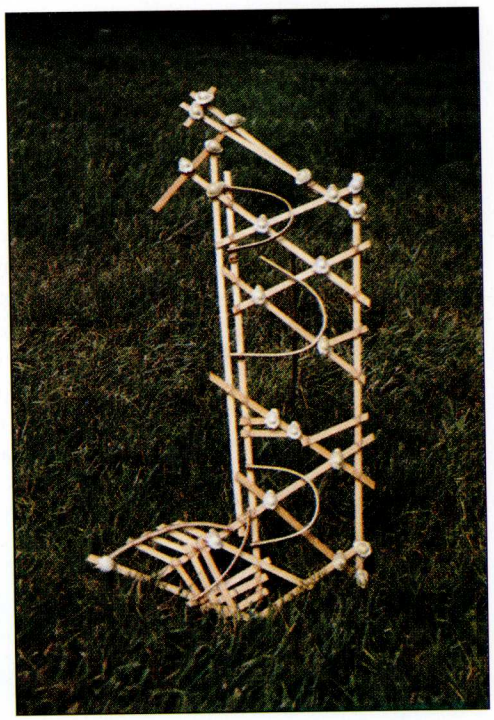


Figure 1.2

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.*

the east China; and to the west the great Western Ocean reaching around the 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 the 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 the circumference of the Earth first calculated?

How did Ptolemy's atlas contribute to a greater understanding of world geography, and how did it produce confusion?

The Middle Ages 1.2

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). They sailed to Iceland in 871 where it is believed that as many as 12,000 immigrants eventually settled. During this time they also journeyed inland on Russian rivers throughout central and eastern Europe and western Asia. Voyages into the Mediterranean Sea led them to Rome and Baghdad. 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

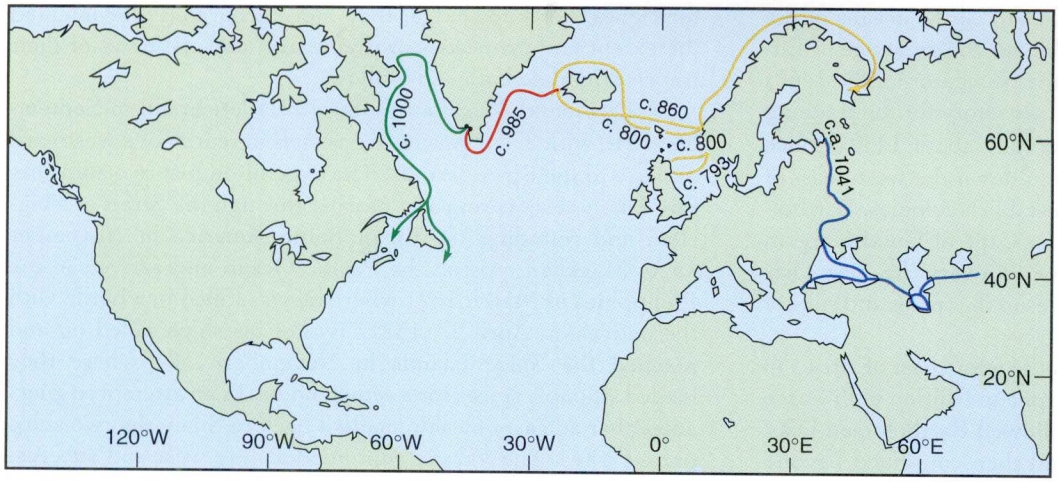


Figure 1.4

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

More Information:
www.mariner.org/age/vikingexp.html

in 1002 and reached North America roughly 500 years before Columbus.

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. 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. 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?

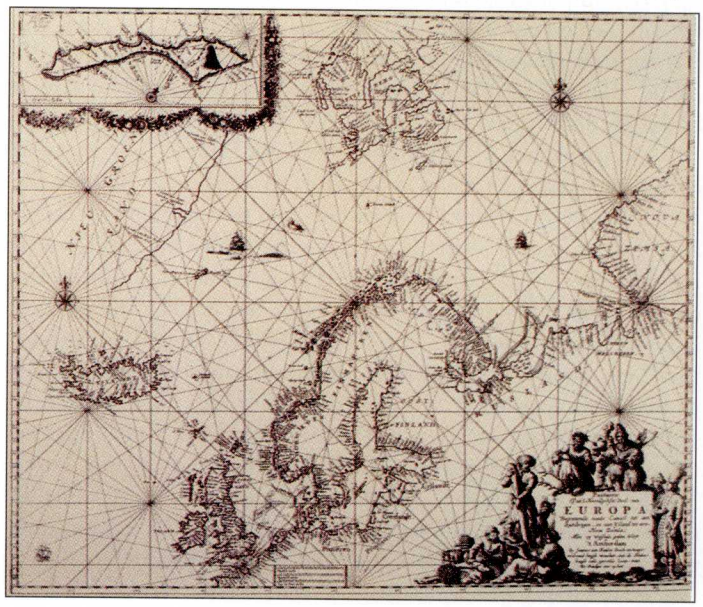


Figure 1.5

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

Voyages of Discovery 1.3

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 the 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 the 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 the circumference of the Earth.

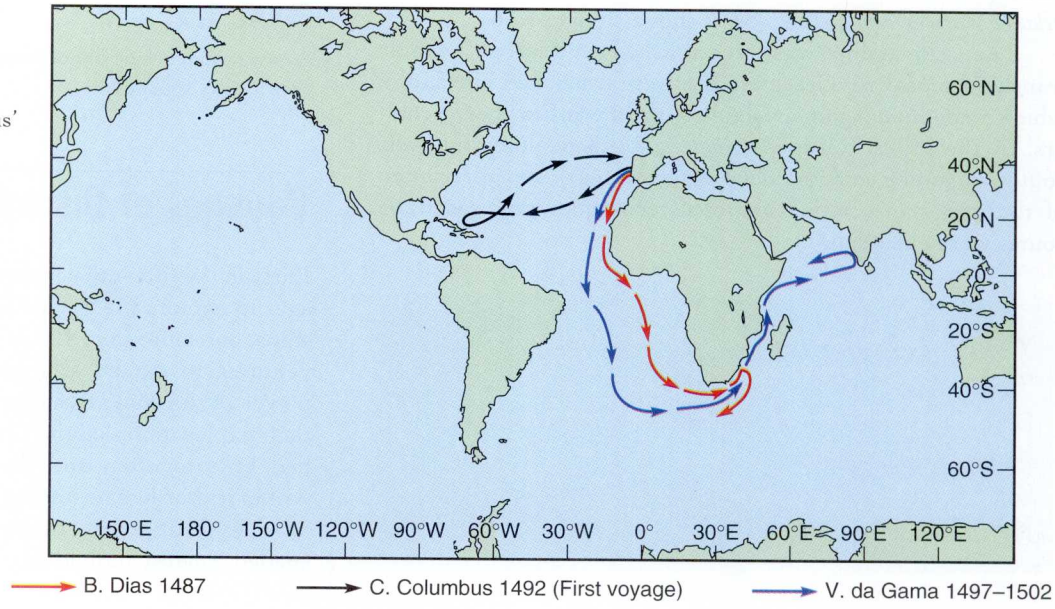
By the latter half of the sixteenth century, adventure, curiosity, and hopes of finding a trading shortcut to China spurred efforts to find a sea passage around the north side of North America. Sir Martin Frobisher (1535?–94) made three voyages in the 1570s, and Henry Hudson (d. 1611) made four voyages 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.

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. 1.7). He was forced to abandon two of

Figure 1.6

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

More Information:
www.mariner.org/age/princehenry.html,
www.mariner.org/age/firstvoyage.html,
www1.minn.net/~keithp/, and
www.mariner.org/age/dagama.html



Captain James Cook (1728–79) made his three great voyages to chart the Pacific Ocean between 1768 and 1779 (fig. 1.9). During his voyages, he explored and charted much of the South Pacific and the coasts of New Zealand, Australia, and northwest North America. He took a copy of Harrison's fourth chronometer on his second voyage of discovery to the south seas, and with this timepiece he was able to produce accurate charts of new areas and to correct previously charted positions. He searched for a way to the Atlantic from the Bering Sea and discovered the Hawaiian Islands, where he was killed. He made soundings to depths of 400 m (1300 ft) and logged accurate observations of winds, currents, and water temperatures. Cook takes his place as one of history's greatest navigators and sailors as well as a fine scientist. His careful and accurate observations produced much valuable information and made him one of the founders of oceanography.

In the United States, Benjamin Franklin (1706–90) became concerned about the amount of time required for news and cargo to travel between England and America. With Captain Timothy Folger, his cousin and a whaling captain from Nantucket, he constructed the 1769 Franklin-Folger chart of the Gulf Stream current (fig. 1.10), which encouraged captains to sail within the Gulf Stream enroute to Europe and to avoid it on the return passage. Since the Gulf Stream carries warm water from low latitudes to high latitudes it is possible to map its location with satellites that measure sea surface temperature. Compare the Franklin-Folger chart in figure 1.10 with a map of the Gulf Stream shown in figure 1.11 based on the average sea surface temperature during 1996.

The U.S. Naval Hydrographic Office, now the U.S. Naval Oceanographic Office, was set up in 1830. In 1842, Lieutenant Matthew F. Maury (1806–73) was assigned to the Hydrographic Office and founded the Naval Depot of Charts. He began a systematic collection of wind and current data from ships' logs. He produced his first wind and current charts of the North Atlantic in 1847; these became a part of the first published atlases of sea conditions and sailing directions. The British estimated that Maury's sailing directions took thirty days off the passage from the British Isles to California, twenty days off the voyage to Australia, and ten days off the sailing time to Rio de Janeiro. In 1855, he published *The Physical Geography of the Sea*. This work includes chapters on the Gulf Stream, the atmosphere, currents, depths, winds, climates, and storms, and the first contour chart of the North Atlantic sea floor. See figure 1.12 for the Gulf Stream chart from this book and compare the change in detail and style with the Franklin-Folger chart in figure 1.10. Many consider Maury's book the first textbook of what we now call oceanography and consider Maury the first true oceanographer. Again, national and commercial interests were the driving forces behind the study of the oceans.

Why was John Harrison's clock important to ocean exploration?

What did Captain James Cook's voyage contribute to the science of oceanography?

Why was Benjamin Franklin interested in the Gulf Stream?

Who was Matthew F. Maury, and what was his contribution to ocean science?

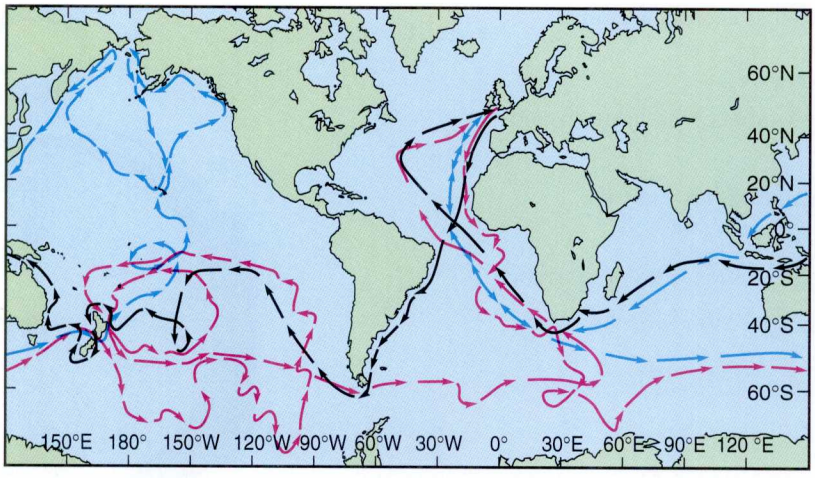


Figure 1.9

The three voyages of Captain James Cook.

More Information: www.mariner.org/age/cook.html, winthrop.webjump.com/jcook.html, and pacific.vita.org/pacific/cook/cook1.htm

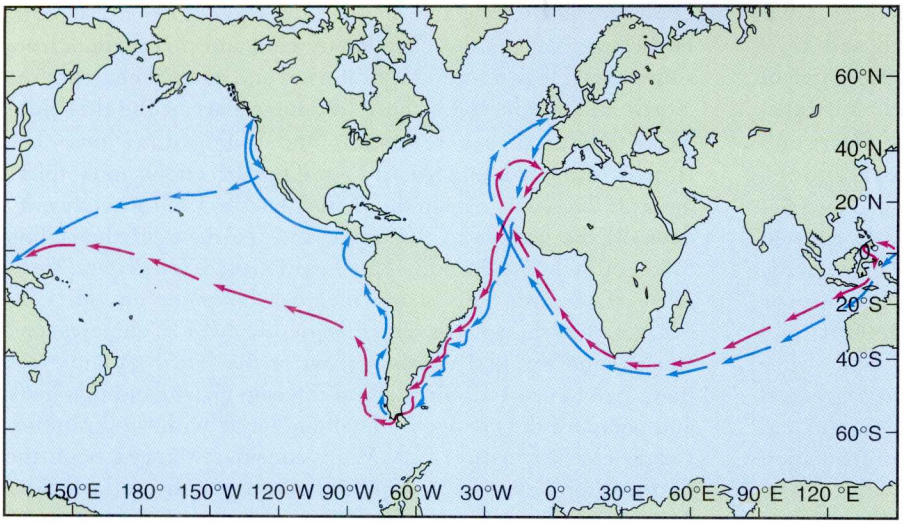


Figure 1.7

The sixteenth-century circumnavigation voyages by Magellan and Drake.

More Information: www.mariner.org/age/magellan.html, www.mariner.org/age/drake.html, and www.mcn.org/2/oseeler/drake.htm

his ships off the coast of South America. He was separated from the other two ships while passing through the Straits of Magellan. During the voyage Drake plundered Spanish shipping in the Caribbean and in Central America and loaded his ship with treasure. In June 1579, Drake landed off the coast of present-day California and sailed north along the coast to the present United States–Canadian border. He then turned southwest and crossed the Pacific Ocean in two months time. In 1580 he completed his circumnavigation and returned home in the *Golden Hind* with a cargo of Spanish gold, to be knighted and treated as a national hero. Queen Elizabeth I encouraged her sea captains' exploits as explorers and raiders because, when needed, their ships and their knowledge of the sea brought military victories as well as economic gains.

What stimulated the long voyages of the fifteenth and sixteenth centuries?

Who was Amerigo Vespucci, and how was he honored?

Why was Magellan's voyage of such great importance?

What is the Northwest Passage? Why was there an interest in finding it?

The Importance of Charts and Navigational Information 1.4

As colonies were established far away from their home countries, and as trade and travel expanded, there was renewed interest in developing better charts and more accurate navigation techniques. To obtain the precise location of landfall or ship's position, it is necessary to know the location of the Sun or the stars related to time, and because early clocks did not work well on rolling ships, precise navigational measurements were not possible on early voyages. In 1714 the British Parliament offered 20,000 pounds sterling for a clock that could keep time with an error not greater than two minutes on a voyage to the West Indies from England. John Harrison, a clock maker, accepted the challenge and built his first sea-going clock in 1735. It was not until 1761 that his fourth model (fig. 1.8) met the test, losing only 51 seconds, on the 81-day voyage.

Figure 1.8

John Harrison's fourth chronometer. A copy of this chronometer was used by Captain James Cook on his 1772 voyage to the southern oceans.

More Information: www.nmm.ac.uk/