Chapter 18 Geology of the Oceans

Learning Objectives

After reading this chapter, completing the exercises within it, and answering the questions at the end, you should be able to:

- Describe the origins of the major topographic features of the sea floor, including continental shelves and slopes, spreading ridges, seamount chains and isolated seamounts, and deep submarine canyons.
- Describe the various components of oceanic crust: pillow basalts, sheeted dykes, gabbro bodies, layered gabbro, and layered ultramafic rock.
- Describe the age distribution of oceanic crust, and explain why all of it is relatively young.
- Summarize the types of sediments and sedimentary rocks that accumulate on the sea floor, and explain why different types of sediment are present in different areas.
- Explain the origins of sea-floor methane hydrates.
- Describe and explain regional variations in the salinity and temperature of ocean water.
- Describe the general nature of major ocean-surface currents and the origins of deep-ocean circulation patterns.
- Explain the importance of ocean currents to our climate.

Figure 18.0.1 Oceanic crust (pillow basalt) from the Paleogene Metchosin Igneous Complex, near Sooke, on Vancouver Island. The view is about 1.5 metres across.

Oceans cover 71% of Earth's surface and hold 97% of Earth's water. The water they contain is critical to plate tectonics, to volcanism, and of course, to life on Earth. It is said that we know more about the surface of the Moon than the floor of the oceans. Whether this is true or not, the important point is that the ocean floor is covered with an average of nearly 4,000 metres of water, and it's pitch black below a few hundred metres so it's not easy to discover what is down there. We know a lot more about the oceans than we used to, but there is still a great deal more to discover.

Earth has had oceans for a very long time, dating back to the point where the surface had cooled enough to allow liquid water, only a few hundred million years after Earth's formation. At that time there were no continental rocks, so the water that was here was likely spread out over the surface in one giant (but relatively shallow) ocean.

Media Attributions

- Figure 18.0.1: © Steven Earle. CC BY.

18.1 The Topography of the Sea Floor

We examined the topography of the sea floor from the perspective of plate tectonics in Chapter 10, but here we are going to take another look at bathymetry from an oceanographic perspective. The topography of the northern Atlantic Ocean is shown in Figure 18.1.1. The important features are the extensive **continental shelves** less than 250 metres deep (pink); the vast deep **ocean plains** between 4,000 and 6,000 metres deep (light and dark blue); the mid-Atlantic ridge, in many areas shallower than 3,000 metres; and the deep ocean trench north of Puerto Rico (8,600 metres).

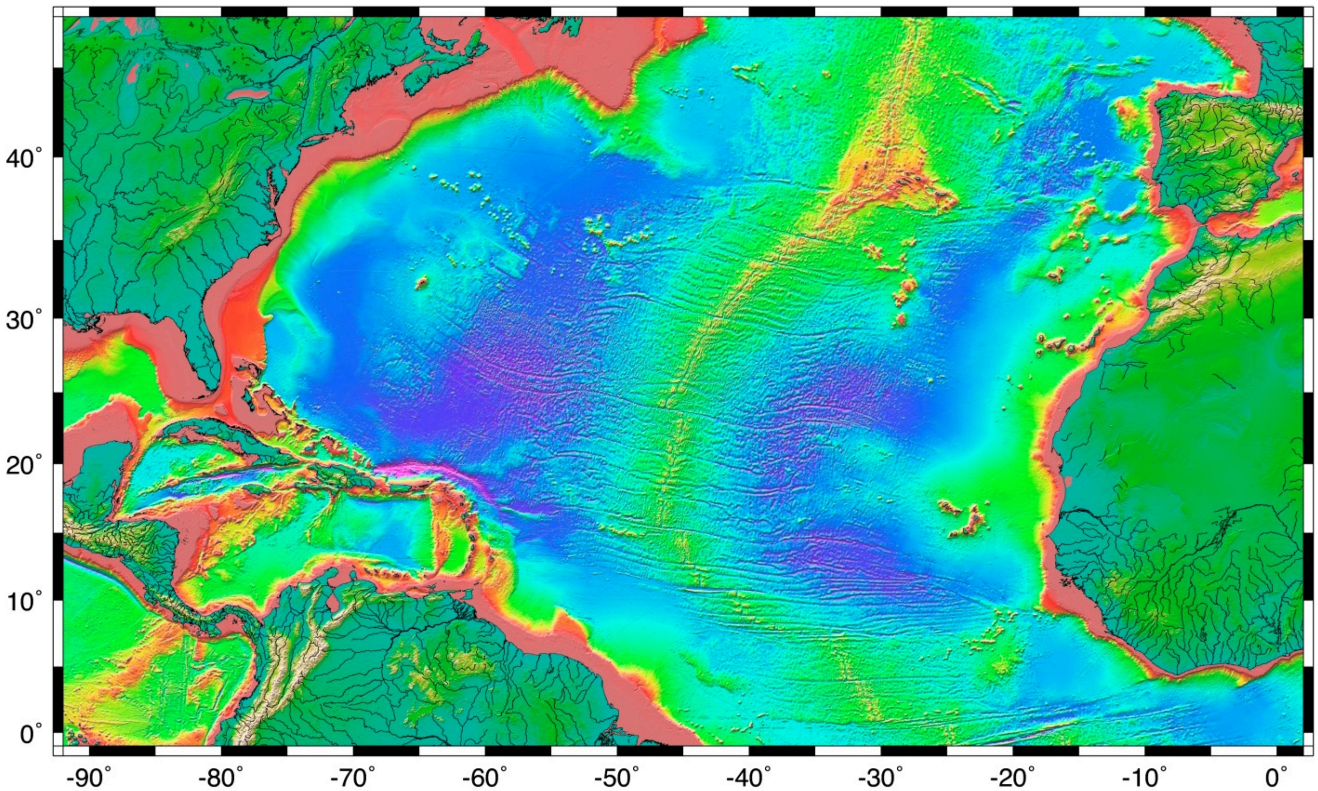

Figure 18.1.1 The topography of the Atlantic Ocean sea floor between 0° and 50° north. Red and yellow colours indicate less than a 2,000 metre depth; green less than 3,000 metres; blue 4,000 metres to 5,000 metres; and purple greater than 6,000 metres. [Image Description]

A topographic profile of the Pacific Ocean floor between Japan and British Columbia is shown in Figure 18.1.2. Be very careful when interpreting this diagram (and others like it), because in order to show the various features clearly the vertical axis is exaggerated, in this case by about 200 times. The floor of the Pacific, like those of the other oceans, is actually very flat, even in areas with seamounts or deep trenches. The vast sediment-covered **abyssal plains** of the oceans are much flatter than any similar-sized areas on the continents.

The main features of the Pacific Ocean floor are the continental slopes, which drop from about 200 metres to several thousand metres over a distance of a few hundred kilometres, the abyssal plains—exceedingly flat and from 4,000 metres to 6,000 metres deep, volcanic seamounts and islands, and trenches at subduction zones that are up to 11,000 metres deep.

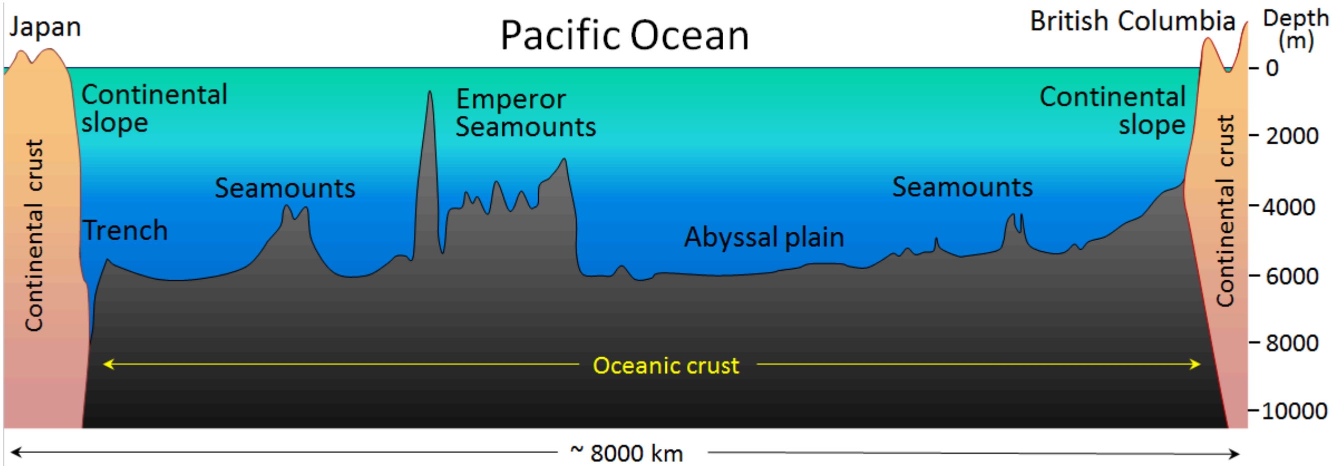

Figure 18.1.2 The generalized topography of the Pacific Ocean sea floor between Japan and British Columbia. The vertical exaggeration is approximately 200 times.

The ocean floor is almost entirely underlain by mafic oceanic crust (mostly basalt and gabbro, as described in more detail below), while the continental slopes are underlain by felsic continental crust (mostly granitic and sedimentary rocks). And, as you'll remember from Chapter 10, the heavier oceanic crust floats lower on the mantle than continental crust does, and that's why oceans are oceans.

The continental shelf and slope offshore from Nova Scotia is shown in Figure 18.1.3. In this passive-margin area (no subduction zone), the shelf is over 150 kilometres wide. On the Pacific coast of Canada, the shelf is less than half as wide. Continental shelves are typically less than 200 metres in depth; 200 metres is also the limit of the **photic zone**, the maximum depth to which sufficient light penetrates to allow photosynthesis to take place. As a result of that photosynthesis, the photic zone is oxygenated, and therefore suitable for animal life. Approximately 90% of marine life is restricted to the photic zone. The photic zone is also known as the **epipelagic zone**. The **mesopelagic zone** extends from 200 metres to 1,000 metres, the **bathypelagic zone** from 1,000 metres to 4,000 metres, and **abyssalpelagic zone** is deeper than 4,000 metres. (**Pelagic** refers to the open ocean, and thus excludes areas that are near to the shores or the ocean floor.)

Although the temperature of the ocean surface varies widely—from a few degrees either side of freezing in polar regions to over 25°C in the tropics—in most parts of the ocean, the water temperature is around 10°C at 1,000 metres depth and about 4°C from 2,000 metres depth all the way to the bottom.

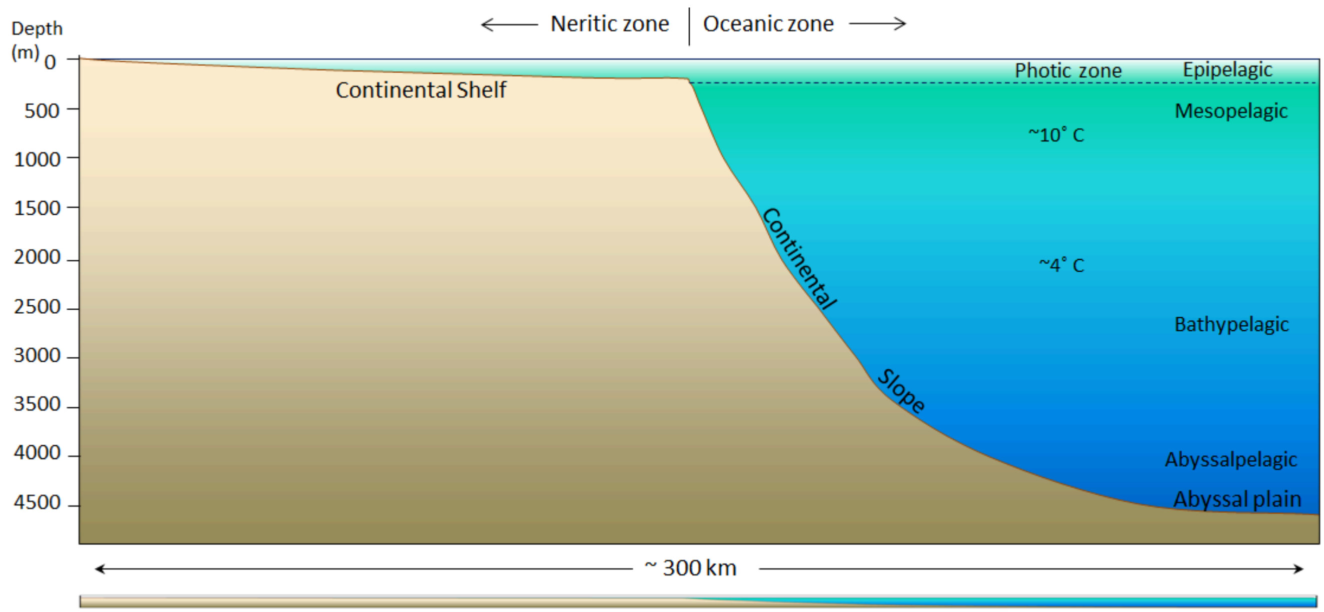

Figure 18.1.3 The generalized topography of the Atlantic Ocean floor within 300 kilometres of Nova Scotia. The vertical exaggeration is approximately 25 times. The panel at the bottom shows the same profile without vertical exaggeration. [Image Description]

The deepest parts of the ocean are within the subduction trenches, and the deepest of these is the Marianas Trench in the southwestern Pacific (near Guam) at 11,000 metres (Figure 18.1.4). There are other trenches in the southwestern Pacific that are over 10,000 metres deep; the Japan Trench is over 9,000 metres deep; and the Puerto Rico and Chile-Peru Trenches are over 8,000 metres deep. Trenches that are relatively shallow tend to be that way because they have significant sediment infill. There is no recognizable trench along the subduction zone of the Juan de Fuca Plate because it has been filled with sediments from the Fraser and Columbia Rivers (or their ancient equivalents).

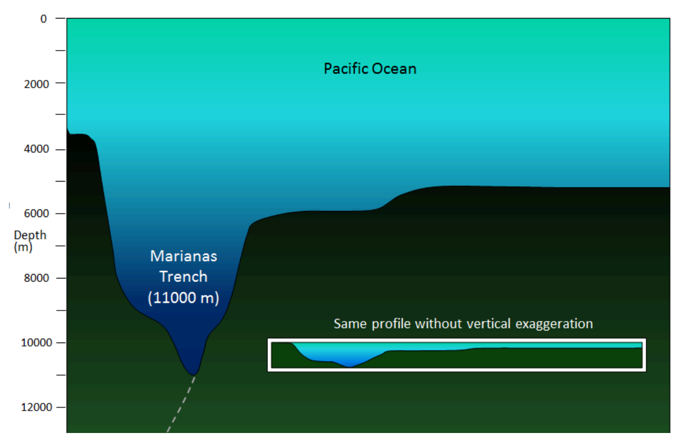

Figure 18.1.4 The generalized topography of the Pacific Ocean floor in the area of the Marianas Trench, near Guam. The dashed grey line represents the subduction of the Pacific Plate (to the right) beneath the Philippine Plate (to the left).

Exercise 18.1 Visualizing sea floor topography

This map shows a part of the sea floor.

1. Identify the following features.
    1. a continental shelf
    2. a continental slope
    3. a spreading ridge
    4. a subduction zone with a deep trench
    5. an abyssal plain
    6. some isolated seamounts
2. Where is this? (North is up.)

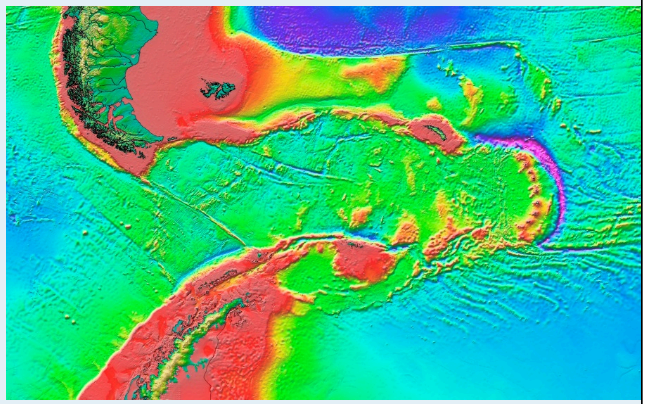

Figure 18.1.5

Image Descriptions

Figure 18.1.1 image description: Along the coast, the Atlantic Ocean is less than 2,000 metres deep. The depth increases farther from shore. In the middle, the Atlantic Ocean can be anywhere from 4000 to over 6,000 metres deep. A ridge stretches across the centre of the Atlantic Ocean in a northeast direction. The ridge causes the ocean depth to decreases to less than 2,000 metres. [Return to Figure 18.1.1]

Figure 18.1.3 image description: The continental shelf stretches out about 150 kilometres from the shore and the depth does not increase more than 300 metres. Once the continental slope begins, the depth continues to drop until it reaches 4500 metres at 300 kilometres from the shore. [Return to Figure 18.1.3]

Media Attributions

- Figure 18.1.1: "Seafloor Topography: Topo 8" by NASA/CNES. Public domain.
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- Figure 18.1.5: "Seafloor Topography: Topo 16" by NASA/CNES. Public domain.

18.2 The Geology of the Oceanic Crust

As we discussed in Chapter 10, oceanic crust is formed at sea-floor spreading ridges from magma generated by decompression melting of hot upward-moving mantle rock (Figure 10.4.3). About 10% of the mantle rock melts under these conditions, producing mafic magma. This magma oozes out onto the sea floor to form pillow basalts (Figure 18.0.1), breccias (fragmented basaltic rock), and flows, interbedded in some cases with limestone or chert. Beneath the volcanic rock are layers with gabbroic sheeted dykes (which sometimes extend up into the pillow layer), gabbroic stocks, and finally layered peridotite (ultramafic rock) at the base. The ultramafic rock of the mantle lies below that. Over time, the igneous rock of the oceanic crust gets covered with layers of sediment, which eventually become sedimentary rock, including limestone, mudstone, chert, and turbidites. The lithologies of the layers of the oceanic crust are shown in Figure 18.2.1.

The age of the oceanic crust has been determined by systematic mapping variations in the strength of the Earth's magnetic field across the sea floor and comparing the results with our understanding of the record of Earth's magnetic field reversal chronology for the past few hundred million years. The ages of different parts of the crust are shown in Figure 18.2.2. The oldest oceanic crust is around 280 Ma in the eastern Mediterranean, and the oldest parts of the open ocean are around 180 Ma on either side of the north Atlantic. It may be surprising, considering that parts of the continental crust are close to 4,000 Ma old, that the oldest sea floor is less than 300 Ma. Of course, the reason for this is that all sea floor older than that has been either subducted or pushed up to become part of the continental crust. For example, there are fragments of sea floor in British Columbia that date back to around 380 and 220 Ma, and there are similar rocks in the Canadian Shield that are older than 3 Ga.

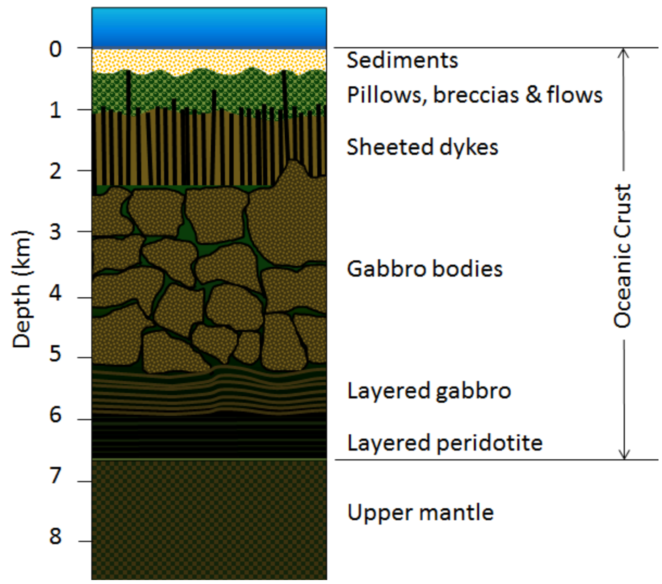

Figure 18.2.1 Schematic representation of the lithologic layers of typical oceanic crust. [Image Description]

As one would expect, the oceanic crust is very young near the spreading ridges (Figure 18.2.2), and there are obvious differences in the rate of sea-floor spreading along different ridges. The ridges in the Pacific and southeastern Indian Oceans have wide age bands, indicating rapid spreading (approaching 10 centimetres per year (cm/y) on each side in some areas), while those in the Atlantic and western Indian Oceans are spreading much more slowly (less than 2 cm/y on each side in some areas).

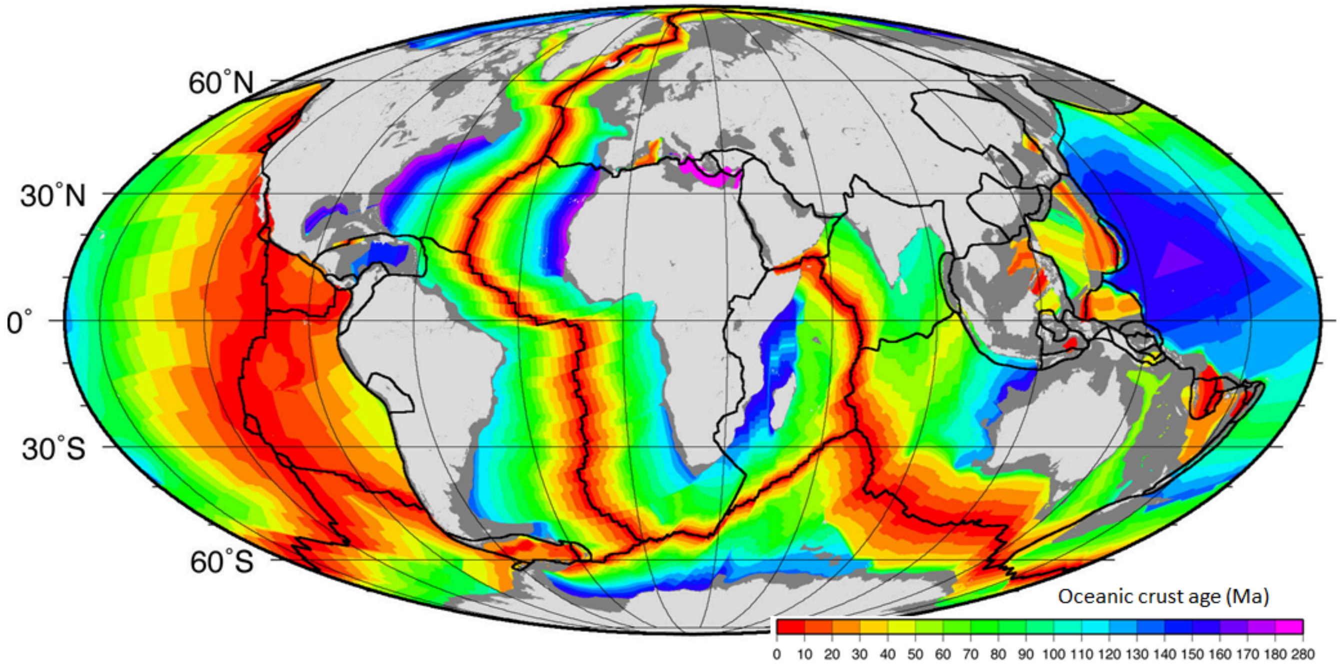

Figure 18.2.2 The age of the oceanic crust.

Exercise 18.2 The age of subducting crust

This map shows the magnetic patterns on the Juan de Fuca plate. The coloured bands represent periods of normal magnetism, while the white bands represent reversed magnetism. A magnetic-reversal time scale is also shown.

1. How old is the oldest part of the Juan de Fuca Plate that is subducting along the Cascadia subduction boundary?
2. How old is the youngest part of the Juan de Fuca Plate that is subducting?

The magnetic patterns and chronology shown here have been colour-coded to make them easy to interpret, but on most such maps the magnetic patterns are shown only as black and white stripes, making it much more difficult to interpret the ages of the sea floor. Magnetic-reversal patterns that have no context (such as the 0 age along the spreading ridge in this case) are very difficult to interpret.

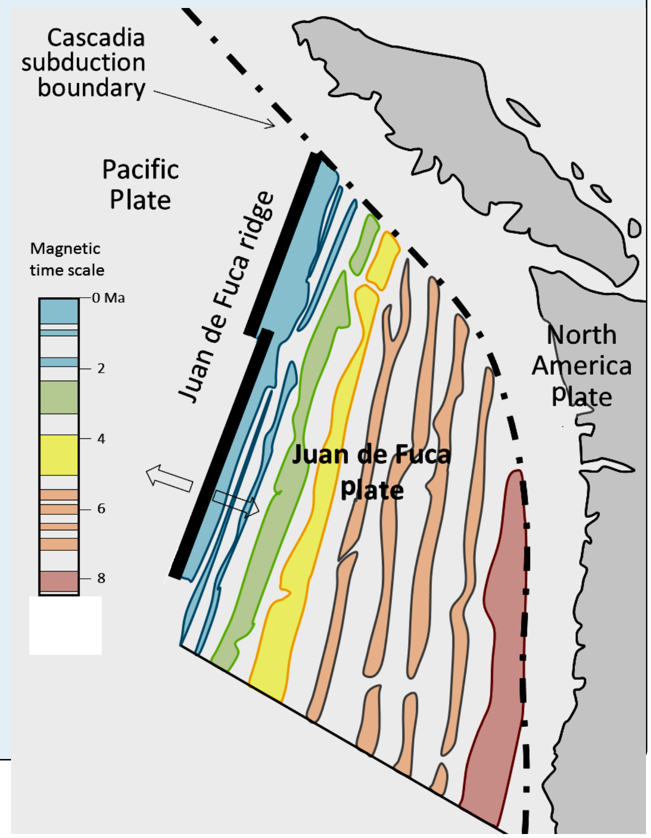

Figure 18.2.3 [Image Description]

As is evident from Figures 18.1.1 and 18.1.2, the sea floor is dotted with chains of seamounts, isolated seamounts, and ocean islands. Almost all of these features are volcanoes, and most are much younger than the oceanic crust on which they formed. Some seamounts and ocean islands are formed above mantle plumes, the best example being Hawaii. The oldest of the Hawaiian/Emperor seamounts is dated at around 80 Ma; it is situated on oceanic crust aged around 90 to 100 Ma. The youngest of the Hawaiian lavas—at Kilauea Volcano on the island of Hawaii—is now more than a year old (last eruption was April 30th 2018). The island is surrounded by oceanic crust that is around 85 Ma old. All of the mantle-plume-derived volcanic islands are dominated by mafic rocks.

Many seamounts are related to subduction along ocean-ocean convergent boundaries. These include the Aleutians, extending from Alaska to Russia, and the Lesser Antilles in the eastern part of the Caribbean.

Some of the linear belts of volcanoes in the Pacific Ocean do not show age-distance relationships like the volcanoes of the Hawaii-Emperor chain or the Galapagos Islands. For example, the Line Islands, which spread out over more than 1,000 kilometres south of the Hawaiian chain, were all formed between 70 and 85 Ma and are interpreted to be related to rifting.

Most tropical islands have associated carbonate reefs, in some cases, as fringes right around the island, and in some cases, as barriers some distance away. In many cases, the reef is there, but the island that is assumed to have led to its formation is gone. The formation of **fringing reefs**, **barrier reefs**, and **atolls** is illustrated in Figure 18.2.4.

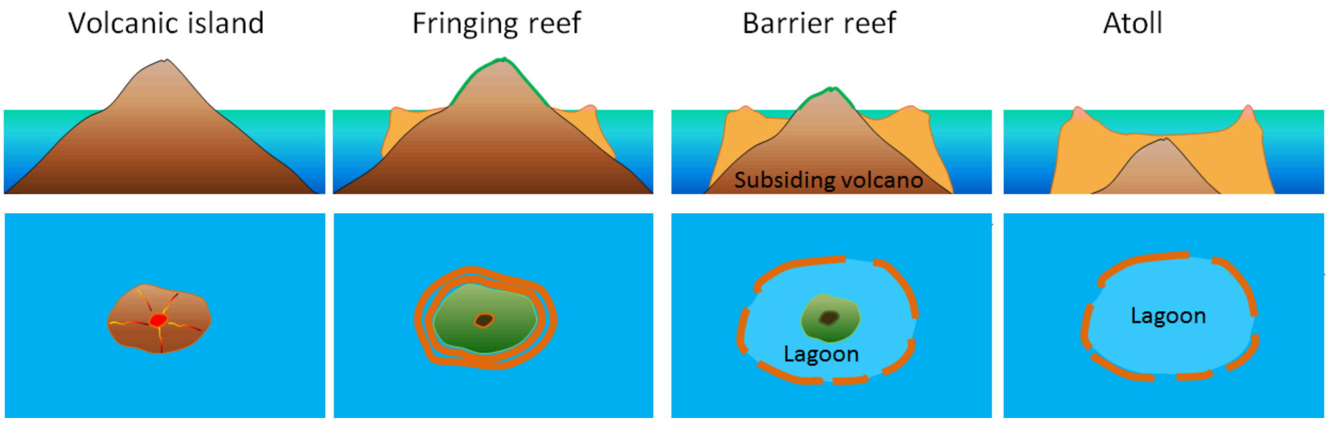

Figure 18.2.4 The formation of a fringing reef, a barrier reef, and an atoll around a subsiding tropical volcanic island. [Image Description]

The key factor in this process is sea-level change, either because of post-glacial sea-level rise, or because of subsidence of a volcano — as it is moved away from a spreading ridge — or both. If the rate of sea-level change is slow enough (e.g., less than 1 cm/year), a reef can keep up and maintain its position at sea level long after its parent volcanic island has disappeared beneath the waves.

Image Descriptions

Figure 18.2.1 image description: Layers in the oceanic crust.

Depth (kilometres)	**Material**
0 to 0.5	Sediments
0.5 to 1	Pillows, breccias, and flows
1 to 2	Sheeted dykes
2 to 5	Gabbro bodies
5 to 6	Layered gabbro
6 to 6.5	Layered peridotite
Greater than 6.5	Upper mantle

[Return to Figure 18.2.1]

Figure 18.2.3 image description: The Juan de Fuca plate lies between the Pacific Plate and the North America Plate along the west coast of Vancouver Island and Washington State. The Juan de Fuca Plate is subducting under the North America Plate along the Cascadia subduction boundary. The Juan de Fuca Plate is youngest along the Juan de Fuca ridge at the Pacific Plate and is older as it moves east. The magnetic time scales shows periods of magnetic reversal, and the ages of the parts of the Juan de Fuca plate that are subducting range from just over 0 Ma in the northwest corner of the plate to over 8 Ma in the southeast corner of the plate. [Return to Figure 18.2.3]

Figure 18.2.4 image description: A volcanic island forms and a fringing reef develops around it in the water. It becomes a barrier reef as the volcanic island subsides and water is able to pool between the island and the reef to form a lagoon. An atoll is formed when the volcano subsides enough that it no longer breaches the ocean surface but the reef remains to form a pool. [Return to Figure 18.2.4]

Media Attributions

- Figures 18.2.1, 18.2.3, 18.2.4: © Steven Earle. CC BY.
- Figure 18.2.2: "Age of oceanic lithosphere" © National Oceanic and Atmospheric Administration. Adapted by Steven Earle. CC BY-SA.

18.3 Sea-Floor Sediments

Except within a few kilometres of a ridge crest, where the volcanic rock is still relatively young, most parts of the sea floor are covered in sediments. This material comes from several different sources and is highly variable in composition, depending on proximity to a continent, water depth, ocean currents, biological activity, and climate. Sea-floor sediments (and sedimentary rocks) can range in thickness from a few millimetres to several tens of kilometres. Near the surface, the sea-floor sediments remain unconsolidated, but at depths of hundreds to thousands of metres (depending on the type of sediment and other factors) the sediment becomes lithified.

The various sources of sea-floor sediment can be summarized as follows:

- **Terrigenous** sediment is derived from continental sources transported by rivers, wind, ocean currents, and glaciers. It is dominated by quartz, feldspar, clay minerals, iron oxides, and terrestrial organic matter.
- Pelagic carbonate sediment is derived from organisms (e.g., **foraminifera**) living in the ocean water (at various depths, but mostly near surface) that make their shells (a.k.a. **tests**) out of carbonate minerals such as calcite.
- Pelagic silica sediment is derived from marine organisms (e.g., **diatoms** and **radiolaria**) that make their tests out of silica (microcrystalline quartz).
- Volcanic ash and other volcanic materials are derived from both terrestrial and submarine eruptions.
- Iron and manganese nodules form as direct precipitates from ocean-bottom water.

The distributions of some of these materials around the seas are shown in Figure 18.3.1. Terrigenous sediments predominate near the continents and within inland seas and large lakes. These sediments tend to be relatively coarse, typically containing sand and silt, but in some cases even pebbles and cobbles. Clay settles slowly in nearshore environments, but much of the clay is dispersed far from its source areas by ocean currents. Clay minerals are predominant over wide areas in the deepest parts of the ocean, and most of this clay is terrestrial in origin. Siliceous oozes (derived from radiolaria and diatoms) are common in the south polar region, along the equator in the Pacific, south of the Aleutian Islands, and within large parts of the Indian Ocean. Carbonate oozes are widely distributed in all of the oceans within equatorial and mid-latitude regions. In fact, clay settles everywhere in the oceans, but in areas where silica- and carbonate-producing organisms are prolific, they produce enough silica or carbonate sediment to dominate over clay.

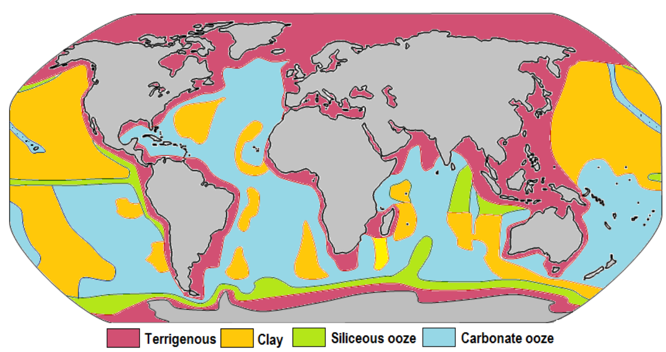

Figure 18.3.1 The distribution of sediment types on the sea floor. Within each coloured area, the type of material shown is what dominates, although other materials are also likely to be present.

Carbonate sediments are derived from a wide range of near-surface pelagic organisms that make their shells out of carbonate (Figure 18.3.2). These tiny shells, and the even tinier fragments that form when they break into pieces, settle slowly through the water column, but they don't necessarily make it to the bottom. While calcite is insoluble in surface water, its solubility increases with depth (and pressure) and at around 4,000 metres, the carbonate fragments dissolve. This depth, which varies with latitude and water temperature, is known as the **carbonate compensation depth**, or CCD. As a result, carbonate oozes are absent from the deepest parts of the ocean (deeper than 4,000 metres), but they are common in shallower areas such as the mid-Atlantic ridge, the East Pacific Rise (west of South America), along the trend of the Hawaiian/Emperor Seamounts (in the northern Pacific), and on the tops of many isolated seamounts.

Figure 18.3.2 Foraminifera from the Ambergris Caye area of Belize. Most of the shells are about 1 millimetre across.

Exercise 18.3 What type of sediment?

The diagram shows the sea floor in an area where there is abundant pelagic carbonate sediment. There is a continent within 100 kilometres of this area, to the right. What type of sediment (coarse terrigenous, clay, siliceous ooze, or carbonate ooze) would you expect at find at locations a, b, c, and d?

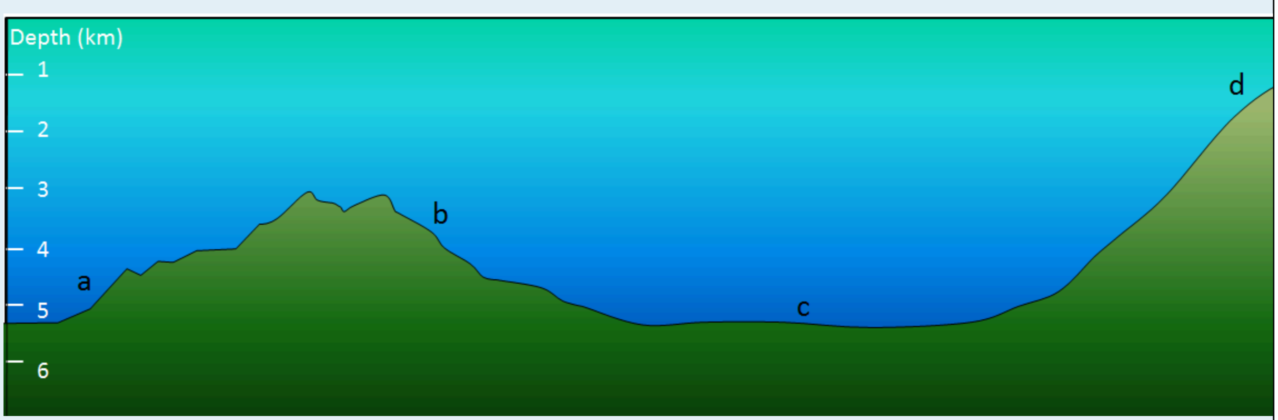

Figure 18.3.3 [Image Description]

See Appendix 3 for Exercise 18.3 answers.

All terrestrial erosion products include a small proportion of organic matter derived mostly from terrestrial plants. Tiny fragments of this material plus other organic matter from marine plants and animals accumulate in terrigenous sediments, especially within a few hundred kilometres of shore. As the sediments pile up, the deeper parts start to warm up (from geothermal heat), and bacteria get to work breaking down the contained organic matter. Because this is happening in the absence of oxygen (a.k.a. **anaerobic** conditions), the by-product of this metabolism is the gas methane (CH4). Methane released by the bacteria slowly bubbles upward through the sediment toward the sea floor.

At water depths of 500 metres to 1,000 metres, and at the low temperatures typical of the sea floor (close to 4°C), water and methane combine to create a substance known as **methane hydrate**. Within a few metres to hundreds of metres of the sea floor, the temperature is low enough for methane hydrate to be stable and hydrates accumulate within the sediment (Figure 18.3.4). Methane hydrate is flammable because when it is heated, the methane is released as a gas (Figure 18.3.4). The methane within sea-floor sediments represents an enormous reservoir of fossil fuel energy. Although energy corporations and governments are anxious to develop ways to produce and sell this methane, anyone that understands the climate-change implications of its extraction and use can see that this would be folly. As we'll see in the discussion of climate change in Chapter 19, sea-floor methane hydrates have had significant impacts on the climate in the distant past.

Figure 18.3.4 Left: Methane hydrate within muddy sea-floor sediment from an area offshore from Oregon. Right: Methane hydrate on fire.

Image Descriptions

Figure 18.3.3 image description: A. is farthest from the continent. D is closest to the continent.

1. A depth of 4.5 kilometres.
2. A depth of 3.5 kilometres.
3. A depth of 5 kilometres.
4. A depth of 1 kilometre, close to the edge of a continent.

[Return to Figure 18.3.3]

Media Attributions

- Figure 18.3.1, 18.3.2, 18.3.3: © Steven Earle. CC BY.
- Figure 18.3.4 (Left): "Gashydrat im Sediment" © Wusel007. CC BY-SA.
- Figure 18.3.4 (Right): "Burning Gas Hydrates" by J. Pinkston and L. Stern (USGS). Public domain.

18.4 Ocean Water

As everyone knows, seawater is salty. It is that way because the river water that flows into the oceans contains small amounts of dissolved ions, and for the most part, the water that comes out of the oceans is the pure water that evaporates from the surface. Billions of years of a small amount of salt going into the ocean—and none coming out (most of the time)—has made the water salty. The salts of the ocean (dominated by sodium, chlorine, and sulphur) (Figure 18.4.1) are there because they are very soluble and they aren't consumed by biological processes (most of the calcium, for example, is used by organisms to make carbonate minerals). If salts are always going into the ocean, and never coming out, one might assume that the oceans have been continuously getting saltier over geological time. In fact this appears not to be the case. There is geological evidence that Earth's oceans became salty early during the Archaean, and that at times in the past, they have been at least half again as salty as they are now. This implies that there must be a mechanism to remove salt from the oceans, and that mechanism is the isolation of some parts of the ocean into seas (such as the Mediterranean) and the eventual evaporation of those seas to create salt beds that become part of the crust. The Middle Devonian Prairie Evaporite Formation of Saskatchewan and Manitoba is a good example of this.

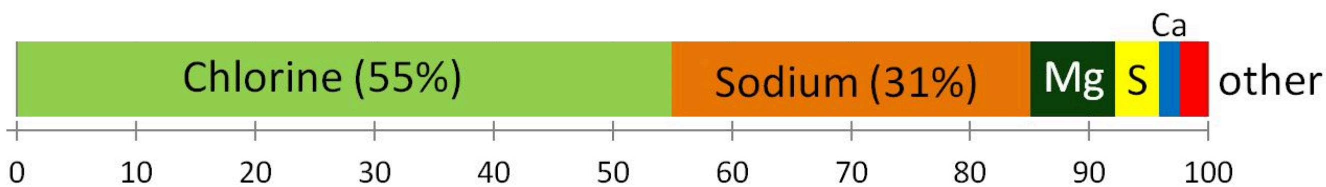

Figure 18.4.1 The proportions (by weight) of the major dissolved elements in ocean water.

The average salinity of the oceans is 35 g of salt per litre of water, but there are significant regional variations in this value, as shown in Figure 18.4.2. Ocean water is least salty (around 31 g/L) in the Arctic, and also in several places where large rivers flow in (e.g., the Ganges/Brahmaputra and Mekong Rivers in southeast Asia, and the Yellow and Yangtze Rivers in China). Ocean water is most salty (over 37 g/L) in some restricted seas in hot dry regions, such as the Mediterranean and Red Seas. You might be surprised to know that, in spite of some massive rivers flowing into it (such as the Nile and the Danube), water does not flow out of the Mediterranean Sea into the Atlantic. There is so much evaporation happening in the Mediterranean basin that water flows into it from the Atlantic, through the Strait of Gibraltar.

In the open ocean, salinities are elevated at lower latitudes because this is where most evaporation takes place. The highest salinities are in the subtropical parts of the Atlantic, especially north of the equator. The northern Atlantic is much more saline than the north Pacific because the Gulf Stream current brings a massive amount of salty water from the tropical Atlantic and the Caribbean to the region around Britain, Iceland, and Scandinavia. The salinity in the Norwegian Sea (between Norway and Iceland) is substantially higher than that in other polar areas.

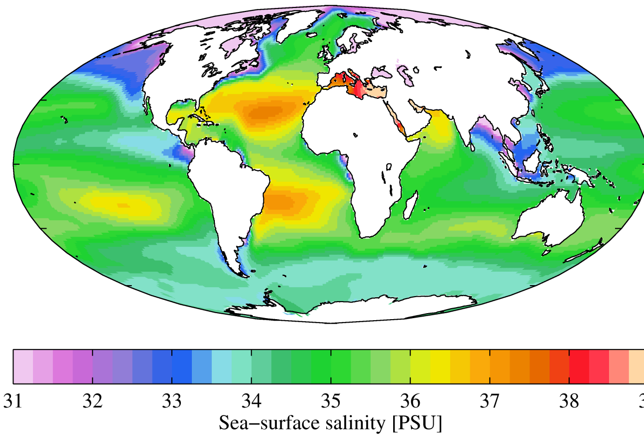

Figure 18.4.2 The distribution of salinity in Earth's oceans and major seas.

Exercise 18.4 Salt chunk

How salty is the sea? If you've ever had a swim in the ocean, you've probably tasted it. To understand how salty the sea is, start with 250 mL of water (1 cup). There is 35 g of salt in 1 L of seawater so in 250 mL (1/4 litre) there is 35/4 = 8.75 or ~9 g of salt. This is just short of 2 teaspoons, so it would be close enough to add 2 level teaspoons of salt to the cup of water. Then stir until it's dissolved. Have a taste!

Of course, if you used normal refined table salt, then what you added was almost pure NaCl. To get the real taste of seawater you would want to use some evaporated seawater salt (a.k.a. sea salt), which has a few percent of magnesium, sulphur, and calcium plus some trace elements.

Figure 18.4.3

See Appendix 3 for [Exercise 18.4 answers](#).

Not unexpectedly, the oceans are warmest near the equator—typically 25° to 30°C—and coldest near the poles—around 0°C (Figure 18.4.4). (Sea water will remain unfrozen down to about -2°C.) At southern Canadian latitudes, average annual water temperatures are in the 10° to 15°C range on the west coast and in the 5° to 10°C range on the east coast. Variations in sea-surface temperatures (SST) are related to redistribution of water by ocean currents, as we'll see below. A good example of that is the plume of warm Gulf Stream water that extends across the northern Atlantic. St. John's, Newfoundland, and Brittany in France are at about the same latitude (47.5° N), but the average SST in St. John's is a frigid 3°C, while that in Brittany is a reasonably comfortable 15°C.

Currents in the open ocean are created by wind moving across the water and by density differences related to temperature and salinity. An overview of the main ocean currents is shown in Figure 18.4.5. As you can see, the northern hemisphere currents form circular patterns (**gyres**) that rotate clockwise, while the southern hemisphere gyres are counter-clockwise. This happens for the same reason that the water in your northern hemisphere sink rotates in a clockwise direction as it flows down the drain; this is caused by the **Coriolis effect**.

Because the ocean basins aren't like bathroom basins, not all ocean currents behave the way we would expect. In the North Pacific, for example, the main current flows clockwise, but there is a secondary current in the area adjacent to our coast—the Alaska Current—that flows counter-clockwise, bringing relatively warm water from California, past Oregon, Washington, and B.C. to Alaska. On Canada's eastern coast, the cold Labrador Current flows south past Newfoundland, bringing a stream of icebergs past the harbour at St. John's (Figure 18.4.7). This current helps to deflect the Gulf Stream toward the northeast, ensuring that Newfoundland stays cool, and western Europe stays warm.

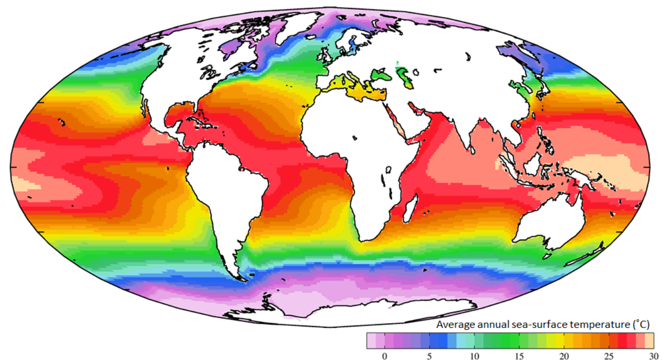

Figure 18.4.4 The global distribution of average annual sea-surface temperatures.

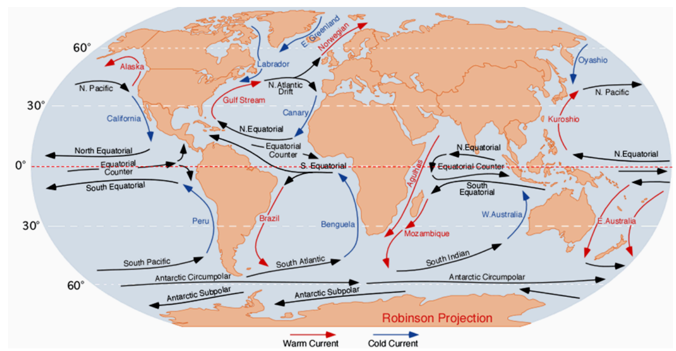

Figure 18.4.5 Overview of the main open-ocean currents. Red arrows represent warm water moving toward colder regions. Blue arrows represent cold water moving toward warmer regions. Black arrows represent currents that don't involve significant temperature changes. [Image Description]

Figure 18.4.6 An iceberg floating past Exploits Island on the Labrador Current

Exercise 18.5: Understanding the Coriolis effect

The Coriolis effect has to do with objects that are moving in relation to other objects that are rotating. An ocean current is moving across the rotating Earth, and its motion is controlled by the Coriolis effect.

Imagine that you are standing on the equator looking straight north and you fire a gun in that direction. The bullet in the gun starts out going straight north, but it also has a component of motion toward the east that it gets from Earth's rotation, which is 1,670 kilometres per hour at the equator. Because of the spherical shape of Earth, the speed of rotation away from the equator is not as fast as it is at the equator (in fact, the Earth's rotational speed is 0 kilometres per hour at the poles) so the bullet actually traces a clockwise curved path across Earth's surface, as shown by the red arrow on the diagram. In the southern hemisphere the Coriolis effect is counterclockwise (green arrow).

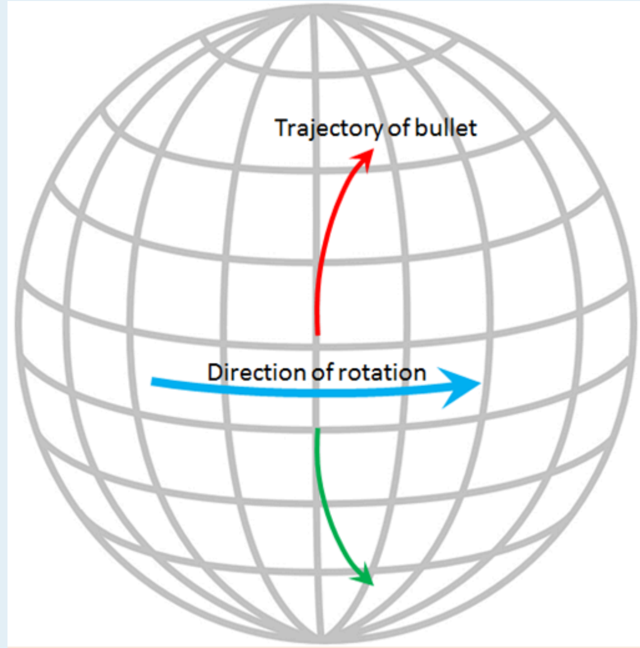

Figure 18.4.7

The Coriolis effect is imparted to the rotations of ocean currents and tropical storms. If Earth were a rotating cylinder, instead of a sphere, there would be no Coriolis effect.

See Appendix 3 for Exercise 18.5 answers.

The currents shown in Figure 18.4.5 are all surface currents, and they only involve the upper few hundred metres of the oceans. But there is much more going on underneath. The Gulf Stream, for example, which is warm and saline, flows past Britain and Iceland into the Norwegian Sea (where it becomes the Norwegian Current). As it cools down, it becomes denser, and because of its high salinity, which also contributes to its density, it starts to sink beneath the surrounding water (Figure 18.4.8). At this point, it is known as **North Atlantic Deep Water** (NADW), and it flows to significant depth in the Atlantic as it heads back south. Meanwhile, at the southern extreme of the Atlantic, very cold water adjacent to Antarctica also sinks to the bottom to become **Antarctic Bottom Water** (AABW) which flows to the north, underneath the NADW.

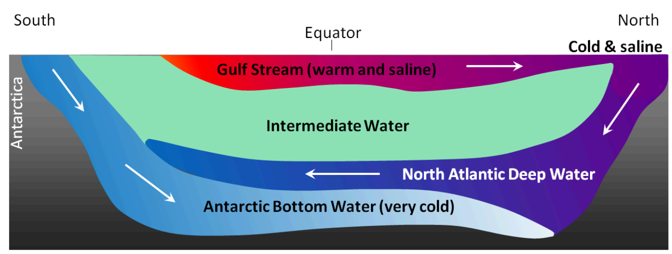

Figure 18.4.8 A depiction of the vertical movement of water along a north-south cross-section through the Atlantic basin.

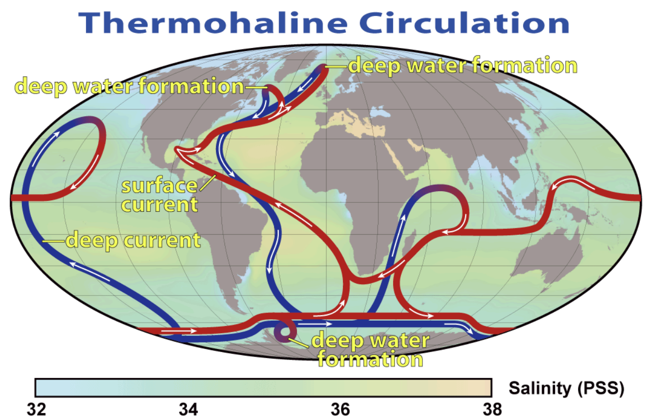

Figure 18.4.9 The thermohaline circulation system, also known as the Global Ocean Conveyor.

The descent of the dense NADW is just one part of a global system of seawater circulation, both at surface and at depth, as illustrated in Figure 18.4.9. The water that sinks in the areas of deep water formation in the Norwegian Sea and adjacent to Antarctica moves very slowly at depth. It eventually resurfaces in the Indian Ocean between Africa and India, and in the Pacific Ocean, north of the equator.

The thermohaline circulation is critically important to the transfer of heat on Earth. It brings warm water from the tropics to the poles, and cold water from the poles to the tropics, thus keeping polar regions from getting too cold and tropical regions from getting too hot. A reduction in the rate of thermohaline circulation would lead to colder conditions and enhanced formation of sea ice at the poles. This would start a positive feedback process that could result in significant global cooling. There is compelling evidence to indicate that there were major changes in thermohaline circulation, corresponding with climate changes, during the Pleistocene Glaciation.

Image Descriptions

Figure 18.4.5 image description: The currents of the world's oceans work together to form a number of general patterns. Currents flow into each other to form larger currents. Groups of currents in the northern hemisphere flow clockwise. This includes groups of currents in the North Pacific Ocean and the North Atlantic Ocean. Currents in the southern hemisphere flow counter-clockwise. This includes groups of currents in the South Pacific Ocean, the South Atlantic Ocean, and the Indian Ocean. Currents flowing towards the equator are colder than the surrounding water. Currents flowing away from the equator are warmer than the surrounding water. Currents below 60° South flow from east to west (or west to east) around Antarctica. Currents along the Equator also flows east to west (or west to east). Currents flowing from east to west (or west to east) are the same temperature as the surrounding water. For a more detailed description of specific currents, refer to the following table, which describes 26 major currents, including their location, direction of flow, and relationship to surrounding currents. They are arranged in alphabetical order. Or, you can [Return to Figure 18.4.5].

Figure 18.4.6 table: Description of the main currents of the ocean and their direction of flow

Name of Current	**Temperature of current compared to the surrounding water**	**Direction of flow**	**Relationship to nearby currents**
Agulhas	A warm current	The Agulhas current flows south from the Arabian peninsula down the east coast of Africa.	The Agulhas current joins with the Mozambique current, which also flows south.
Alaska	A warm current	The Alaska current flows north up the west coast of the United States and Canada before circling to the west once it reaches Alaska	The Alaska current flows into the Oyashio current
Antarctic Circumpolar	No temperature difference	The Antarctic Circumpolar current flows east to circle around Antarctica.	The Antarctic Circumpolar flows east above the Antarctic Subpolar, which flows west.
Antarctic Subpolar	No temperature difference	The Antarctic Subpolar current flows west along the coast of Antarctica.	The Antarctic Subpolar current flows west below the Antarctic Circumpolar current, which flows east.
Benguela	A cold current	The Benguela current flows north along the south west coast of Africa.	The Benguela current flows into the South Equatorial current and is fed by the South Atlantic current.
Brazil	A warm current	The Brazil current flows south along the east coast of South America.	The Brazil current flows into the South Atlantic current and is fed by the south branch of the South Equatorial current.
California	A cold current	The California current flows south from the southwest coast of the United States down along the west coast of Mexico.	The California current flows into the North Equatorial current and is fed by the North Pacific current.
Canary	A cold current	The Canary current flows from south along the north west coast of Africa from Morocco to Sengal.	The Canary current flows into the North Equatorial current and is fed by the North Atlantic Drift.

Name of Current	**Temperature of current compared to the surrounding water**	**Direction of flow**	**Relationship to nearby currents**
East Australian	A warm current	The East Australian currents flow from the equator and south, past the east coast of Australia. One flows between New Zealand and Australia, and the other flows past the east side of New Zealand.	The East Australian currents flow into the South Pacific current and they are fed by the South Equatorial current.
East Greenland	A cold current	The East Greenland current flows south along the east coast of Greenland.	The East Greenland current flows into the Labrador current.
Equatorial Counter	No temperature difference.	The Equatorial Counter current flows east along the equator. It is broken up into three sections: One in the Pacific Ocean, one in the Atlantic Ocean, and one in the Indian Ocean.	The Equatorial Counter current flows east between the North Equatorial and the South Equatorial currents, which both flow west.
Gulf Stream	A warm current	The Gulf Stream flows north from the Caribbean along the east coast of the United States.	The Gulf Stream flows into the North Atlantic Drift current and is fed by the North Equatorial current.
Kuroshio	A warm current	The Kuroshio current flows north along the east coast of the Philippines and Japan.	The Kuroshio current flows into the North Pacific current and is fed by the North Equatorial current.
Labrador	A cold current	The Labrador current flows south along the eastern coast of Canada to the northern United States.	The Labrador current is partially fed by the East Greenland current. Once it reaches the northern United States, it flows past the Gulf Stream.
Mozambique	A warm current	The Mozambique current flows south along the east coast of Madagascar and into the Southern Ocean.	The Mozambique current flows into the South Indian current and is fed by the South Equatorial current.

Name of Current	**Temperature of current compared to the surrounding water**	**Direction of flow**	**Relationship to nearby currents**
North Atlantic Drift	No temperature difference	The North Atlantic Drift current flows east across the Atlantic Ocean from the north coast of the United States to the south coast of Spain.	The North Atlantic Drift current splits to flow north into the Norwegian current and to flow south into the Canary current. It is fed by the Gulf Stream.
North Equatorial	No temperature difference.	The North Equatorial current flows west just above the equator. It is broken up into three sections: One in the Pacific Ocean, one in the Atlantic Ocean, and one in the Indian Ocean.	The North Equatorial current in the Pacific Ocean flows into the Kuroshio current and is fed by the California current. The North Equatorial current in the Atlantic Ocean flows into the Gulf Stream and is fed by the Canary current. The North Equatorial current in the Indian Ocean turns at Africa to join the Equatorial Counter current.
North Pacific	No temperature difference	The North Pacific current flows west across the Pacific Ocean from Japan to the south coast of the United States.	The North Pacific current flows into the California current and is fed by the Kuroshio current.
Norwegian	A warm current	The Norwegian current flows north from the north coast of the United Kingdom to along the coast of Norway.	This current is fed by the northern branch of the North Atlantic Drift current and flows into the Arctic Ocean.
Oyashio	A cold current	The Oyashio current flows south along the east coast of Russia.	The Oyashio current clashes with the Kuroshio current, which flows north into the North Pacific current.
Peru	A cold current	The Peru current flows north along the central west coast of South America.	The Peru current flows into the South Equatorial current and is fed by the South Pacific current.
South Atlantic	No temperature difference	The South Atlantic current flows from the south tip of South America to towards the south tip of Africa.	The South Atlantic current flows into the Benguela current and is fed by the Brazil current.

Name of Current	Temperature of current compared to the surrounding water	Direction of flow	Relationship to nearby currents
South Equatorial	No temperature difference	The South Equatorial current flows west just below the equator. It is broken up into three sections: One in the Pacific Ocean, one in the Atlantic Ocean, and one in the Indian Ocean.	The South Equatorial current in the Pacific Ocean flows into the East Australian currents and is fed by the Peru current. The South Equatorial current in the Atlantic Ocean flows north and south: North along the north east coast of South America and south into the Brazil current. It is fed by the Benguela current. The South Equatorial current in the Indian Ocean flows into the Mozambique current and is fed by the West Australian current.
South Indian	No temperature difference	The South Indian current flows from the southern part of the Indian ocean towards the south west coast of Australia.	The South Indian current flows into the West Australian current and is fed by the Mozambique current.
South Pacific	No temperature difference	The South Pacific current flows east from the south east coast of Australia to the south west coast of South America.	The South Pacific current flows into the Peru current and is fed by the East Australian current.
West Australian current	A cold current	The West Australian current flows north along the west coast of Australia.	The West Australian current flows into the South Equatorial current and is fed by the South Indian current.

[Return to Figure 18.4.5]

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Summary

The topics covered in this chapter can be summarized as follows:

Section	Summary
18.1 The Topography of the Sea Floor	The oceans are about 4,000 metres deep on average, but they also have a wide range of topographical features, including shallow continental shelves, continental slopes, continuous ridges related to plate divergence, numerous isolated seamounts, and deep submarine canyons at subduction zones.
18.2 The Geology of the Oceanic Crust	Most oceanic crust forms during sea-floor spreading and is characterized by pillow basalts, sheeted dykes, gabbro bodies, layered gabbro, and layered ultramafic rock. The oldest parts of the sea floor are older than 200 Ma, but most of the sea floor is younger than 100 Ma. Seamounts are common and almost all are volcanoes, related to mantle plumes, subduction, or other processes. In tropical regions, ocean islands tend to be surrounded by carbonate reefs.
18.3 Sea-Floor Sediments	Almost all of the sea floor is covered by young sediments and sedimentary rocks, derived either from erosion of continents or from marine biological processes. Clastic sediments, some quite coarse, predominate on shelves and slopes. Terrigenous clays are distributed across the sea floor, but in areas where either carbonate- or silica-forming organisms thrive, the sediments are likely to be dominated by carbonate or silica oozes. Methane hydrates, derived from bacterial decomposition of organic matter, form within sediments on shelves and slopes.
18.4 Ocean Water	Average ocean water has about 35 g/L of salt, mostly made up of chlorine and sodium, but also including magnesium, sulphur, and calcium. Salinity levels are highest in the tropics where evaporation is greatest. Sea-surface temperatures range from less than 0°C at the poles to over 25°C in equatorial regions. Open-ocean currents, which generally rotate clockwise in the northern hemisphere and counter-clockwise in the south, are critically important in redistributing heat on Earth. Deep-ocean currents, driven by density differences, are another key part of the heat redistribution system. Changes to current patterns or intensity have significant implications for global climate.

Questions for Review

See Appendix 2 for answers to review questions.

1. What is the origin of the sediments that make up continental shelves? Why are the shelves on the eastern coast of North America so much wider than those along the west coast?
2. The ocean trenches at some subduction zones are relatively shallow. What is one explanation for this?
3. What are the main lithological components of oceanic crust, and how does this rock form?
4. Referring to Figure 18.8, determine the age of the oldest sea floor in the Indian Ocean.

5. Explain why relatively coarse terrigenous sediments (e.g., sand) tend to accumulate close to the continents, while terrigenous clay is dispersed all across the ocean floor.
6. Although clay is widely dispersed in the oceans, in some areas, deep-sea sediments are dominated by clay, while in others they are dominated by carbonate or silica ooze. Why do these differences exist?
7. Explain why carbonate sediments are absent from the deepest parts of the oceans.
8. What is the source of the carbon that is present in sea-floor methane hydrate deposits?
9. Where are the saltiest parts of the oceans? Why?
10. Explain why sea-surface water with the greatest density is found in the north Atlantic, as shown on Figure A.
11. What type of ocean currents result from the relatively dense water in the north Atlantic?

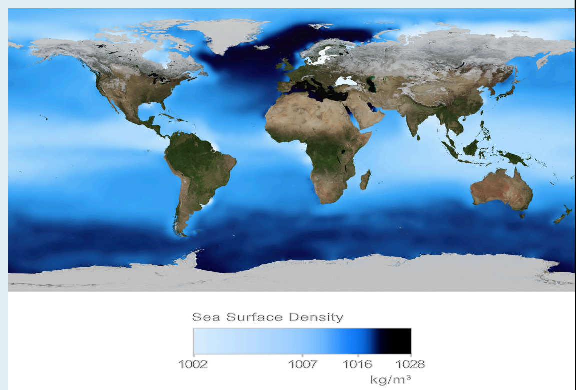

Figure A

12. How do the open-ocean currents affect the overall climate patterns on Earth?

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