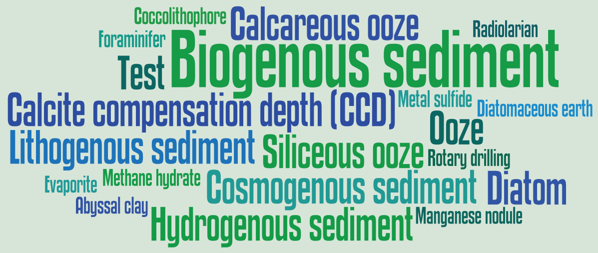
4

Marine Sediments



Before you begin reading this chapter, use the glossary at the end of this book to discover the meanings of any of the words in the word cloud above you don't already know.

Why are **sediments** (*sedimentum* = settling) interesting to oceanographers? Although ocean sediments appear to be little more than eroded particles and fragments of dirt, dust, and other debris that have slowly settled out of the water by the process of **suspension settling** and accumulated on the ocean floor (Figure 4.1), they reveal much about Earth's history. For example, over millions of years, the thick deposit of sediment that accumulates on the ocean floor often contains microscopic fossils that provide clues to the past geographic distributions of marine organisms. Marine sediments are also useful for determining the pattern of ancient ocean circulation, the movement of the sea floor, and even the timing and severity of global extinction events. Further, marine sediments reveal a detailed history of Earth's past climate, thus providing insight into today's climate changes. Remarkably, sediments that accumulate over time on the sea floor comprise a nearly continuous, undisturbed record of Earth history unlike anything on land. In essence, marine sediments represent Earth's largest museum with displays of Earth history dating back millions of years.

Over time, sediments can become *lithified* (*lithos* = stone, *fic* = making)—turned to rock—and form *sedimentary rock*. More than half of the rocks exposed on the continents are sedimentary rocks deposited in ancient ocean environments and uplifted onto land by plate tectonic processes. Perhaps surprisingly, even the tallest mountains on the continents—far from any ocean—contain telltale marine fossils, which indicate that these rocks originated on the ocean floor in the geologic past. For example, the summit of the world's tallest mountain (Mount Everest in the Himalaya Mountains) consists of limestone, which is a type of rock that originated as sea floor deposits.

Climate Connection

Particles of marine sediment come from worn pieces of rocks, as well as living organisms, minerals dissolved in water, and even from outer space. Clues to sediment origin are found in its mineral composition and its **texture** (the size and shape of its particles).

This chapter begins with a brief discussion about how marine sediments are collected and the important information they reveal about Earth history. Then the four main types of sediment are examined, with regard to their characteristics, origin, and distribution (Table 4.1). Note that Table 4.1 summarizes much of the content within this chapter and so it can be used as a road map of topics to help you organize information as you learn about marine sediments. Mixtures of marine sediment and sediment distribution are also considered. Finally, the chapter concludes with a discussion of the resources that marine sediments provide.

For each of the four main types of sediment (*first column*), the table shows important aspects of its composition (*second column*), sources/origin (*third column*), and distribution/main locations found (*fourth column*).

ESSENTIAL LEARNING CONCEPTS

At the end of this chapter, you should be able to:

4.1 Demonstrate an understanding of how marine sediments are collected and what historical events they reveal.

4.2 Describe the characteristics of lithogenous sediment.

4.3 Describe the characteristics of biogenous sediment.

4.4 Describe the characteristics of hydrogenous sediment.

4.5 Describe the characteristics of cosmogenous sediment.

4.6 Specify how the distribution of pelagic and neritic deposits is determined by proximity to sediment sources and mechanisms of transport.

4.7 Identify the various resources that marine sediments provide.

> *"From the sediments the history of the ocean emerged with all its wonders . . . "*
>
> —*Wolf H. Berger,* Oceans: Reflections on a Century of Exploration (*2009*)

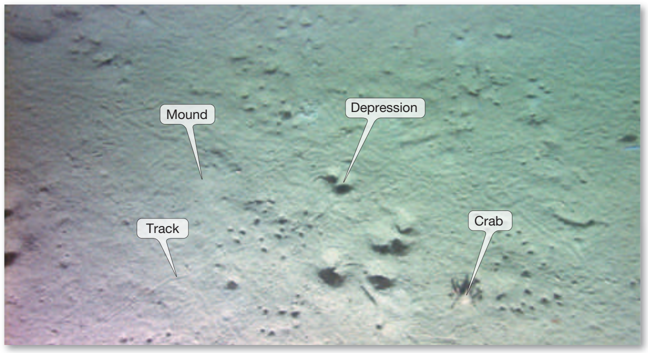


Figure 4.1 **Oceanic sediment.** View of typical deep-ocean floor, which is covered with a thick blanket of fine particles that have slowly settled onto the sea floor by the process of suspension settling. The depressions, mounds, and tracks are made by bottom-dwelling organisms. The crab in the lower right is about 4 inches (10 cm) across.

4.1 How Are Marine Sediments Collected, and What Historical Events Do They Reveal?

One of the difficulties of studying marine sediments is collecting adequate samples from the deep-ocean floor. Until relatively recently, the inaccessibility of the deep ocean has hindered the collection of marine sediments, especially those beneath the surface of the sea floor.

Collecting Marine Sediments

Collecting sediments suitable for analysis from the deep ocean is an arduous process. During early exploration of the oceans, a bucket-like device called a *dredge* was used to scoop up sediment from the deep-ocean floor for analysis. This technique, however, was tedious and had many limitations. For example, it often didn't work right and the dredge came up empty. It also disturbed the sediment and could only gather samples from the surface of the ocean floor. Later, the *gravity corer*—a hollow steel tube with a heavy weight on top—was thrust into the sea floor to collect

TABLE 4.1 CLASSIFICATION OF MARINE SEDIMENTS

Type	Composition		Sources/Origin		Distribution/Main locations where sediment currently forms
Lithogenous	*Continental margin*	Rock fragments Quartz sand Quartz silt Clay		Rivers; coastal erosion; landslides	Continental shelf
				Glaciers	Continental shelf in high latitudes
				Turbidity currents	Continental slope and rise; ocean basin margins
	Oceanic	Quartz silt Clay		Wind-blown dust; rivers	Abyssal plains and other regions of the deep-ocean basins
		Volcanic ash		Volcanic eruptions	
Biogenous	*Calcium carbonate/ calcite ($CaCO_3$)*	Calcareous ooze (microscopic)	*Warm surface waters*	Coccolithophores (algae) Foraminifers (protozoans)	Low-latitude regions; sea floor above CCD; along mid-ocean ridges and the tops of submarine volcanic peaks
		Shells and coral fragments (macroscopic)		Macroscopic shell-producing organisms	Continental shelf; beaches
				Coral reefs	Shallow low-latitude regions
	Silica ($SiO_2 \cdot nH_2O$)	Siliceous ooze	*Cold surface waters*	Diatoms (algae) Radiolarians (protozoans)	High-latitude regions; sea floor below CCD; upwelling areas where cold, deep water rises to the surface, especially that caused by surface current divergence near the equator
Hydrogenous	Manganese nodules (manganese, iron, copper, nickel, cobalt)		Precipitation of dissolved materials directly from seawater due to chemical reactions		Abyssal plain
	Phosphorite (phosphorous)				Continental shelf
	Oolites ($CaCO_3$)				Shallow shelf in low-latitude regions
	Metal sulfides (iron, nickel, copper, zinc, silver)				Hydrothermal vents at mid-ocean ridges
	Evaporites (gypsum, halite, other salts)				Shallow restricted basins where evaporation is high in low-latitude regions
Cosmogenous	Iron–nickel spherules Tektites (silica glass)		Space dust		In very small proportions mixed with all types of sediment and in all marine environments
	Iron–nickel meteorites		Meteors		Localized near meteor impact structures

the first **cores** (cylinders of sediment and rock). Although the gravity corer could sample below the surface, its depth of penetration was limited. Today, specially designed ships perform **rotary drilling** to collect cores from the deep ocean.

In 1963, the U.S. National Science Foundation began funding a program that borrowed drilling technology from the offshore oil industry to obtain long sections of core from deep below the surface of the ocean floor. The program united four leading oceanographic institutions (Scripps Institution of Oceanography in California; Rosenstiel School of Atmospheric and Oceanic Studies at the University of Miami, Florida; Lamont-Doherty Earth Observatory of Columbia University in New York; and the Woods Hole Oceanographic Institution in Massachusetts) to form the *Joint Oceanographic Institutions for Deep Earth Sampling (JOIDES)*. The oceanography departments of several other leading universities later joined JOIDES.

The first phase of the **Deep Sea Drilling Project (DSDP)** was initiated in 1966, when the specially designed drill ship *Glomar Challenger* was launched. It had a tall drilling rig resembling a steel tower. Cores could be collected by drilling into the ocean floor in water up to 6000 meters (3.7 miles) deep. From the initial cores collected, scientists confirmed the existence of sea floor spreading by documenting that (1) the age of the ocean floor increased progressively with distance from the mid-ocean ridge (see Figure 2.11), (2) sediment thickness increased progressively with distance from the mid-ocean ridge (see Figure 4.24), and (3) Earth's magnetic field polarity reversals were recorded in ocean floor rocks (see Figure 2.10).

Although the oceanographic research program was initially financed by the U.S. government, it became international in 1975, when West Germany, France, Japan, the United Kingdom, and the Soviet Union also provided financial and scientific support. In 1983, the Deep Sea Drilling Project became the **Ocean Drilling Program (ODP)**, with 20 participating countries under the supervision of Texas A&M University and a broader objective of drilling the thick sediment layers near the continental margins.

In 1985, the *Glomar Challenger* was decommissioned and replaced by the drill ship *JOIDES Resolution* (**Figure 4.2**). The new ship also has a tall metal drilling rig to conduct *rotary drilling*. The drill pipe is in individual sections of 9.5 meters (31 feet), and sections can be screwed together to make a single string of pipe up to 8200 meters (27,000 feet) long (Figure 4.2). The drill bit, located at the end of the pipe string, rotates as it is pressed against the ocean bottom and can drill up to 2100 meters (6900 feet) into the sea floor. Like twirling a soda straw into a layer cake, the drilling operation crushes the rock around the outside and retains a cylinder of rock (a *core sample*) on the inside of the hollow pipe. A core can then be raised to the surface from inside the pipe, cut in half, and analyzed using state-of-the-art laboratory facilities on board the *Resolution*. Worldwide, more than 2000 holes have been drilled into the sea floor using this method, allowing the collection of cores (**Figure 4.3**) that provide scientists with valuable information about Earth history, as recorded in sea floor sediments.

In 2003, the ODP was replaced by the **Integrated Ocean Drilling Program (IODP)**, and, in 2013, its name was updated to *International Ocean Discovery Program (IODP): Exploring the Earth under the Sea*. This new international effort continues over five decades of scientific collaboration that seeks to recover geological data and samples from beneath the ocean floor to study the history and dynamics of Planet Earth. In addition, the program does not rely on just one drill ship but uses multiple vessels for exploration. For example, one

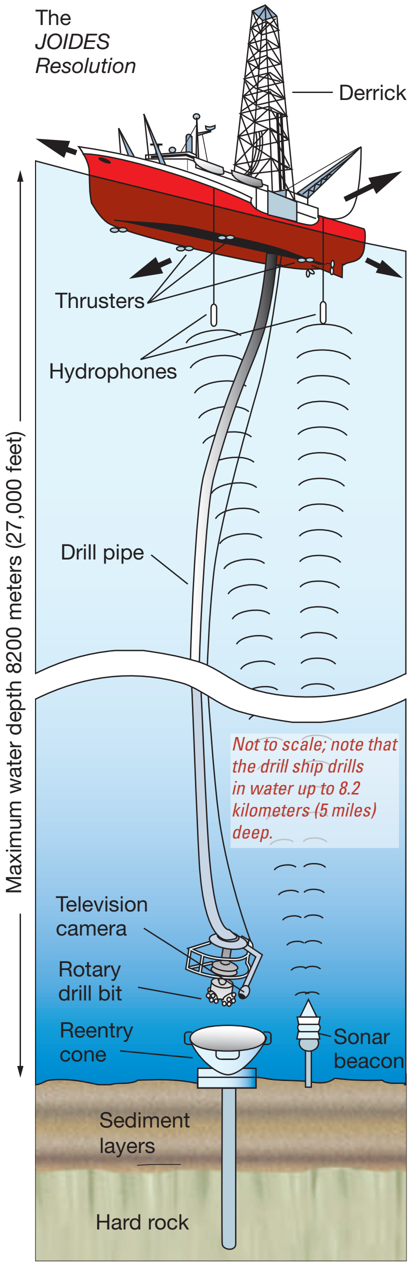


Figure 4.2 **Rotary drilling from the *JOIDES Resolution*.** Using its array of thrusters, the JOIDES Resolution (*photo*) can remain in one place at the surface while performing rotary drilling, which is shown diagrammatically (*right*).

Figure 4.3 **An ocean sediment core.** Cylinders of sediment and rock called *cores* are retrieved from the ocean floor and then cut in half for examination. Oldest layers are at the bottom of the core and youngest are at the top.

RECAP

Marine sediments accumulate on the ocean floor and contain a record of Earth history, including past environmental conditions.

of the new vessels that began operations in 2007 is a state-of-the-art drill ship named *Chikyu* (which means "Planet Earth" in Japanese) that can drill up to 7000 meters (23,000 feet) into the sea floor. Plans to upgrade the vessel with new drilling technology will allow it to drill even deeper, perhaps as deep as through Earth's crust into the mantle. The program's primary mission is to collect cores that will allow scientists to better understand the properties of the deep crust, the microbiology of the deep-ocean floor, Earth's climate change patterns, and earthquake mechanisms. For example, shortly after the devastating 2011 Tohoku-Oki Earthquake and resulting tsunami, the *Chikyu* drillship began an expedition to the Japan Trench to drill into the fault zone near the site of the earthquake to study earthquake-generated heat from friction by taking detailed temperature measurements beneath the sea floor.

Environmental Conditions Revealed by Marine Sediments

Marine sediments provide a wealth of information about past conditions on Earth. As sediment accumulates on the ocean floor, it preserves the materials—and the conditions of the environment—that existed in the overlying water column. By carefully analyzing cylindrical cores of sediment collected from the sea floor and interpreting them (**Figure 4.4**), Earth scientists can infer past environmental conditions such as sea surface temperature, nutrient supply, abundance of marine life, atmospheric winds, ocean current patterns, volcanic eruptions, major extinction events, changes in Earth's climate, and the movement of tectonic plates. In fact, most of what is known of Earth's past geology, climate, and biology has been learned through studying ancient marine sediments.

Climate Connection

Interdisciplinary Relationship

Paleoceanography

The study of how the ocean, atmosphere, and land have interacted in the past to produce changes in ocean chemistry, circulation, biology, and climate is called **paleoceanography** (*paleo* = ancient, *ocean* = the marine environment, *graphy* = description of), a branch of oceanography that relies on sea floor sediments to gain insight into these past changes. Recent paleoceanographic studies, for example, have linked changes in deep-ocean circulation with rapid climate change. In the North Atlantic Ocean, cold, relatively salty water sinks and forms a body of water called *North Atlantic Deep Water*. Water in this deep current circulates through the global ocean, driving deep-ocean circulation and global heat transport, which, in turn, impacts global climate. This is widely viewed as one of the most climatically sensitive regions on Earth, and North Atlantic sea floor sediments from the past several million years have revealed that the region has experienced abrupt changes to its ocean–atmosphere system, triggered by fluctuations of freshwater from melting glaciers. Understanding the timing, mechanisms, and causes of this abrupt climate change is one of the major challenges facing paleoceanography today.

Climate Connection

CONCEPT CHECK 4.1 | Demonstrate an understanding of how marine sediments are collected and what historical events they reveal.

1 Using Table 4.1, list and describe the characteristics of the four main types of marine sediment.

2 Describe the process of how a drill ship like the *JOIDES Resolution* obtains core samples from the deep-ocean floor.

3 What types of past environmental conditions can be inferred by studying cores of sediment?

4.2 What Are the Characteristics of Lithogenous Sediment?

Lithogenous sediment (*lithos* = stone, *generare* = to produce) is derived from preexisting rock material that originates on the continents or islands from erosion, volcanic eruptions, or blown dust. Note that lithogenous sediment is sometimes referred to as **terrigenous sediment** (*terra* = land, *generare* = to produce).

Figure 4.4 **Examining deep-ocean sediment cores.** Sediment cores reveal interesting aspects of Earth history such as the past geographic distributions of marine organisms, ocean circulation changes, major extinctions, and Earth's past climate.

Origin of Lithogenous Sediment

Lithogenous sediment begins as rocks on continents or islands. Over time, **weathering** agents such as water, temperature extremes, and chemical effects break rocks into smaller pieces, as shown in Figure 4.5. When rocks are in smaller pieces, they can be more easily **eroded** (picked up) and transported. This eroded material is the basic component of which all lithogenous sediment is composed.

Eroded material from the continents is carried to the oceans by streams, wind, glaciers, and gravity (Figure 4.6). Each year, stream flow alone carries about 20 billion metric tons (44 trillion pounds) of sediment to Earth's continental margins; almost 40% is provided by runoff from Asia.

Transported sediment can be deposited in many environments, including bays or lagoons near the ocean, as deltas at the mouths of rivers, along beaches at the shoreline, or further offshore across the continental margin. It can also be carried beyond the continental margin to the deep-ocean basin by turbidity currents, as discussed in Chapter 3.

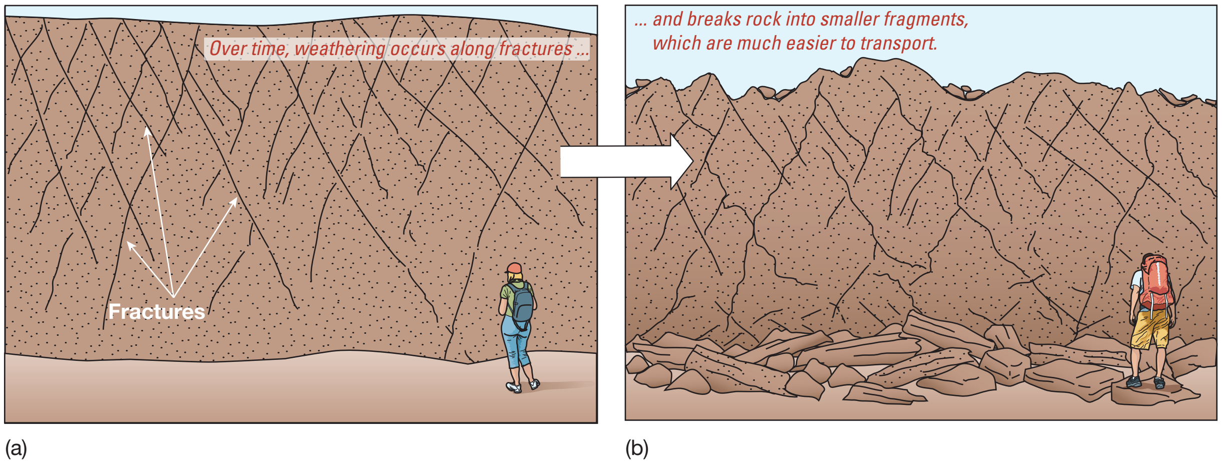
The greatest quantity of lithogenous material is found around the margins of the continents, where it is constantly moved by high-energy currents along the shoreline and in deeper turbidity currents. Lower-energy currents distribute finer components that settle out onto the deep-ocean basins. Microscopic particles from wind-blown dust or volcanic eruptions can even be carried far out over the open ocean by prevailing winds. These particles are deposited into the ocean either as the wind speed decreases or when they serve as nuclei around which raindrops and snowflakes form, and ultimately settle onto the sea floor as fine layers of sediment.

Composition of Lithogenous Sediment

The composition of lithogenous sediment reflects the material from which it was derived. All rocks are composed of discrete crystals of naturally occurring compounds called *minerals*. One of the most abundant, chemically stable, and durable minerals in Earth's crust is **quartz**, composed of silicon and oxygen in the form of SiO_2—the same composition as ordinary glass. Quartz is a major component of most rocks. Because quartz is resistant to abrasion, it can be transported long distances and deposited far from its source area. The majority of lithogenous deposits—such as beach sands—are composed primarily of quartz (Figure 4.7).

A large percentage of lithogenous particles that find their way into deep-ocean sediments far from continents are transported by prevailing winds that remove small particles from the continents' subtropical desert regions. The map in Figure 4.8 shows a close relationship between

Figure 4.5 **Weathering of a rock outcrop.**



the location of microscopic fragments of lithogenous quartz in the surface sediments of the ocean floor and the strong prevailing winds in the desert regions of Africa, Asia, and Australia. Satellite observations of dust storms (Figure 4.8, *inset*) confirm this relationship. Sediment is not the only item transported by wind. In fact, scientists have documented the transportation of a variety of airborne substances—including viruses, pollutants, and even living insects—from Africa all the way across the Atlantic Ocean to North America.

Sediment Texture

One of the most important properties of lithogenous sediment is its texture, including its **grain size**.[1] The **Wentworth scale of grain size** (Table 4.2) indicates that particles can be classified as boulders (largest), cobbles, pebbles, granules, sand, silt, or clay (smallest). Sediment size is proportional to the energy needed to lay down a deposit. Deposits laid down where wave action is strong (areas of high energy) may be composed primarily of larger particles—cobbles and boulders. Fine-grained particles, on the other hand, are deposited where the energy level is low and the current speed is minimal. When clay-sized particles—many of which are flat—are deposited, they tend to stick together by cohesive forces. Consequently, higher-energy conditions than what would be expected based on grain size alone are required to erode and transport clays. In general, however, lithogenous sediment tends to become finer with increasing distance from shore. This relationship is mostly because high-energy transporting mechanisms predominate close to shore and lower-energy conditions exist in the deep-ocean basins.

The texture of lithogenous sediment also depends on its **sorting**. Sorting is a measure of the uniformity of grain sizes and indicates the

(a) Stream: Po River, Italy, which displays a prominent delta and a visible sediment plume in the water.

(b) Wind: Dust storm approaching a military base, Australia.

(c) Glacier: Riggs Glacier, Glacier Bay National Park, Alaska, which displays a dark stripe of sediment along its length called a *medial moraine*.

(d) Gravity, which creates landslides: Del Mar, California.

Figure 4.6 **Sediment transport mechanisms.** Photos showing various ways sediment can be transported, including **(a)** streams, **(b)** wind, **(c)** glaciers, and **(d)** gravity.

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[1] Sediment grains are also known as particles, fragments, or clasts.

selectivity of the transportation process. For example, sediments composed of particles that are primarily the same size are well sorted—such as in coastal sand dunes, where winds can only pick up a certain size particle. Poorly sorted deposits, on the other hand, contain a variety of different sized particles and indicate a transportation process capable of picking up clay- to boulder-sized particles. An example of poorly sorted sediment is that which is carried by a glacier and left behind when the glacier melts.

Distribution of Lithogenous Sediment

Marine sedimentary deposits can be categorized as either neritic or pelagic. **Neritic deposits** (*neritos* = of the coast) are found on continental shelves and in shallow water near islands; these deposits are generally coarse grained. Alternatively, **pelagic deposits** (*pelagios* = of the sea) are found in the deep-ocean basins and are typically fine grained. Moreover, lithogenous sediment in the ocean is ubiquitous: At least a small percentage of lithogenous sediment is found nearly everywhere on the ocean floor.

NERITIC DEPOSITS Lithogenous sediment dominates most neritic deposits. Lithogenous sediment is derived from rocks on nearby landmasses, consists of coarse-grained deposits, and accumulates rapidly on the continental shelf, slope, and rise. Examples of lithogenous neritic deposits include beach deposits, continental shelf deposits, turbidite deposits, and glacial deposits.

Beach Deposits Beaches are made of whatever materials are locally available. Beach materials are composed mostly of quartz-rich sand that is washed down to the coast by rivers but can also be composed of a wide variety of sizes and compositions. This material is transported by waves that crash against the shoreline, especially during storms.

Continental Shelf Deposits At the end of the last ice age (about 10,000 years ago), glaciers melted and sea level rose. As a result, many rivers of the world today drop their sediment in drowned river mouths rather than carry it onto the continental shelf as they did during the geologic past. This explains why, in many areas, the sediments that cover the continental shelf—called *relict* (*relict* = left behind) *sediments*—were deposited from 3000 to 7000 years ago and are not covered by sediments discharged by rivers today. These relict sediments presently cover about 70% of the world's continental shelves. In other areas, deposits of sand ridges on the continental shelves appear to have been formed more recently than the most recent ice age and at present water depths.

Climate Connection

Turbidite Deposits As discussed in Chapter 3, **turbidity currents** are underwater avalanches that periodically move down the continental slopes and carve submarine canyons. Turbidity currents also carry vast amounts of neritic material. This material spreads out as deep-sea fans, comprises the continental rise, and gradually thins toward the abyssal plains. These deposits are called **turbidite deposits** and are composed of characteristic layering called *graded bedding* (see Figure 3.12).

Glacial Deposits Poorly sorted deposits containing particles ranging from boulders to clays may be found in the high-latitude[2] portions of the continental shelf. These **glacial deposits** were laid down during the most recent ice age by glaciers that covered the continental shelf and eventually melted. Glacial deposits are currently

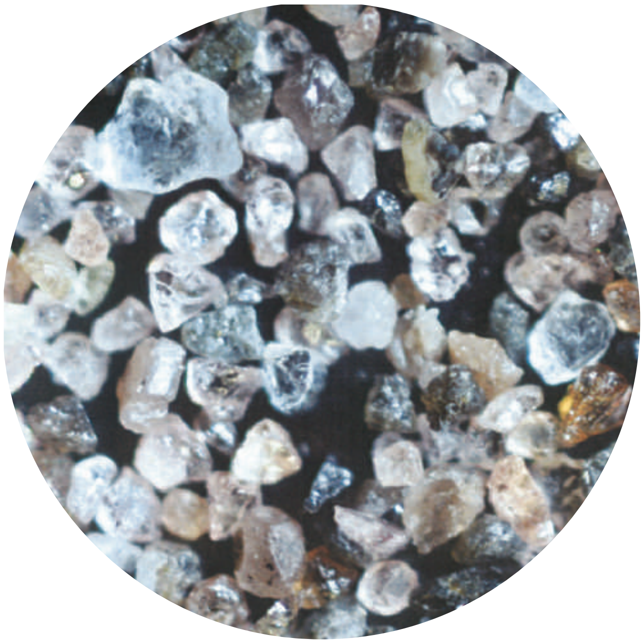

Figure 4.7 **Lithogenous beach sand.** Photomicrograph of well-sorted lithogenous beach sand, which is composed mostly of particles of white quartz plus small amounts of other minerals. This sand, from North Beach, Hampton, New Hampshire, is magnified approximately 23 times.

STUDENTS SOMETIMES ASK . . .

How effective is wind as a transporting agent?

Any material that gets into the atmosphere—including dust from dust storms, soot from forest fires, specks of pollution, and ash from volcanic eruptions—is transported by wind and can be found as deposits on the ocean floor. Every year, wind storms lift an estimated 3 billion metric tons (6.6 trillion pounds) of this material into the atmosphere, where it gets transported around the globe. As much as three-quarters of these particles—mostly dust—come from Africa's Sahara Desert; once airborne, they are carried out across the Atlantic Ocean (see Figure 4.8). Much of this dust falls in the Atlantic, and that's why ships traveling downwind from the Sahara Desert often arrive at their destinations quite dusty. Some of it falls in the Caribbean (where the pathogens it contains have been linked to stress and disease among coral reefs), in Bermuda (where past accumulations have produced the island's red soils), the Amazon (where its iron and phosphorus fertilize nutrient-poor soil), and across the southern United States as far west as New Mexico. The dust also contains bacteria and pesticides—even African desert locusts have been transported alive across the Atlantic Ocean during strong wind storms!

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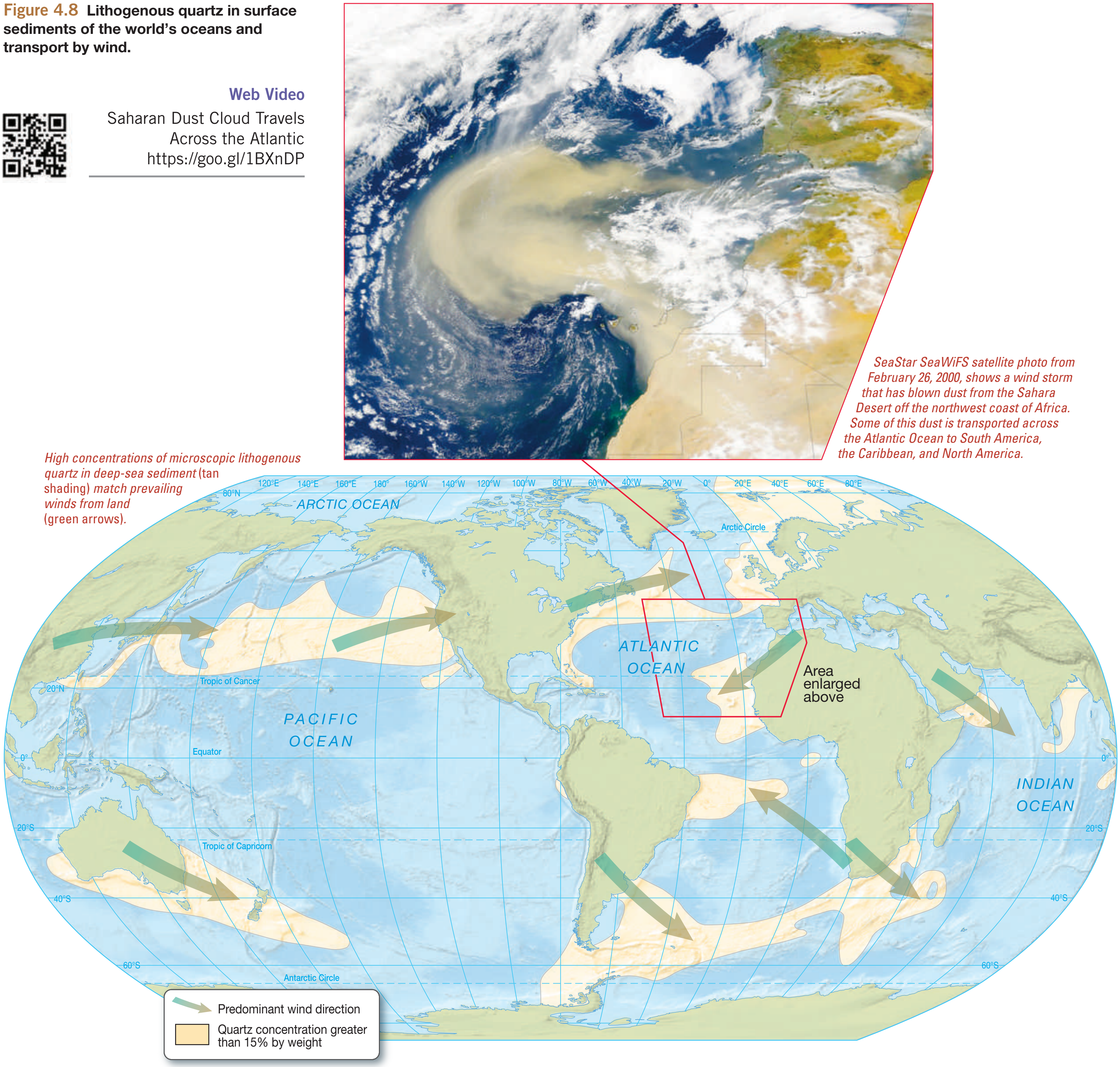
[2] High-latitude regions are those far from the equator (either north or south); low latitudes are areas close to the equator.

Figure 4.8 **Lithogenous quartz in surface sediments of the world's oceans and transport by wind.**

Web Video
Saharan Dust Cloud Travels Across the Atlantic
https://goo.gl/1BXnDP



SeaStar SeaWiFS satellite photo from February 26, 2000, shows a wind storm that has blown dust from the Sahara Desert off the northwest coast of Africa. Some of this dust is transported across the Atlantic Ocean to South America, the Caribbean, and North America.

High concentrations of microscopic lithogenous quartz in deep-sea sediment (tan shading) *match prevailing winds from land* (green arrows).

forming around the continent of Antarctica and around Greenland by **ice rafting**. In this process, rock particles trapped in glacial ice are carried out to sea by icebergs that break away from coastal glaciers. As the icebergs melt, lithogenous particles of many sizes are released and settle onto the ocean floor.

PELAGIC DEPOSITS Turbidite deposits of neritic sediment on the continental rise can spill over into the deep-ocean basin. However, most pelagic deposits are composed of fine-grained material that accumulates slowly on the deep-ocean floor.

TABLE 4.2 WENTWORTH SCALE OF GRAIN SIZE FOR SEDIMENTS

Size range (millimeters)	Particle name		Grain size	Example	Energy of the depositional environment
Above 256	Boulder	Gravel	Coarse-grained	Coarse material found in streambeds near the source areas of rivers and along some beaches	High energy
64 to 256	Cobble				
4 to 64	Pebble				
2 to 4	Granule				
$^1/_{16}$ to 2	Sand			Beach sand	
$^1/_{256}$ to $^1/_{16}$	Silt			Feels gritty in teeth	
$^1/_{4096}$ to $^1/_{256}$	Clay		Fine-grained	Microscopic; feels sticky	Low energy

Scale in millimeters

Pelagic lithogenous sediment includes particles that have come from volcanic eruptions, windblown dust, and fine material that is carried by deep-ocean currents.

Abyssal Clay **Abyssal clay** is composed of at least 70% (by weight) fine, clay-sized particles from the continents. Even though they are far from land, deep abyssal plains contain thick sequences of abyssal clay deposits composed of particles transported great distances by winds or ocean currents and deposited on the deep-ocean floor. Because abyssal clays contain oxidized iron, they are commonly red-brown or buff in color and are sometimes referred to as **red clays**. The predominance of abyssal clay on abyssal plains is caused not by an abundance of clay settling on the ocean floor but by the absence of other material that would otherwise dilute it.

RECAP

Lithogenous sediment is produced from preexisting rock material, is found on most parts of the ocean floor, and can occur as thick deposits close to land.

CONCEPT CHECK 4.2 | Describe the characteristics of lithogenous sediment.

1 Describe the origin, composition, texture, and distribution of lithogenous sediment.

2 Why is most lithogenous sediment composed of quartz grains? What is the chemical composition of quartz?

3 What is the difference between neritic and pelagic deposits? Give examples of lithogenous sediment found in each.

4.3 What Are the Characteristics of Biogenous Sediment?

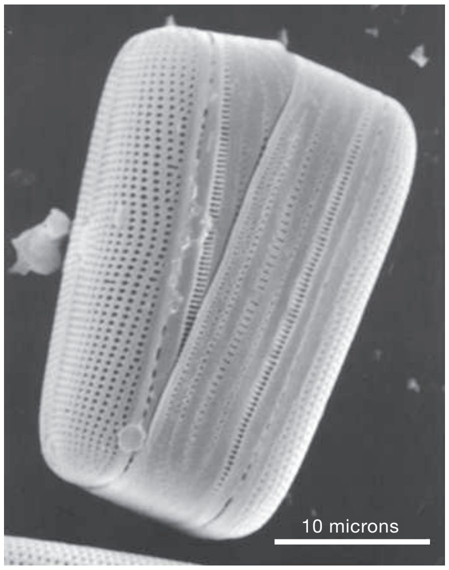
Biogenous sediment (*bio* = life, *generare* = to produce) (also called *biogenic sediment*) is derived from the remains of hard parts of once-living organisms.

Origin of Biogenous Sediment

Biogenous sediment begins as the hard parts (shells, bones, and teeth) of living organisms ranging from minute algae and protozoans to fish and whales. When organisms that produce hard parts die, their remains settle onto the ocean floor and can accumulate as biogenous sediment.

Interdisciplinary Relationship

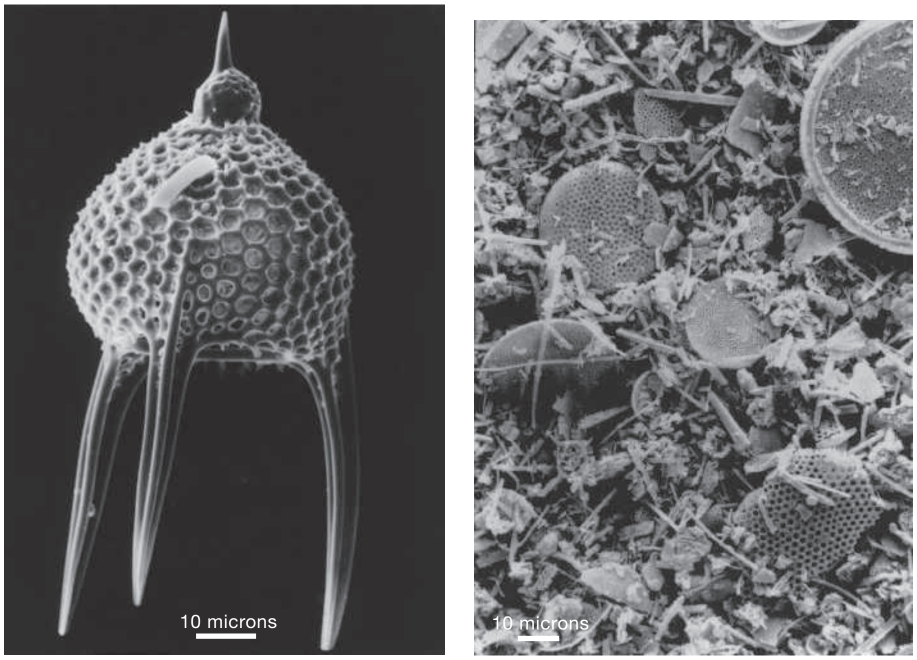
Biogenous sediment can be classified as either macroscopic or microscopic. **Macroscopic biogenous sediment** is large enough to be seen without the aid of a microscope and includes shells, bones, and teeth of large organisms.



(a) Diatom, showing how the two parts of the diatom's test fit together.

Except in certain tropical beach localities where shells and coral fragments are numerous, this type of sediment is relatively rare in the marine environment, especially in deep water where fewer organisms live. Much more abundant is **microscopic biogenous sediment**, which contains particles so small they can be seen well only through a microscope. Microscopic organisms produce tiny shells called **tests** (*testa* = shell) that begin to sink after the organisms die and continually rain down in great numbers onto the ocean floor. These microscopic tests can accumulate on the deep-ocean floor and form deposits called **ooze** (*wose* = juice). As its name implies, ooze resembles very fine-grained, mushy material.[3] Technically, biogenous ooze must contain at least 30% biogenous test material by weight. What comprises the other part—up to 70%—of an ooze? Commonly, it is fine-grained lithogenous clay that is deposited along with biogenous tests in the deep ocean. By volume, much more microscopic ooze than macroscopic biogenous sediment exists on the ocean floor.

The organisms that contribute to biogenous sediment are chiefly **algae** (*alga* = seaweed) and **protozoans** (*proto* = first, *zoa* = animal). Algae are primarily aquatic, eukaryotic,[4] photosynthetic organisms, ranging in size from microscopic single cells to large organisms like giant kelp. Protozoans are any of a large group of single-celled, eukaryotic, usually microscopic organisms that are generally not photosynthetic.



(b) Radiolarian.

(c) Siliceous ooze, showing mostly fragments of diatom tests.

Figure 4.9 **Microscopic siliceous tests.** Scanning electron micrographs of various siliceous tests.

Composition of Biogenous Sediment

The two most common chemical compounds in biogenous sediment are **calcium carbonate** ($CaCO_3$, which forms the mineral **calcite**) and **silica** (SiO_2). Often, the silica is chemically combined with water to produce $SiO_2 \cdot nH_2O$, the hydrated form of silica, which is called *opal.*

Interdisciplinary Relationship

SILICA Most of the silica in biogenous ooze comes from microscopic algae called **diatoms** (*diatoma* = cut in half) and protozoans called **radiolarians** (*radio* = a spoke or ray).

Because diatoms photosynthesize, they need strong sunlight and are found only within the upper, sunlit surface waters of the ocean. Most diatoms are free-floating, or **planktonic** (*planktos* = wandering). The living organism builds a glass greenhouse out of silica as a protective cov-ering and lives inside. Most species have two parts to their test that fit together like a petri dish or pillbox (Figure 4.9a). The tiny tests are perforated with small holes in intricate patterns to allow nutrients to pass in and waste products to pass out. Where diatoms are abundant at the ocean surface, thick deposits of diatom-rich ooze can accumulate below on the ocean floor. When this ooze lithifies, it becomes **diatomaceous earth**,[5] a lightweight white rock composed of diatom tests and clay (Diving Deeper 4.1).

Radiolarians are microscopic single-celled protozoans, most of which are also planktonic. As their name implies, they often have long spikes or rays of silica protruding from their siliceous shell (Figure 4.9b). They do not photosynthesize but rely on external food sources such as bacteria and other plankton. Radiolarians typically

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[3] Ooze has the consistency of toothpaste mixed about half and half with water. As a way to remember this term, imagine walking barefoot across the deep-ocean floor and having the fine sediment there *ooze* between your toes.

[4] Eukaryotic (*eu* = good, *karyo* = the nucleus) cells contain a distinct membrane-bound nucleus.

[5] Diatomaceous earth is also called diatomite, tripolite, or kieselguhr.

OCEANS AND PEOPLE

DIVING DEEPER 4.1

DIATOMS: THE MOST IMPORTANT THINGS YOU HAVE (PROBABLY) NEVER HEARD OF

> *"Few objects are more beautiful than the minute siliceous cases of the diatomaceae: were these created that they might be examined and admired under the higher powers of the microscope?"*
>
> *—Charles Darwin (1872)*

Diatoms are microscopic single-celled photosynthetic organisms. Each one lives inside a protective silica test, most of which contain two halves that fit together like a shoebox and its lid. First described with the aid of a microscope in 1702, their tests are exquisitely ornamented with holes, ribs, and radiating spines unique to individual species. The fossil record indicates that diatoms have been on Earth since the Jurassic Period (180 million years ago), and more than 70,000 species of diatoms have been identified.

Diatoms live for a few days to as much as a week, can reproduce sexually or asexually, and occur individually or linked together into long communities. They are found in great abundance floating in the ocean and in certain freshwater lakes but can also be found in many diverse environments, such as on the undersides of polar ice, on the skins of whales, in soil, in thermal springs, and even on brick walls.

When marine diatoms die, their tests rain down and accumulate on the sea floor as siliceous ooze. Hardened deposits of siliceous ooze, called *diatomaceous earth*, can be as much as 900 meters (3000 feet) thick. Diatomaceous earth consists of billions of minute silica tests and has many unusual properties: It is lightweight, has an inert chemical composition, is resistant to high temperatures, and has excellent filtering properties. Diatomaceous earth is used to produce a variety of common products (Figure 4A). The main uses of diatomaceous earth include:

- Filters (for refining sugar, separating impurities from wine, straining yeast from beer, and filtering swimming pool water)
- Mild abrasives (in toothpaste, facial scrubs, matches, and household cleaning and polishing compounds)
- Absorbents (for chemical spills, in cat litter, and as a soil conditioner)
- Chemical carriers (in pharmaceuticals, paint, and even dynamite)

Other products from diatomaceous earth include optical-quality glass (because of the pure silica content of diatoms) and space shuttle tiles (because they are lightweight and provide good insulation). Diatomaceous earth is also used as an additive in concrete, a filler in tires, an anticaking agent, a natural pesticide, and even a building stone in the construction of houses.

Further, the vast majority of oxygen that all animals breathe is a by-product of photosynthesis by diatoms. In addition, each living diatom contains a tiny droplet of oil. When diatoms die, their tests containing droplets of oil accumulate on the sea floor and are the beginnings of petroleum deposits, such as those found offshore of California.

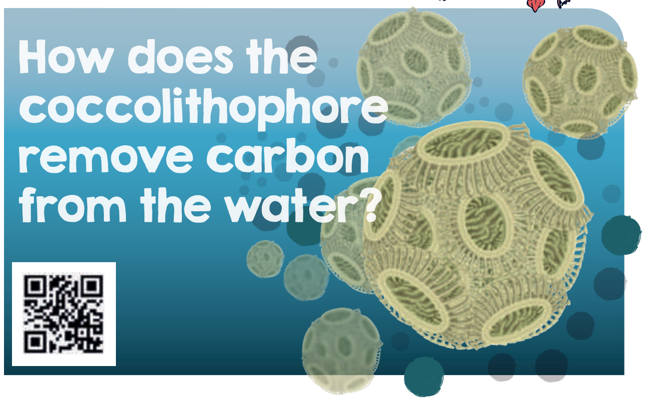
Given their many practical applications, it is difficult to imagine how different our lives would be without diatoms!

GIVE IT SOME THOUGHT

1. What are several reasons diatoms are so remarkable? List products that contain or are produced using diatomaceous earth.

Figure 4A **Products containing or produced using diatomaceous earth (diatom *Thalassiosira eccentrica*, inset).**

4.1 Squidtoons



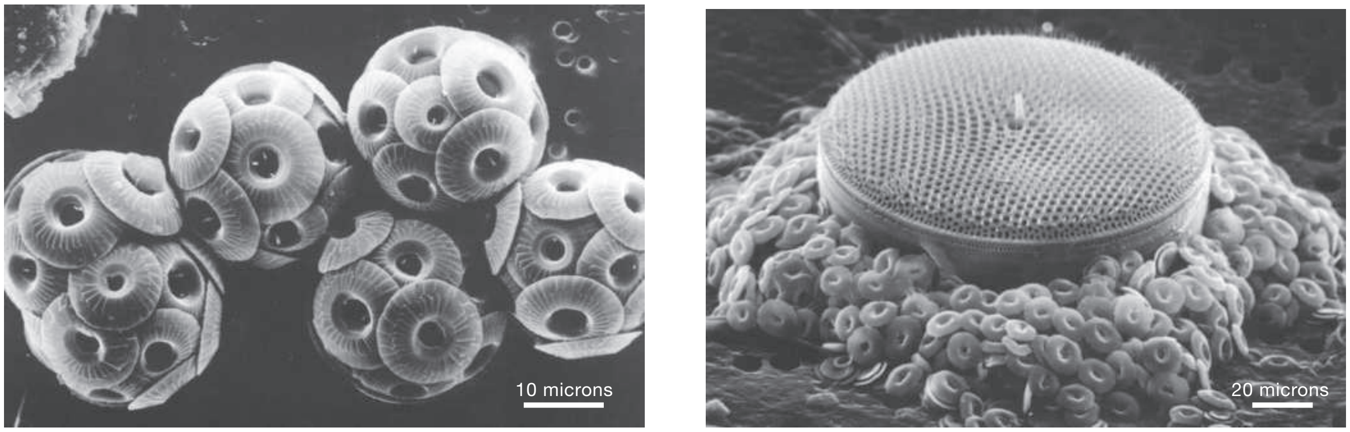
https://goo.gl/RYtRi6

display well-developed symmetry, which is why they have been described as the "living snowflakes of the sea."

The accumulation of siliceous tests of diatoms, radiolarians, and other silica-secreting organisms produces **siliceous ooze** (Figure 4.9c).

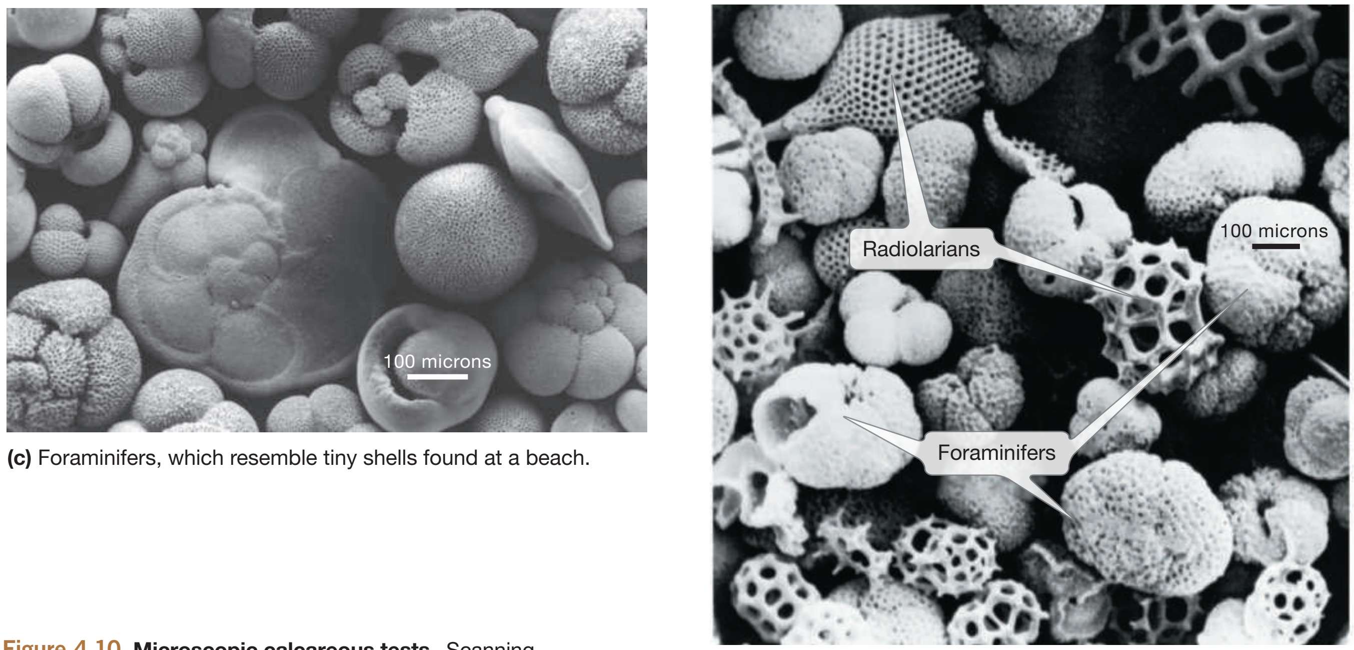
CALCIUM CARBONATE Two significant sources of calcium carbonate biogenous ooze are the **foraminifers** (*foramen* = an opening)—close relatives of radiolarians—and microscopic algae called **coccolithophores** (*coccus* = berry, *lithos* = stone, *phorid* = carrying).

Coccolithophores are single-celled algae, most of which are planktonic. Coccolithophores produce thin plates or shields made of calcium carbonate, 20 or 30 of which overlap to produce a spherical test (Figure 4.10a). Like diatoms, coccolithophores photosynthesize, so they need sunlight to live. Coccolithophores are really, *really* small. In fact, coccolithophores are about 10 to 100 times smaller than most diatoms (Figure 4.10b), which is why coccolithophores are often called **nannoplankton** (*nanno* = dwarf, *planktos* = wandering).



(a) Coccolithophores, which resemble tiny spheres.

(b) Diatom (siliceous) surrounded by coccoliths (calcareous).



(c) Foraminifers, which resemble tiny shells found at a beach.

(d) Calcareous ooze, which also includes some siliceous radiolarian tests.

Figure 4.10 **Microscopic calcareous tests.** Scanning electron micrographs (*above*) and photomicrographs (*below*) of various calcareous tests.

When the organism dies, the individual plates (called **coccoliths**) disaggregate and can accumulate on the ocean floor as coccolith-rich ooze. When this ooze lithifies over time, it forms a white deposit called **chalk**, which is used for a variety of purposes (including writing on chalkboards). The White Cliffs of southern England are composed of hardened, coccolith-rich calcium carbonate ooze, which was deposited on the ocean floor and has been uplifted onto land (**Figure 4.11**). Deposits of chalk the same age as the White Cliffs are so common throughout Europe, North America, Australia, and the Middle East that the geologic period in which these deposits formed is named the Cretaceous (*creta* = chalk) Period.

Foraminifers are single-celled protozoans, many of which are planktonic, ranging in size from microscopic to macroscopic. They do not photosynthesize, so they must ingest other organisms for food. Foraminifers produce a hard calcium carbonate test in which the organism lives (**Figure 4.10c**). Most foraminifers produce a segmented or chambered test, and all tests have a prominent opening in one end. Although very small in size, the tests of foraminifers resemble the large shells that one might find at a beach.

Deposits comprised primarily of tests of foraminifers, coccoliths, and other calcareous-secreting organisms are called **calcareous ooze** (**Figure 4.10d**).

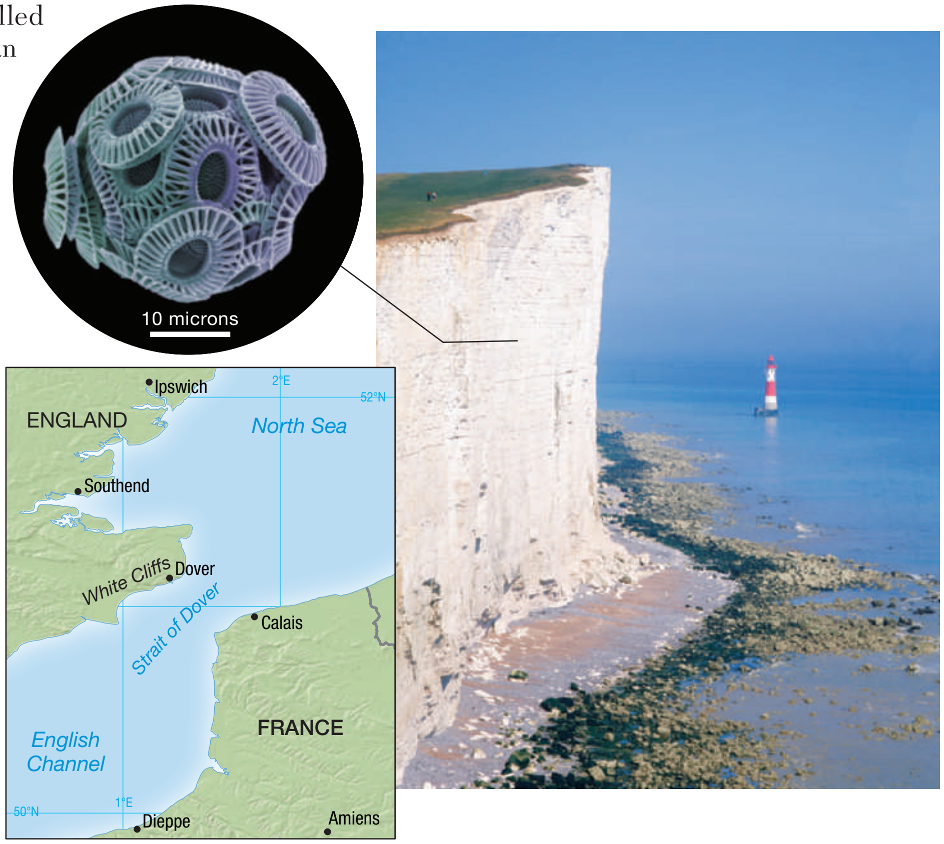


Figure 4.11 The White Cliffs of southern England. The White Cliffs near Dover in southern England are composed of chalk, which is hardened coccolith-rich calcareous ooze. Inset shows a colored image of the coccolithophore *Emiliana huxleyi*.

Distribution of Biogenous Sediment

Biogenous sediment is one of the most common types of pelagic deposits. The distribution of biogenous sediment on the ocean floor depends on three fundamental processes: (1) productivity, (2) destruction, and (3) dilution.

Productivity is the number of organisms present in the surface water above the ocean floor. Surface waters with high biologic productivity contain many living and reproducing organisms—conditions that are likely to produce biogenous sediments. Conversely, surface waters with low biologic productivity contain too few organisms to produce biogenous oozes on the ocean floor.

Destruction occurs when skeletal remains (tests) dissolve in seawater at depth. In some cases, biogenous sediment dissolves before ever reaching the sea floor; in other cases, it is dissolved before it has a chance to accumulate into deposits on the sea floor.

Dilution occurs when the deposition of other sediments decreases the percentage of the biogenous sediment found in marine deposits. For example, other types of sediments can dilute biogenous test material below the 30% necessary to classify it as ooze. Dilution occurs most often because of the abundance of coarse-grained lithogenous material in neritic environments, so biogenous oozes are uncommon along continental margins.

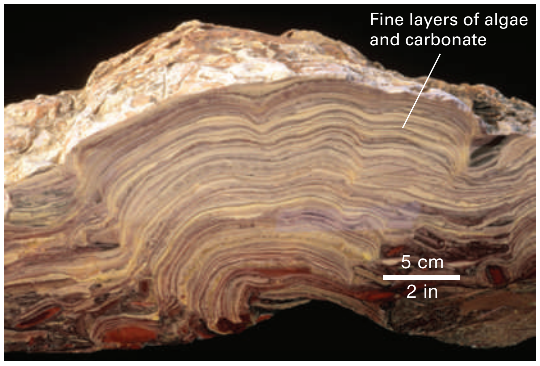
NERITIC DEPOSITS Although neritic deposits are dominated by lithogenous sediment, both microscopic and macroscopic biogenous material may be incorporated into lithogenous sediment in neritic deposits. In addition, biogenous carbonate deposits are common in some areas.

Carbonate Deposits **Carbonate** minerals are those that contain CO_3 in their chemical formula—such as calcium carbonate, $CaCO_3$. Rocks from the marine environment composed primarily of calcium carbonate are called **limestones**. Most limestones contain fossil marine shells, suggesting a biogenous origin, while other carbonate-containing rocks

Interdisciplinary Relationship

(a) Location map of Shark Bay, Australia.

(b) Shark Bay stromatolites, which form in high-salinity tidal pools and reach a maximum height of about 1 meter (3.3 feet).



(c) Profile view through a stromatolite, showing its internal fine layering.

Figure 4.12 Stromatolites. Stromatolites are bulbous algal mats that grow in warm, shallow, high-salinity water such as in Shark Bay, Australia.

appear to have formed directly from seawater without the help of any marine organism. Modern environments where calcium carbonate is currently being deposited (such as in the Bahama Banks, Australia's Great Barrier Reef, and the Persian Gulf) suggest that carbonate deposits are formed in shallow, warm-water shelves and around tropical islands as coral reefs and beaches.

Ancient marine carbonate deposits constitute 2% of Earth's crust and 25% of all sedimentary rocks on Earth. In fact, marine limestones form the underlying bedrock of Florida and many Midwestern states, from Kentucky to Michigan and from Pennsylvania to Colorado. Percolation of groundwater through these deposits has dissolved the limestone to produce sinkholes and, in some cases, spectacular caverns.

Stromatolites **Stromatolites** are lobate structures consisting of fine layers of carbonate that form in specific warm, shallow-water environments such as the high salinity tidal pools in Shark Bay, Western Australia (Figure 4.12). Cyanobacteria[6] produce these deposits by trapping fine sediment in mucous mats. Other types of algae produce long filaments that bind carbonate particles together. Like tree rings being added as a tree grows, layer upon layer of these algae colonize the surface, forming a bulbous structure. In the geologic past—particularly from about 1 to 3 billion years ago—conditions were ideal for the development of stromatolites, so stromatolite structures hundreds of meters high can be found in rocks from these ages.

PELAGIC DEPOSITS Microscopic biogenous sediment (ooze) is common on the deep-ocean floor because there is so little lithogenous sediment deposited at great distances from the continents that could dilute the biogenous material.

Siliceous Ooze Siliceous ooze contains at least 30% of the hard remains of silica-secreting organisms. When the siliceous ooze consists mostly of diatoms, it is called *diatomaceous ooze*. When it consists mostly of radiolarians, it is called *radiolarian ooze*. When it consists mostly of single-celled silicoflagellates—another type of protozoan—it is called *silicoflagellate ooze*.

The ocean is undersaturated with silica at all depths, which means that any solid particle made up of silica will tend to dissolve in seawater. In fact, if living diatoms, radiolarians, and silicoflagellates were not hard at work creating their silica-containing tests, they would dissolve, too! As a consequence, the destruction of siliceous biogenous particles (that is, the tests of dead organisms drifting to the sea floor), by dissolving in seawater, occurs continuously and slowly at all depths. How can siliceous ooze accumulate on the ocean floor if it is being dissolved? One way is to accumulate the siliceous tests faster than seawater can dissolve them. For instance, many tests sinking at the same time will create a deposit of siliceous ooze on the sea floor below (Figure 4.13).[7] Once buried beneath other siliceous tests, they are no

Web Animation
The Accumulation of Siliceous Ooze
https://goo.gl/2XEQww

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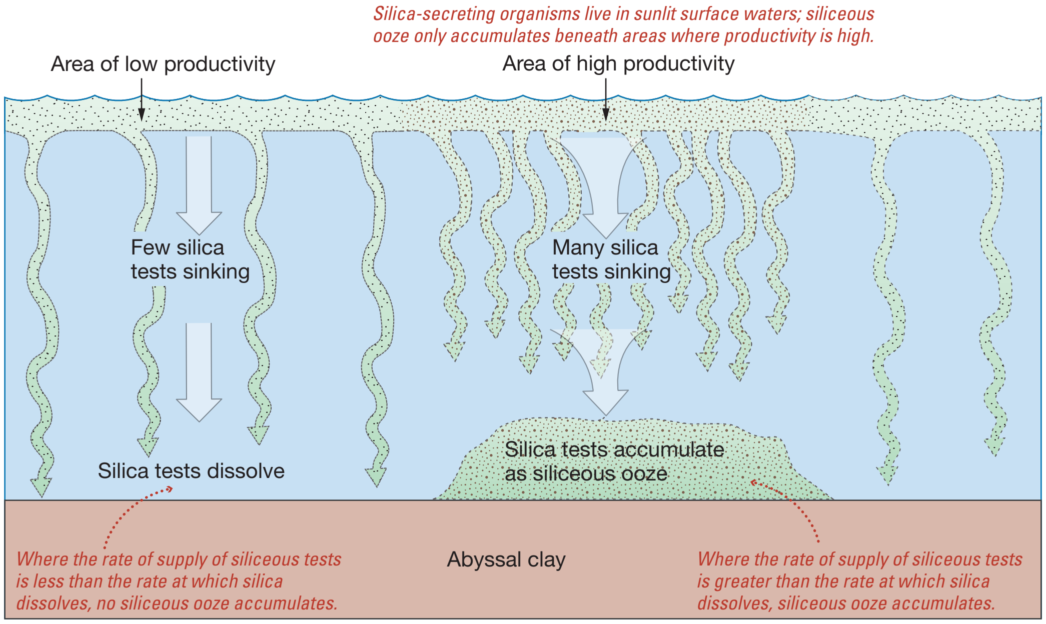
[6] Cyanobacteria (*kuanos* = dark blue) are simple, ancient creatures whose ancestry can be traced back to some of the first photosynthetic organisms on Earth.

[7] An analogy to this is trying to get a layer of sugar to form on the bottom of a cup of hot coffee. If a few grains of sugar are slowly dropped into the cup, a layer of sugar won't accumulate. If a whole bowl full of sugar is dumped into the coffee, however, a thick layer of sugar will form on the bottom of the cup.

longer exposed to the dissolving effects of seawater. Thus, siliceous ooze is commonly found in areas below surface waters with high biologic productivity of silica-secreting organisms.

Calcareous Ooze and the CCD Calcareous ooze contains at least 30% of the hard remains of calcareous-secreting organisms. When it consists mostly of coccolithophores, it is called *coccolith ooze*. When it consists mostly of foraminifers, it is called *foraminifer ooze*. One of the most common types of foraminifer ooze is *Globigerina ooze*, named for a foraminifer that is especially widespread in the Atlantic and South Pacific oceans. Other calcareous oozes include *pteropod oozes* and *ostracod oozes*.


Silica-secreting organisms live in sunlit surface waters; siliceous ooze only accumulates beneath areas where productivity is high.

Where the rate of supply of siliceous tests is less than the rate at which silica dissolves, no siliceous ooze accumulates.

Where the rate of supply of siliceous tests is greater than the rate at which silica dissolves, siliceous ooze accumulates.

SmartFigure 4.13 Accumulation of siliceous ooze.
https://goo.gl/4iUEf1

The destruction of calcium carbonate (calcite) varies with depth. At the warmer surface and in the shallow parts of the ocean, seawater is generally saturated with calcium carbonate, so calcite does not dissolve. In the deep ocean, however, the colder water contains greater amounts of carbon dioxide, which forms carbonic acid and causes calcareous material to dissolve. The higher pressure at depth also helps speed the dissolution of calcium carbonate.

The depth in the ocean at which the pressure is high enough, and the amount of carbon dioxide in deep-ocean waters is great enough, to begin dissolving calcium carbonate is called the **lysocline** (*lusis* = a loosening, *cline* = slope). Below the lysocline, calcium carbonate dissolves at an increasing rate with increasing depth until the **calcite compensation depth (CCD)**[8] is reached (Figure 4.14). At the CCD and greater depths, sediment does not usually contain much calcite because it readily dissolves; even the thick tests of foraminifers dissolve within a day or two. In essence, calcite accumulates only near the tops of the tall peaks that rise off the sea floor and extend above the CCD but dissolves at deeper depths associated with the base of the peaks. This situation creates the marine equivalent of a mountain's "snow line," but with deposits of light-colored calcite on the mountaintop instead of frozen water.

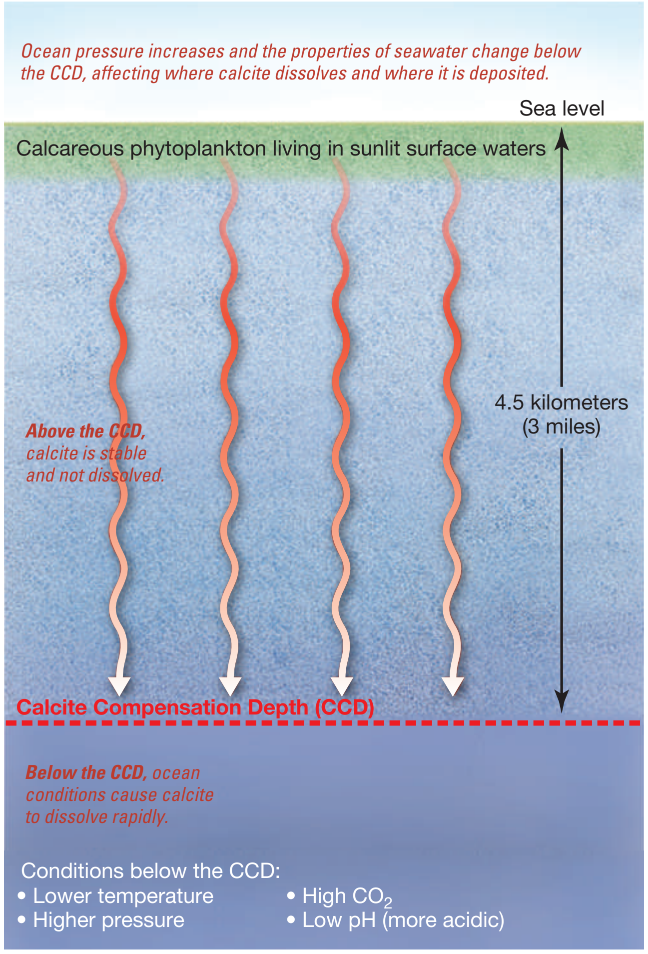
Interdisciplinary Relationship

The CCD, on average, is 4500 meters (15,000 feet) below sea level, but depending on the chemistry of the deep ocean, it may be as deep as 6000 meters (20,000 feet) in portions of the Atlantic Ocean or as shallow as 3500 meters (11,500 feet) in the Pacific Ocean. The depth of the lysocline also varies from ocean to ocean but averages about 4000 meters (13,100 feet).

In the geologic past, higher concentrations of carbon dioxide in the atmosphere have led to increased amounts of dissolved carbon dioxide in the ocean, thereby making the ocean more acidic and causing the CCD to rise. Currently, scientists have documented an increase in ocean acidity due to higher levels of atmospheric carbon dioxide caused by human-caused emissions. Increased ocean acidity and its effect on marine life are discussed in Chapter 16, "The Oceans and Climate Change."

Climate Connection

Because of the CCD, modern carbonate oozes are generally rare below 5000 meters (16,400 feet). Still, buried deposits of ancient calcareous ooze are found beneath the CCD. How can calcareous ooze exist below the CCD? The necessary conditions are shown in Figure 4.15. The mid-ocean ridge is a topographically high


Ocean pressure increases and the properties of seawater change below the CCD, affecting where calcite dissolves and where it is deposited.

Above the CCD, calcite is stable and not dissolved.

Below the CCD, ocean conditions cause calcite to dissolve rapidly.

Conditions below the CCD:
- Lower temperature
- Higher pressure
- High CO_2
- Low pH (more acidic)

Figure 4.14 Characteristics of water above and below the calcite compensation depth (CCD).

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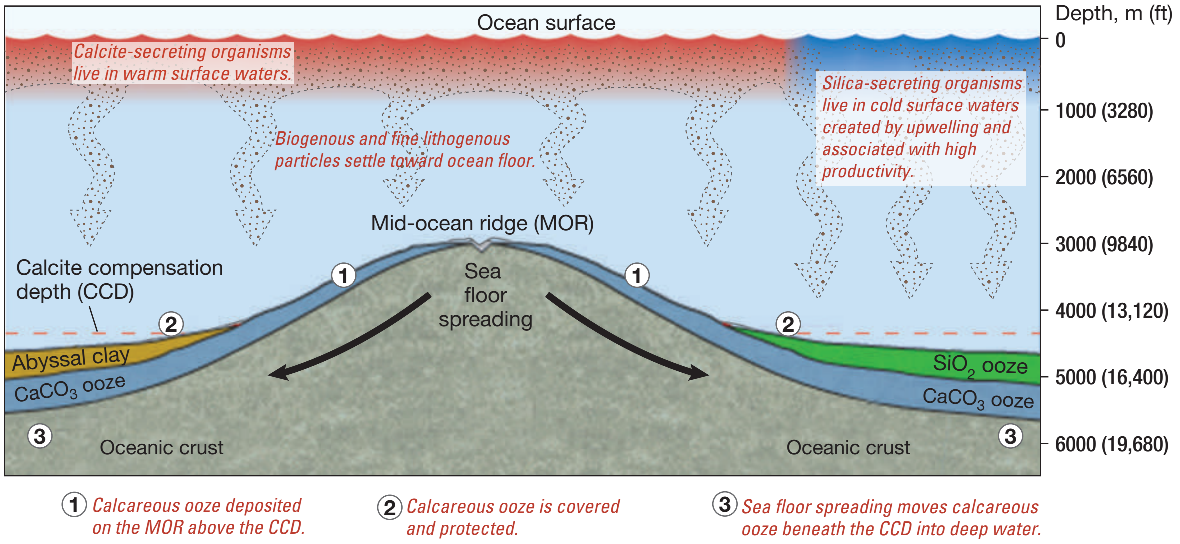
[8] Because the mineral calcite is composed of calcium carbonate, the *calcite compensation depth* is also known as the *calcium carbonate compensation depth* or the *carbonate compensation depth*. All go by the handy abbreviation CCD.



SmartFigure 4.15 Sea floor spreading and sediment accumulation. Relationships among carbonate compensation depth (CCD), the mid-ocean ridge, sea floor spreading, productivity, and destruction that allow calcareous ooze to be preserved below the CCD. https://goo.gl/s9vIsw

Web Animation
How Calcareous Ooze Can Be Found Beneath the CCD
https://goo.gl/h3rDxA

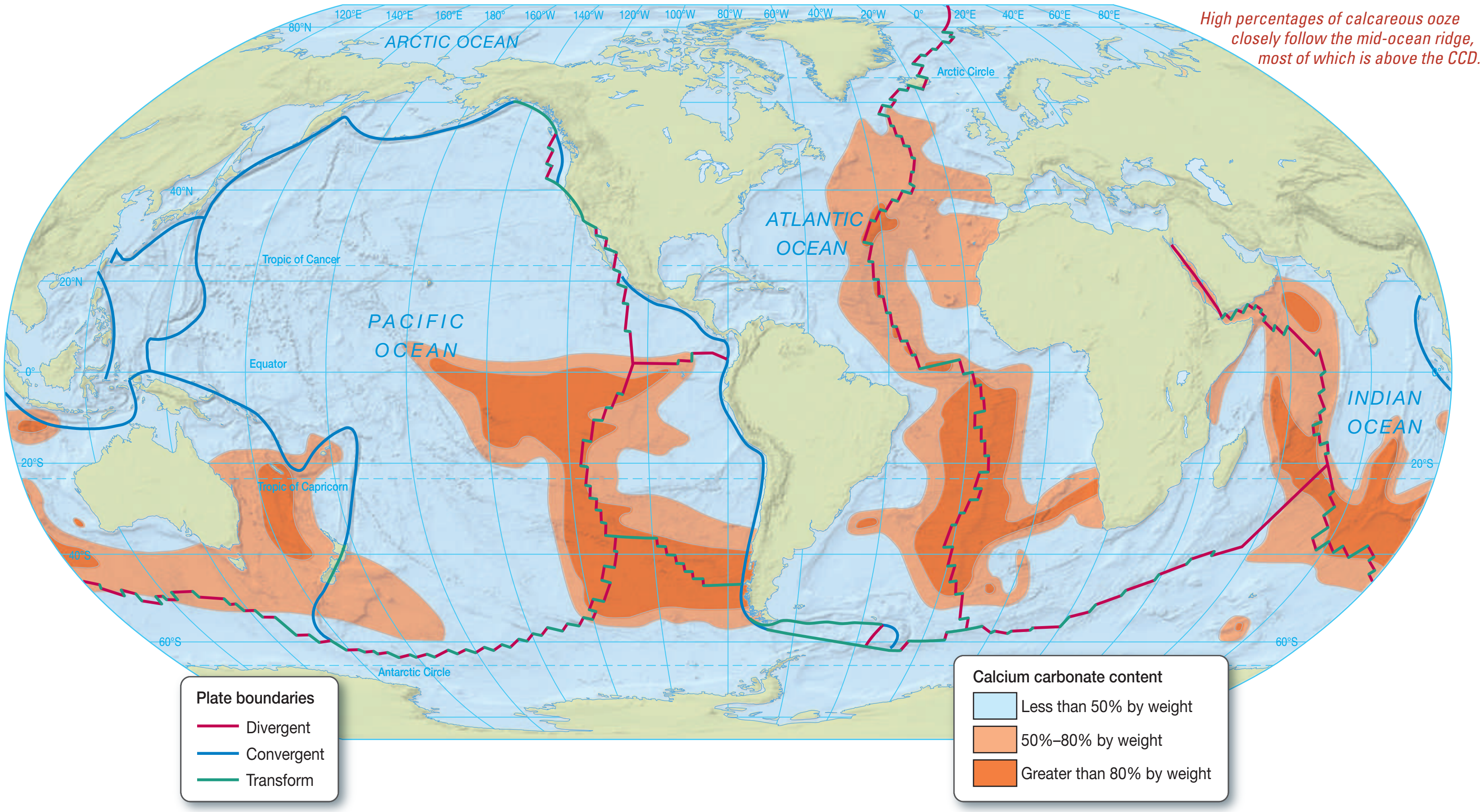


Figure 4.16 Distribution of calcium carbonate in modern surface sediments.

feature that rises above the sea floor. It often pokes up above the CCD, even though the surrounding deep-ocean floor is below the CCD. Thus, calcareous ooze deposited on top of the mid-ocean ridge does not dissolve. However, sea floor spreading causes the newly created sea floor and the calcareous sediment on top of it to move into deeper water away from the ridge, eventually being transported below the CCD. This calcareous sediment will dissolve below the CCD unless it is covered by some deposit that is unaffected by the CCD (such as siliceous ooze or abyssal clay).

The map in Figure 4.16 shows the percentage (by weight) of calcium carbonate in the modern surface sediments of the ocean basins. High concentrations of

SmartTable 4.3 COMPARISON OF ENVIRONMENTS INTERPRETED FROM DEPOSITS OF SILICEOUS AND CALCAREOUS OOZE IN SURFACE SEDIMENTS

	Siliceous ooze	Calcareous ooze
Surface water temperature above sea floor deposits	Cool	Warm
Main location found	Sea floor beneath cool surface water in high latitudes	Sea floor beneath warm surface water in low latitudes
Other factors	Upwelling brings deep, cold, nutrient-rich water to the surface	Calcareous ooze dissolves below the CCD
Other locations found	Sea floor beneath areas of upwelling, including along the equator	Sea floor beneath warm surface water in low latitudes along the mid-ocean ridge

calcareous ooze (sometimes exceeding 80%) are found along segments of the mid-ocean ridge, but little is found in deep-ocean basins below the CCD. For example, in the northern Pacific Ocean—one of the deepest parts of the world ocean—there is very little calcium carbonate in the sediment. Calcium carbonate is also rare in sediments accumulating beneath cold, high-latitude waters where calcareous-secreting organisms are relatively uncommon.

Table 4.3 compares the environmental conditions that can be inferred from siliceous and calcareous oozes. It shows that siliceous ooze typically forms below cool surface water regions, including areas of **upwelling** where deep-ocean water comes to the surface and supplies nutrients that stimulate high rates of biological productivity. Calcareous ooze, on the other hand, is found on the shallower areas of the ocean floor beneath warmer surface water.

SmartTable 4.3 **Comparison of environments interpreted from deposits of siliceous and calcareous ooze in surface sediments.**
https://goo.gl/H5uBwg

RECAP

Biogenous sediment is produced from the hard remains of once-living organisms. Microscopic biogenous sediment is especially widespread and forms deposits of ooze on the ocean floor.

CONCEPT CHECK 4.3 | Describe the characteristics of biogenous sediment.

1 Describe the origin, composition, and distribution of biogenous sediment.

2 List the two major chemical compounds of which most biogenous sediment is composed and two examples of the microscopic organisms that produce them. Sketch and label these organisms.

3 Technically, what must a biogenous ooze contain to be classified as ooze? What other component do all oozes contain?

4 If siliceous ooze is slowly but constantly dissolving in seawater, how can deposits of siliceous ooze accumulate on the ocean floor?

5 Explain the stages of progression that result in calcareous ooze existing below the CCD.

4.4 What Are the Characteristics of Hydrogenous Sediment?

Hydrogenous sediment (*hydro* = water, *generare* = to produce) is derived from the dissolved material in water.

Origin of Hydrogenous Sediment

Interdisciplinary Relationship

Seawater contains many dissolved materials. Chemical reactions within seawater cause certain minerals to come out of solution, or **precipitate** (change from the dissolved to the solid state). Precipitation usually occurs when there is a *change in conditions*, such as a change in temperature or pressure or the addition of chemically active fluids. To make rock candy, for instance, a pan of water is heated and sugar is added. When the water is hot and the sugar dissolved, the pan is removed from the heat, and the sugar water is allowed to cool. The *change in temperature* causes the sugar to become

(a) Manganese nodules, including some that are cut in half.

(b) Close-up of a baseball-sized manganese nodule cut in half, revealing its central nucleation object and layered internal structure.

(c) An abundance of manganese nodules on a portion of the deep South Pacific Ocean floor about 4 meters (13 feet) across.

Figure 4.17 **Manganese nodules.**

oversaturated, which causes it to precipitate. As the water cools, the sugar precipitates on anything that is put in the pan, such as pieces of string or kitchen utensils.

Composition and Distribution of Hydrogenous Sediment

Although hydrogenous sediments represent a relatively small portion of the overall sediment in the ocean, they have many different compositions and are distributed in diverse environments of deposition.

MANGANESE NODULES **Manganese nodules** are rounded, hard lumps of manganese, iron, and other metals typically 5 centimeters (2 inches) in diameter up to a maximum of about 20 centimeters (8 inches). When cut in half, they often reveal a layered structure formed by precipitation around a central nucleation object (Figures 4.17a and 4.17b). The nucleation object may be a piece of lithogenous sediment, coral, volcanic rock, a fish bone, or a shark's tooth. Manganese nodules lie on sediment in vast expanses of abyssal plains, potentially covering some 60% of the ocean basin at a typical water depth of about 5 kilometers (3.1 miles). Manganese nodules can sometimes occur in concentrations of about 100 nodules per square meter (square yard); in rare cases, they exist in even greater abundance (Figure 4.17c), resembling a scattered field of golf ball- to baseball-sized nodules. The formation of manganese nodules requires extremely low rates of lithogenous or biogenous input so that the nodules are not buried.

The major components of these nodules are manganese hydroxide (around 30% by weight) and iron hydroxide (around 20%). The element manganese is important for making high-strength steel alloys. Other accessory metals present in manganese nodules include copper (used in electrical wiring, in pipes, and to make brass and bronze), nickel (used to make stainless steel), and cobalt (used as an alloy with iron to make strong magnets and steel tools). Although the concentration of these accessory metals is usually less than 1%, they can exceed 2% by weight, which may make them attractive sources for these metals in the future.

The origin of manganese nodules has puzzled oceanographers since manganese nodules were first discovered in 1872 during the voyage of HMS *Challenger*.[9] If manganese nodules are truly hydrogenous and precipitate from seawater, then how can they have such high concentrations of manganese (which occurs in seawater at concentrations often too small to measure accurately)? Furthermore, why are the nodules on *top* of ocean floor sediment and not buried by the constant rain of sedimentary particles?

Unfortunately, nobody has definitive answers to these questions. Perhaps manganese nodules are created by one of the slowest chemical reactions known—on average, they grow at a rate of about 5 millimeters (0.2 inch) per *million years*. Scientific studies suggest that the formation of manganese nodules may be aided by bacteria and an as-yet-unidentified marine organism that intermittently lifts and

STUDENTS SOMETIMES ASK . . .

I've been to Hawaii and seen a black sand beach, which forms when lava flows into the ocean and is broken up by waves. Is the black sand hydrogenous sediment?

No. Many active volcanoes in the world have black sand beaches that are created when waves break apart dark-colored volcanic rock. The material that produces the black sand is derived from a continent or an island, so it is considered lithogenous sediment. Even though molten lava sometimes flows into the ocean, the resulting black sand could never be considered hydrogenous sediment because the lava was never *dissolved* in water.

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[9] For more information about the accomplishments of the *Challenger* expedition, see MasteringOceanography Web Diving Deeper 5.2.

rotates them. Other studies reveal that the nodules don't form continuously over time but in spurts that are related to specific conditions such as a low sedimentation rate of lithogenous clay and strong deep-water currents. Remarkably, the larger the nodules are, the faster they grow. The origin of manganese nodules is widely considered the most interesting unresolved problem in marine chemistry.

PHOSPHATES Phosphorus-bearing compounds (**phosphates**) occur abundantly as coatings on rocks and as nodules on the continental shelf and on banks at depths shallower than 1000 meters (3300 feet). Concentrations of phosphates in such deposits commonly reach 30% by weight and indicate abundant biological activity in surface water above where they accumulate. Because phosphates are valuable as fertilizers, ancient marine phosphate deposits that have been uplifted onto land are extensively mined to supply agricultural needs.

CARBONATES The two most important carbonate minerals in marine sediment are calcite and **aragonite**. Both are composed of calcium carbonate ($CaCO_3$), but aragonite has a different crystalline structure that is less stable and transforms into calcite over time. Carbonates are widely used in the construction industry, in the production of cement, and they are commonly used medicinally as calcium supplements or antacids.

As previously discussed, most carbonate deposits are biogenous in origin. However, hydrogenous carbonate deposits can precipitate directly from seawater in tropical climates to form aragonite crystals less than 2 millimeters (0.08 inch) long. In addition, **oolites** (*oo* = egg, *lithos* = rock) are small calcite spheres 2 millimeters (0.08 inch) or less in diameter that have layers like an onion and form in some shallow tropical waters where concentrations of $CaCO_3$ are high. Oolites are thought to precipitate around a nucleus and grow larger as they roll back and forth on beaches by wave action, but some evidence suggests that a type of algae may aid their formation.

METAL SULFIDES Deposits of **metal sulfides** are associated with hydrothermal vents and black smokers along the mid-ocean ridge. These deposits contain iron, nickel, copper, zinc, silver, and other metals in varying proportions. Transported away from the mid-ocean ridge by sea floor spreading, these deposits can be found throughout the ocean floor and can even be uplifted onto continents(see MasteringOceanography **Web Diving Deeper 2.3**).

EVAPORITES Generally, **evaporite minerals** form wherever there are high evaporation rates (dry climates) accompanied by restricted open ocean circulation. One such example is the Mediterranean Sea, which contains thick deposits of evaporites on its floor that suggest that sometime in the geologic past, the sea completely dried up (see MasteringOceanography **Web Diving Deeper 4.1**). As water evaporates in these dry areas, the remaining seawater becomes saturated with dissolved minerals, which then begin to precipitate (form a solid). Because they are heavier than seawater, the minerals sink to the bottom or form a white crust of evaporite minerals around the edges of these areas (Figure 4.18). Collectively termed "salts," some evaporite minerals, such as *halite* (common table salt, NaCl), taste salty, and some, such as the calcium sulfate minerals *anhydrite* ($CaSO_4$) and *gypsum* ($CaSO_4 \cdot H_2O$), do not.

Figure 4.18 **Evaporative salts cover the floor of a seasonally flooded basin.** After seasonal rains at Death Valley, California, the high evaporation rate causes salts (white material) to precipitate out, resulting in this extensive salt flat.

RECAP

Hydrogenous sediment is produced when dissolved materials precipitate out of solution, producing a variety of materials, and are found in localized concentrations on the ocean floor.

CONCEPT CHECK 4.4 | Describe the characteristics of hydrogenous sediment.

1 Describe the origin, composition, and distribution of hydrogenous sediment.

2 Describe manganese nodules, including what is currently known about how they form.

4.5 What Are the Characteristics of Cosmogenous Sediment?

Cosmogenous sediment (*cosmos* = universe, *generare* = to produce) is derived from extraterrestrial sources.

Origin, Composition, and Distribution of Cosmogenous Sediment

Forming a very small but important component of the overall sediment on the ocean floor, cosmogenous sediment consists of two main types: microscopic **spherules** and macroscopic **meteor** debris.

Microscopic spherules are small globular masses. Some spherules are composed of silicate rock material and show evidence of being formed by extraterrestrial impact events on Earth or other planets that eject small molten pieces of crust into space. These **tektites** (*tektos* = molten) then rain down on Earth and can form *tektite fields*. Other spherules are composed mostly of iron and nickel (Figure 4.19), and these form in the asteroid belt between the orbits of Mars and Jupiter when asteroids collide. This material constantly rains down on Earth as a general component of *space dust* or *micrometeorites* captured by Earth's gravity. Although about 90% of micrometeorites are destroyed by frictional heating as they enter the atmosphere, it has been estimated that as much as 300,000 metric tons (661 million pounds) of space dust reach Earth's surface each year, which equates to about 10 kilograms (22 pounds) every second of every day! The iron-rich space dust that lands in the oceans often dissolves in seawater. Glassy tektites, however, do not dissolve as easily and sometimes comprise minute proportions of various marine sediments.

Macroscopic meteor debris is rare on Earth but can be found associated with meteor impact sites. Evidence suggests that throughout time meteors have collided with Earth at great speeds and that some larger ones have released energy equivalent to the explosion of multiple large nuclear bombs. To date, nearly 200 meteorite impact structures have been identified on Earth, most of them on land, but new ones are being discovered on the ocean floor (see MasteringOceanography Web Diving Deeper 4.2). The debris from meteors—called **meteorite** material—settles out around the impact site and is either composed of silicate rock material (called *chondrites*) or iron and nickel (called *irons*).

STUDENTS SOMETIMES ASK . . .

How are scientists able to identify cosmogenous sediment? I mean, how can they tell that it's extraterrestrial?

Cosmogenous sediment can be differentiated from other sediment types primarily by its structure but also by its composition. Cosmogenous sediment can be either silicate rock or rich in iron—both of which are common compositions of lithogenous sediment. However, glassy fragments indicative of melting (called tektites) are uniquely cosmogenous, as are iron-rich spherules (see Figure 4.19). Compositionally, cosmogenous particles from outer space typically contain more nickel than those that originate in other ways; most of the nickel in Earth's crust sank below the surface during density stratification early in Earth's history.

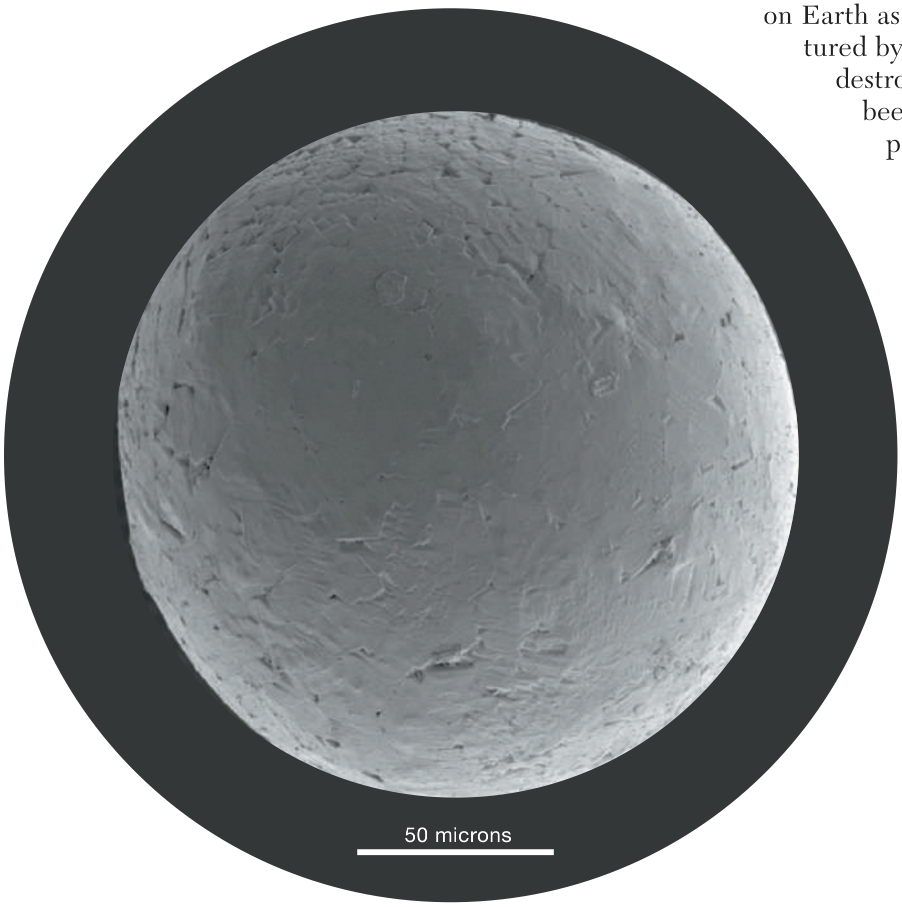


Figure 4.19 **Microscopic cosmogenous spherule.** Scanning electron micrograph of an iron-rich spherule of cosmic dust.

RECAP

Cosmogenous sediment is produced from materials originating in outer space and includes microscopic space dust and macroscopic meteor debris.

CONCEPT CHECK 4.5 | Describe the characteristics of cosmogenous sediment.

1 Describe the origin, composition, and distribution of cosmogenous sediment.

2 Describe the most common types of cosmogenous sediment and give the probable source of these particles.

4.6 How Are Pelagic and Neritic Deposits Distributed?

The ocean is a messy place. Lithogenous and biogenous sediment rarely occur as absolutely pure deposits that do not contain other types of sediment. As a result, most marine sediments occur as mixtures.

Mixtures of Marine Sediment

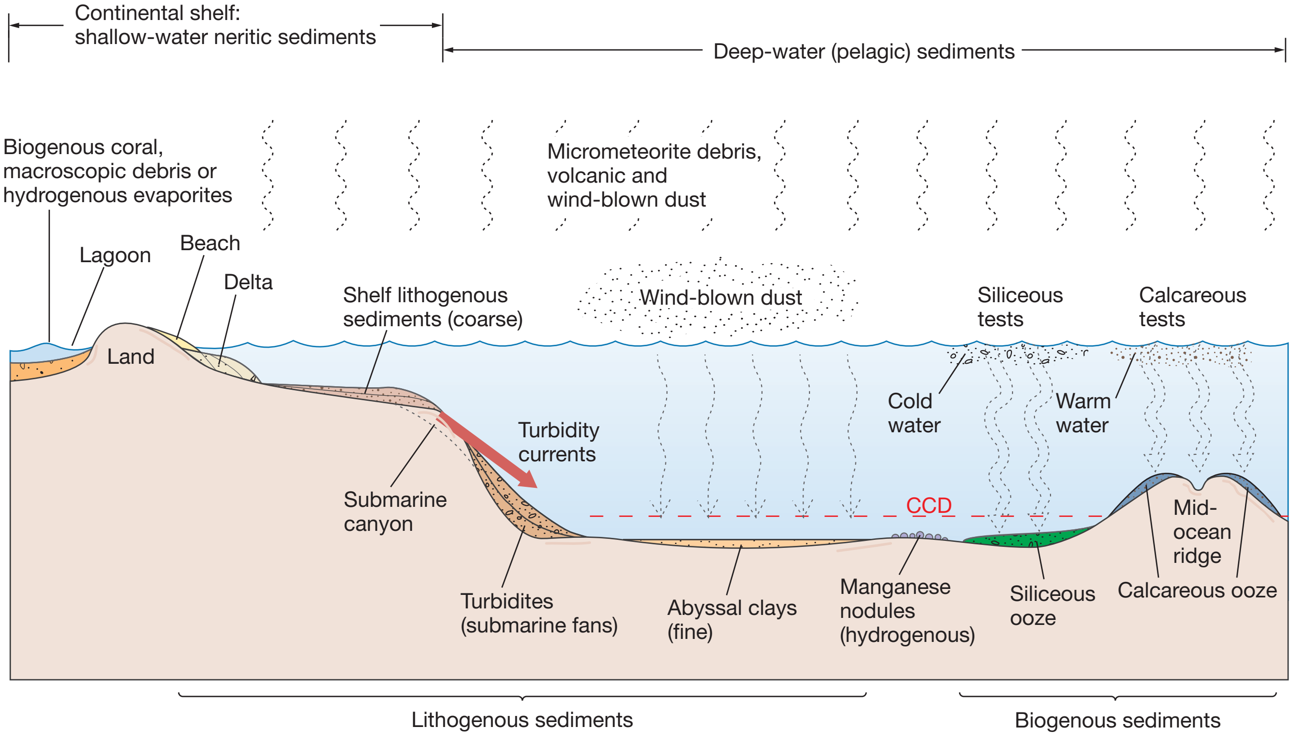
There are many types of mixtures of marine sediment. Consider the following examples:

- Most calcareous oozes contain some siliceous material and vice versa (see, for example, Figure 4.10d).
- The abundance of clay-sized lithogenous particles throughout the world and the ease with which they are transported by winds and currents means that these particles are incorporated into every sediment type.
- The composition of biogenous ooze includes up to 70% fine-grained lithogenous clays.
- Most lithogenous sediment contains small percentages of biogenous particles.
- There are many types of hydrogenous sediment.
- Tiny amounts of cosmogenous sediment are mixed in with all other sediment types.

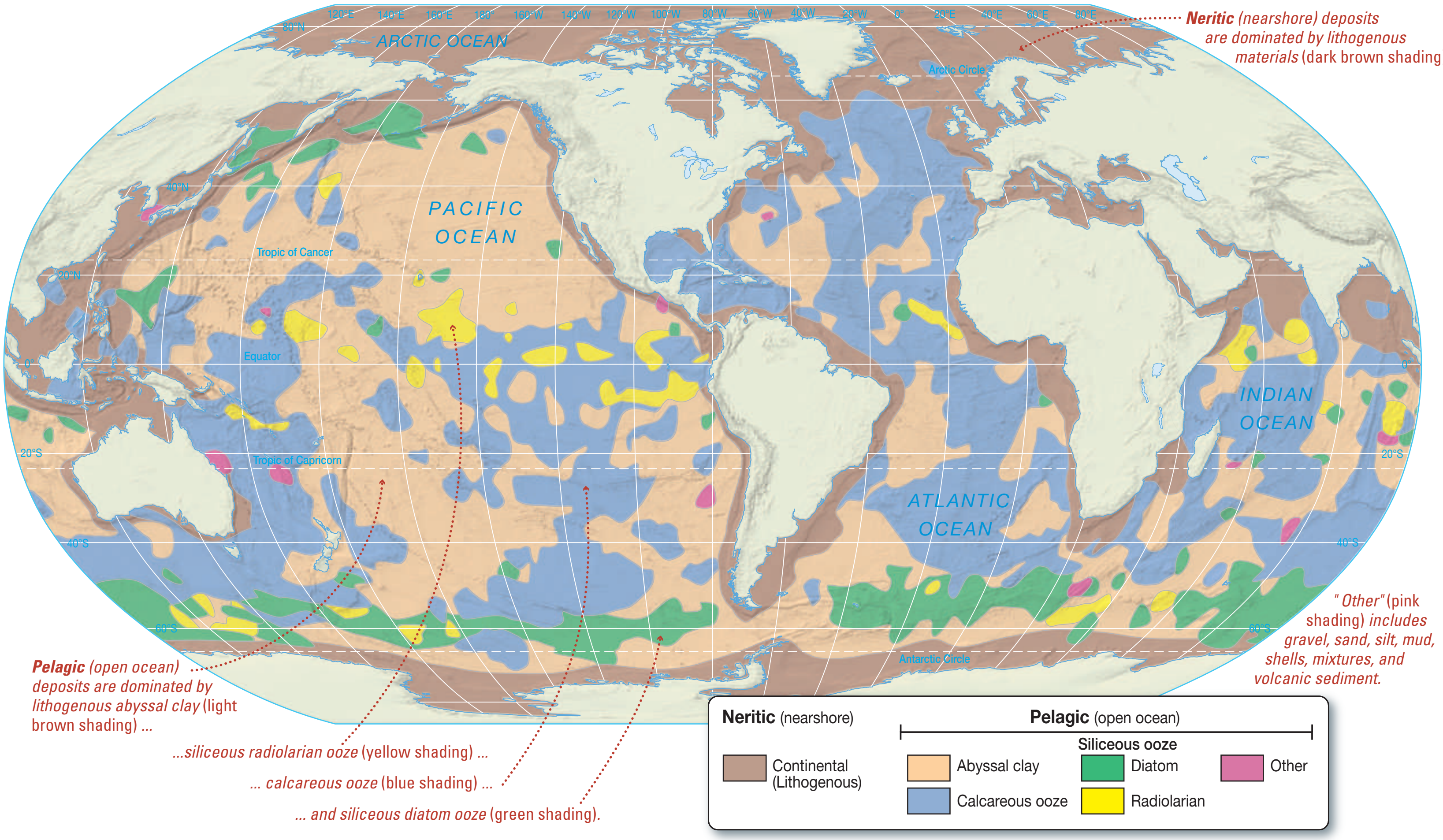
Deposits of sediment on the ocean floor are usually a mixture of different sediment types. Figure 4.20 shows the distribution of sediment across a passive continental margin and illustrates how mixtures can occur. Typically, however, one type of sediment dominates, which allows the deposit to be classified as primarily lithogenous, biogenous, hydrogenous, or cosmogenous.

RECAP

Although most ocean sediment is a mixture of various sediment types, it is usually dominated by lithogenous, biogenous, or hydrogenous material.



SmartFigure 4.20 Distribution of sediment across a passive continental margin. Schematic profile view of various sediment types and their distribution across an idealized passive continental margin and extending out to a mid-ocean ridge. https://goo.gl/07cWpo



***Neritic** (nearshore) deposits are dominated by lithogenous materials* (dark brown shading).

***Pelagic** (open ocean) deposits are dominated by lithogenous abyssal clay* (light brown shading) …

…siliceous radiolarian ooze (yellow shading) …

… calcareous ooze (blue shading) …

… and siliceous diatom ooze (green shading).

"Other" (pink shading) *includes gravel, sand, silt, mud, shells, mixtures, and volcanic sediment.*

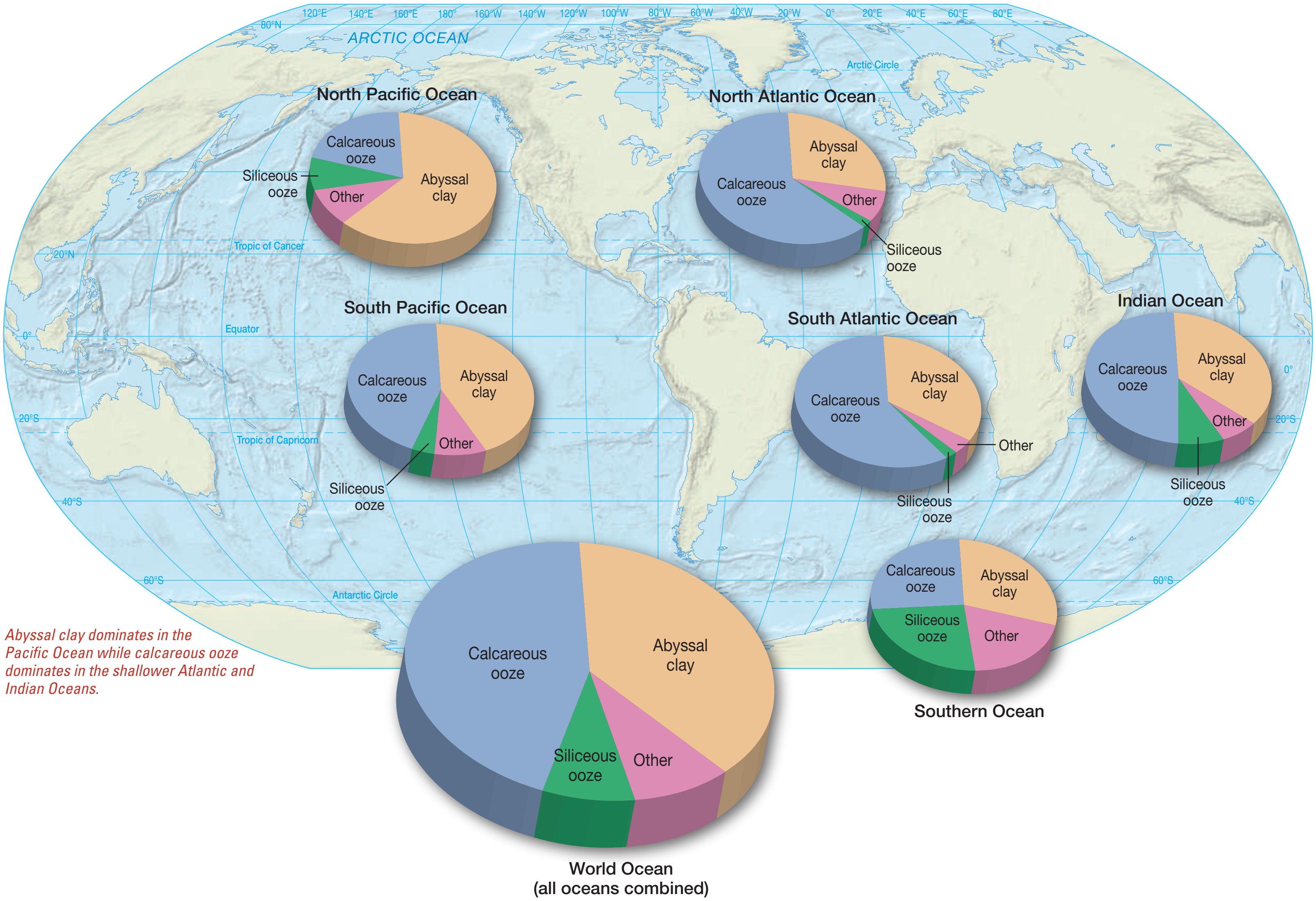
SmartFigure 4.21 Distribution of neritic (nearshore) and pelagic (open ocean) sediments.
https://goo.gl/0sxYZs

Neritic Deposits

Neritic (nearshore) deposits cover about one-quarter of the ocean floor, and pelagic (deep-ocean basin) deposits cover the other three-quarters. The map in **Figure 4.21** shows the distribution of neritic and pelagic deposits in the world's oceans. Coarse-grained lithogenous neritic deposits dominate continental margin areas (*dark brown shading*), which is not surprising because lithogenous sediment is derived from nearby continents. Although neritic deposits usually contain biogenous, hydrogenous, and cosmogenous particles, these constitute only a minor percentage of the total sediment mass.

Pelagic Deposits

Figure 4.21 shows that pelagic deposits are dominated by biogenous calcareous oozes (*blue shading*), which are found on the relatively shallow deep-ocean areas along the mid-ocean ridge. Biogenous siliceous oozes are found beneath areas of unusually high biological productivity such as the northernmost North Pacific Ocean, surrounding Antarctica (*green shading*, where diatomaceous ooze occurs), and the equatorial Pacific (*yellow shading*, where radiolarian ooze occurs). Fine lithogenous pelagic deposits of abyssal clays (*light brown shading*) are common in deeper areas of the ocean basins, such as in the North Pacific. Hydrogenous and cosmogenous sediment comprise only a small proportion of pelagic deposits in the ocean.



Abyssal clay dominates in the Pacific Ocean while calcareous ooze dominates in the shallower Atlantic and Indian Oceans.

Figure 4.22 **Pelagic sediment types within each major ocean.** World map and accompanying pie charts showing the relative amount of deep-ocean floor covered by each of the three main pelagic sediment types: abyssal clay, siliceous ooze, and calcareous ooze. Pie chart for the world ocean (*below left*) displays data from all oceans combined.

Figure 4.22 shows the proportion of each ocean floor that is covered by the pelagic deposits abyssal clay, calcareous ooze, and siliceous ooze. The world ocean (combined) pie chart shows that calcareous ooze is the most dominant sediment worldwide, covering about 45% of the deep-ocean floor. The world ocean pie chart also shows that abyssal clay covers about 38% and siliceous ooze about 8% of the world ocean floor area. If you examine the individual ocean pie charts, they show that the amount of ocean basin floor covered by calcareous ooze decreases in deeper ocean basins because they generally lie beneath the CCD. The dominant oceanic sediment in the deepest basin—the North Pacific—is abyssal clay (see also Figure 4.21). Conversely, calcareous ooze is the most widely deposited sediment in the shallower Atlantic and Indian Oceans. Note that siliceous oozes cover a smaller percentage of the ocean floor because regions of high productivity of organisms that produce silica tests are generally restricted to the equatorial region (for radiolarians) and the high latitudes such as near Antarctica and the far northern Pacific (for diatoms). Table 4.4 shows the average rates of deposition of selected marine sediments in neritic and pelagic deposits.

RECAP

Neritic deposits occur close to shore and are dominated by coarse lithogenous material. Pelagic deposits occur in the deep ocean and are dominated by biogenous oozes and fine lithogenous clay.

TABLE 4.4 AVERAGE RATES OF DEPOSITION OF SELECTED MARINE SEDIMENTS

Type of sediment/deposit	Average rate of deposition (per 1000 years)	Thickness of deposit after 1000 years equivalent to . . .
Coarse lithogenous sediment, neritic deposit	1 meter (3.3 feet)	A meter stick
Biogenous ooze, pelagic deposit	1 centimeter (0.4 inch)	The diameter of a dime
Abyssal clay, pelagic deposit	1 millimeter (0.04 inch)	The thickness of a dime
Manganese nodule, pelagic deposit	0.001 millimeter (0.00004 inch)	A microscopic dust particle

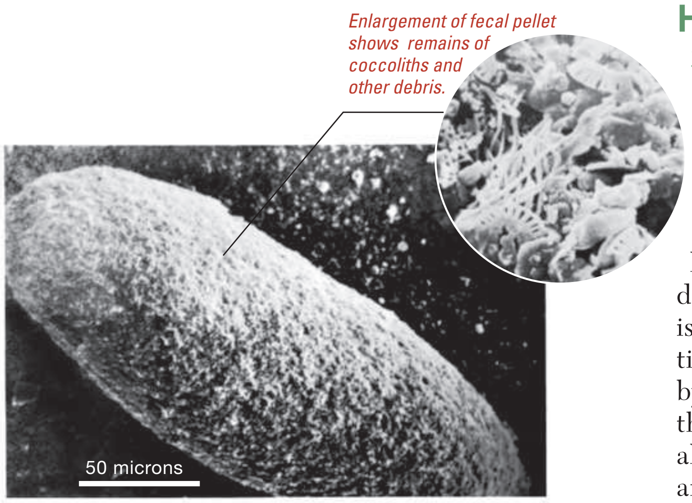


Figure 4.23 Fecal pellet. Photomicrograph of a fecal pellet, which is large enough to sink rapidly from the surface to the ocean floor.

How Sea Floor Sediments Represent Surface Conditions

Because of their tiny size and the enormous distance to the sea floor, microscopic biogenous tests should take from 10 to 50 years to sink from the ocean surface where the organisms lived to the abyssal depths where biogenous ooze accumulates. During this time, even a sluggish horizontal ocean current of only 0.05 kilometer (0.03 mile) per hour could carry tests as much as 22,000 kilometers (13,700 miles) before they settled onto the deep-ocean floor. Why, then, do biogenous tests on the deep-ocean floor closely reflect the population of organisms living in the surface water directly above? Remarkably, about 99% of the particles that fall to the ocean floor do so as part of *fecal pellets*, which are produced by tiny animals that eat algae and protozoans living in the water column, digest their tissues, and excrete their hard parts. These pellets are full of the remains of algae and protozoans from the surface waters (Figure 4.23) and, though still small, are large enough to sink to the deep-ocean floor in only 10 to 15 days. Once fecal pellets settle onto the ocean floor, the organic material in them is quickly consumed by bacteria and other microbes, releasing the indigestible, inorganic hard parts to the sediment.

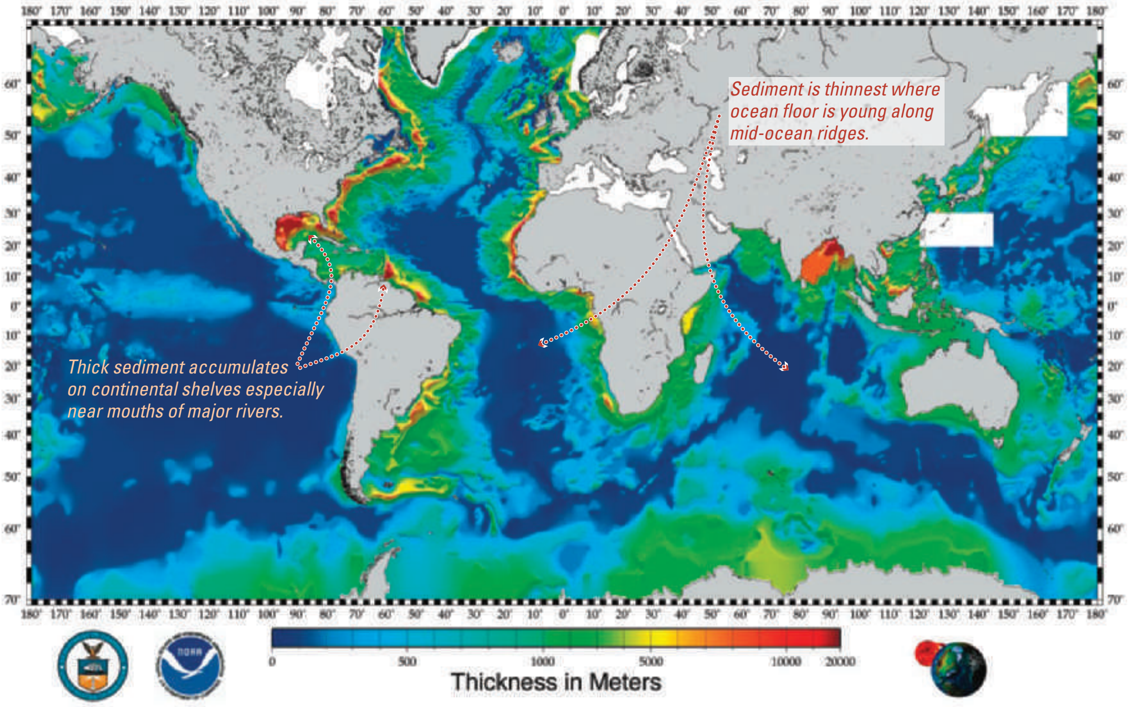


Figure 4.24 Marine sediment thickness. Map showing the thickness of sediments in the oceans and marginal seas. Thickness shown in meters; dark blue color represents thinnest sediments, and red represents thickest sediment accumulations. White color indicates no available data.

Worldwide Thickness of Marine Sediments

Figure 4.24 is a map of marine sediment thickness. The map shows that areas of thick sediment accumulation occur on the continental shelves and rises, especially near the mouths of major rivers. The reason sediments in these locations are so thick is because they are close to major sources of lithogenous sediment. Conversely, areas where marine sediments are thinnest are where the ocean floor is young, such as along the crest of the mid-ocean ridge. Since sediments accumulate slowly in the deep ocean and the sea floor is continually being created here, there hasn't been enough time for much sediment to accumulate. However, as the sea floor moves away from the mid-ocean ridge, it gets progressively older and carries a thicker pile of sediments.

CONCEPT CHECK 4.6 Specify how the distribution of pelagic and neritic deposits is determined by proximity to sediment sources and mechanisms of transport.

1 Why is it so rare to find a pure marine sediment type? Give some examples of mixtures of sediment.

2 Why is lithogenous sediment the most common neritic deposit? Why are biogenous oozes the most common pelagic deposits?

3 How do fecal pellets help explain why the particles found in the ocean surface waters are closely reflected in the particle composition of the sediment directly beneath? Why is this unexpected?

4.7 What Resources Do Marine Sediments Provide?

The sea floor is rich in potential mineral and organic resources. Much of these resources, however, are not easily accessible, so their recovery involves technological challenges and high cost. Nevertheless, let's examine some of the most appealing exploration targets.

Energy Resources

The main energy resources associated with marine sediments are *petroleum* and *gas hydrates*.

PETROLEUM The ancient remains of microscopic organisms, buried within marine sediments before they could decompose, are the source of today's **petroleum** (oil and natural gas) deposits. Of the nonliving resources extracted from the oceans, more than 95% of the economic value is in petroleum products.

Interdisciplinary Relationship

The percentage of world oil produced from offshore regions has increased from small amounts in the 1930s to more than 30% today. Most of this increase results from continuing technological advancements employed by offshore drilling platforms (Figure 4.25). Major offshore reserves exist in the Persian Gulf, in the Gulf of Mexico, off Southern California, in the North Sea, and in the East Indies. Additional reserves are probably located off the north coast of Alaska and in the Canadian Arctic, below Asian seas, and off the coast of Africa and Brazil. With almost no likelihood of finding major new reserves on land, future offshore petroleum exploration will continue to be intense, especially in deeper waters of the continental margins. However, a major drawback to offshore petroleum exploration is the inevitable oil spills caused by inadvertent leaks or blowouts during the drilling process.

GAS HYDRATES **Gas hydrates**, which are also known as *clathrates* (*clathri* = a lattice), are unusually compact chemical structures made of water and natural gas. They form only when high pressures squeeze chilled water and gas molecules into an icelike solid. Although hydrates can contain a variety of gases—including carbon dioxide, hydrogen sulfide, and larger hydrocarbons such as ethane and propane—**methane hydrates** are by far the most common hydrates in nature. Gas hydrates occur beneath Arctic permafrost areas on land and under the ocean floor, where they were discovered in 1976.

Interdisciplinary Relationship

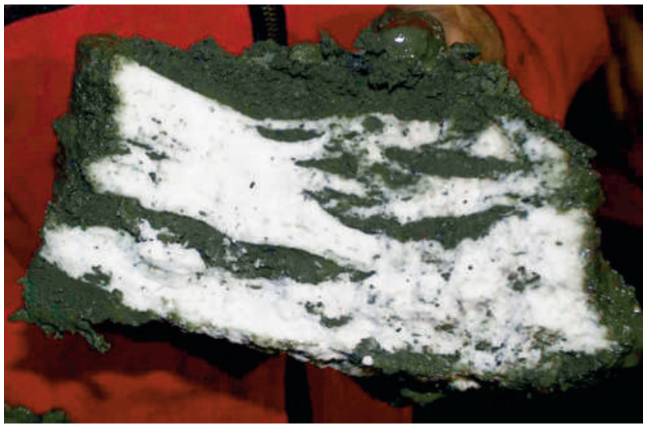
Deep-ocean sediments, where pressures are high and temperatures are low, are ideal environments for water and natural gas combine in such a way that the gas is trapped inside a lattice-like cage of water molecules. Vessels that have drilled into gas hydrates have retrieved cores of mud mixed with chunks or layers of gas hydrate

STUDENTS SOMETIMES ASK . . .

Are there any areas of the ocean floor where no sediment is being deposited?

Various types of sediment accumulate on nearly all areas of the ocean floor in the same way dust accumulates in all parts of your home (which is why marine sediment is often referred to as "marine dust"). Even the deep-ocean floor far from land receives small amounts of windblown material, microscopic biogenous particles, and space dust. There are some places in the ocean, however, where very little sediment accumulates. A few such places include: (1) the South Pacific Bare Zone east of New Zealand, where a combination of factors limit sediment accumulation, (2) along the continental slope, where there is active erosion by turbidity and other deep-ocean currents, and (3) along the mid-ocean ridge, where the age of the sea floor is so young (because of sea floor spreading) and the rates of sediment accumulation far from land are so slow that there hasn't been enough time for sediments to accumulate.

Figure 4.25 **Offshore oil-drilling platform.** Constructed on tall stilts, drilling platforms are important for extracting petroleum reserves from beneath the continental shelves.



(a) A sample retrieved from the ocean floor shows layers of white icelike gas hydrate mixed with mud.

(b) Gas hydrates decompose when exposed to surface conditions and release natural gas, which can be ignited.

Figure 4.26 **Gas hydrates.** Gas hydrates are icelike substances that form in deep-ocean sediments and are composed of natural gas combined with frozen water.

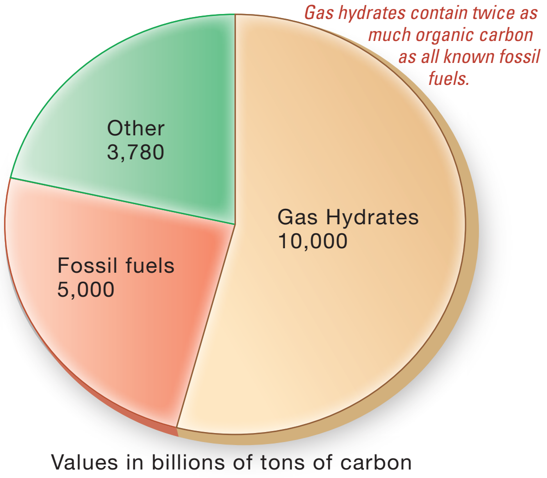


Figure 4.27 **Organic carbon in Earth reservoirs.** Pie chart showing the distribution of various types of organic carbon; "other" includes sources such as soil, peat, and living organisms.

"ice" that fizzle and decompose quickly when exposed to the relatively warm, low-pressure conditions at the ocean surface. Gas hydrates may resemble chunks of ice but ignite when lit by a flame because methane and other flammable gases are released as gas hydrates vaporize (Figure 4.26).

Most oceanic gas hydrates are created when bacteria break down organic matter trapped in sea floor sediments, producing methane gas with minor amounts of ethane and propane. These gases can be incorporated into gas hydrates under high-pressure and low-temperature conditions. Most ocean floor areas below 525 meters (1720 feet) provide these conditions, but gas hydrates seem to be confined to continental margin areas, where high productivity surface waters enrich ocean floor sediments below with organic matter.

Studies of the deep-ocean floor reveal that at least 50 sites worldwide may contain extensive gas hydrate deposits. Interestingly, sea floor methane seeps support a rich community of organisms, many of which are species new to science.

The release of methane from the sea floor to the atmosphere can have dramatic effects on global climate. Research suggests that at various times in the geologic past, changes in sea level or sea floor instability have released large quantities of methane, which is the third-most-important greenhouse gas after water vapor and carbon dioxide. In fact, analysis of sea floor sediments off Norway suggests that an abrupt increase in global temperature about 55 million years ago was driven by an explosive release of gas hydrates from the sea floor. Today, a major concern is that recent climate changes could warm ocean waters enough to release additional methane that is trapped beneath the seabed, causing even more warming. Sudden releases of methane hydrates have also been linked to underwater slope failure, which can cause *seismic sea waves*, or *tsunami* (see Chapter 8, "Waves and Water Dynamics").

Climate Connection

Some estimates indicate that as much as 20 quadrillion cubic meters (700 quadrillion cubic feet) of methane are locked up in marine sediments containing gas hydrates. This is equivalent to about *twice* as much carbon as Earth's coal, oil, and conventional gas reserves combined (Figure 4.27), so gas hydrates may potentially be the world's largest source of usable energy.

In spite of the energy potential that gas hydrates possess, several drawbacks exist. One major drawback in exploiting reserves of gas hydrate is that they rapidly decompose at surface temperatures and pressures. Another problem is that they are typically too dispersed within the sea floor to make collecting them economically feasible. An additional concern is that during commercial extraction of methane hydrates, methane could be accidentally released into the atmosphere, exacerbating fossil fuel–driven climate changes. Although technological advancements may be able to solve many of the specific challenges of safely extracting methane from deposits of gas hydrates, there are additional scientific, engineering, and environmental questions that need to be addressed before commercial operations can produce fuel from hydrates. Nonetheless, a multinational research team is currently evaluating the economic potential of collecting methane hydrates in the Nankai Trough off Japan and could begin producing methane as early as 2016.

Climate Connection

Other Resources

Other resources associated with marine sediments include *sand and gravel, evaporative salts, phosphorite, manganese nodules and crusts*, and *rare-earth elements*.

SAND AND GRAVEL Sand and gravel, which includes both rock fragments that are washed out to sea and shells of marine organisms, is mined by offshore barges using suction dredges. This material is primarily used as aggregate in concrete, as fill material in grading projects, and on recreational beaches. In terms of economic value, offshore sand and gravel is the second largest sea floor deposit behind petroleum.

Offshore deposits are a major source of sand and gravel in New England, New York, and throughout the Gulf Coast. Many European countries, Iceland, Israel, and Lebanon also depend heavily on such deposits.

Some offshore sand and gravel deposits are rich in valuable minerals. Gem-quality diamonds, for example, are recovered from gravel deposits on the continental shelf offshore of South Africa and Australia, where waves rework them during times of lower sea level. Sediments rich in tin have been mined offshore of southeast Asia from Thailand to Indonesia. Platinum and gold have been found in deposits offshore of gold mining areas throughout the world, and some Florida beach sands are rich in titanium. The largest unexplored potential for metallic minerals in offshore sand deposits may exist along the west coast of South America, where rivers have transported Andean metallic minerals.

EVAPORATIVE SALTS When seawater evaporates, the salts increase in concentration until they can no longer remain dissolved, so they precipitate out of solution and form **salt deposits** (Figure 4.28). Extensive sea floor salt deposits indicate that entire seas such as the Mediterranean Sea completely dried up in the geologic past (see MasteringOceanography Web Diving Deeper 4.1).

The most economically useful salts are *gypsum* and *halite*. Gypsum is used in plaster of Paris to make casts and molds and is the main component in gypsum board (wallboard or sheet rock). Halite—common table salt—is widely used for seasoning, curing, and preserving foods. It is also used to de-ice roads, in water conditioners, in agriculture, and in the clothing industry for dying fabric.

In addition, halite is used in the production of chemicals such as sodium hydroxide (to make soap products), sodium hypochlorite (for disinfectants, bleaching agents, and PVC piping), sodium chlorate (for herbicides, matches, and fireworks), and hydrochloric acid (for use in chemical applications and for cleaning scaled pipes). The manufacture and use of salt is one of the oldest chemical industries.[10]

PHOSPHORITE (PHOSPHATE MINERALS) **Phosphorite** is a sedimentary rock consisting of various phosphate minerals containing the element phosphorus, an important plant nutrient. Consequently, phosphate deposits can be used to produce phosphate fertilizer. Although there is currently no commercial phosphorite mining occurring in the oceans, the marine reserve is estimated to exceed 45 billion metric tons (99 trillion pounds). Phosphorite occurs in the ocean at depths of less than 300 meters (1000 feet) on the continental shelf and slope in regions of upwelling and high productivity.

Some shallow sand and mud deposits contain up to 18% phosphate. Many phosphorite deposits occur as nodules, with a hard crust formed around a nucleus. The nodules may be as small as a sand grain or as large as 1 meter (3.3 feet) in diameter and may contain more than 25% phosphate. For comparison, most land sources of phosphate have been enriched to more than 31% by groundwater leaching. Florida, for example, has large phosphorite deposits and supplies about one-quarter of the world's phosphates.

MANGANESE NODULES AND CRUSTS *Manganese nodules* are rounded, hard, golf- to tennis-ball-sized lumps of metals that contain significant concentrations of manganese, iron, and smaller concentrations of copper, nickel, and cobalt, all of which have a variety of economic uses. In the 1960s, mining companies began to assess the feasibility of mining manganese nodules from the deep-ocean floor

STUDENTS SOMETIMES ASK . . .

When will we run out of oil?

Not anytime soon. However, from an economic perspective, when the world runs completely out of oil—a finite resource—is not as relevant as when production begins to taper off. When this happens, we will run out of the *abundant* and *cheap* oil on which all industrialized nations depend. Several oil-producing countries are already past the peak of their production—including the United States and Canada, both of which peaked in 1972. Current estimates indicate that sometime within the next few decades, more than half of all known and likely-to-be-discovered oil will be gone. Other experts have suggested that petroleum production has already reached its plateau. However, recent advances in the controversial method of hydraulic fracturing (called *fracking*) have reversed the decline in U.S. oil production, which is now once again near its peak. Still, once the decline begins, it will be increasingly costly to produce oil, and prices will rise dramatically—unless demand declines proportionately or other sources such as coal, extra-heavy oil, tar sands, or gas hydrates become readily available.

Figure 4.28 **Mining sea salt.** A salt mining operation at Scammon's Lagoon, Baja California, Mexico. Low-lying areas near the lagoon are allowed to flood with seawater, which evaporates in the arid climate and leaves deposits of salt that are then collected.

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[10] An interesting historical note about salt is that part of a Roman soldier's pay was in salt. That portion was called the *salarium*, from which the word *salary* is derived. If a soldier did not earn it, he was not worth his salt.

(Figure 4.29). The map in Figure 4.30 shows that vast areas of the sea floor contain manganese nodules, particularly in the Pacific Ocean.

Technologically, mining the deep-ocean floor for manganese nodules is possible. However, the political issue of determining international mining rights at great distances from land has hindered exploitation of this resource. In addition, environmental concerns about mining the deep-ocean floor have not been fully addressed. Evidence suggests that it takes at least several million years for manganese nodules to form and that their formation depends on a particular set of physical and chemical conditions that probably do not last long at any location. In essence, they are a nonrenewable resource that will not be replaced for a very long time once they are mined.

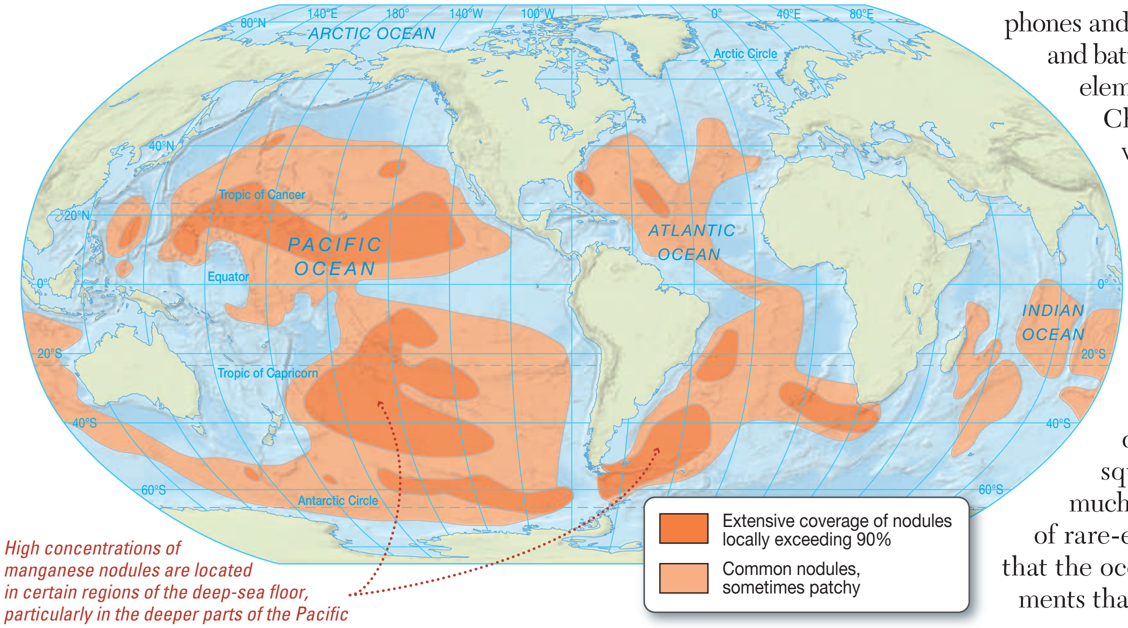
Of the five metals commonly found in manganese nodules, cobalt is the only metal deemed “strategic” (essential to national security) for the United States. It is required to produce dense, strong alloys with other metals for use in high-speed cutting tools, powerful permanent magnets, and jet engine parts. Currently, the United States must import all of its cobalt from large deposits in southern Africa. However, the United States has considered deep-ocean nodules and **crusts** (hard coatings on other rocks) as a more reliable source of cobalt.

In the 1980s, cobalt-rich manganese crusts were discovered on the upper slopes of islands and seamounts that lie relatively close to shore and within the jurisdiction of the United States and its territories. The cobalt concentrations in these crusts are about one-and-a-half times as rich as the best African ores and at least twice as rich as deep-sea manganese nodules. However, interest in mining these deposits has faded because of lower metal prices from land-based sources.

RARE-EARTH ELEMENTS *Rare-earth elements*—an assortment of 17 chemically similar metallic elements such as lanthanum and neodymium—are used in a variety of electronic, optical, magnetic, and catalytic applications. For example, rare-earth elements are used in a host of technological gadgets from cell phones and television screens to fluorescent light bulbs and batteries in electric cars. Demand for rare-earth elements has skyrocketed in recent years, with China supplying about 90% of the current world demand.

Over millions of years, deep-sea hot springs associated with the mid-ocean ridge pulled rare-earth elements out of seawater and enriched them in sea floor muds. A recent study of rare-earth elements on the floor of the Pacific Ocean indicated that some locations are particularly enriched. For example, an area of the sea floor near Hawaii measuring 1 square kilometer (0.4 square mile) holds as much as 25,000 metric tons (55 million pounds) of rare-earth elements. Overall, estimates suggest that the ocean floor might hold more rare-earth elements than all the known deposits on land.

Figure 4.29 **Mining manganese nodules.** Manganese nodules can be collected by dredging the ocean floor. This metal dredge is shown unloading nodules onto the deck of a ship.



High concentrations of manganese nodules are located in certain regions of the deep-sea floor, particularly in the deeper parts of the Pacific and Atlantic Oceans.

Figure 4.30 **Distribution of manganese nodules on the sea floor.**

RECAP

Ocean sediments contain many important resources, including petroleum, gas hydrates, sand and gravel, evaporative salts, phosphorite, manganese nodules and crusts, and rare-earth elements.

CONCEPT CHECK 4.7 | Identify the various resources that marine sediments provide.

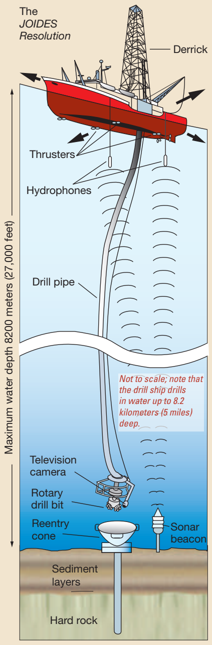
1 Discuss the present importance and the future prospects for the production of petroleum, sand and gravel, phosphorite, manganese nodules and crusts, and rare-earth elements.

2 What are gas hydrates, where are they found, and why are they important?

ESSENTIAL CONCEPTS REVIEW

4.1 How are marine sediments collected, and what historical events do they reveal?

- Sediments that accumulate on the ocean floor are *classified by origin* as *lithogenous* (derived from rock), *biogenous* (derived from organisms), *hydrogenous* (derived from water), or *cosmogenous* (derived from outer space).
- The existence of *sea floor spreading was confirmed when the* Glomar Challenger *began the Deep Sea Drilling Project* to sample ocean sediments and the underlying crust, which was continued by the *Ocean Drilling Program's* JOIDES Resolution. Today, the *Integrated Ocean Drilling Program* continues the important work of retrieving sediments from the deep-ocean floor.
- Analysis and interpretation of marine sediments reveal that *Earth has had an interesting and complex history* including *mass extinctions*, the *drying of entire seas*, *global climate change*, and the *movement of tectonic plates*.



Study Resources

MasteringOceanography Study Area Quizzes, Web Video

Critical Thinking Question

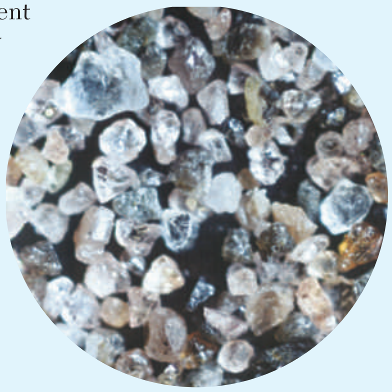
A sediment core is retrieved from the middle of the North Pacific Ocean, about 1000 kilometers (620 miles) south of the Aleutian Islands (Alaska), and at a water depth of 5000 meters (16,400 feet). The core contains coral reef fossils, which are only found in shallow, tropical waters. Develop a hypothesis that could explain this occurrence. Also, develop a test for your hypothesis.

Active Learning Exercise

It has been said that in the early days of oceanography, collecting marine sediments using a dredge was akin to collecting land samples from a hot air balloon using a bucket—at a height above the ground of several kilometers (a few miles) and at night. With another student in class, evaluate the effectiveness of this type of sample collection (for example, is it representative of the environment being sampled?).

4.2 What are the characteristics of lithogenous sediment?

- *Lithogenous sediments reflect the composition of the rock from which they were derived.* Sediment *texture*—determined in part by the size, sorting, and rounding of particles—is affected greatly by how the particles were transported (by water, wind, ice, or gravity) and the energy conditions under which they were deposited. *Coarse lithogenous material dominates neritic deposits* that accumulate rapidly along the margins of continents, while *fine abyssal clays are found in pelagic deposits.*



Study Resources

MasteringOceanography Study Area Quizzes, Web Video

Critical Thinking Question

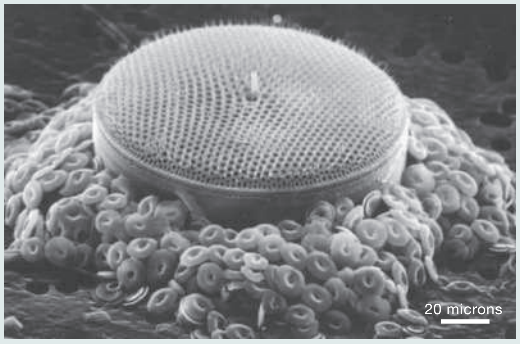
Explain why lithogenous sediment tends to become finer-grained with increasing distance from shore.

Active Learning Exercise

With another student in class, discuss how a deposit with a coarse grain size indicates whether it was deposited by a high- or low-energy transporting mechanism. Give several examples of various transporting mechanisms that would produce such a deposit.

4.3 What are the characteristics of biogenous sediment?

- *Biogenous sediment consists of the hard remains* (shells, bones, and teeth) *of organisms*. These are composed of either *silica* (SiO_2) from diatoms and radiolarians or *calcium carbonate* ($CaCO_3$) from foraminifers and coccolithophores. *Accumulations of microscopic shells* (tests) of organisms must comprise at least 30% of the deposit for it to be classified as *biogenic ooze*.
- *Biogenous oozes are the most common type of pelagic deposits.* The rate of biological productivity, relative to the rates of destruction and dilution of biogenous sediment, determines whether abyssal clay or oozes will form on the ocean floor. *Siliceous ooze* will form only below areas of high biologic productivity of silica-secreting organisms at the surface. *Calcareous ooze* will form only above the *calcite compensation depth (CCD)*—the depth where seawater dissolves calcium carbonate—although it can be covered and transported into deeper water through sea floor spreading.



Study Resources

MasteringOceanography Study Area Quizzes, MasteringOceanography Web Animations, Web Video

Critical Thinking Question

How do oozes differ from abyssal clay? Discuss how productivity, destruction, and dilution combine to determine whether an ooze or abyssal clay will form on the deep-ocean floor.

Active Learning Exercise

Working with another student in class, sketch and label two examples of silica-secreting organisms that produce biogenous ooze and two examples of calcareous-secreting organisms that produce biogenous ooze.

4.4 What are the characteristics of hydrogenous sediment?

- *Hydrogenous sediment* includes manganese nodules, phosphates, carbonates, metal sulfides, and evaporites that *precipitate directly from water* or are formed by the interaction of substances dissolved in water with materials on the ocean floor. Hydrogenous sediments represent a relatively small proportion of marine sediment and are distributed in many diverse environments.

Study Resources

MasteringOceanography Study Area Quizzes, MasteringOceanography Web Diving Deeper 4.1

Critical Thinking Question

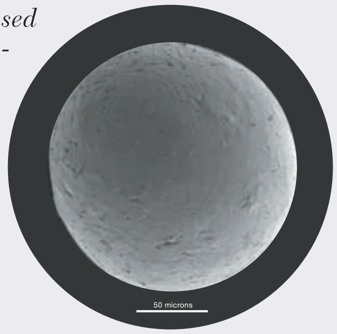
Construct a table that shows the various types of hydrogenous sediment and list both their origin and how they are used by humans.

Active Learning Exercise

Working with another student in class, design a hypothesis and an associated test to determine if manganese nodules form steadily over time or if they form episodically (in spurts).

4.5 What are the characteristics of cosmogenous sediment?

- *Cosmogenous sediment is composed of either macroscopic meteor debris* or *microscopic iron–nickel and silicate spherules* that result from asteroid collisions or extraterrestrial impacts. Minute amounts of cosmogenous sediment are mixed into most other types of ocean sediment.



Study Resources

MasteringOceanography Study Area Quizzes, MasteringOceanography Web Diving Deeper 4.2

Critical Thinking Question

Using MasteringOceanography Web Diving Deeper 4.2, describe what happened on Earth at the Cretaceous–Tertiary (K–T) boundary. What evidence was used to confirm the event, and what environmental effects did it cause?

Active Learning Exercise

Working with another student in class, discuss why micrometeorites don't form extensive sea floor deposits, even though they are constantly raining down though Earth's atmosphere.

4.6 How are pelagic and neritic deposits distributed?

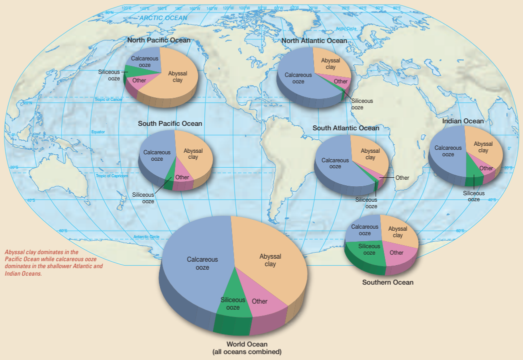
- Although *most ocean sediment is a mixture of various sediment types*, it is usually dominated by lithogenous, biogenous, hydrogenous, or cosmogenous material.
- *The distribution of neritic and pelagic sediment is influenced by many factors*, including proximity to sources of lithogenous sediment, productivity of microscopic marine organisms, the depth of the ocean floor, and the distribution of various sea floor features. *Fecal pellets* rapidly transport biogenous particles to the deep-ocean floor and cause the composition of sea floor deposits to match the organisms living in surface waters immediately above them.

Study Resources

MasteringOceanography Study Area Quizzes

Critical Thinking Question

Using the depositional rates shown in Table 4.4, how long would it take to make a deposit 1 meter (3.3 feet) thick of biogenous ooze? A deposit 1 meter (3.3 feet) thick of abyssal clay?



Active learning Exercise

Working with another student in class, compare neritic and pelagic deposits (for example, describe their location, composition, thickness, and distribution on the sea floor).

4.7 What resources do marine sediments provide?

- *The most valuable nonliving resource from the ocean today is petroleum*, which is recovered from below the continental shelves and used as a source of energy. *Gas hydrates* include vast deposits of ice-like material that may someday be used as a source of energy. Other important resources include *sand and gravel* (including deposits of valuable minerals), *evaporative salts, phosphorite, manganese nodules and crusts*, and *rare-earth elements*.

Study Resources

MasteringOceanography Study Area Quizzes

Critical Thinking Question

A company wants to mine sea floor minerals. What technological issues would there be for developing a mining operation on the sea floor? Also, evaluate the environmental factors that should be considered before mining materials on the sea floor.

Active Learning Exercise

Working with another student in class, research the Internet to make a list of the everyday products that are made from these sea floor deposits: (1) the components found in manganese nodules and crusts and (2) the elements that comprise the rare-earth elements.

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Water molecules and the ocean. The objects shown in this image are water molecules, magnified by many orders of magnitude. Most surface water on Earth is in the ocean; a single droplet of water contains more water molecules than there are grains of sand on a large beach.