Introduction to Ocean Sciences

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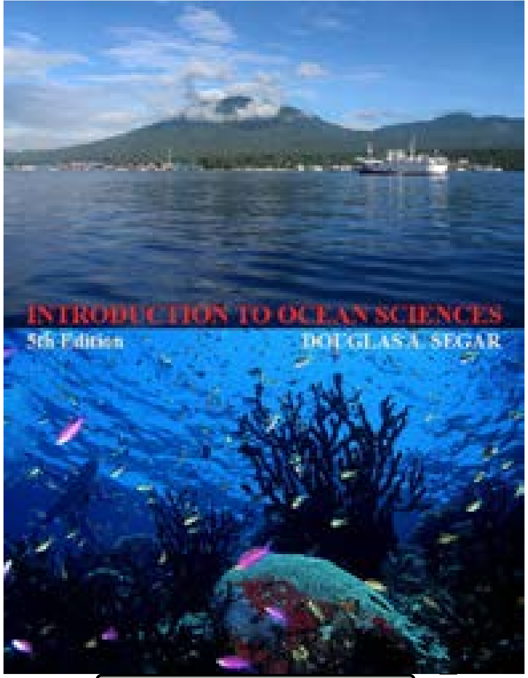

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CHAPTER 3

Studying the Oceans

CRITICAL CONCEPTS USED IN THIS CHAPTER

CC1 Density and Layering in Fluids

CC6 Salinity, Temperature, Pressure, and Water Density

CC10 Modeling

CC14 Phototrophy, Light, and Nutrients

Developments in scuba diving technology are revolutionizing marine sciences. The strange-looking backpack on the diver shown in the image on the far right is a scuba system that removes carbon dioxide so that the gases can be rebreathed many times and uses a computer to control the mixture of air, oxygen, and helium that the diver breathes. This unit allows divers to make very deep dives and return to the surface safely without the many hours of decompression that are usually needed. The spectacular nudibranch shown in the photo to the right is one of many never-before-seen species found on a number of very deep dives made with the "rebreather" in Papua New Guinea. It was collected from a depth of about 130 m. Scuba is normally limited to a maximum depth of about 50 m

This chapter will introduce you to the tools and techniques used by oceanographers and explain why the oceans are so difficult to study. Some of the tools described in the chapter are now obsolete, but only by understanding how ingenious oceanographers need to be to overcome the difficulties of studying the oceans can we appreciate why we still do not know more about them. This understanding is also necessary for a full appreciation of the immense value of technologies, such as the Global Positioning System (GPS), advanced satellite sensors, autonomous underwater vehicles and computers that can rapidly analyze and graphically portray massive amounts of data.

DIFFICULTIES OF STUDYING THE OCEAN ENVIRONMENT

Why did it take so long to discover the most fundamental secrets of the oceans? Why did we not know of the existence of the immense mountain chains passing through all the oceans until we were already looking beyond the Earth and launching satellites and humans into space? The answer lies in the hostility of the oceans to oceanographers and to their instruments. In many ways, the ocean depths are more difficult to explore than the surface of the moon or Mars.

A principal focus of oceanographers in developing techniques and instruments to study the oceans has always been, and still is, to overcome the many problems unique to studying the oceans. The most important of these problems are the following:

- Visiting the ocean depths is difficult because we cannot breathe in water.
- Water absorbs light and other **electromagnetic radiation,** such as radar and radio waves, severely limiting their use for remote sensing in the oceans.
- The oceans are extremely deep.
- Pressure in the ocean depths is extremely high.
- Seawater is corrosive.
- The sea surface is dynamic.

"Seeing" through Ocean Water

Compared to the atmosphere, water is a much more efficient absorber of electromagnetic radiation, including radio and radar waves and ultraviolet, infrared, and visible light. In all but the shallowest areas, the seafloor cannot be seen by the naked eye or with any type of optical telescope. Even in the clearest ocean water, we see at best a distorted image of the seafloor, and only where the maximum depth is a few tens of meters at most. Because we cannot see the seafloor, mapping the ocean floor was more difficult than mapping the surface of the moon. Only in the 1920s did oceanographers discover that sound waves could be used as their "eyes" to see the seafloor. Oceanographers also discovered that the magnetic and **gravity** fields of the seafloor could be sensed through the depths of ocean water. Even so, our ability to study the deep ocean is still limited by its lack of transparency to electromagnetic radiation. For example, radar and other instruments carried on satellites can produce extraordinarily detailed maps of the planet's land surface in a matter of days, but they cannot map the seafloor directly because most electromagnetic radiation cannot penetrate the depths of the oceans. However, satellite sensors can map the seafloor topography indirectly by making very precise measurements of sea surface height. Satellite instruments can also be used to produce excellent maps of ocean surface features, including wave patterns, sea surface temperatures, and the abundance of **photosynthetic** life in the near-surface waters.

Inaccessibility

The average depth of the oceans is 3800 m, and the greatest depth is 11,040 m. These depths are farther below sea level than the average and greatest elevations of the land are above sea level. The average land elevation is 840 m, and the maximum elevation, at Mount Everest, is 8848 m. Most of the ocean floor is as remote from sea level as the highest mountain peaks are. Put another way, most commercial airplanes fly roughly as high above the land as the deepest parts of the ocean are below the sea surface.

Until the recent development of autonomous underwater vehicles (AUVs) oceanographers had to lower instruments or samplers, usually on a wire, and then haul them back up to the ship to take a sample of the deep-ocean waters or **sediment,** . Because the oceans are so deep, the process of lowering an instrument or sampler, probing or sampling the water column or seafloor, and retrieving the instrument is extremely time-consuming. Sometimes many hours need to be spent getting a single sample of mud or bottom water at one place on the ocean floor. In contrast, a scientist studying the land can collect many samples of rock, soil, plants, and animals much more efficiently. AUVs can now perform some of these sampling missions but they too take a lot of time to travel from surface to seafloor and back.

Research vessels, most of which travel at only about 20 km•h^{-1}, consume large amounts of time and fuel going to and returning from sampling locations far from land. Until the development of the satellite-based Global Positioning System (GPS) for civilian use in the 1980s navigation far from land was difficult. Location or relocation of a specific sampling site was much more difficult than on land. Because research vessels operating in the open ocean can cost tens of thousands of dollars a day to operate, the large amount of time needed to sample the deep oceans means that few samples can be collected during any oceanographic cruise and that each sample is very expensive to obtain. Therefore, samples of the seafloor, oceanic waters, and organisms living in the oceans have been obtained only at intervals of tens of kilometers throughout most areas of the oceans, especially the deep oceans. The advent of autonomous sampling vehicles now allows sampling frequency, especially sampling of some water properties to be drastically increased at lower costs.

Pressure

The pressure of the atmosphere at sea level is about 1.03 kg•cm^{-2}, or 1 atmosphere (atm). On a journey to space, a space capsule is subject to a 1-atm pressure change because the atmospheric pressure in outer space is effectively zero. Therefore, manned spacecraft must have hulls that can withstand a 1-atm pressure difference. Because most electronic equipment can operate without any problem at zero atmospheric pressure, unmanned satellites need no protection against pressure differences. In contrast, on a journey into the oceans, the pressure increases by 1.03 kg•cm^{-2} (or an additional 1 atm) for each 10 m of depth. Hence, the pressure at 100 m is 11 times as high as the pressure at sea level (1 atm of air pressure plus 10 atm of water pressure).

In the deepest part of the oceans, at 11,000 m, the pressure is a truly astounding 1101 times as high as atmospheric pressure, or over 1100 kg•cm^{-2}, which is more than a tonne of pressure per square centimeter. Therefore, manned submersibles designed to dive to the greatest depth of the oceans need hulls capable of withstanding a greater than 1000-atm pressure difference. Most submersibles are not designed to dive that deep, but even shallow dives to 1000 m require hulls that can withstand a greater than 100-atm pressure difference. Submarines and submersibles must have hulls of thick metal, and viewing ports of thick, durable glass or plastic. Deep-diving manned submersibles must be massive, even when made of strong, light materials, such as titanium. In addition, submersible hulls must withstand the metal-fatiguing stresses of repetitive pressurization and depressurization. These requirements make deep-diving submersibles almost prohibitively expensive.

Conductivity, Corrosion, and Fouling

Seawater poses a problem for unmanned instrument packages because most of these rely on electrical components. Such components will not work if immersed in seawater, because seawater conducts electricity and causes short-circuiting. Oceanographic instruments must be placed inside watertight containers called "housings" that must be able to withstand oceanic pressures, because the interiors of the housings normally remain at atmospheric pressure.

Seawater is extremely corrosive, as divers and other water sports enthusiasts quickly discover when they forget to wash their equipment with freshwater. Therefore, all wires, cables, sampling devices, and instrument housings must be protected. Iron and most steels corrode quickly in seawater, so special marine-grade steel or other materials must be used to minimize corrosion. These materials were not available to early oceanographers, who used more expensive and heavier materials, such as brass and bronze. Steel is still the best material available for wires to lower and raise most instrument packages or samples. Even so, the most corrosion-resistant steel wires must usually be further protected by a coating of grease or plastic. Most measurements of trace metals and organic compounds dissolved in seawater were useless until the past several decades because of contaminants from corroding wire and metal sampler parts, and from the grease.

In addition to corrosion problems, a variety of marine organisms **foul** instruments that are left in the ocean to record data for days, weeks, or months, as is necessary for some studies. Some marine organisms, such as **barnacles**, quickly adhere to and colonize the surface of virtually any solid material. Instruments that rely on freely moving parts or on a clean surface-to-seawater contact can quickly be rendered inoperable by such biological fouling.

Wave Motion

Perhaps the most obvious difficulty faced by oceanographers is that the ocean surface is dynamic, and research vessels therefore cannot provide a stable platform on which to work. The perils of working on a rolling and pitching vessel are many. First and foremost, oceanographers must battle seasickness. In addition, they suffer mental and physical fatigue and disorientation caused by working long hours at odd times of day on an unstable platform (many shipboard research activities are continuous 24 hours a day). Oceanographers treasure the rare days of calm seas. Satellites now allow some scientists to remain on land and direct scientific studies remotely using fast data and video communications. However, except for those limited tasks that can now be performed by autonomous vehicles, vessels must still be manned by skilled technicians and seamen. Besides the personal hardships, dangers and difficulties are associated with the deployment and retrieval of often extremely heavy instrument packages over the side of a research vessel. The sight of heavy equipment swinging wildly on a wire from a crane over the deck of a ship when seas are rough is indeed frightening. Hanging over the side of a ship in a storm to clamp instruments that must be attached at certain intervals to a heaving wire is an experience few people would relish.

Less obvious than seasickness and the perils of equipment deployment and retrieval, but just as difficult, are the problems associated with using scientific instruments and performing scientific experiments in shipboard laboratories. Most scientific instruments are delicate and made to be used in a normal vibration-free and motion-free laboratory environment. The lurching, pounding, and vibrating to which such equipment is subjected at sea quickly expose any weaknesses. Equipment often must be specially designed or modified to operate reliably at sea. In addition, all equipment must be clamped or tied down in bad **weather**.

Logistics

A profusion of other, lesser problems is associated with studying the oceans. For example, on a research vessel hundreds of miles, and therefore days and tens of thousands of dollars, away from port, broken equipment cannot be taken to a repair shop, a technician cannot be called in, and spare parts cannot be picked up at a store. Oceanographers and research vessel crews have become skilled and ingenious at using available materials to fix equipment at sea. Nevertheless, even the greatest ingenuity sometimes fails, and research efforts must be postponed until the next cruise to the appropriate location, which may be several years later. Such postponements can also be caused by bad weather that slows or prevents work at sea, although most ocean research cruises are planned to allow some leeway for bad-weather days.

In the rest of this chapter, just a few of the many and varied techniques, instruments, and samplers used by oceanographers of yesteryear and today are briefly reviewed. As you study this material, keep in mind the difficulties of working in and on the oceans.

THE UNSEEN DOMAIN

By the middle of the nineteenth century, very few land areas remained unexplored by Western civilization. A wealth of knowledge had been obtained about the sizes, locations, and shapes of the landmasses, and their mountain ranges, plains, rivers, and lakes. However, there still was almost no knowledge of what lay below the surface of the oceans. The oceans were known to cover two-thirds of the Earth's surface and to be very deep, with the exception of limited areas around continents, islands, and **reefs.** It was also known that the near-surface waters of the seas abounded with fishes and other creatures, and that much of the seafloor was covered by various types of **sediment.** However, as late as the mid-nineteenth century, the deepest ocean waters were believed to lie stagnant and unmoving in the ocean basins, and the deep waters and deep-sea floor were thought to be devoid of life.

This state of ignorance began to change in the latter half of the nineteenth century, when the first telegraph cables were laid on the seabed and the *Challenger* undertook its expedition. Despite subsequent intensive studies, the oceans remained largely a mystery for decades. For example, not until the 1950s did oceanographers begin to realize that an immense chain of undersea mountains runs through all the oceans. The first comprehensive and generally accurate **bathymetric** map was produced in 1959, and corrections and refinements continue today.

BATHYMETRY

People have long needed to map seafloor **topography** to navigate safely past obstructions such as submerged rocks and reefs. In addition, they have long been curious about the depth of water over the seafloor. Measurement of ocean water depth is called bathymetry.

Soundings

For centuries, the only way to explore any seafloor deeper

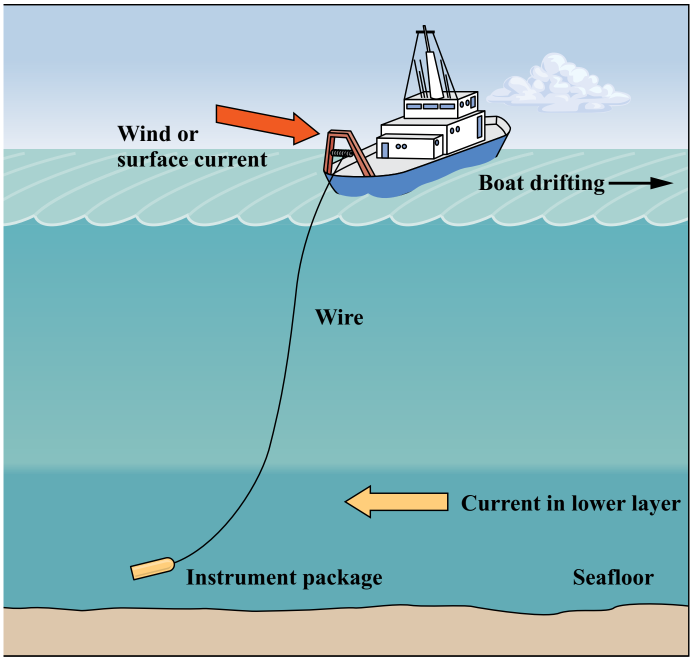


FIGURE 3-1 Winds and currents can deform the vertical path of an instrument package or sounding weight on the end of a wire. Currents in the surface layer or winds that blow the vessel across the ocean surface can "tow" the instrument package or weight through the water. Therefore, a length of wire that is greater than the depth must be payed out for the instruments to reach the seafloor. Currents in lower layers can further complicate the path of the wire, particularly in very deep water where several kilometers of wire must be payed out for the instrument package to reach the seafloor.

than the few tens of meters that could be reached by pearl divers or in crude diving bells was by lowering a line into the water with a weight attached. The length of line payed out (on a ship, letting out line is referred to as "paying out") before the weight hit the bottom indicated the water depth—a measurement called a **sounding.** This method led to the unit of depth called the "fathom," which was used almost exclusively for nautical charts until it was supplanted in recent decades by the meter. The fathom was originally 5½ feet, or the length of line between the outstretched arms of the man hauling the sounding line back aboard the ship. Originally, all depths were measured as a count of the number of such lengths of line that were hauled back aboard after the sounding weight hit the bottom. Later the fathom was changed to exactly 6 feet, and sounding lines, particularly those used for deeper soundings, had knots or ribbons tied at measured intervals to improve the sounding accuracy.

A modification of sounding with line and weight was used to collect samples of bottom sediment. The bottom of the weight, usually lead, was hollowed out and fitted with a lump of tallow. When the tallow hit the bottom, a small amount of bottom sediment adhered to it, unless the weight hit a rocky bottom. Early nautical charts included a description of the type of seafloor based on such samples. Seafloor composition was categorized as sand, silt, or mud, with the mud color sometimes noted. Many modern nautical charts, particularly those of shallow coastal waters, still include that information.

Sounding technology saw a major technological advance during the 1885 voyage of the USS *Tuscarora.*. On the ship's voyage, which was to study possible routes for a telephone cable between America and Japan, the sounding line was replaced by a single strand of piano wire with a weight attached at its end. The wire was deployed from a drum and hauled back by a winch. Because hauling with a winch was much faster than hand-hauling, the *Tuscarora* could make several deep soundings each day. Despite this improvement, fewer than about 6000 soundings had been made in depths greater than 1000 fathoms (1800 m) by 1910. Hence, fewer than 6000 depth measurements had been made in an area that represents about 40% of the Earth's surface, an area nearly 30 times as large as the combined surface area of the 48 contiguous states of the United States. Knowledge of the topography of the deep-ocean floors was only rudimentary, even as late as the beginning of World War I (1914). Consider how good our maps of the mountains, plains, and river valleys of the United States would be if the country were covered in cloud and had been studied solely by lowering a wire through the clouds to the ground at only 200 locations.

Sounding Errors and Problems

Taking soundings using a line or wire is a tedious process that poses additional problems, many of which must still be overcome when wires are being used to lower instrument packages. For example, determining when the weight on the wire has reached the bottom is difficult in deep water. Several kilometers of line or wire is sufficiently heavy to continue to pull more wire from the drum, even when the weight at the end has hit the bottom. Watching for a reduction in how fast the wire pays out or for a slackening of the tension in the wire, each of which occurs when weight is reduced by bottom impact, can sometimes help to overcome this problem. However, these techniques are very difficult, especially in bad **weather,** even using electronic wire-tension measurement systems. As the ship rolls, the head of the crane or the A-frame over which the wire is payed out moves up and down in relation to the sea surface. When a considerable length of wire has been payed out, its weight and drag in the water prevent it from moving up and down with the ship's roll. As a result, it stretches and contracts, and the wire tension fluctuates. Therefore, wires must be several times stronger than would be necessary to carry only their own weight and the weight of any instruments attached to them.

When wires are used to lower instruments, **currents** and the action of the wind on the research vessel can also cause problems. Because the ship is slowly blown along the sea surface by the wind, it tends to move sideways from the weight or instrument package on the wire that is far below. The drag of the wire and its weight tend to prevent the wire from following the ship's sideways motion. Therefore, the wire does not drop vertically to the bottom (Fig. 3-1). If subsurface currents flow in directions different from that of the research vessel's wind drift, or from that of currents at other depths, the wire's vertical path through the water can have a complex *S* shape or other curve (Fig. 3-1). Because a wire never falls through a deep water column vertically, more wire than the actual depth of water beneath the research vessel must be let out if the end of the wire is to reach the seafloor. Therefore, all line and wire soundings in deep water were incorrect. The actual depth was always less than the measured depth.

A more practical problem associated with lowering instruments or wires over the side of a research vessel is that the wind or currents can blow the vessel over the top of the wire or bend the wire under the vessel. The wire can end up stretched tight

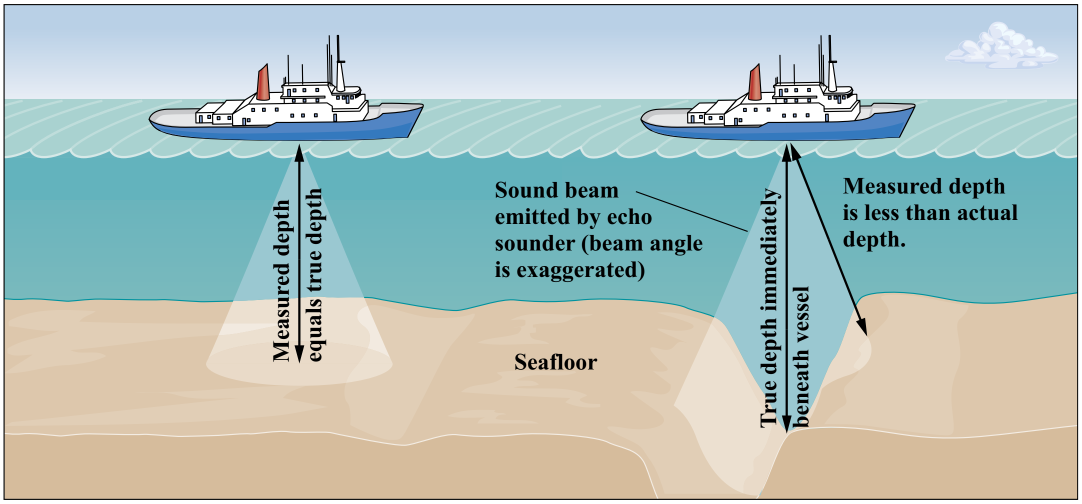


FIGURE 3.2 Echo sounders measure the depth of water beneath a vessel by measuring how much time a sound pulse takes to travel from the vessel to the seafloor and back. Because sound travels in seawater at about 1500 m•s^{-1}, a sound pulse takes 2 s to return to the research vessel when the water depth is 1500 m. The sound pulses spread out over a narrow angle as they travel downward from the vessel. Thus, particularly where the depth is great, they are reflected off a large area of seafloor. Because the first part of the echo to return is used to measure the depth, measured depths are often inaccurate.

across the ship's hull as it passes underneath. Continuing to lower or raise the wire in this situation could damage the ship's hull or break the wire. Therefore, most oceanographic research vessels are specifically designed to be capable of turning slowly around the wire without moving forward. This ability is usually provided by a bow thruster propeller located in a tunnel near the bow of the ship. The propeller is set at right angles to the ship's normal direction of travel and can be used to push the bow of the ship to one side or the other.

Echo Sounders

In response to the sinking of the *Titanic* in 1912, Reginald Fessender, a former assistant to Thomas Alva Edison, invented a device that could detect an iceberg almost 5 km away by sending a sound signal through the water and detecting the return echo. That sound navigation and ranging equipment, which became known as **sonar,** was quickly developed into a device for hunting submarines. After the invention of sonar, it was a simple matter to orient the sound source to point vertically downward (**Fig. 3-2**) and to detect the echo from the seafloor. The speed of sound in seawater is known, as are the relatively small changes in this speed with **salinity** and temperature. Hence, if the distribution of salinity and temperature with depth is known from other measurements, the depth of the water below a ship can be determined

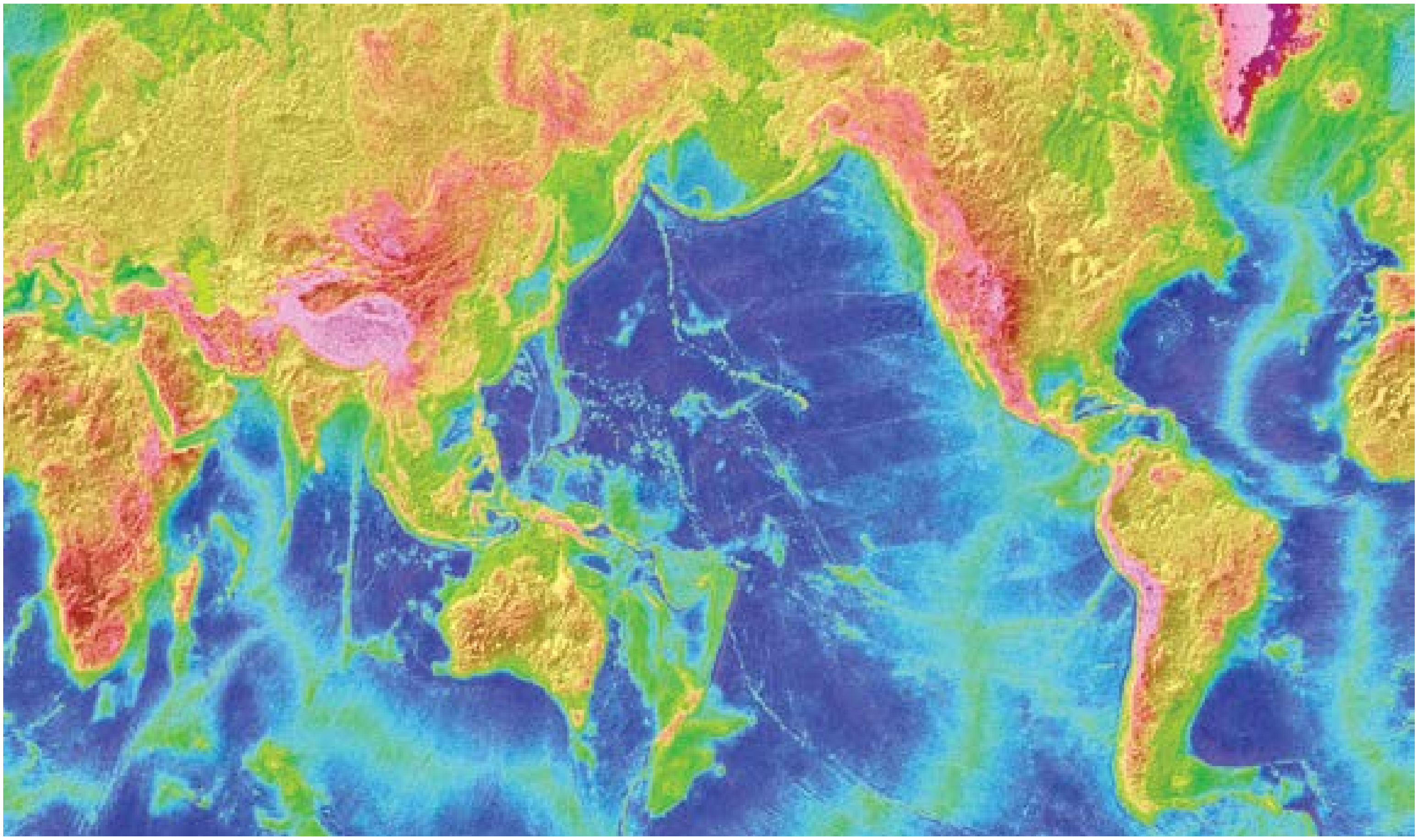


Figure 3-3. Mercator projection map of the seafloor and land surface elevation. Seafloor elevation data were obtained from ship generated precision depth recorder data and satellite measurements of sea surface height data (Date were obtained from many sources). The satellite sea surface height data provides a resolution sufficient that seafloor topography features of a scale greater than about 20-25km are identified in the map. For a large scale version of this map go to **http://www.reefimages.com/oceans/0303.html**

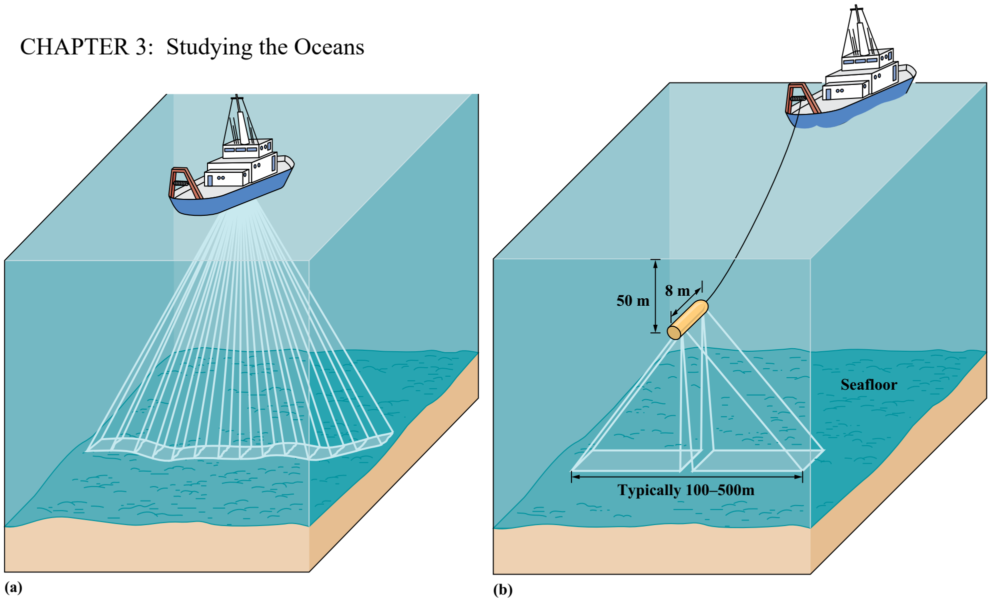
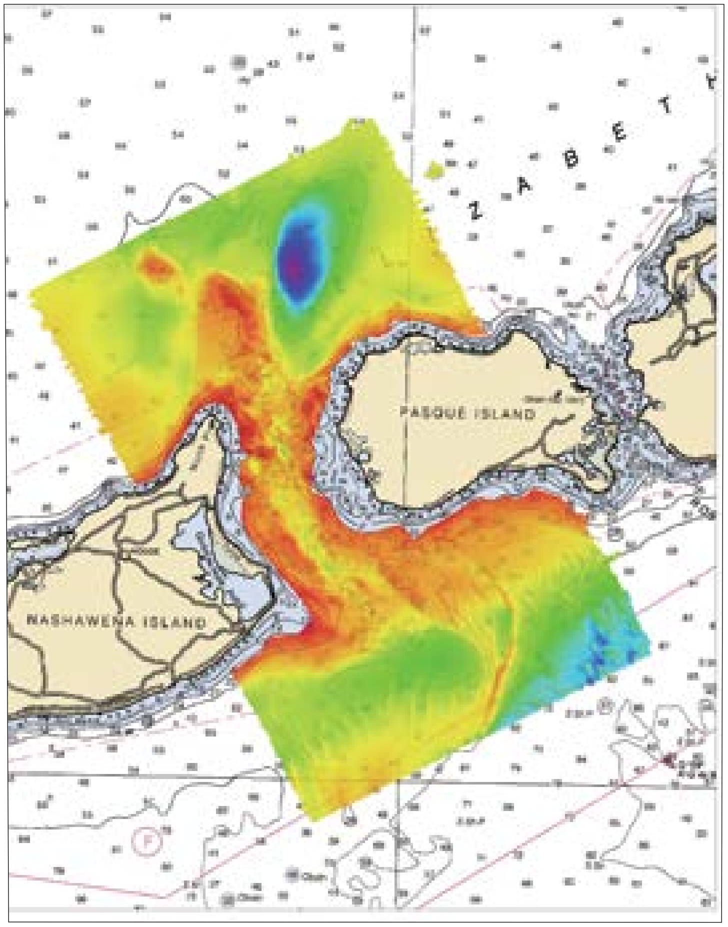


FIGURE 3-4. Modern seafloor topography measurements. (a) The Sea Beam multibeam sonar system uses up to 200 or more separate narrow beams spread out under the ship. (b) Sidescan sonar uses a broad sound beam sent from a towed fish and computer processing of the returning echoes. (c) Both systems produce much more detailed seafloor maps than were previously possible. The colored area of this map shows the detailed topography revealed by a wide-area sonar survey of Quick's Hole, Massachusetts. The surrounding nautical chart shows the much less detailed maps that conventional sonar can produce.



by measurement of the time taken for the sound to travel to the seafloor and back. The first truly successful echo sounder depth recordings were made in the North Sea in 1920 by the German scientist Alexander Behm. Subsequently, knowledge of bottom topography developed rapidly as echo sounding equipment was improved and installed in more vessels.

The great advantage of echo sounders was that they could obtain essentially continuous records of the water depth below a moving ship. By the mid-twentieth century, every research vessel was equipped with an extremely precise echo sounder called a "precision depth recorder" (PDR). Standard operating procedures on most research vessels required that the PDR be operated continuously, and that depths and precise ship positions be recorded while the vessel was under way. PDR depth measurements, although much more accurate than soundings, also have limitations. Because the PDR records only the depth of water directly under the ship's track, depths between two ship tracks still must be inferred by interpolation. Unless depth recordings from many ship tracks cover a given area of ocean floor, major features such as undersea hills and mountains may be overlooked. In addition, the PDR measures only the depth of the closest echo from under the vessel (**Fig. 3-2**). Even PDRs with very narrow beam widths receive echoes from a relatively large area of ocean floor. Hence, a nearby hill can cause the depth to be recorded as shallower than it really is, and narrow valleys and depressions can be missed completely (**Fig. 3-2**).

The depth information generated by research vessels after World War II had to be plotted by hand, which proved to be a daunting task. Of course, depths are now recorded electronically and processed by computers, but computers did not become practical for use at sea until the 1970s. The first truly comprehensive map of the ocean floor was completed by Bruce Heezen and Marie Tharp in 1959. Compiling it was an enormous and tedious undertaking that involved matching depth and position (navigation) data from thousands of hours of PDR recordings made by many vessels without the aid of computers. Navigation errors were corrected by comparison of the depths of each ship, recorded where ship track lines crossed. Depth data were then entered painstakingly on a blank map and carefully contoured, and a three-dimensional representation was drawn exactingly by hand. The map generated by this massive project was truly revolutionary.

To understand this, look at a typical atlas map that shows all the oceans as a featureless uniform blue expanse, then look at **Figure 3-3**. This revelation of previously unseen seafloor topography that rivals the greatest mountain chains and other features of the continents was, for oceanographers and others, like being introduced to an entirely new planet. Heezen and Tharp, and the many other people who spent years gathering data or otherwise helping to create the map, made a contribution to human knowledge that today remains startling, profound, and beautiful.

Since 1959, PDR surveys of the oceans have continued on almost all research vessels during their entire time at sea. Nevertheless, most of the ocean floor is still very poorly mapped by this technique. In fact, vast areas of the deep oceans are mapped by PDRs at a level of detail equivalent to mapping the United States only by measuring elevations along the interstate highways. Look

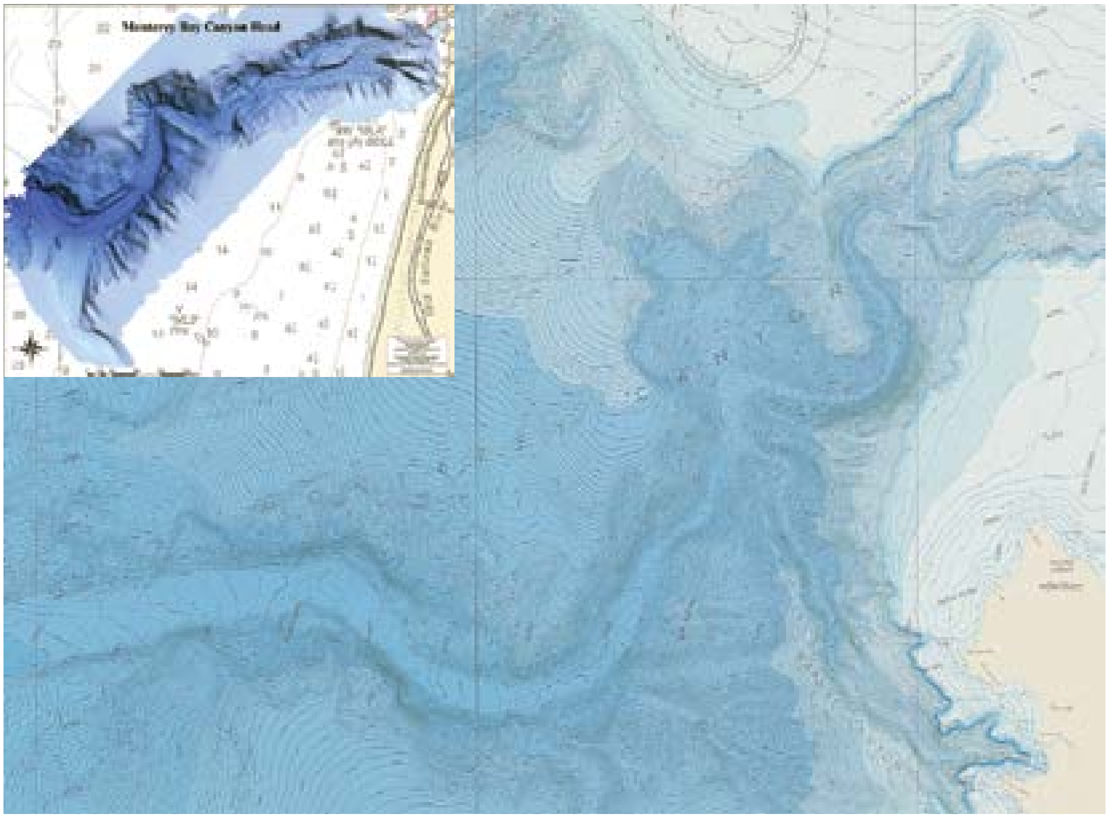


FIGURE 3-5. Bathymetric map of the Monterey Canyon region in central California, produced with data from multibeam sonar surveys. Compare the level of detail of this map with that of older navigation maps that you may have seen for other areas. The inset shows a 3-dimensional rendering of the submarine canyon that crosses the lower half of the larger map.

at a road atlas and think about what topography we would have missed if we had mapped the United States from topographic data taken only along this highway system.

Wide-Area Echo Sounders

In the 1960s, echo sounding was revolutionized by the simultaneous development in the United States and England of somewhat different approaches to determining the seafloor topography within a wide swath under, and to either side of, a vessel track. In the American system, called “multibeam sonar” or “swath,” up to 200 or more narrow sound beams are broadcast in a fan pattern beneath the ship (**Fig. 3-4a**), and the depth (corrected for the angle) is recorded for each beam. In the British system, called “sidescan sonar,” two wider sound beams are broadcast at an angle, one to each side and downward from a streamlined instrument enclosure called a “fish” towed underwater behind the vessel (**Fig. 3-4b**). In this system, echoes from different broadcast angles within each beam return to the fish at different times, depending on the angle and therefore the distance from the fish. Within the prolonged returning sequence of echoes from each outgoing pulse, the intensity of the echo received varies according to distance and the bottom topography. Strong portions of the returning echo sequence indicate that the bottom is sloped up toward the fish. Weak echoes indicate a slope away from the fish. These represent the front and back sides of the hill, respectively.

The two wide-area echo sounding systems have somewhat different uses because each is better suited to mapping certain types of bottom terrain in certain depths of water. Each system requires powerful and sophisticated computer technology to process the signals received. Both methods provide dramatically improved maps and reveal previously unknown canyons, valleys, hills, and other features of the seafloor (**Fig. 3-4c**). Spectacularly detailed charts of coastal waters developed with the new echo sounding systems are now being produced as each area is surveyed. The extraordinarily precise and detailed map in **Figure 3-5** was very important in 1989 when the Loma Prieta earthquake occurred just north of Monterey, California. Using this map with post earthquake surveys and **submersible** observations, oceanographers were able for the first time to study submarine effects of an earthquake, such as the many small mud slides that occurred.

Wide area echo sounders are now deployed in autonomous floats that can survey an area without the need for constant attention from a surface vessel. However, such systems are still expensive to build and operate so, although they will speed up the rate at which the ocean floor is surveyed in detail it will still take decades or longer before the majority of the sea floor is surveyed at the level of detail in **Figure 3-5**.

Ocean Topography from Satellites

Unlike research vessels and autonomous floats, satellites have been able to survey the world’s oceans with unprecedented comprehensiveness in just a few days albeit at lower resolution than wider area sonar can achieve.

The *Seasat* satellite launched in 1978 made the first satellite-based maps of the ocean surface, from which the topography of the seafloor can be deduced. The sea surface topography was measured by a radar altimeter carried on board the satellite. The height of the sea surface can be used to map the seafloor topography because it is affected by the depth of the ocean below it. Rock is denser than water, so rocks have a slightly higher gravitational attraction than water. Therefore, the sea surface is slightly higher over an undersea mountain than it is over a deeper area (the mountain “pulls” water toward it from the sides to create “mounds”). There are now several satellites in orbit that provide satellite altimetry data that have made it possible to map the entire world’s ocean floor. This data has led to the discovery of hundreds of previously unknown **seamounts, fracture zones,** and other topographic features in areas where depth recordings had not been made by ships. By 2023, high resolution radar satel-

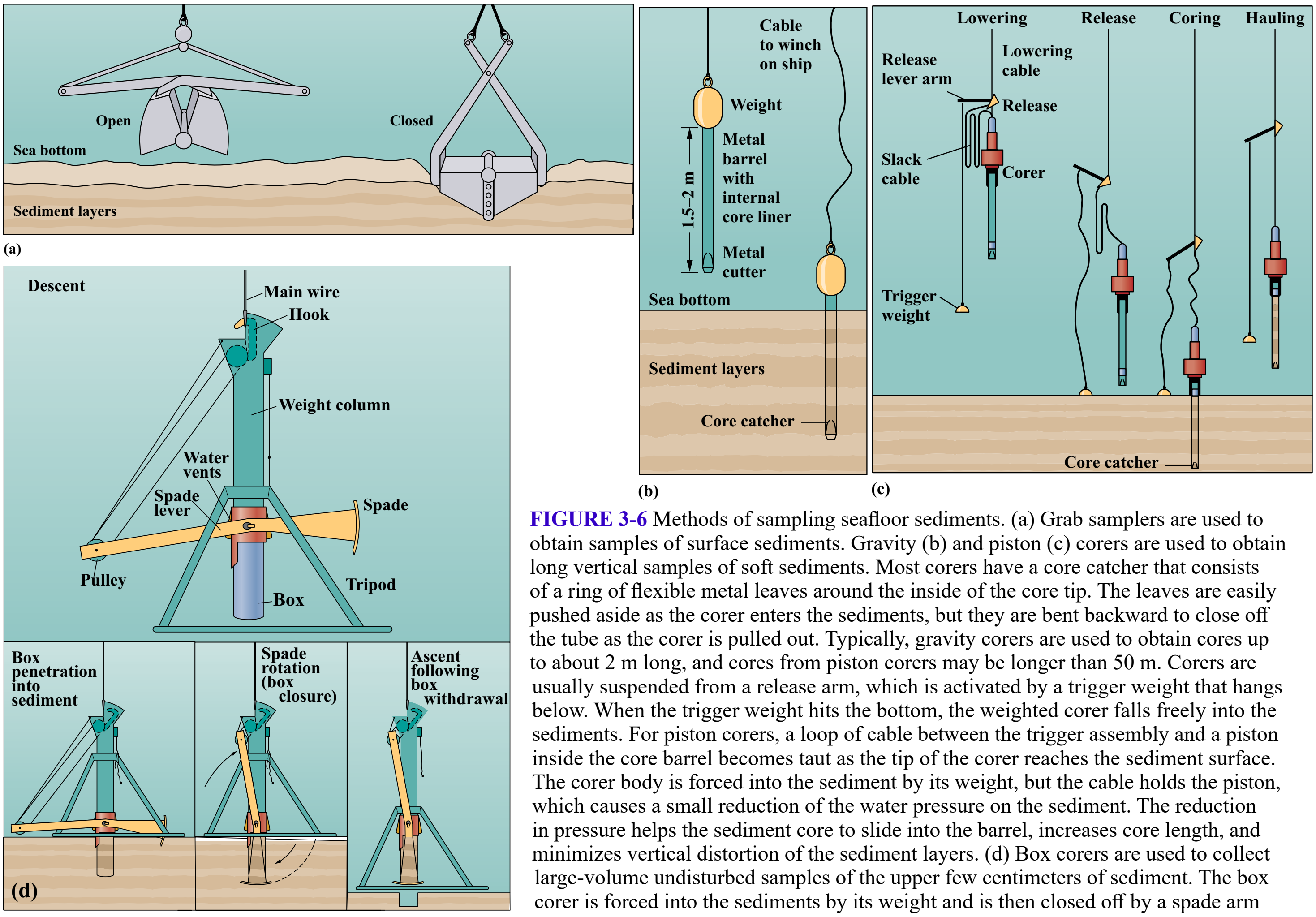


FIGURE 3-6 Methods of sampling seafloor sediments. (a) Grab samplers are used to obtain samples of surface sediments. Gravity (b) and piston (c) corers are used to obtain long vertical samples of soft sediments. Most corers have a core catcher that consists of a ring of flexible metal leaves around the inside of the core tip. The leaves are easily pushed aside as the corer enters the sediments, but they are bent backward to close off the tube as the corer is pulled out. Typically, gravity corers are used to obtain cores up to about 2 m long, and cores from piston corers may be longer than 50 m. Corers are usually suspended from a release arm, which is activated by a trigger weight that hangs below. When the trigger weight hits the bottom, the weighted corer falls freely into the sediments. For piston corers, a loop of cable between the trigger assembly and a piston inside the core barrel becomes taut as the tip of the corer reaches the sediment surface. The corer body is forced into the sediment by its weight, but the cable holds the piston, which causes a small reduction of the water pressure on the sediment. The reduction in pressure helps the sediment core to slide into the barrel, increases core length, and minimizes vertical distortion of the sediment layers. (d) Box corers are used to collect large-volume undisturbed samples of the upper few centimeters of sediment. The box corer is forced into the sediments by its weight and is then closed off by a spade arm that cuts through the sediment and under the box.

lites had identified more than 43,000 seamounts of which only about 16,000 have been mapped by sonar.

Data from satellites and from shipboard PDR surveys have all been combined to provide a detailed view of the ocean floor (Fig. 3-3). However, the resolution of these maps is still such that features as large as several kilometers across may be missing. Limitations inherent to satellite bathymetry make it unlikely that substantially better resolution can ever be obtained except where detailed wide-area sonar surveys are made.

In contrast to ocean floor mapping, the mapping of the planets and their moons was completed quickly and easily by scientists using radar, cameras and modern computers aboard planetary probes such as *Mariner, Voyager,* and *Mars Global Surveyor* spacecraft. In addition, the resolution and comprehensiveness of our maps of Mars, Venus, and the Earth's moon are much better than our seafloor maps. This comparison illustrates the difficulty of studying the oceans.

SEAFLOOR SEDIMENTS

The seafloor is covered by sediment ranging in thickness from zero on a small fraction of the ocean floor to several kilometers. As Chapter 6 discusses, many secrets of the Earth's history are to be found in these sediments. Because the sediments slowly accumulate layer upon layer, history is preserved in sequence; sediment becomes older at progressively greater depths below the seafloor. The upper few to tens of centimeters of sediment are especially important because many living organisms inhabit these sediments, and because processes that affect the fate of chemicals in and on sediment particles are also concentrated in this zone. Therefore, oceanographers are interested in obtaining two basic types of sediment samples:

- Samples that contain an undisturbed sequence of the layers of sediment from the sediment surface down as far as necessary to cover a long period of history
- Large samples of the top few tens of centimeters of sediment, within which most non-microscopic organisms live.

Aside from samples taken in very shallow water, the earliest sediment samples retrieved from the oceans were those that adhered to the lump of tallow at the end of a sounding line. Such samples were useful only for a gross characterization of sediment color and the size and type of the sediment grains. When he explored Baffin Bay in search of a Northwest Passage in 1820, Sir John Ross had his blacksmith construct a "deep-sea clam." That device, the forerunner of grab samplers used today, collected several kilograms of greenish mud containing living worms and other animals from depths of almost 2000 m.

Grab Samplers and Box Corers

In its basic design, a grab sampler consists of a sealed metal container, usually with two halves that open at a top hinge like a clamshell (Fig. 3-6a). The sampler is lowered with the clamshell jaws open, and it sinks into the sediments when it hits the bottom. A mechanism causes its two halves to close as it is pulled up, thus grabbing a sample of sediment.

Grab samplers are relatively light and simple to operate, but they can disturb and partially mix the sediment they retrieve. To minimize disturbance, box corers often are used. A box corer consists of a supporting framework that is lowered to sit on the seafloor, a heavily weighted box with an open bottom that sinks about 20 to 30 cm into the sediment, and a blade that slices under the box from the side to hold the sediment in the box when the frame is retrieved (**Fig. 3-6d**). Because they have a wide opening, box corers can collect large amounts of sediment, but they often weigh several hundred kilograms and are difficult to deploy from research vessels.

Gravity and Piston Corers

To take deeper sediment samples, corers are used. Corers consist of a tube that is open at the bottom end like an apple corer. The tube is forced vertically into the sediment. When the tube is pulled out of the sediment, the core is usually held inside by a core catcher (**Fig. 3-6b,c**). There are two basic types of corers: the **gravity** corer and the piston corer. Gravity corers are allowed to fall freely on the end of a cable; they strike the bottom with great force and are driven into the sediment by weights mounted at the top of the core tube (**Fig. 3-6b**). Piston corers, and sometimes gravity corers, are attached to a release mechanism at the end of a cable (**Fig. 3-6c**). In a piston corer, the action of the piston helps the core slide into the core barrel so that longer cores can be obtained, and it helps minimize vertical distortion and disturbance of the core's sediment layers.

In very sandy sediment or other special situations, gravity and piston corers cannot penetrate. Special corers must be used that force the core barrel into the sediment, either by vibrating it mechanically or by forcing air or water down the outside of the barrel to blow the sediment away.

The smallest corers weigh a few tens of kilograms and take short cores (up to about half a meter long); the largest weigh several tonnes and can take cores more than 50 m long. Deploying and retrieving one of the largest corers, which may be well over 50 m in total length, is an exacting task and this task is now performed by computer driven mechanical systems on specially equipped research vessels.

Unfortunately, and to the frustration of researchers who may have waited hours for the sampler to be lowered and retrieved if the water is deep, grab samplers and corers often fail to penetrate or close properly. There are several reasons for such failures. For example, the sampler might impact the seafloor at too great an angle if currents distort the wire from the vertical as discussed earlier, or the sampled material might jam in the closure mechanism. Even a tiny opening in the closure mechanism can cause the sample to be lost as the sampler is hauled back through the water column.

Drilling Ships

To study older layers, scientists must explore deeper in the ocean sediment than can be reached by corers. In addition, the bedrock beneath the ocean sediment holds valuable clues to the history of the Earth and its oceans. In 1968, the United States began using a unique drilling ship, the *Glomar Challenger,* to sample the deeper sediment layers and rocks. The ship was capable of drilling holes in the ocean floor in water as deep as 6 km and could collect drill-core samples from depths up to about 2000 m below the seafloor. The Deep Sea Drilling Program (DSDP) used the vessel to obtain more than a thousand cores from throughout the world's oceans. These core samples helped to confirm the theories of **seafloor spreading** and **continental drift** (**Chap. 4**).

In 1983, the DSDP was succeeded by the Ocean Drilling Program (ODP), an international cooperative program funded jointly by the United States, Canada, West Germany, France, Japan, the United Kingdom, Australia, and, at one time, the Soviet Union. The *Glomar Challenger* was replaced by the more sophisticated *JOIDES Resolution.* In 1990, in a water depth of 5700 m, 2500 km south of Japan, the *JOIDES Resolution* drilled through 200 m of recently formed volcanic rock and 460 m of sediment lying below it. A sample of sediment was retrieved that was estimated to be 170 million years old and is believed to be the oldest remaining ocean floor sediment, except for that found on small fragments of tectonic plates that have avoided subduction.

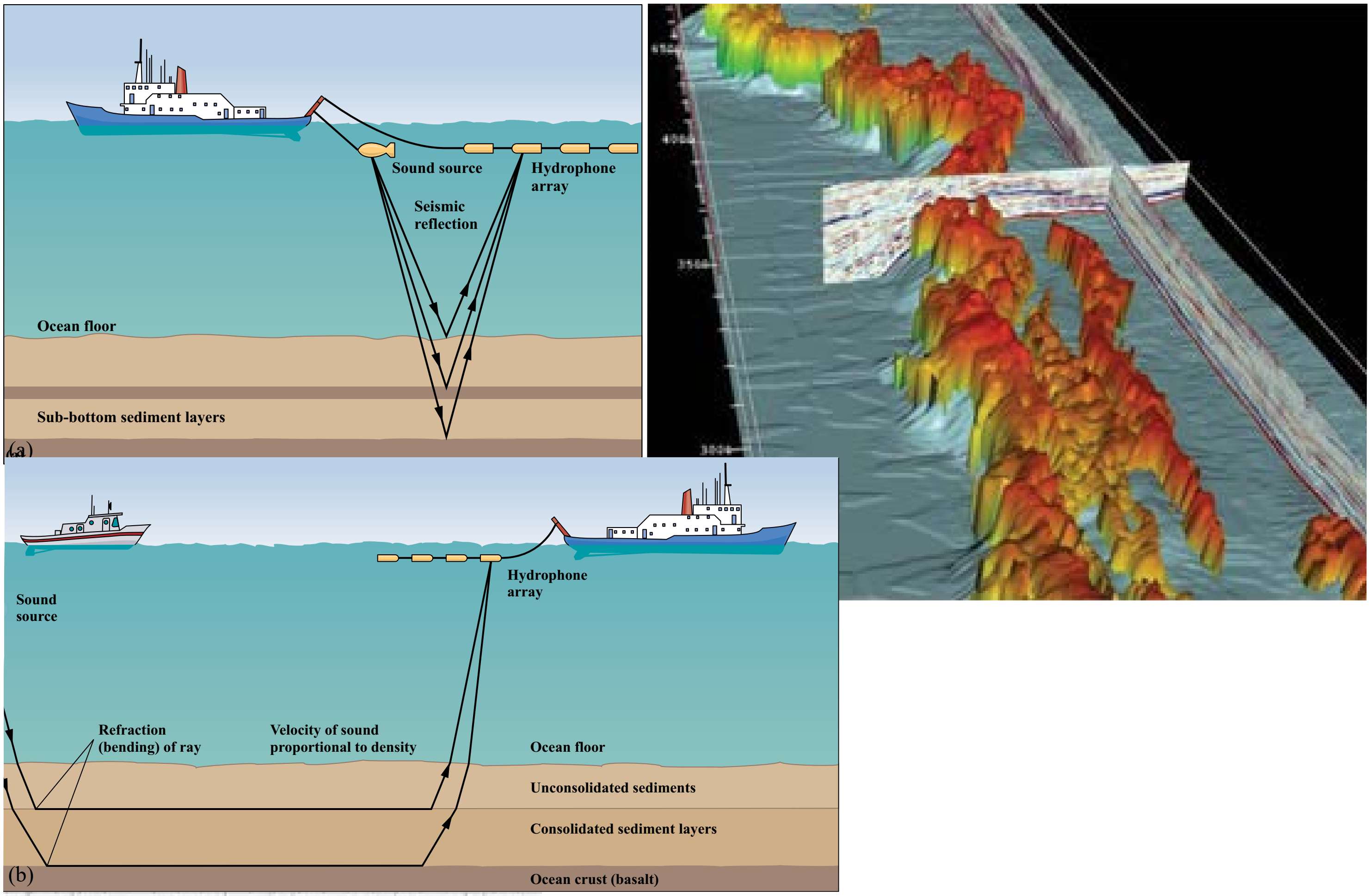
In 2003, the ODP was succeeded by the Integrated Ocean Drilling Program and then the Integrated Ocean discovery Program (both IODP), led jointly by the United States and Japan. This program operates two drilling ships, the *Joides Resolution* and a newer Japanese vessel called *Chikyu.* The *Chikyu* is capable of drilling holes as deep as 6 km beneath the seafloor, far surpassing the 2-km limit of the *JOIDES Resolution.* The *Chikyu* is also able to drill in shallower water, and it has the ability to prevent blowouts (uncontrolled releases of gas or oil) if it penetrates formations that contain oil and gas which allows *Chikyu* to drill in many locations where the *JOIDES Resolution* can not. This program is scheduled to end in 2024 but is likely to be renewed.

Seismic, Magnetic, and Gravity Studies

Because obtaining corer or drill-core samples is time-consuming and expensive, oceanographers can sample directly only a small number of locations. Fortunately, certain remote sensing techniques can provide information about the sediment and in areas where actual seafloor samples are not available. Seismic profiling and the measurement of magnetic and gravitational fields are the principal techniques used to obtain such information.

Like sonar measurements, seismic profiling uses a sound wave or shock wave. The sound wave passes through the ocean water into the sediment and is partially reflected at each depth where the type of sediment changes or a volcanic rock layer begins (**Fig. 3-7**). Because ocean sediments are built up layer upon layer, many such echoes, each of which corresponds to the top of a layer, are reflected from within most ocean sediments. Returning echoes are monitored with a string of **hydrophones,** devices that record sound waves, towed behind the research vessel. The sound waves received by each of the hydrophones have traveled different distances within the sediment layers and so are received at different times (**Fig. 3-7a,b**). Seismic profiles reveal structural features of the sediment that are hidden below the seafloor, including **faults,** tilting of the layers, and buried mountain tops. Modern seismic profiling systems use multiple sound sources and multiple strings of hydrophones towed behind the research vessel. Using powerful computers to analyze the resulting data, these systems can produce detailed three-dimensional images of the sediments or rock beneath the seafloor (**Fig. 3-7c,d**).

Because sound travels at different speeds in different types of sediment and rock, seismic profiles can aid in determining the nature of each layer of sediment. Distinct sediment layers in many parts of the ocean can be traced for hundreds of kilometers in all directions. Hence the layers found in seismic maps can often be correlated to the layers of sediment and rock retrieved by drilling



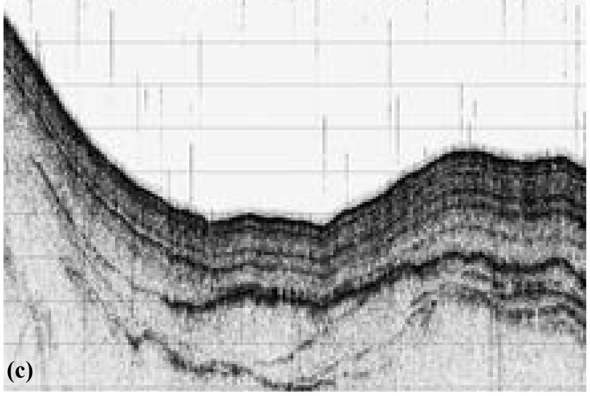


FIGURE 3-7 Seismic profiling. Two techniques are used: (a) seismic reflection, in which sound pulses penetrate the seafloor and are reflected off sedimentary layers; and (b) seismic refraction, in which sound pulses are refracted (bent) at interfaces between layers of sediment and then travel back out to be received by a second ship. At one time, the sound source was provided by dynamite sticks thrown overboard to explode just under the water surface. However, the sound source typically now used is an air gun that periodically fires a burst of compressed air into the water at a depth of about 15 to 35 m. The sound waves are generated by the collapse of the air bubbles produced by each burst. (c) A typical seismic profile shows rugged seafloor topography overlaid by sediment layers. (d) A 3-dimensional seismic image of an ancient reef structure buried beneath the sediments off Nova Scotia, Canada. The light colored 2-dimensional sections across the center of the image and along the right side show just how much more information the 3-dimensional image can convey.

or coring.

Sediment and rock on or below the seafloor also can be studied by precise measurement of changes in gravitational-field or magnetic-field strength. Tiny changes in magnetic-field strength are detected by instruments towed behind a research vessel as it passes over seafloor sediment and rocks that have variable magnetization. Gravitational-field strength also changes slightly at different locations because the Earth is not perfectly round, and because denser sediment and rocks exert a slightly greater gravitational pull than less dense or lighter sediment at the same depth. Therefore, extremely small changes in gravitational-

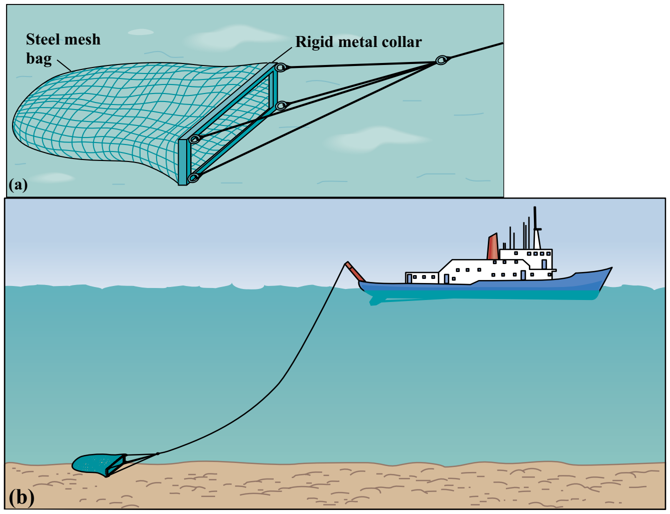


FIGURE 3-8 (a) Rock dredges are used to obtain samples of rock from seafloor where there is little or no sediment cover and to collect nodules that lie on the sediment surface. (b) The dredge is lowered on a cable and towed across the seafloor. Sediment passes into and through the net, while nodules and loose rocks are retained. The metal collar breaks off rocks from a rocky seafloor.

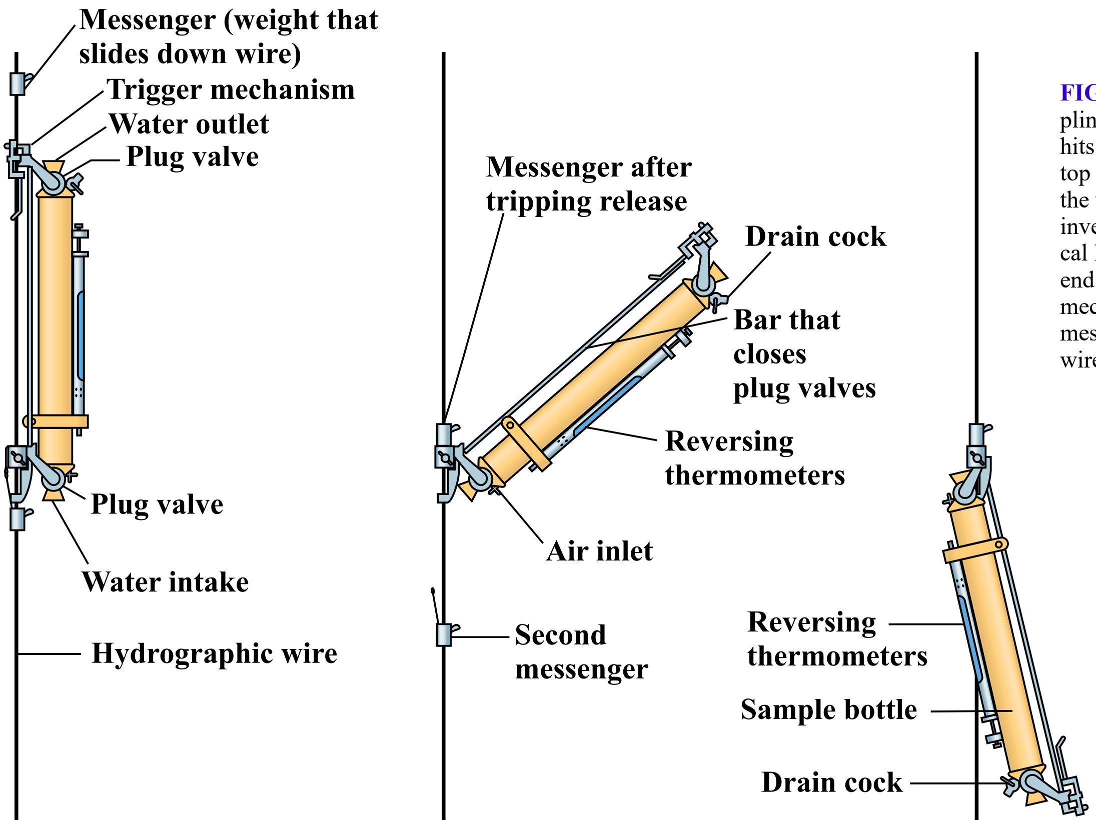


FIGURE 3-9 Nansen water-sampling bottle. When the messenger hits the trigger mechanism, the top of the bottle is released from the wire, the bottle falls into an inverted position, and a mechanical linkage closes valves at each end of the bottle. The trigger mechanism also releases a second messenger, which slides down the wire to the next sampling bottle.

field strength detected by instruments carried on research ships provide information about the sediment and rock below, especially the presence of mountains of volcanic rock overlain by less dense sediment.

Dredges

Although most ocean floor is covered by thick sediment, rocky outcrops also are present, and some areas of the seafloor are partially covered with **manganese nodules** and **phosphorite nodules** (Chap. 8). Because corers and drills are not able to sample such surface rocks, dredges are commonly used. A dredge consists of a net of metal chain or nylon mesh with one end held open by a strong, rigid, metal frame (Fig. 3-8).

FIGURE 3-10 A GoFlo water-sampling bottle. This ingeniously designed bottle is lowered through the sea surface in a closed configuration to avoid contamination. At a depth of a few feet, a pressure-sensitive trigger opens both ends of the bottle. The bottle is closed again by means of a messenger or other triggering device when the bottle is at the required sampling depth.

Dredges are often massive because the rocks in many areas must be broken off of solid **lava** flows. When a dredge snags on such rocks, considerable force is needed to break the rock and release the dredge. Therefore the cable used for lowering and towing dredges must be extremely strong. Steel cables 1 cm or more in diameter are sometimes required. In very deep water, 10,000 m or more of cable weighing several tonnes is required. Because the drum on which the heavy dredge cable is stored and the winch needed to drive the drum are huge, only a few of the largest research vessels can deploy the largest dredges. Submersibles, ROVs, or AUVs discussed later in the chapter, now perform some of this type of sampling.

CHEMICAL AND PHYSICAL OCEANOGRAPHY

Oceanographers are interested in understanding temporal and spatial variations (that is, variations over time and space) in the concentrations of the many chemicals dissolved in seawater or associated with **suspended sediment**. Most of these chemicals are found in seawater at very low concentrations (Chap 5) that make their concentration measurement very difficult. As a result, most chemical concentrations cannot yet be measured directly by instruments lowered into the ocean, and samples of water from selected locations and depths must normally be collected and brought back to a research vessel or onshore laboratory.

Sampling Bottles

In all but shallow water, where samples can be pumped up through a hose, water samples are collected in specially designed bottles. Usually the sampling bottles are designed to descend in an open configuration that allows continuous flushing with seawater, as otherwise they would quickly be crushed by the increasing pressure. Several sampling bottles can be attached at intervals on a wire to sample at different depths during one lowering. When the bottles are at the requisite depths, a brass or stainless-steel messenger is attached to the wire (Fig. 3-9). The messenger slides down the wire and hits a trigger mechanism on the shallowest bottle, causing the bottle to close and releasing another messenger attached under the bottle. Thus, each bottle releases a new messenger to slide down the wire and close the next-deeper bottle.

For many years, most water sampling was done with Nansen bottles (Fig. 3-9). These have been replaced by newer designs developed primarily to collect larger samples or to avoid sample contamination. Because concentrations of some important trace metals and organic compounds in seawater are extremely low (Chap. 5), oceanographers must often collect large volumes (sometimes tens or hundreds of liters) of seawater per sample, and then use sophisticated chemical techniques to extract and concentrate the chemicals before even the most advanced and sensitive analytical instruments can measure the concentration.

Avoiding Sample Contamination

Contamination of the sample must be avoided during its journey from the ocean depths to the laboratory. Contamination comes from many sources, including the metals, plastics, and other materials of the sampling bottle, the metal of the **hydrographic** wire, and the grease that covers the wire to protect it from corrosion. Dust, oil, and vapors in the ship and laboratory atmosphere are other potential **contaminants.**

An especially difficult contamination problem is caused by the thin **surface microlayer** (about 0.1 mm thick or less) that covers all the oceans. The microlayer always contains higher concentrations of many chemicals than the seawater below, and it can be further contaminated by discharges, such as oily cooling water from the research vessel, and by paint and corrosion chips from the vessel's hull. Sampling bottles that remain open as they are lowered through the sea surface retain a film on the inside of the sampling bottle deposited by the surface microlayer. This film can significantly contaminate the sample. Several ingenious sampler designs, including the GoFlo bottle (Fig. 3-10), prevent surface microlayer contamination.

The GoFlo bottle is carefully cleaned and sealed in the closed position on the research vessel before being lowered through the surface. A pressure-sensitive mechanism opens the bottle automatically once it is a few meters below the surface. The bottle can then be closed at the required sampling depth.

For chemical parameters not affected by surface microlayer contamination, one of many other sampler designs can be used. Samplers that collect 10 liters of seawater are used routinely in many applications, and very large samplers that collect hundreds of liters are used for special analyses.

Determining the Depth of Sampling

Seawater in the oceans forms a series of horizontal layers, each of which is often only a few meters thick (Chap. 10). Water moves great distances within these layers, but it mixes only slowly with the water in the next layer above or below. Chemical oceanographers usually want to sample within each of the layers, and sometimes at closer depth intervals across the interfaces between layers. Unless the precise depths of the layers are known, selecting the exact spacing of water-sampling bottles along the

FIGURE 3-11 (a) Reversing thermometers like these are attached to a water-sampling bottle in a rack. (b) When the bottle is closed, the rack and thermometers are turned upside down (reversed). The protected thermometer records the true temperature, while the unprotected thermometer records a temperature that is slightly too high because the mercury reservoir is squeezed slightly by the increased pressure at depth. The temperature difference between the thermometers can be used to determine the depth at which the thermometers were reversed. Reversing thermometers are still used to calibrate CTDs, which are instrument packages that measure conductivity, temperature, and depth electronically.

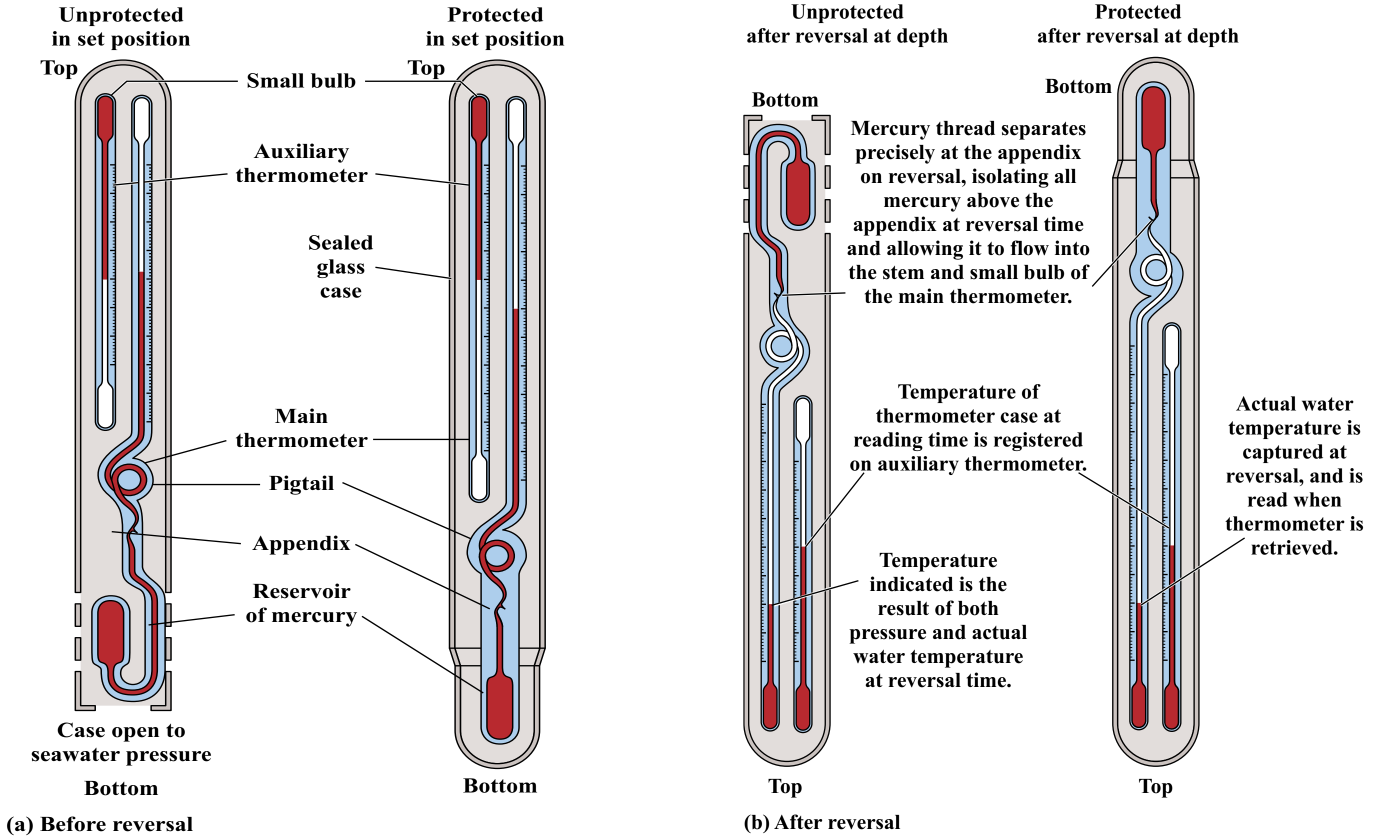


FIGURE 3-12 Rosette water sampler. The sample bottles, some fitted with thermometer racks, are arranged in a rosette pattern around an electronic device that enables researchers on the ship above to close individual sample bottles at selected depths through an electrical signal sent down the hydrographic cable. The round frame below the water-sampling bottle rack usually contains a CTD and possibly other sensors, such as turbidity-measuring devices.

wire is impossible. In addition, even if samplers are placed correctly along the wire, the depth at which each sampler is closed can be affected by curvature of the wire caused by currents or vessel drift (**Fig. 3-1**).

Density increases with depth in the oceans, so depth may be estimated by measuring density. Temperature and salinity are the two primary parameters that determine the water density, so density may be calculated and depth estimated by measurement of these two parameters. Salinity, temperature, and density relationships are discussed in **CC6** and **Chapter 5**. The approximate depth from which a sample is obtained can often be determined if the temperature and salinity of the water at the depth at which a sampler is closed are measured. Salinity can be determined by measurement of the **electrical conductivity** of the sample of seawater collected after it has been returned to the laboratory. However, the temperature of the sample changes as it is retrieved so, before the development of sensitive electronic thermometers, the temperature had to be recorded at depth when the sampler is closed. This temperature measurement was achieved by a "reversing thermometer" mounted on the outside of the sampler (**Fig. 3-11a**). The thermometer on a Nansen bottle reverses with the bottle itself (**Fig. 3-9**), but other sampling bottles, which do not themselves reverse, have an externally mounted thermometer rack that rotates mechanically through 180° as the bottle is closed (**Fig. 3-12**). To accurately determine the depth of sampling, two reversing thermometers can be used, one protected and one unprotected from pressure changes with depth (**Fig. 3-11b**). This method is so accurate it is still used today to calibrate the electronic temperature sensors now used.

Instrument Probes and Rosette Samplers

Using water sampling bottles and reversing thermometers to determine salinity, temperature, and depth is tedious and only provides data at those depths at which samples are taken. This method was replaced in the 1970s by instrument packages containing electronic sensors attached to a wire that make measurements continuously as they are lowered and raised. These packages are called **CTDs,** for conductivity (electrical), temperature, and depth (or sometimes "STDs," for salinity, temperature, and depth), because electrical conductivity is measured to determine salinity (**Chap. 5**). CTDs have many advantages over sampling bottles, especially their ability to read salinity and temperature continuously as a function of depth. Such sensors, or probes, have enabled oceanographers to observe small-scale variations in the layered structure of ocean water that cannot be discerned from widely spaced bottle samples. The wire used to lower CTDs can both supply electrical power to the sensor package and return the sensor signal to a processing unit in the ship's laboratory. Therefore, these CTDs enable scientists to see instantly the variations of salinity and temperature with depth. The special CTD wires, which have electrical conductors running throughout their length (often tens of thousands of meters), are much more expensive than the simple steel wire used previously, but the advantages justify the extra cost and complexity.

Although oceanographers no longer need to use water-sampling bottles to determine salinity, temperature, and depth, samples of water still must be collected and returned to the laboratory for analysis of most dissolved chemicals. The dissolved constituents and the importance of variations in their concentrations are discussed in **Chapters 5, 12, and 16**. If the sampling bottles are mounted around a CTD, samples can be taken at precise locations within the various water layers. Each bottle can be closed when the CTD readings in the shipboard laboratory show the bottle to be at the appropriate depth. For this purpose, a rosette sampler (**Fig. 3-12**) is used that consists of a rack for mounting 12 or more sample bottles around the CTD sensor package and an electronically operated trip mechanism. Signals sent down the support wire to the trip mechanism close each sampling bottle individually.

There is great interest in developing sensors to add to the CTD that would continuously measure dissolved concentrations of important chemicals. Dissolved oxygen, **pH,** and **turbidity** are among the relatively few parameters for which reliable sensors exist. To date, none of the other sensors are as reliable and sensitive as the salinity, temperature, and depth sensors are. However, a wide range of chemical sensors are now beginning to reach the stage of development where they are providing useful data.

Measuring Currents

Oceanographers are interested in studying the movement of

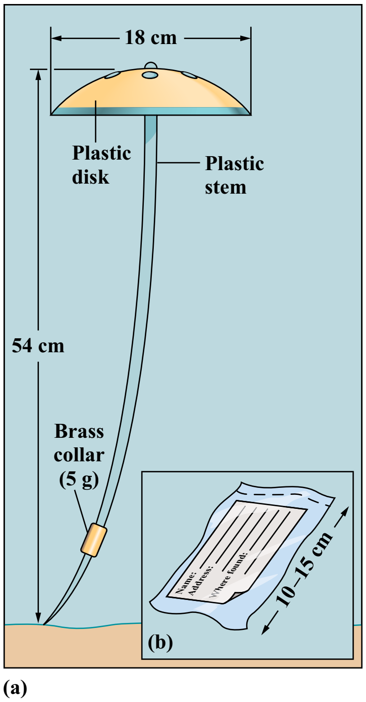


FIGURE 3-13 Surface and seabed drifters. (a) The seabed drifter is weighted such that its bottom tip drags along the seafloor as the plastic disk section “catches” the current and moves with it. (b) The surface drift card is usually a simple postage-paid return postcard sealed in plastic that offers a small reward to any finder who sends it back to the researcher and reports where (usually on a beach) and when it was found. The card floats flat on the water surface and moves with surface currents.

water in currents that are present throughout the ocean depths. The speed and direction of currents can be computed from salinity and temperature distributions in the oceans (**Chap. 8**), and water movements can also be studied by the use of chemical or **radioactive tracers** dissolved in the water. These indirect methods, especially when combined with mathematical modeling techniques (**CC10**), are extremely valuable for studying the movements of water averaged over large distances (tens of kilometers or more) and long periods of time (months or longer).

Because tracers are much less useful in studying the small-scale details of current distributions and their variability with time, a variety of systems are used to measure currents directly. There are three basic types:

- *Passive devices* flow with a current wherever it goes and periodically or continuously report their position.
- *Current meters* are anchored and periodically or continuously measure the speed and direction of water flowing past them.
- *Remote sensing systems* can measure currents at various depths beneath a moving research vessel or at various depths from a fixed mooring.

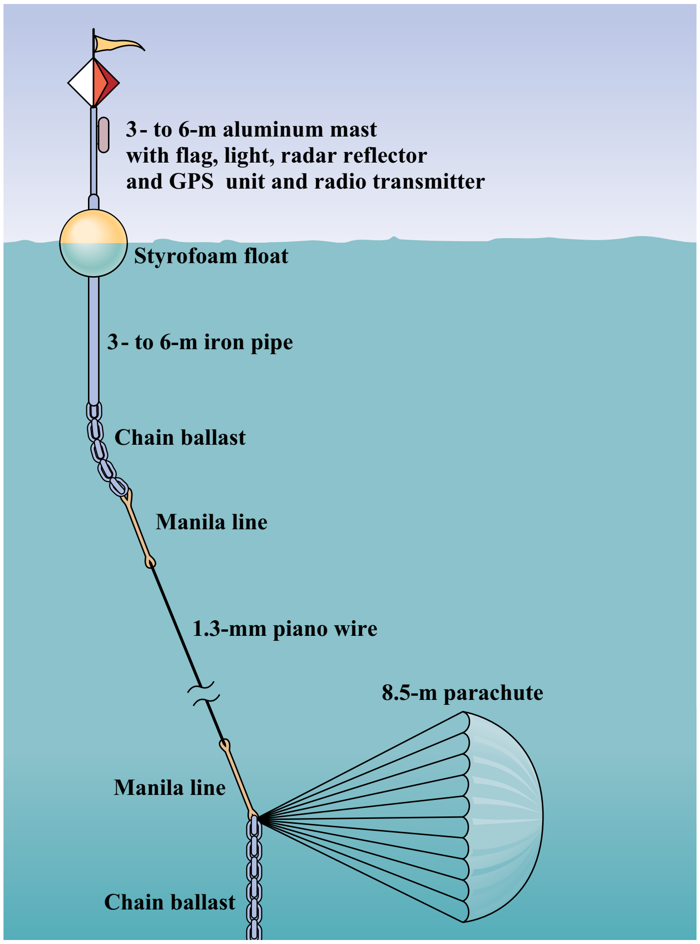
Drifters, Drogues, and Floats.

The simplest method of measuring currents in the coastal zone is to use drifters. Drifters are designed to float on the surface of the water or are weighted and designed to sink very slowly to the seafloor, where they are easily picked up and moved by even the gentlest bottom current (**Fig. 3-13a**). Drift cards (**Fig. 3-13b**) are thrown overboard in large numbers at a fixed location. Like a message in a bottle, they drift on the surface with the ocean currents until they wash up on a beach. Each card is numbered and bears a message asking whoever finds it to return it to the oceanographer with details of where and when it was found. The finder is often paid a small reward for return of the card. Drift cards are a very inexpensive means of gaining information about mean current directions, especially in coastal regions, where currents are often very complex and variable. Drift cards are particularly valuable in studies of the probable fate of wastes discharged or oil spilled at specific locations. Surface currents can also be studied with floats, whose movements can be followed remotely by radio signals received from a transmitter mounted on the float.

Current speed and direction both vary with depth in the oceans. Currents flowing below the surface can be studied with two types of passive systems. In shallow coastal waters, parachute drogues are often useful. A drogue consists of a parachute attached to a weight and to a measured length of wire. The other end of the wire is attached to a float, usually with a radar reflector mounted on it. The parachute opens and is pulled down to a known depth by the weight (**Fig. 3-14**). Once at the assigned depth, the parachute drogue “sails” in the current, dragging the surface float behind it. Such devices cannot be used in deep water layers, because of the excessive drag of the long wire.

Currents in deep waters can be measured with neutrally buoyant floats. The simplest versions are self-contained instrument packages, mounted in one or more hollow tubes and weighted so that their density is precisely the same as the density of the seawater at the depth at which the float is to operate (**CC1**). These floats are deployed from a research vessel and sink through the water column until they reach a predetermined depth. The float contains a pinger, an electronic system that produces short sound pulses, or “pings.” The sound emitted by the pinger is followed from listening stations aboard research vessels or onshore.

FIGURE 3-14 Parachute drogue. The parachute is deployed at a selected depth (usually less than 100 m), where it sails along with the current, dragging the surface float after it. The research ship can follow the movements of the float by visual observations, with radar, or remotely through a global positioning system unit and radio transmitter mounted on the float

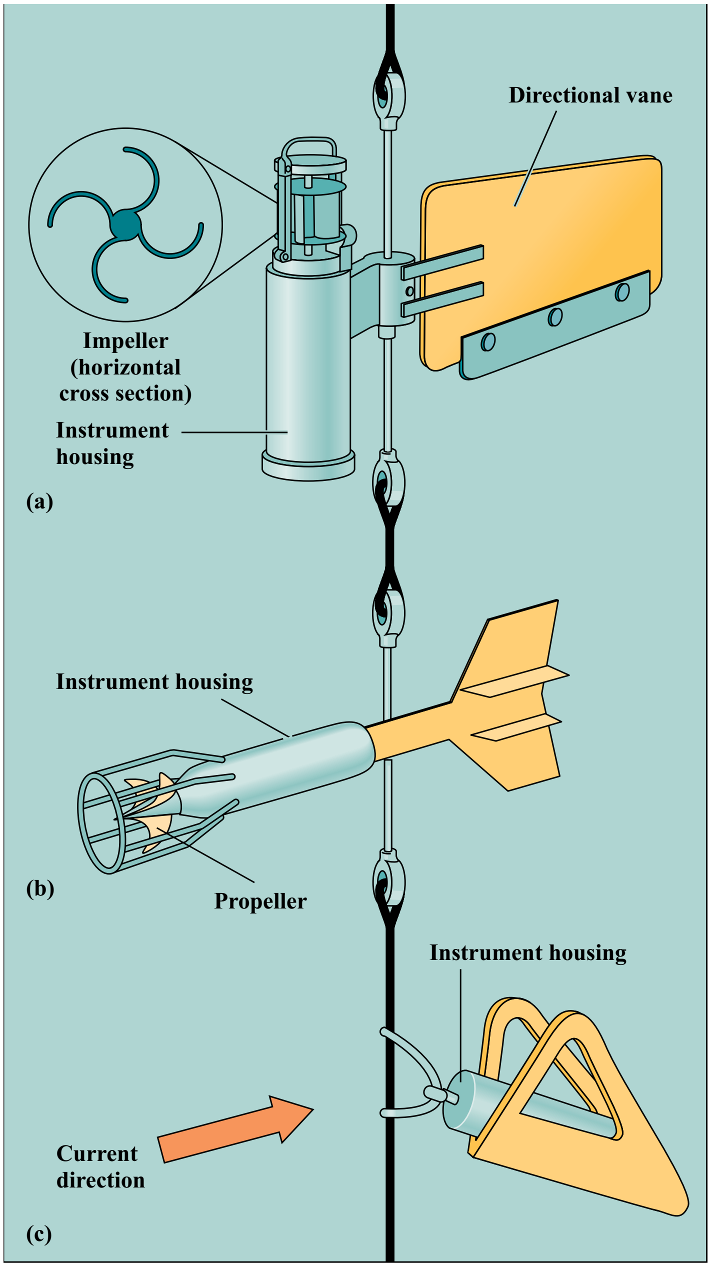


The position of a float is determined by triangulation from two or more listening stations. Such floats have been followed for months as they move in the complex currents and eddies of the ocean depths (**Chap. 8**). Modern versions of these floats are called “autonomous floats,” and they are capable of moving back and forth vertically through the water column, recording conductivity, temperature and other data. These floats periodically revisit the surface to send their data back to a ship or shore station by radio. These floats do not have a means of recording their exact position during their time below the surface. Global Positioning System (GPS) sensors are small enough that they can be mounted in the floats, but GPS and other electromagnetic wave–based positioning systems cannot work below the ocean surface because ocean water effectively absorbs this radiation. However, current speed and direction, averaged over the depths visited by the floats and the time interval between surface visits, can be calculated from the precise locations of the floats measured each time the float surfaces to report its data.

Mechanical Current Meters.

Many current meters remain in a fixed location, measuring the rate and direction of the water flowing past them. Three types of such meters were once common before the development of acoustic current meters: (1) those having an impeller whose axis is oriented vertically (**Fig. 3-15a**); (2) those having a propeller oriented to face the current (**Fig. 3-15b**); and (3) those that rely on the current to tilt the meter body at an angle from its normal vertical position (**Fig. 3-15c**). In each case the meter is oriented to align itself with the current direction by one or more vanes or fins, just like a weather vane. These current meters are usually suspended at intervals below the surface on wire moorings (**Fig. 3-15d**). The entire mooring, including the float at the top of the wire, is often deployed well below the water surface. The string of meters is left to record currents for days, weeks, or even months, and then recovered by the release of weights from the bottom of the wire with an acoustic signal sent from the recovery ship to an acoustic release. This method of deployment is often necessary to avoid having the meters cut free or stolen by curious ship crews or by misguided fishers concerned about their nets catching on the mooring.

Current meters deployed on moorings normally contain internal devices that continuously record current speed and direction. Current direction is recorded by continuous readings of the



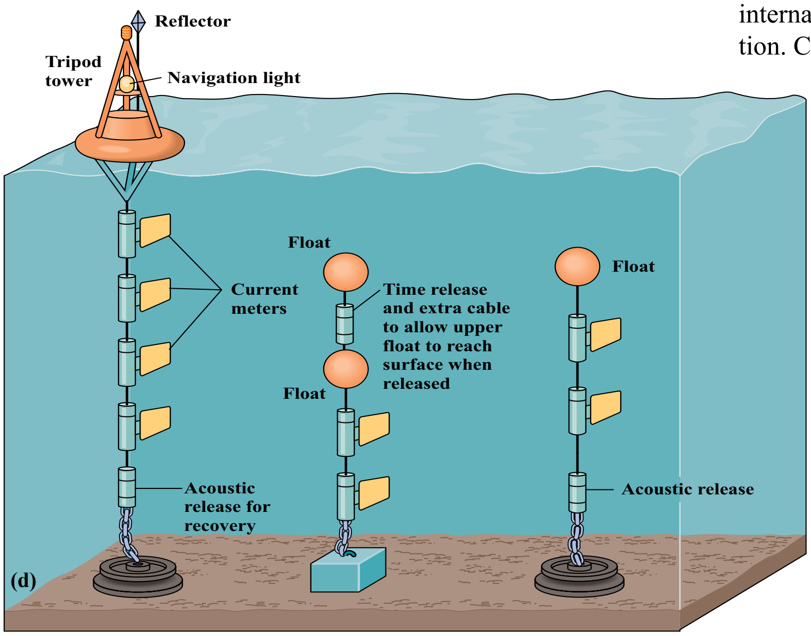


FIGURE 3-15 Typical designs for current meters are (a) a meter that measures current speed by the rate of rotation of a rotor that behaves much like a waterwheel (this type of rotor is known as a “Savonius rotor” or an “impeller”), (b) a meter that measures current speed by the rate of rotation of a propeller, and (c) a meter that measures current speed by the angle to which the meter is pushed by the current. Vanes or fins are used to orient the meter in the current. Current speed and direction, measured with a magnetic compass inside the instrument housing, are usually recorded on tape in the meter, and the records are read when the meter is retrieved. (d) Current meters are typically deployed in vertical strings, such as the three different configurations shown here, all moored to the seafloor. They are often left in place for weeks or months and then retrieved, usually by means of a release mechanism that is activated by a timer or an acoustic signal from the recovery ship. Often the current meter moorings are entirely below the surface to discourage theft and to reduce navigation hazards.

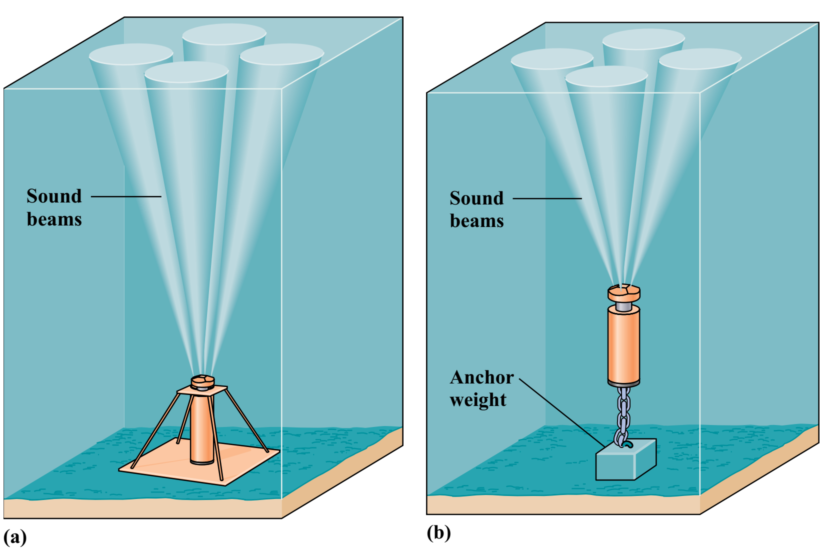


FIGURE 3-16 Doppler acoustic current meters can be (a) mounted on the seabed, (b) moored in mid water, or (c) mounted in a ship's hull facing downward. The sound beams sent out by the meter are reflected off particles in the water, and the frequency of the sound in the returning echo is changed according to the direction and speed of the particles that move with the current.

position of a magnetic compass mounted inside the meter body. Depending on the meter design (**Fig. 3-15a–c**), current speed is measured by the speed of rotation of the impeller or rotor or by the angle of the meter's tilt from the vertical.

Most current meters are sophisticated and expensive electronic instruments. However, currents have been measured with much simpler systems in some shallow coastal waters. The most ingenious and least expensive system consists of a sealed glass bottle partially filled with sealing wax and containing a magnetic needle attached to a piece of cork. The neck of the bottle is tied with string to a LifeSaver candy, and a weight, such as a rock, is attached to another string, which is also tied to the candy. The bottle is heated on board the ship to melt the wax, and the "current meter" is dropped into the water, where the weight pulls it to the bottom. Once on the seafloor, the bottle on its string is held at an angle by the current, the wax solidifies in the cold water, and soon the candy dissolves, releasing the buoyant bottle from the weight to float back to the surface. The wax surface, which was horizontal when the wax solidified, lies at an angle to the bottom of the bottle. That angle is a measure of the current speed. The bottle also records the current direction because the magnetic needle, which was facing north as it floated in the wax, is locked in place as the wax sets.

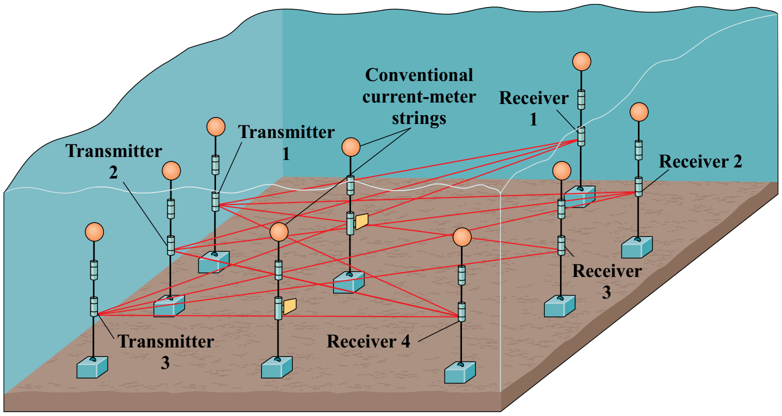
Acoustic Current Meters.

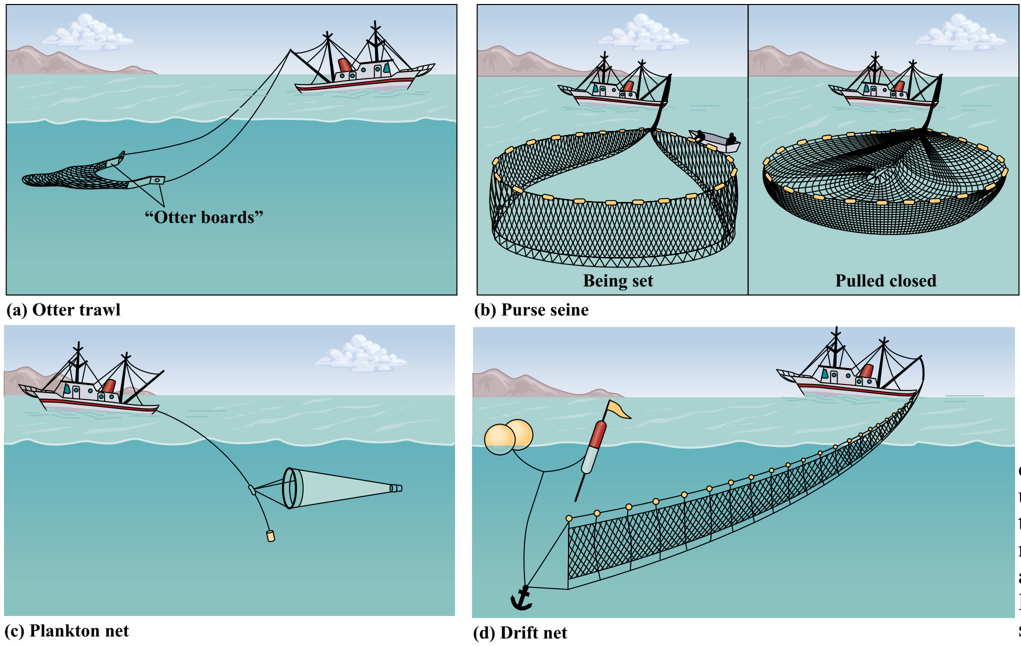
Remote sensing acoustic current meters simultaneously measure current speed and direction at multiple depths. Such meters can be mounted looking upward (**Fig. 3-16a,b**), or mounted on a ship looking downward (**Fig. 3-16c**). They send several narrow-beam sound pulses into the water column that are angled away from the meter in different directions. The returning echoes, which come from particles at different depths in the water column, are recorded from each of the beams. The current speed and direction are calculated from the Doppler shift of the sound **frequency** in the returning echoes. The Doppler shift is the same phenomenon that makes the pitch of a train whistle change as it passes. When the train is approaching— or, in this context, when current is flowing toward the acoustic meter—the pitch is increased. When the train is moving away—or when the current is flowing away from the acoustic meter—the pitch is decreased producing a deeper (more bass) tone.

Remote sensing Doppler current meters have the advantage of simultaneously measuring currents at all depths above or below the meter and within the meter's maximum operating range of 100 m or more. They are particularly useful in locations where current-meter moorings are not possible, such as in busy shipping lanes and **estuaries** with very fast currents. Such meters are widely used but they are expensive and they collect large amounts of data, including sound intensity, Doppler shift, and instrument orientation and tilt, which must be processed through complex computer analyses to yield data on current speed and direction.

Another technique, acoustic **tomography,** is capable of making simultaneous observations of water movements or currents within large areas of the ocean. The system is the acoustic equivalent of the computerized axial tomography (CAT) scan used to produce three-dimensional images of internal parts of the human body. The acoustic tomography system consists of several sound sources and receivers moored at different locations within a study area that can be hundreds of kilometers across (**Fig. 3-17**). Sound is emitted by each source and received by each receiver, so numerous pathways of sound traveling between sources and receivers are possible. The sound velocity along each of the pathways is affected by such water characteristics as depth, temperature, and salinity. When currents flow within the study area, they change the distribution of temperature and salinity and therefore the average speed of sound along the source–receiver pathways. Powerful computer data analysis techniques are used to convert the small variations in travel times between each source and receiver into a detailed picture of the water property distributions and movements within the array boundaries.

FIGURE 3-17 A typical acoustic tomography array. Sound pulses sent from each transmitter are received by each of the receivers.





(a) Otter trawl **(b) Purse seine** **(c) Plankton net** **(d) Drift net**

FIGURE 3-18 Many different types of nets are used to sample pelagic and benthic organisms. (a) The otter trawl uses two "otter boards" that "sail" in the current created by the movement of the vessel as the net is towed. The sailing motion of the otter boards forces the end of the net to stay open. (b) The purse seine is towed quickly around a school of fish and then drawn up under the fish, preventing their escape. (c) Plankton nets are extremely fine mesh nets with a jar or bucket attached at the narrow end to collect plankton as the net is towed through the water. Some plankton nets can be opened and closed on commands from the surface vessel in order to sample only selected depths and locations. Some have current meters attached to measure the volume of water sampled as it flows through the net. (d) Drift nets may be deployed for miles across the ocean, where they catch anything too large to swim through the net. Even large animals, such as dolphins and sharks, may become entangled and die

SAMPLING LIVING ORGANISMS IN THE SEA

Almost all terrestrial **species** spend their entire lives within a narrow zone that extends from a few tens of meters above the tops of the trees to a few meters below the Earth's surface. Therefore, terrestrial organisms are relatively easy to study, as they are readily accessible and visible to the scientist. In contrast, ocean life is present throughout the thousands of meters depth of ocean waters (**pelagic** species) and for several meters, or more, into the sediment (**benthos,** or **benthic** species).

Special Challenges of Biological Oceanography

Although pelagic marine life is concentrated in the upper few hundred meters of the sea, scientists cannot readily enter the oceans to observe it. Therefore, most marine biological studies depend on methods of capturing the undersea creatures and bringing them back to a research vessel or onshore laboratory. Collecting biological samples from a given ocean location and depth is a daunting task that poses five major problems, which add to the general problems of working in the oceans discussed previously:

- Pelagic life is widely dispersed in three dimensions. Therefore, large volumes of water must be sampled or searched before representatives of all, or even most, species in any part of the ocean are captured.
- The species that make up ocean life range in size from microscopically small **bacteria, archaea,** and **viruses** to giant whales. Therefore, no single method of sampling can capture all important species in a particular study location.
- Many species of ocean life actively swim and avoid any sampling device lowered into their **environment.**
- Many species are extremely delicate and are literally torn apart by contact with sampling devices that are dragged through the water.
- Many species that live in the cold, dark, high-pressure, deep-ocean environment cannot survive the changes in these temperature or pressure as they are brought to the surface.

Nets, Water Samples, and Traps

The sampling devices most often used to collect pelagic species are nets towed through the water. Nets of different overall sizes and mesh sizes must be used for different types of organisms (**Fig. 3-18**). Small nets with very fine mesh are used to sample **phytoplankton** and **zooplankton,** and progressively larger nets and meshes are used to capture fishes and **invertebrates.** Net samples may be collected by simply lowering a net from a stationary ship and hauling it back on board. However, biologists usually want to collect samples from a specific depth, so most sampling with nets is performed by towing a weighted net slowly behind the research vessel.

Nets can be let out on a known length of cable over the stern of the ship, towed for a time, and then retrieved. However, without instrumentation the biologist does not know the exact depth of the net tow, how much of the catch came from shallower depths as the net was let out or retrieved, or how much water passed through the net. The amount of water passing through the net during a tow must be known if the concentration or population density of the species caught is to be determined. Many sampling nets now have various types of recording-depth gauges to measure the depth at which the net is towed. Modern nets can also be designed to be kept closed until reaching the desired sampling depth, and then opened, towed, and closed again before retrieval. In addition, many nets carry flow meters similar to impeller-driven current meters (**Fig. 3-15a**) to measure

FIGURE 3-19 Lobster pots (or traps) are designed such that the lobsters can crawl into the pot to eat the bait left inside, but then cannot escape

FIGURE 3-20 Underwater habitats, such as Aquarius, shown here in the Florida Keys, enable scientists to live and work up to several tens of meters underwater for several days without incurring decompression sickness. However, at the end of their stay they must undergo very long decompression periods in a decompression chamber.

the distance the net is towed while it is sampling. To calculate the volume of water sampled by the net, the measured tow distance is multiplied by the cross-sectional area of the net opening. Some nets are equipped with video cameras to record species that evade the net.

The smallest pelagic organisms in the oceans (bacteria, archaea, viruses, and phytoplankton) can be sampled by collecting water in sampling bottles such as those described earlier. **Plankton** and microorganisms are often sampled by surrogate parameters. For example, investigators often estimate the total **biomass** of **photosynthetic** plankton by measuring the total **chlorophyll** (**CC14**) concentration. In addition, they can estimate the concentrations of some other groups of microorganisms by measuring the concentrations of other pigments similar to chlorophyll or by measuring the concentrations of specific types of **genetic** material such as **DNA**. Sharks, large fishes, and squid that avoid nets are sampled with fishing lines and lures. Fishes and other large invertebrates that live on the seafloor are sampled with trawl nets towed across soft sediment bottoms (**Fig. 3-18a**) or by dredges similar to those used to collect rocks from the seafloor (**Fig. 3-8**). Smaller benthic organisms are collected by means of sediment collection devices such as grab samplers and box corers. On the ship, the finer sediment is washed through one or more sieves to isolate such organisms.

Fishes and invertebrates that are particularly adept at eluding nets can be caught in a variety of traps. The animals are attracted to the traps with bait or lures. In the dark deeper waters or at night, they may also be attracted by light. Many types of traps have been used. Almost all allow the organism to enter the trap easily in pursuit of the bait or lure, but make it difficult or impossible for the organism to escape. The lobster pot is the best known of such traps (**Fig. 3-19**).

Fragile Organisms

Organisms that are fragile and easily damaged by nets are particularly difficult to collect. Such organisms are numerous in the oceans. Many float freely in near-surface open-ocean waters (**Chap. 14**), and many live in **communities** at **hydrothermal vents** (**Chap. 17**). Fragile organisms can be collected only by being captured carefully in closed jars or bottles.

Fragile organisms from the upper layers of the open ocean can be collected by divers. The divers drift or swim until they encounter an interesting organism, and then they guide the organism into an open jar that they seal immediately. Fragile or elusive small fishes and other organisms can also be sampled by a simple syringelike device called a “slurp gun.” The diver places the open mouth of the gun near the organism and simply sucks it into the slurp gun body by withdrawing a plunger. Slurp guns are particularly useful for collecting small organisms from within cracks and holes in **coral reefs,** and they are the most environmentally sound means of collecting small tropical fishes for aquariums.

In waters deeper than **scuba** divers can reach, fragile organisms must be collected from research submersibles, ROVs or AUVs. The collection methods are the same as those used by divers, but the jars, slurp guns, or other collecting devices must be manipulated by remote control or complex autonomous systems.

Migrations and Behavior

Although the occurrence or concentration of a species within a given area is an important parameter, it tells us little about the organism’s life cycle—including, for example, its migration, feeding, and reproduction. Observations by divers, submersibles, and remote cameras can provide some of this information, but only for species that do not migrate large distances or through great depths during the activities under observation. However, many species, including whales and other **marine mammals,** turtles, and many fish species, do sometimes swim large distances and dive to substantial depths to feed or reproduce. Some of these behaviors can be studied remotely. For example, **schools** of fish can sometimes be followed by sonar, and whales can be tracked by their songs, which can be heard at great distances. However, these are at best inadequate techniques. Recent advances in the miniaturization of electronics have led to the creation of a number of small sensing packages that can be attached to, for example, the skin of a whale to gather data on time, depth, and temperature. The instrument package stays attached for some time and then is released, floats back up to the surface, and is either recovered or sends its data to shore by radio. These instru-

FIGURE 3-21 A typical submersible, such as the Johnson Sea Link shown in this photograph, consists of a glass or plastic sphere inside a hull. The scientists descend within the sphere, which is provided with air and heat. Motors, articulated arms, and many different designs of samplers and cameras are mounted outside the sphere. These are used to provide propulsion and collect samples

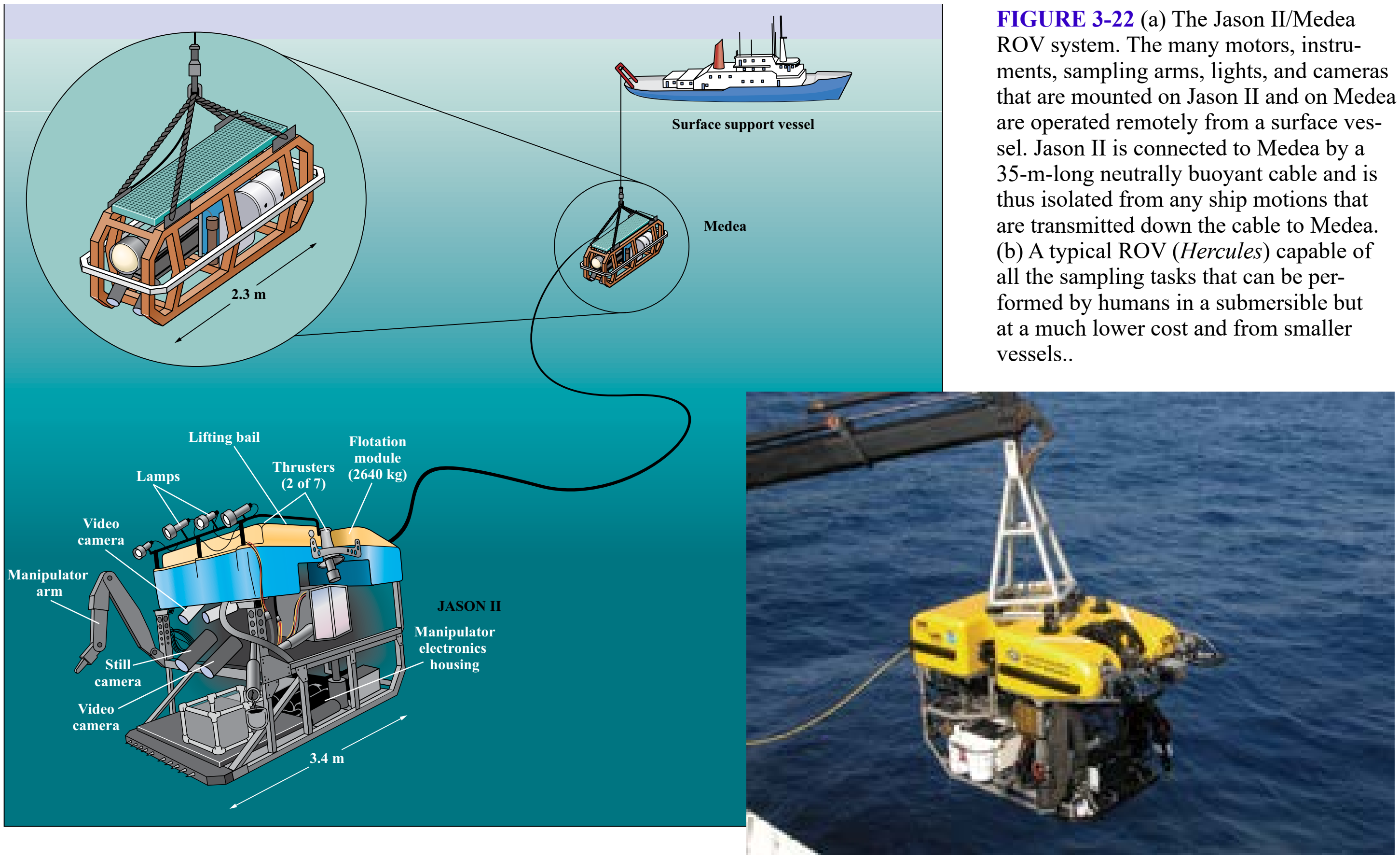


FIGURE 3-22 (a) The Jason II/Medea ROV system. The many motors, instruments, sampling arms, lights, and cameras that are mounted on Jason II and on Medea are operated remotely from a surface vessel. Jason II is connected to Medea by a 35-m-long neutrally buoyant cable and is thus isolated from any ship motions that are transmitted down the cable to Medea. (b) A typical ROV (*Hercules*) capable of all the sampling tasks that can be performed by humans in a submersible but at a much lower cost and from smaller vessels..

ment packages are becoming steadily more sophisticated and now may include other sensors or video cameras. One particularly interesting package contains a microphone and recording device. Attached to whales, this device has been used to record the changes in diving behavior caused when a whale swims into the sound field generated by a surface sonar unit.

SCUBA, MANNED AND UNMANNED SUBMERSIBLES

Many tasks can be performed only, or are performed best, when oceanographers are able to see what they are sampling or measuring. For example, some areas of the seafloor are characterized by jumbled rock formations and highly variable assemblages of organisms. In such areas, geological oceanographers can best identify and collect rocks and sediment of interest if they can visually inspect and select samples. Similarly, biologists can ensure that they are collecting the important species if they are able to see and select the organisms to be sampled. For many species, particularly those that do not survive transfer to an aquarium or laboratory, biologists can study feeding, defense, movement, and reproduction only if they can observe the species in its natural **habitat.**

Scuba and Habitats

In shallow waters, sampling is often performed by scuba divers. However, because of the dangers of the bends and nitrogen narcosis, scuba divers cannot descend safely below about 90 m and they can remain underwater for only a short time.

Scuba equipment supplies a diver with air at the pressure that corresponds to the diver's depth. Thus, the pressure of the air breathed increases with depth. Divers are susceptible to two dangerous syndromes. The first of these, nitrogen narcosis, occurs when high-pressure air causes high concentrations of nitrogen to build up in the bloodstream. This causes symptoms very similar to those of alcohol intoxication—with possible consequences similar to drinking and driving. The second ailment, the bends, is a different life-threatening medical problem. It is caused by breathing high-pressure air at depth for too long and then returning to the surface too quickly. As the depth and immersion time of a dive increase, nitrogen continues to dissolve into the diver's bloodstream and then transfers into other body tissues. If the diver returns to the surface too rapidly, the excess nitrogen in the blood and tissues cannot escape quickly enough and forms damaging gas bubbles in the body.

One way of extending the length of time that scuba divers can remain at depth safely is to use an underwater habitat (**Fig. 3-20**). Scientists can live for days or weeks in such habitats, which are pressurized and anchored on the seafloor. The scientists can safely make multiple scuba excursions to research sites at approximately the same depth as the habitat, as long as they return to the habitat and not to the surface. Although underwater habitats have many valuable uses, particularly for behavioral and other biological studies, their utility is limited. They are expensive to maintain and operate, they cannot readily be moved to new research sites, and they cannot significantly increase the maximum depth at which scientists can work using scuba. In addition, to avoid the bends, scientists who live in habitats for a week or more must spend several days in a decompression chamber at the end of their stay, even if the habitat is only a few meters deep.

Manned Submersibles

Most of the ocean floor and almost all of the ocean volume are too deep for scuba divers to reach. Marine scientists have used a variety of research submersibles to visit and work at greater depths. Manned oceanographic research submersibles are small submarines usually designed to carry no more than two or three scientists. They enable the scientists to observe and photograph organisms and the seafloor. Equipment is often attached to the outside of the submersible to collect organisms, rocks, sediment, and water samples that can be selected visually by the submersible's occupants.

The first recorded successful use of a submarine was in 1620. The vessel, built by a Dutchman, Cornelius Drebbel, had a waterproof outer skin of leather and was propelled by 12 oarsmen. It was reported to be able to stay as deep as 4 or 5 m underwater for several hours. Between 1620 and the 1930s, many different submarines were developed, but they were used primarily as warships. Today, the vast majority of submarines are still warships that are not suited to, or used for, most oceanographic research.

During their early development, research submersibles had very limited capabilities because they were built primarily to transport explorers who sought to dive to ever-greater depths. Such explorers usually performed scientific observations as only a secondary interest. Early submersibles, called "bathyscaphes" or "bathyspheres," provided little more than windows and lights for their occupants to view the oceans and seafloor, and most were not equipped to collect samples. In addition, most early submersibles could only sink to the seafloor and then drift with the currents or move short distances. Therefore, positioning a submersible precisely at a previously selected site on the seafloor was not possible.

The exploration phase of research submersibles climaxed in 1960 when the bathyscaphe *Trieste* visited the deepest part of the ocean, the Mariana Trench, 10,850 m below the ocean surface. Since 1960, many new submersibles have been designed, but almost none of these are capable of reaching the depths achieved by the *Trieste.* Most are designed for much shallower dives. Recent advancements in submersible design have centered on improving the submersible's ability to find precise locations on the seafloor, travel across the seafloor during a single dive, and collect samples at selected locations. Modern submersibles are strange-looking vessels with one or more protruding robot arms and a variety of baskets, other sample-collecting devices, video cameras, and measuring instruments that hang from the hull within reach of a robot arm (**Fig. 3-21**). They also carry powerful lights because sunlight does not penetrate more than a few hundred meters of seawater. Submersibles are now used for a variety of undersea observations, particularly observations of underwater volcanic features and of hydrothermal vents and their unique biological communities (**Chaps. 6, 15**).

Unfortunately, submersibles have disadvantages that limit their usefulness. Most submersibles must have a large surface vessel to carry or tow them to the research site, with a large crew to launch, retrieve, maintain, and repair them. Because submersibles are very expensive, the cost of each dive is extremely high in relation to the cost of other oceanographic research efforts. Submersibles have very small interior crew spaces, so dives of several hours are an uncomfortable ordeal for the pilot and passengers. The discomfort, the need to carry air-recycling systems for the crew compartment, and the limited battery power available to operate the motors, life-support system, and scientific equipment are all factors that limit the maximum duration of each dive. Limited dive duration restricts the area that can be studied on each dive, particularly in deep waters where the submersible may spend several hours descending and ascending.

FIGURE 3-23 The yellow cylindrical object is an An Argo float system about to be deployed from a research vessel to begin its long unattended journey through the ocean depths.

Remotely Operated Vehicles

Many of the limitations of submersibles can be overcome by use of a remotely operated vehicle (ROV). The basic ROV consists of a television camera mounted on a frame or sled. An electric motor, which drives a propeller, and electronically controllable steering devices are also mounted on the sled. The sled is attached to a surface ship by a cable through which power is supplied from the ship, video images are transmitted to the shipboard laboratory, and steering signals are sent to the sled. ROVs are much less expensive than submersibles and can spend many more hours underwater. They can be deployed from much smaller research vessels than the ones that carry submersibles; they do not require the difficult, expensive, and time-consuming procedures and equipment needed to protect the lives of submersible crews and passengers; and they can allow several scientists at the same time, rather than the one or two in a submersible, to view the seafloor and to direct sampling activities.

The sampling and measurement operations performed with submersibles involve remote manipulation of robot arms and other equipment located outside the submersible. Because nearly identical equipment can be mounted on ROV sleds, they can perform the same tasks as submersibles, but they can be operated remotely by a pilot sitting comfortably in front of a video monitor in a ship's laboratory. In fact, if steerable video cameras are mounted on the ROV, the shipboard ROV operator has a better view of the environment than a submersible operator has, because the submersible operator's vision is often restricted to several small, fixed window ports. In addition, an ROV enables several scientists of different disciplines to take part in each "dive" and to participate, either from the research vessel or remotely by video link, in deciding when and where samples should be collected. Although they are less glamorous than research submersibles, ROVs may eventually replace almost all submersibles for ocean science.

Perhaps the most famous, although scientifically not very useful, achievement of modern research submersibles was the successful exploration of the wreck of the *Titanic* and the recovery of some of its artifacts. What is not widely known is that the manned submersible dives to the *Titanic* were made possible by the work of an advanced ROV, the *Argo*. It performed the lengthy

FIGURE 3-24 The yellow cylindrical object with wings and fins is a Slocum Glider about to be deployed from a research vessel. Basic gliders can be small and easily deployed, while larger gliders can support longer missions and more complex instrumentation

and difficult search for the wreck and the video exploration of the wreck and surrounding debris field. This preliminary work made it possible to send submersibles some months later to explore the wreck further and collect artifacts. Another ROV, *Jason Jr.,* was used in the subsequent exploration of the *Titanic* by the submersible *Alvin*. *Jason Jr.* was attached to the *Alvin* rather than to a surface ship.

The *Jason II/Medea* system, developed since the exploration of the *Titanic*, is an example of sophisticated ROV systems now used (**Fig. 3-22**). *Medea* is attached to a surface research vessel by a long cable. It carries lights, a video camera, and other instruments to survey the seafloor as it is positioned just above it. *Medea* can operate to depths of about 6500 m. *Jason II* is an ROV attached to *Medea* by a cable 35 m long. Once *Medea* has located an interesting area of seafloor, *Jason II* can be sent out to make a much more detailed survey of the area surrounding *Medea*'s location. *Jason II* can be maneuvered very precisely because it is not connected directly to the cable attached to the ship above. Consequently, *Jason II* is isolated from the sometimes substantial ship motions that are partially transferred down the cable to *Medea*, which enables *Jason II* to more easily locate and collect samples on the seafloor. The *Jason II/Medea* system can remain at work continuously on the seafloor for periods of a week or more. Such systems can locate or relocate themselves on the seafloor with a precision of a few meters by analysis of the travel times of sound pulses transmitted from the surface vessel, and from transponders mounted on the vehicles and anchored to the seafloor in a triangle surrounding the study area.

Autonomous Floats and Gliders

Even ROVs may eventually become obsolete as the development of autonomous underwater vehicles (AUVs) is now progressing rapidly. An AUV is a vehicle that moves through the ocean with no human occupants and with no direct connection to surface vessels or submersibles. It performs exploration and sampling tasks according to preprogrammed instructions or through limited communication of data and instructions to and from remote operators. The simplest and most widely used example of an AUV may be *Argo* (not the same as the ROV *Argo* mentioned earlier) (**Fig. 3-23**) and other similar floats. These are autonomous instrument packages programmed to alternately descend and ascend through the water column collecting data on the properties of **water masses.** They transmit their data to shore by radio each time they reach the surface. The floats are part of the Global Climate Observing System/Global Ocean Observing System (GCOS/GOOS), which now has about 4,000 of these floats deployed throughout the world oceans. Some of these floats are now being equipped with add additional sensors to measure parameters such as dissolved oxygen concentration, pH, nitrate concentration, chlorophyll-a concentrations, suspended particle concentration and ambient light levels. These additional sensors are not yet proven to be as accurate and durable as the basic pressure and temperature and salinity (electrical conductivity) but are expected to yield useful data and to be improved over time.,

One particularly interesting development of AUVs is the development of gliders. These look somewhat similar to the unmanned aerial drones now used by the military (**Fig 3-24**). The most interesting feature of some of these gliders is that they can generate their own power by diving repeatedly between the warm surface water and colder water below and exploiting this temperature difference to generate electricity. This gives gliders the potentially for deployments of virtually unlimited length of time and enables them to cover very large distances in the oceans in a single deployment. To become most useful to science future AUVs, including gliders will require the development and application of sophisticated new subsea robotics, artificial intelligence, and other technologies for underwater observation, sampling, and communications that can be incorporated in the AUV.

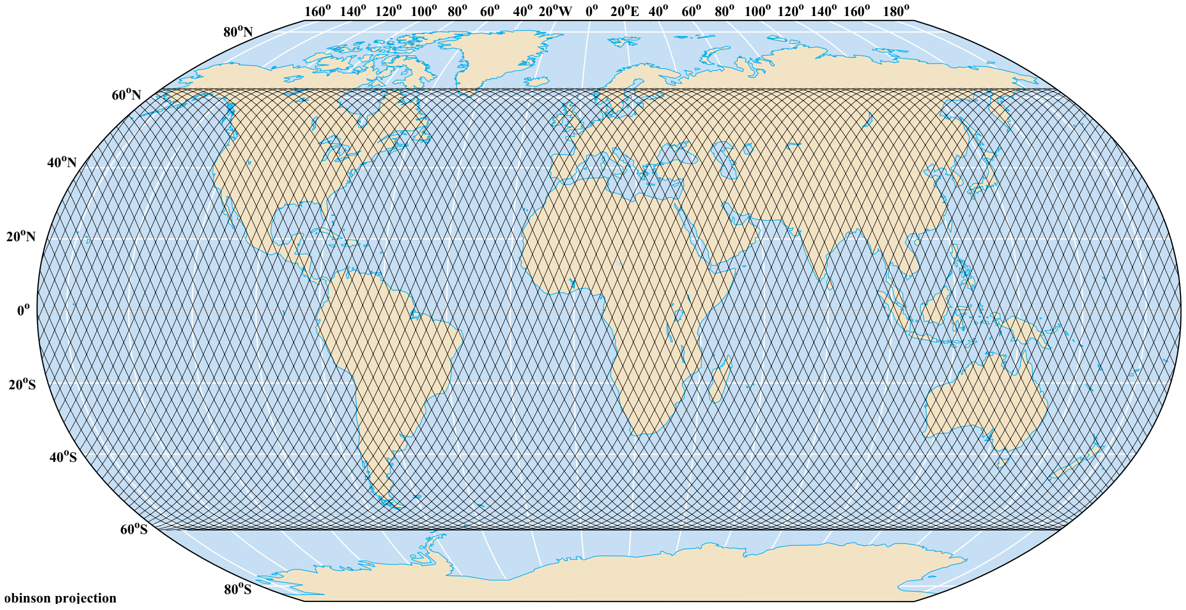


FIGURE 3.25 The TOPEX/Poseidon satellite travels in an orbit that is typical of satellites used for ocean observations: 1366 km high and inclined at 66° to the equator. This orbit allows coverage of 95% of the ice-free oceans every 10 days. The satellite's position is known to within 10 cm from the Earth's center. The network of curved lines on the map schematically illustrates the path that the satellite follows in each 10-day period.

SATELLITES

Satellite observations have truly revolutionized marine sciences. From a satellite, the entire surface of the world's oceans can be surveyed in just a few days (**Fig. 3-25**). In addition, large areas of the oceans can be surveyed comprehensively every few days or even hours. Such **synoptic** observations from satellites have enabled oceanographers to observe day-to-day, month-to-month, and year-to-year changes in ocean phenomena, including surface currents, surface water temperatures, waves, phytoplankton and suspended-sediment concentrations, and ice cover. Before satellites, such temporal changes could be observed only at fixed locations or within small regions because surface vessels cannot survey large regions quickly or often. Ships may take several weeks to complete a survey of several hundred square kilometers, whereas ocean conditions can change very rapidly, for example during storms. Hence, observations obtained at the beginning and end of a ship survey often describe very different states of the ocean. The degree to which satellite observations have provided a new view of the oceans is demonstrated by the number of figures in this text that present satellite data to describe important ocean processes.

Satellite observations of the oceans are made with a variety of devices, including radar, **lasers,** and color- and infrared-sensing scanners. Although satellites are excellent platforms from which oceanographers can make rapid and comprehensive observations of the oceans, their value is limited because the sensors they carry rely primarily on **electromagnetic radiation,** which does not penetrate ocean water effectively. Therefore, most satellite observations record features and processes of only the upper few meters of the oceans, and they provide only limited information about processes below the upper layer. However, satellites using radar can be successfully used to monitor sea surface height to a precision that allows filtering their data on different frequencies to monitor ocean depth (**Chap.4**), sea level rise, wave energy, tidal height variations, sea ice extent and thickness, and even internal waves and eddies well below the surface.

Satellites have made a special contribution to oceanography as aids to navigation. Until satellite navigation systems were developed, research ships far from land could not determine their locations with great accuracy. When clouds prevented star and sun sightings for several days, a vessel's position could be determined only with an uncertainty that often exceeded several kilometers. The most recent and accurate satellite navigation system is the Global Positioning System (GPS), which can determine a position anywhere on the Earth's surface to within a few meters. Precise navigation enables oceanographers to locate and map small features of the seafloor and to revisit precise locations on subsequent research cruises.

Satellites have also enabled high band width communications between land based research facilities and research vessels, platforms and AUVs. This allows researchers to interactively participate in ocean sampling and other studies without ever leaving their home laboratory as they can monitor activities and communicate by video. This has reduced costs as fewer personnel are needed on research vessels, but its more important impact my be that it makes it possible for a researcher who encounters an unknown species or an unusual occurrence to immediately bring experts in the relevant fields of studies, wherever they may be in the world, into the study immediately to direct or suggest any additional study that might need to be done.

Routine satellite observations of the oceans have many practical uses other than navigation and scientific research. For example, they are used by fishers to locate the best fishing grounds on the basis of surface water temperatures and by ships' captains to save fuel by avoiding storms or currents. They are also used to forecast weather, especially **hurricanes** and other storms, and to determine iceberg locations. The growing list of parameters that can be determined by satellites include currents and circulation patterns, internal waves and eddies, ocean surface temperature and salinity, surface wind patterns, **wave heights** and sea state, bathymetry, sea level rise, chlorophyll and plankton concentrations, distribution of river plumes, concentration of suspended sediment, beach **erosion,** and **shoreline** changes. Satellite observations of oceanic and atmospheric temperatures and other parameters will be particularly important in monitoring the enhanced **greenhouse effect** and its potential impact on world **climate,** sea level, and biological processes, and in improving our ability to understand and predict such phenomena.

COMPUTERS AND MODELING

The development of computers revolutionized ocean sciences just as it has other aspects of human society. Ocean sciences are particularly dependent on computers for two important functions: analysis and display of the geographic and depth variations in important parameters, and data analysis using mathematical models.

Almost all studies conducted by ocean scientists involve parameters or processes that vary both geographically and with depth and over time. Data of importance to ocean processes must therefore be organized in a three-dimensional framework (four dimensions if one includes time) and displayed visually for analysis and interpretation. Many of the illustrations in this text display data on maps or on vertical map sections. As we discussed earlier in this chapter, the relatively simple seafloor map that Heezen and Tharp generated by hand before the advent of computers was a massive undertaking. Computerized mapping now makes the development of such maps much simpler and quicker, even given the massive amounts of data that can be generated by satellites and automated sensors. Most computerized mapping is now done using Geographic Information Systems (GIS). GIS is designed to store data for any parameter that is collected at a specific location and time—for example, salinity, temperature, phytoplankton concentration, light intensity. The GIS system stores each data point referenced to its geographic coordinates (three-dimensional to include depth, where appropriate) and collection time. Simple-to-use software tools allow data for multiple parameters to be overlaid on each other (spatially and temporally) for comparison and analysis, and for these results to be displayed in a variety of ways.

Ocean sciences are heavily dependent on mathematical modeling, described in **CC10**, because the processes studied occur on very variable time and space scales, and many processes, especially biological parameters and interactions, are characterized by very limited data. Global climate models, used to investigate ocean-atmosphere interactions, greenhouse-induced global climate change, global weather patterns, and many other questions, rely particularly heavily on computers. As explained in **Chapter 8**, the scale of water motion in the ocean is one-tenth the scale of atmospheric motions that contribute to weather and climate. Furthermore, oceans are more complex vertically than the atmosphere. As a result, if the ocean part of the global model is to operate effectively, it must be split into model cells that are smaller and separated into more layers vertically than the atmosphere is. Thus, the ocean component of these models can require as much as four orders of magnitude more computer time than the atmospheric component requires. For these models, this is significant because it can take months of time even on the fastest supercomputers to run the models through just a few years of simulated climate.

CHAPTER SUMMARY

Difficulties of Studying the Ocean Environment.

Because water effectively absorbs all electromagnetic radiation, oceanographers can "see" through the ocean waters only by using sound waves, which travel through water with relatively little absorption.

The oceans average almost 4 km in depth. Observation and sampling instruments must be lowered through the water column—a time-consuming and expensive process. Until recently, precise navigation was extremely difficult away from sight of land, and resampling a specific location was nearly impossible.

Submersibles and instruments lowered through the ocean water column must be able to withstand very great pressure changes and the corrosiveness of seawater. They must also avoid fouling by organisms. Electrical equipment must be isolated from contact with seawater because seawater is an electrical conductor.

Oceanographers and their instruments must operate reliably on research ships that vibrate from engine noise, and that roll and pitch with wave action. Faulty equipment must be repaired at sea with available parts and personnel.

Mapping the Ocean Floor.

Until 1920, the only way to determine the depth of water under a ship was to lower a weight on the end of a line or wire until it touched bottom, and then measure the length of wire let out. This method was tedious and inaccurate, especially in deep waters. It was also prone to errors because it was difficult to determine when the weight reached the seafloor and because the path of the line or wire through the water column was distorted by currents.

In 1920, echo sounders were developed that measured the time taken for a sound ping to travel from ship to seafloor and back. Precision echo sounders were operated continuously on all research ships, and the data were used in the 1950s to produce the first detailed maps of seafloor topography.

Newer echo sounders send sound pulses spread over a wide area to either side of a research vessel, and the multiple echoes are processed by computer. The data are used to create detailed three-dimensional seafloor maps. Satellites can measure sea surface height so accurately that the data can be used to map the seafloor based on slight variations of sea surface height caused by gravity differences over the varying seafloor topography.

Seafloor Sediments.

Samples of seafloor sediment are obtained for several purposes by a variety of techniques. Samples of the upper few tens of centimeters of sediment are used to study recent sediment processes or the biology of the sediment. They are usually obtained with grab samplers or box corers.

Long vertical cores are obtained to study the history of sediment that is accumulated layer by layer. They are obtained by corers or by drilling. Drilling ships are very expensive to operate but can retrieve very long cores. Samples of rocks from the seafloor are obtained by dredges.

Indirect methods of studying sediments include gravity and magnetic-field strength measurements and seismic techniques in which sound pulses are echoed off layers of buried sediment.

Chemical and Physical Oceanography.

Water samples must be collected to determine most parameters of seawater chemistry and to study microscopic organisms. Samples are collected in bottles lowered to the desired depth, where they are closed and then retrieved. Sample contamination from the sampler materials and wire and from surface waters is often a problem because of the very low concentrations of some constituents. Some parameters, notably pressure (depth), conductivity (salinity), and temperature can be determined ***in situ*** by electronic sensors.

Currents are measured by tracking drifters, drogues, or floats as they move with the current; by the use of fixed current meters that measure the speed of rotation of a rotor or the tilt of the meter in the current; and by acoustic remote sensing of the movements of suspended sediment.

Living Organisms in the Sea.

Sampling marine organisms is difficult because pelagic species are widely dispersed, species vary greatly in size, some species avoid samplers, and some delicate species are damaged by samplers. Pelagic species are collected by nets, water-sampling devices, traps, and fishing lines. Benthic species are collected by grab samplers, dredges, and trawl nets. Some species can be collected or observed only by the use of scuba or submersibles.

Scuba, Manned and Unmanned Submersibles.

Marine organisms in shallow waters, less than a few tens of meters deep, can be observed and sampled best by scuba divers. Scuba divers can spend only a few hours a day underwater unless they live in expensive underwater habitats. Marine organisms in deeper waters can be observed and sampled from manned submersibles, but these vessels are very expensive and can remain submerged for only a few hours. Unmanned remotely operated vehicles (ROVs) using television cameras and robot arms are more economical and can remain submerged longer. Autonomous underwater vehicles (AUV) are becoming used extensively and are rapidly becoming more capable.

Satellites.

Satellite-mounted sensors can be used to measure parameters and characteristics of near-surface waters, including temperature, concentrations of phytoplankton, concentrations of suspended sediment, and surface currents and waves. Satellite observations can cover large areas almost simultaneously and repeat these observations frequently, which is not possible with research ships or fixed monitoring systems. Seafloor topography can be observed by very precise satellite radar measurements of sea surface elevation. Satellite navigation systems have dramatically improved oceanographers' abilities to map and return to specific features of the oceans.

Computers and Modeling.

Computers have contributed substantially to the development of ocean sciences, primarily by organizing and displaying geographic data and by performing mathematical modeling of complex systems.

KEY TERMS

You should recognize and understand the meaning of all terms that are in boldface type in the text. All those terms are defined in the Glossary. The following are some less familiar key scientific terms that are used in this chapter and that are essential to know and be able to use in classroom discussions or exam answers.

acoustic
bathymetry
benthic
benthos
CTD
current
electromagnetic radiation
frequency
hydrographic
hydrophone
hydrothermal vent
pelagic
phytoplankton
plankton
sediment
sonar
sounding
submersible
suspended sediment
synoptic
tomography
topography
tracer
zooplankton

STUDY QUESTIONS

1. Why do we still know less, in some ways, about the floor of the oceans than we do about the surface of the moon?
2. What are the principal difficulties encountered in determining ocean depth and mapping the seafloor?
3. Why do oceanographers still use many different types of sampling equipment to obtain samples from the seafloor?
4. If you were designing a sampler to obtain samples of water from deep in the oceans, what factors would you need to consider?
5. Why do we believe there are many species of marine animals living in the deep sea that have never been seen or sampled?
6. Do you think manned submersibles are necessary for ocean study? Explain your answer. Describe the types of studies for which they are most useful.
7. Will satellites ever completely replace research vessels? Why or why not?
8. Why is accurate navigation important to ocean studies? Discuss the reasons.
9. What methods are used to obtain information about the sediments on and below the seafloor?
10. What methods are used to obtain information about the chemistry of and organisms living in the water column of the deep oceans?
11. Why is it easier to study ocean sediments than to study ocean water chemistry or organisms that live in the deep-ocean water column?

CRITICAL THINKING QUESTIONS

1. The process of lowering and retrieving instruments to the ocean floor often takes much longer than is planned at a particular site. What might be some of the reasons for such delays?
2. You are planning the deployment, lowering, and retrieval of an instrument package to sample the seafloor in the deepest part of the Atlantic Ocean. How do you decide where to sample, and what do you need to do to ensure that the samples are taken at this precise location?
3. You are shown an instrument package that weighs several hundred pounds and is sitting on the deck of a research ship. You are told to deploy the package from the ship, lowering it to the seafloor, at a depth of 2 km. What do you need in order to do this, and how can you arrange to do this safely if the ship is in an area of strong wave action?
4. Before reading this chapter, did you know that the pressure changes associated with space travel are much less than those associated with travel into the depths of the oceans? Besides pressure changes, what other challenges can you think of that travel in space and in the deep oceans have in common?
5. Many oceanographers who first saw the Heezen and Tharp world ocean floor map in the 1970s and 1980s felt that they were being introduced to an entirely new planet. Why was this so? When did you first see a map of the ocean floor such as this? Why do you think many people are still completely unaware that there are long mountain chains on the ocean floor?
6. Suppose you are looking for the lost city of Atlantis, which, according to legend, sank beneath the waves. You have been told the approximate geographic location of Atlantis. What information do you need to select a sampling device that is capable of locating the city?
7. A research paper published in 1970 reported that the concentrations of several trace metals (zinc, copper, and iron) in North Atlantic Ocean waters appear to vary within a narrow range, but also appear to vary randomly with depth and location. Should you believe these data? What would you look for in the research paper to help you decide?
8. A grab sampler is lowered to the seafloor at a location that has never before been sampled, and it comes back closed but empty. What are the possible reasons for this result?
9. Undoubtedly, there are many species presently unknown to science that live in the deep oceans. It has been speculated that most of these are free-swimming in the water column and do not live sedentary lives in or on the sediment. Do you think this is a reasonable hypothesis? Why or why not?

CRITICAL CONCEPTS REMINDERS

CC1 Density and Layering in Fluids: Water in the oceans is arranged in layers according to water density.

CC6 Salinity, Temperature, Pressure, and Water Density: Sea water density is controlled by temperature, salinity, and to a lesser extent, pressure..Density is higher at lower temperatures, higher salinities, and higher pressures. Movements of water below the ocean surface layer are driven primarily by density differences.

CC10 Modeling: Complex environmental systems, including the oceans and atmosphere, can best be studied by using conceptual and mathematical models. .

CC14 Phototrophy, Light, and Nutrients: Chemosynthesis and phototrophy (which includes photosynthesis) are the processes by which simple chemical compounds are made into the organic compounds of living organisms. The oxygen in the Earth's atmosphere is present entirely as a result of photosynthesis.

CREDITS

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