Chapter 13: Coastal Oceanography

Learning Objectives

After reading this chapter you should:

- recognize the various zones of a beach
- understand how the relationship between swash and backwash determines the composition of a beach
- understand the concept of longshore transport
- know the different erosional and depositional structures created by longshore transport
- understand the issues associated with different forms of hard stabilization: groins, jetties etc.
- know what an estuary is
- know the four types of geological estuaries, and how they form
- know the four types of estuaries based on salinity and mixing patterns

For most people, their image of the coast is the place where the land meets the sea, most likely in the form of a beach. But it is more than just the narrow strip along the water line; technically the term "coast" refers to the range of land over which the ocean has an effect on climate, foliage, and other environmental processes. This range may extend for tens of kilometers inland from the water's edge. Furthermore, what we recognize as the coast today, may not have been a coastal area in the past, as sea level has varied from about 6 m above to 125 m below its current height over the past two million years.

This chapter begins with the features of coastal regions, the processes that shape the coastline, and how humans try to control these processes. Following that, we will examine the different types of estuaries that are found in coastal areas.

13.1 Beaches

For most people, when they think of coastal areas they picture a beach, and the beach that they imagine is probably a typical sandy beach composed of quartz sand grains (section 12.2). But beaches are comprised of whatever types of sediments are dominant in the local area. For example, parts of Hawaii and Iceland are famous for their black sand beaches, made up of eroded basalt and other volcanic materials. The beautiful tropical white sand beaches we see in travel ads are largely composed of the crushed calcium carbonate remains of coral skeletons (much of which has been chewed up and excreted by a fish before we happily run our toes through it!) Other beaches may lack sand altogether and instead be dominated by small shells, or larger rocks or pebbles (Figure 13.1.1).

Figure 13.1.1 *Various beach substrates. Clockwise from top left: Punaluu Black Sand Beach, Hawaii, USA (Diego Delso [CC BY-SA 3.0], via Wikimedia Commons); Shell Beach, Shark Bay, Western Australia (Brian W. Schaller (Own work) [CC BY-NC-SA 3.0], via Wikimedia Commons); white coral sand beach in the Maldives (http://www.elitedivingagency.com/, [CC BY-SA 3.0] via Wikimedia Commons); rocky beach at Killbear Provincial Park in Ontario, Canada (John Vetterli (originally posted to Flickr as Beach) [CC BY-SA 2.0], via Wikimedia Commons).*

The shoreline is divided up into multiple zones (Figure 13.1.2). The **backshore** is the region of the beach above the high tide line, which is only submerged under unusually high wave conditions, such as during storms. The

foreshore lies between the high tide and low tide lines; it is submerged during high tide and is exposed during low tide. The **nearshore** extends from the low tide line to the depth where wave action is no longer influenced by the bottom, i.e. to where the depth exceeds the wave base (section 10.1). Finally, the **offshore** zone represents the depths beyond the nearshore region.

Along the beach itself, the area above the high tide line is called the **berm**, which is usually dry and relatively flat. The berm often ends with a berm crest or berm **scarp**, which is a steeper wall carved out by wave action that leads down to the foreshore. The foreshore has a number of other names, including the **beach face**, the **intertidal** or **littoral zone**, and if the area is fairly flat, the **low tide terrace**. Just off shore from the beach there are often **longshore bars** and longshore troughs running parallel to the beach. The longshore bars are accumulations of sand that are deposited by wave action and longshore currents (section 13.2). The decrease in depth above longshore bars is what often causes waves to start to break well before reaching the beach (section 10.3).

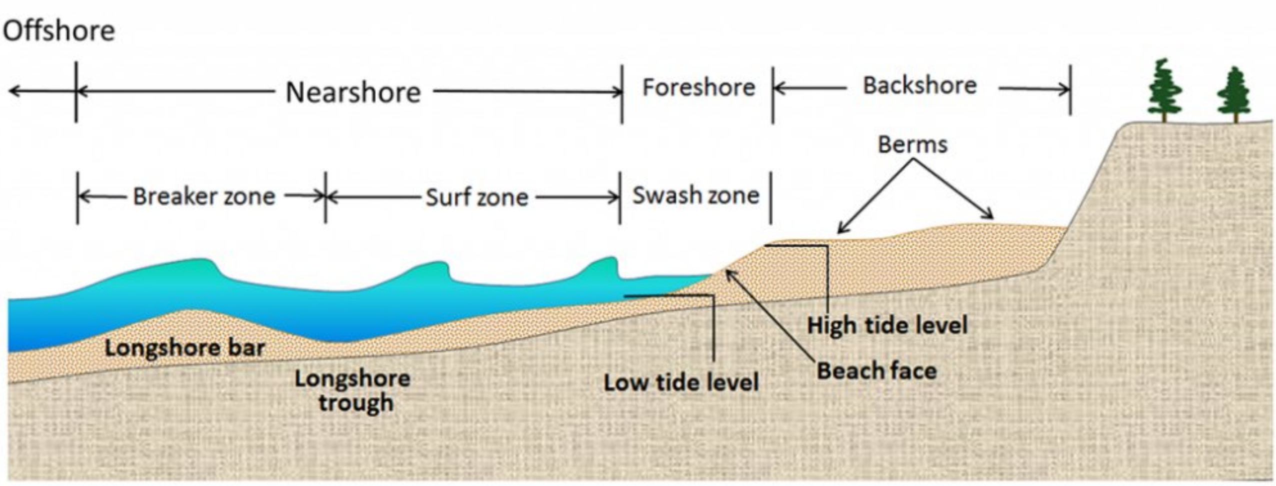

Figure 13.1.2 *The zones of a typical beach (Modified by PW from Steven Earle, "Physical Geology").*

The sand or other particles that make up the beach are distributed by wave action. The water that moves over a beach through incoming waves is called **swash**, and it also contains suspended sand grains that can get deposited on the beach. Some of the swash percolates into the sand while the rest of the water washes back out as **backwash** as the wave recedes. Backwash removes sand from the beach and returns it to the ocean. Sand will therefore be deposited or eroded depending on which process is dominant. If wave action is light, a lot of incoming water gets absorbed by the sand, so swash dominates. Under heavier waves the beach becomes saturated with water, so less can be absorbed, and backwash is dominant. This leads to seasonal cycles in beach structure; waves are heavier during the winter as a result of stormier conditions at sea, so backwash dominates and sand is removed from the beach and deposited offshore in longshore bars. In the summer the waves are gentler, swash dominates, and the sand is transported from the longshore bar and deposited on the shore to create a wider, sandy beach (Figure 13.1.3).

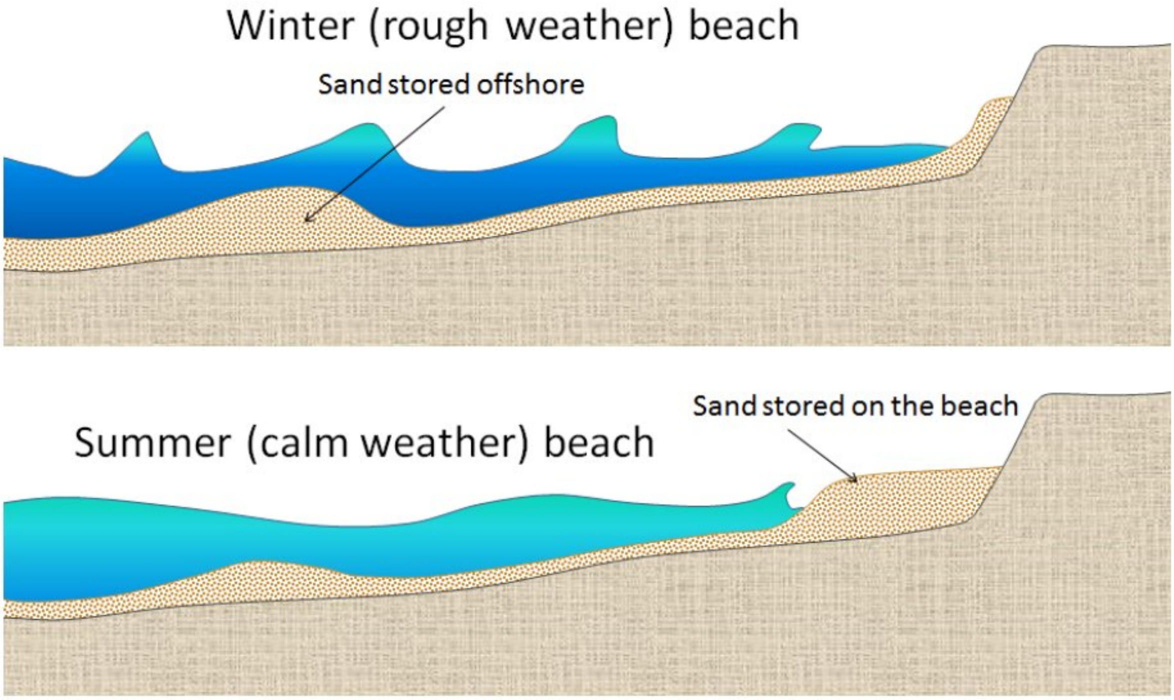

Figure 13.1.3 *The differences between summer and winter on beaches in areas where the winter conditions are rougher and waves have a shorter wavelength but higher energy. In winter, sand from the beach is stored offshore (Steven Earle, "Physical Geology").*

13.2 Longshore Transport

*Modified from "Physical Geology" by Steven Earle**

We learned in section 10.3 that refraction causes waves to approach parallel to shore. However, most waves still reach the shore at a small angle, and as each one arrives, it pushes water along the shore, creating what is known as a **longshore current** within the surf zone (the areas where waves are breaking) (Figure 13.2.1). Longshore currents can move up to 4 km/hr, strong enough to carry people with them, as everyone knows who has been swimming in the ocean only to look up and see that they have been carried far down the beach from their towel!

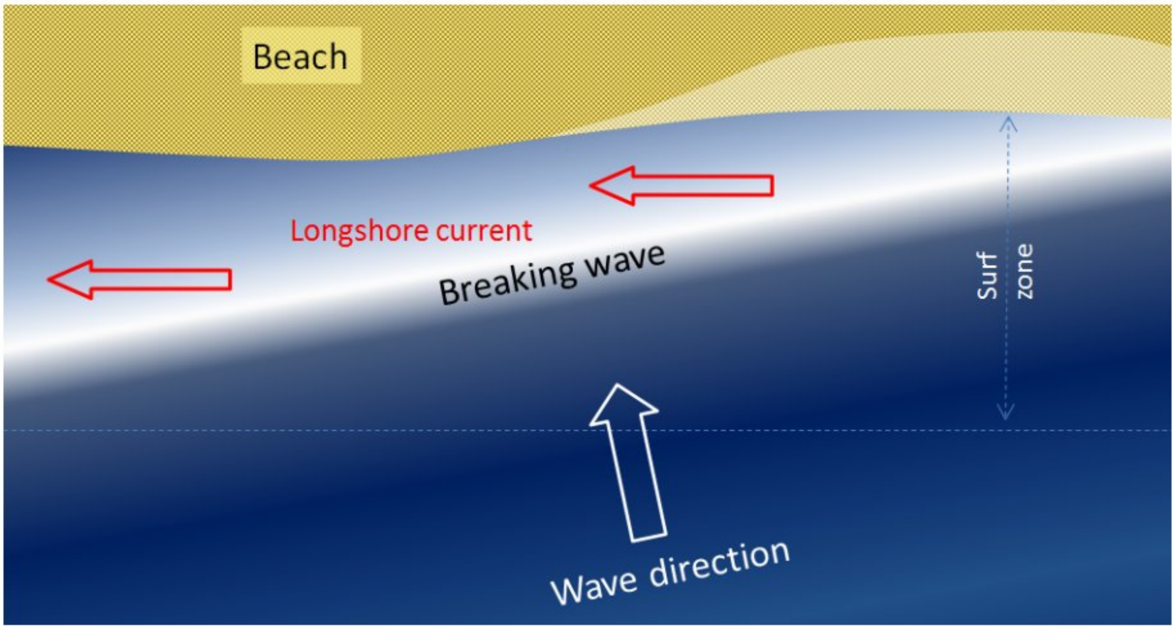

Figure 13.2.1 *Longshore currents are caused by waves approaching shore at a small angle, moving water parallel to the shore (Steven Earle, "Physical Geology").*

Another important effect of waves reaching the shore at an angle is that when they wash up onto the beach, they do so at an angle, but when that same wave water washes back down the beach, it moves straight down the slope of the beach (Figure 13.2.2). The upward-moving water, known as the swash, pushes sediment particles along the beach, while the downward-moving water, the backwash, brings them straight back. With every wave that washes up and then down the beach, particles of sediment are moved along the beach in a zigzag pattern.

The combined effects of sediment transport within the surf zone by the longshore current and sediment movement along the beach by swash and backwash is known as **longshore transport**, or **littoral drift**. Longshore transport moves a tremendous amount of sediment along coasts (both oceans and large lakes) around the world, and it is responsible for creating a variety of depositional features that we will discuss in section 13.4. The net movement of sediment due to longshore transport is to the south along both coasts of the continental United States, because the storms and high winds that originally create the swell tend to occur at higher latitudes and move to the south.

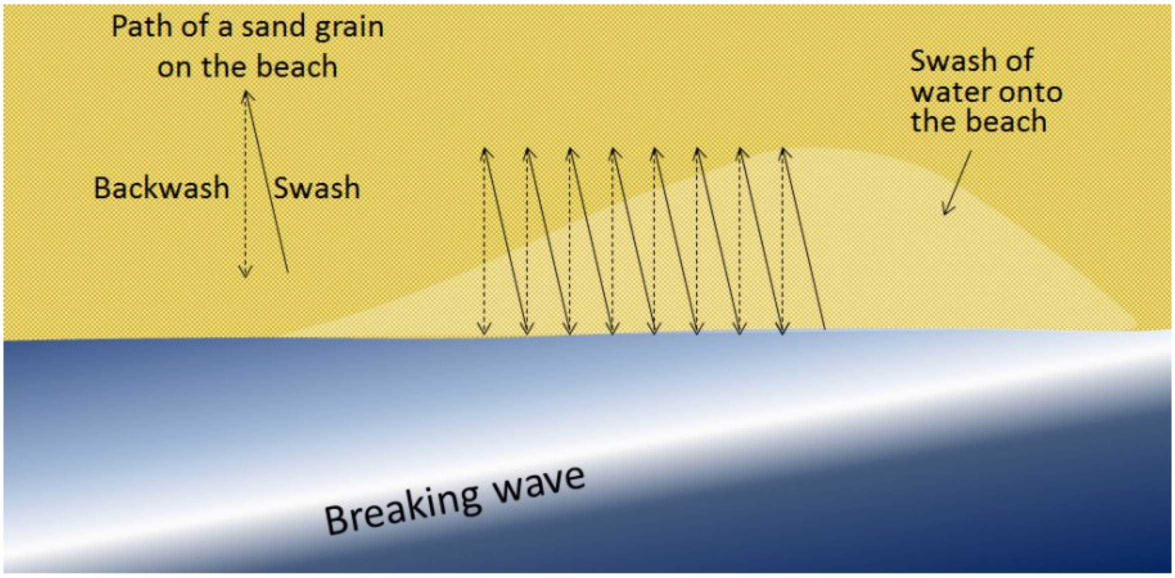

Figure 13.2.2 *The zigzag pattern of sediment movement along a beach creating longshore transport. In this figure the longshore transport moves particles to the left (Steven Earle, "Physical Geology").*

A **rip current** (often incorrectly called a "rip tide"; they are not really related to tides) is another type of current that develops in the nearshore area, and has the effect of returning water that has been pushed up to the shore by incoming waves or accumulated through longshore currents, particularly converging longshore currents. Rip currents often occur where there is a channel between sandbars that makes it easier for the retreating water to escape. As shown in Figure 13.2.3, rip currents flow straight out from the shore, and because the water is directed through a narrow space, the current can be very strong. The currents lose strength quickly just outside of the surf zone, but they can be dangerous to swimmers who get caught in them and are pulled away from shore. Swimmers caught in a rip current should not try to swim directly back to shore, as it is difficult to fight the current and the swimmer can quickly tire. Instead, swim parallel to the beach for a short distance until you are outside of the rip current, and then you can easily swim to shore.

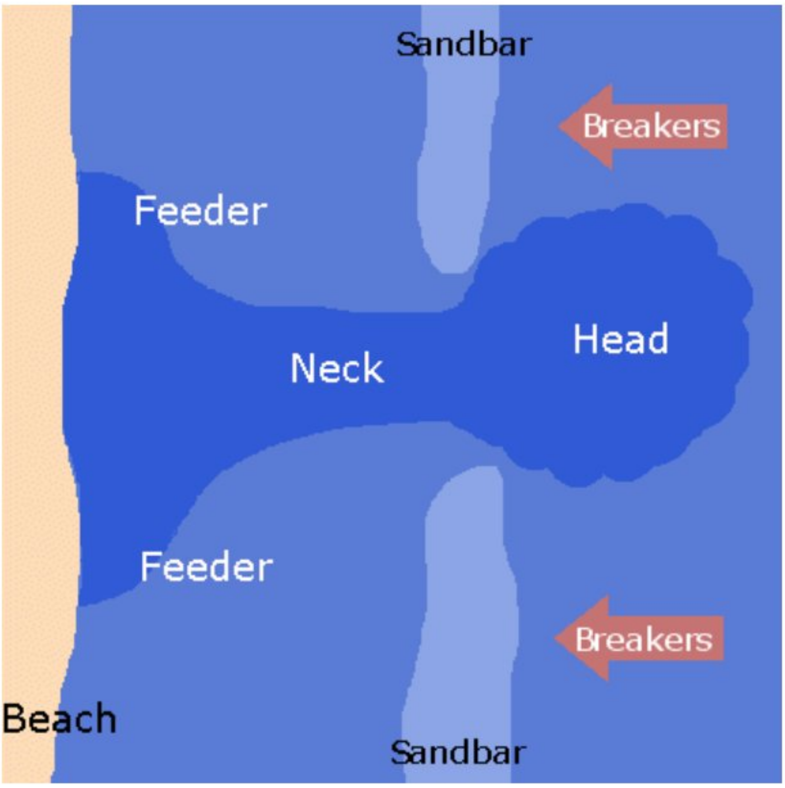

Figure 13.2.3 *Creation of a rip current from wave action and longshore transport. Water accumulates on the beach, and then rushes out to sea through a narrow channel, creating a strong current (National Weather Service, Wilmington, NC (NOAA) [Public domain], via Wikimedia Commons).*

Rip currents are visible in Figure 13.2.4, a beach at Tunquen in Chile near Valparaiso. As is evident from the photo, the rips correspond with embayments in the beach profile. Three of them are indicated with arrows, but it appears that there may be several others farther along the beach.

Figure 13.2.4 *Rip currents along a beach in Chile, indicated by the arrows. Longshore currents converging in a curved beach have nowhere to go but straight back out to sea, creating a rip current (Steven Earle, "Physical Geology").*

13.3 Landforms of Coastal Erosion

*Modified from "Physical Geology" by Steven Earle**

Large waves crashing onto a shore bring a tremendous amount of energy that has a significant eroding effect, and several unique erosion features commonly form on rocky shores with strong waves.

When waves approach an irregular shore, they are slowed down to varying degrees, depending on differences in the water depth, and as they slow, they are bent or refracted (section 10.3). In Figure 13.3.1, wave energy is represented by the blue arrows. That energy is evenly spaced out in the deep water, but because of refraction, the energy of the waves is being focused on the **headlands**. On irregular coasts, the headlands receive much more wave energy than the intervening bays, and thus they are more strongly eroded. The result of this is **coastal straightening**, where an irregular coast will eventually become straightened, although that process may take millions of years.

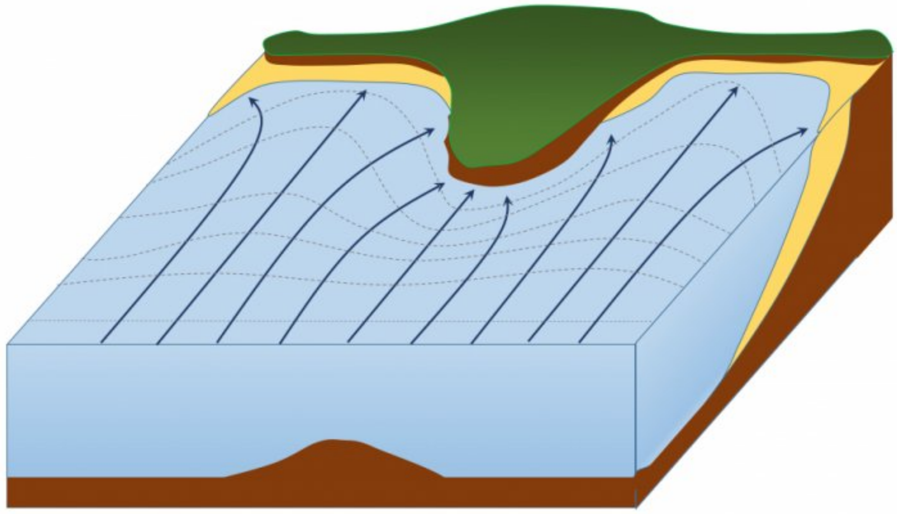

Figure 13.3.1 *The approach of waves (blue lines) towards a coastal headland. The blue arrows represent wave energy; most of that energy is focused on the headlands, causing greatest erosion in this area (PW).*

Wave erosion is greatest in the surf zone, where the wave base is impinging strongly on the seafloor and where the waves are breaking. The result is that the substrate in the surf zone is typically eroded to a flat surface known as a **wave-cut platform** (or **wave-cut terrace**) (Figure 13.3.2). A wave-cut platform extends across the intertidal zone.

Figure 13.3.2 *A wave-cut platform in bedded sedimentary rock on Gabriola Island, B.C. The wave-eroded surface is submerged at high tide (Steven Earle, "Physical Geology").*

Arches and **sea caves** form as a result of the erosion of relatively non-resistant rock. Wave action and strong longshore currents can carve a cave into a headland, and if the erosion extends all the way through, it becomes an arch. If a hole develops in the ceiling of a cave, a **blowhole** can be created, shooting water into the air when waves crash in the cave. An arch in the Barachois River area of western Newfoundland, Canada, is shown in Figure 13.3.3. This feature started out as a sea cave, and then, after being eroded from both sides, became an arch. During the winter of 2012-2013, the arch collapsed, leaving a small stack at the end of the point.

Figure 13.3.3 *Top: An arch in tilted sedimentary rock at the mouth of the Barachois River, Newfoundland, July 2012. Bottom: The same location in June 2013. The arch has collapsed and a small stack remains (Photo: Dr. David Murphy, used with permission in Steven Earle, "Physical Geology").*

The tower of rock left behind from a collapsed arch is called a **sea stack** (Figure 13.3.4). But sea stacks can also form during the formation of wave-cut platforms or other features, when relatively resistant rock that does not get completely eroded remains behind to form the stack.

Figure 13.3.4 *A sea stack, likely created from the collapse of a sea arch (Doug Lee [CC BY-SA 2.0], via Wikimedia Commons).*

Figure 13.3.5 summarizes the process of transformation of an irregular coast into a straightened coast with **sea cliffs** (wave-eroded escarpments) and the remnants of stacks, arches, and wave-cut platforms. The next stages of this process would be the continued landward erosion of the sea cliffs and the complete erosion of the stacks and wave-cut platforms in favor of a continuous and nearly straight sandy beach.

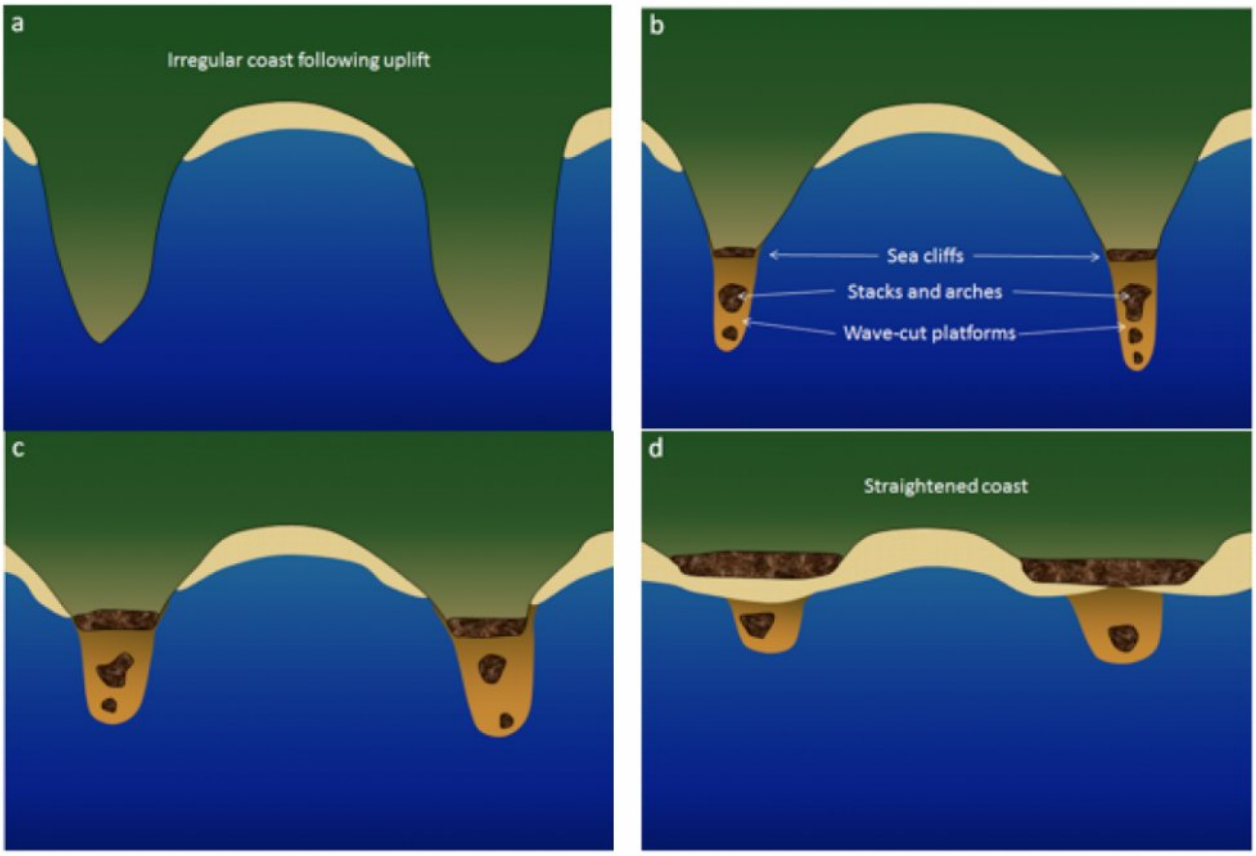

Figure 13.3.5 *Evolution of a straightened coast through the erosion to stacks and arches, sea cliffs, and wave-cut platforms (Steven Earle, "Physical Geology").*

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13.4 Landforms of Coastal Deposition

*Modified from "Physical Geology" by Steven Earle**

Some coastal areas are dominated by erosion, an example being the Pacific coast of North America, while others are dominated by deposition, examples being the Atlantic and Caribbean coasts of the United States. But on almost all coasts, both deposition and erosion are happening to varying degrees most of the time, although in different places. On deposition-dominant coasts, the coastal sediments are still being eroded from some areas and deposited in others.

On coasts that are dominated by depositional processes, most of the sediment being deposited typically comes from large rivers. Much of the sediment is immediately deposited at the mouth of the river, creating large fan-shaped **deltas**. An obvious example is where the Mississippi River flows into the Gulf of Mexico at New Orleans; another is the Yellow (Huang He) River in China (Figure 13.4.1).

Figure 13.4.1 *The Yellow River delta in China, created by one of the most sediment-laden rivers on Earth (NASA [Public domain], via Wikimedia Commons).*

The evolution of sandy depositional features on sea coasts is primarily influenced by waves and currents, especially longshore currents. As sediment is transported along a shore, either it is deposited on beaches, or it creates other depositional features. A **spit**, for example is an elongated sandy deposit that extends out into open water in the direction of a longshore current (Figure 13.4.2).

Figure 13.4.2 *Farewell Spit, on the northern shore of New Zealand's South Island (By NASA/GSFC/METI/ERSDAC/JAROS, and U.S./Japan ASTER Science Team (NASA's Earth Observatory) [Public domain], via Wikimedia Commons).*

A spit that extends across a bay to the extent of closing, or almost closing it off, is known as a **baymouth bar** (Figure 13.4.3). Most bays have streams flowing into them, and since this water has to get out, it is rare that a baymouth bar will completely close the entrance to a bay.

Figure 13.4.3 *Left: Illustration of a baymouth bar and tombolo (Steven Earle, "Physical Geology"). Right: A baymouth bar at the mouth of the Klamath River in northern California (Linda Tanner, https://www.flickr.com/photos/goingslo/5827465324, Creative Commons CC-BY 2.0).*

Tombolos are common where islands are abundant, and they typically form where there is a wave shadow behind a nearshore island (Figure 13.4.4). This becomes an area with reduced energy, and so the longshore current slows and sediments accumulate. Eventually enough sediments accumulate to connect the island to the mainland with a tombolo (Figure 13.4.5).

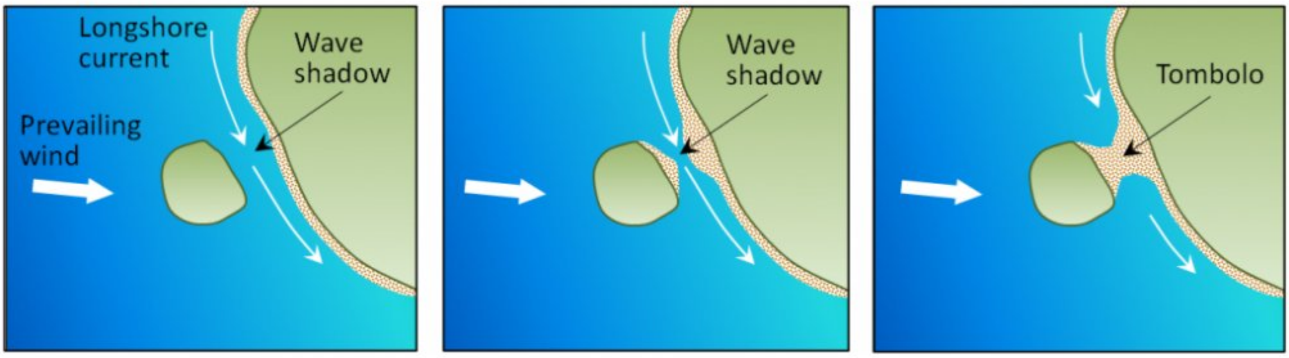


Figure13.4.4 *Formation of a tombolo. In the wind shadow of an island, there is little wave action, so the sediment moved by longshore transport gets deposited, eventually linking the island to the mainland (Steven Earle, "Physical Geology").*

Figure 13.4.5 *A stack (with a wave-cut platform) connected to the mainland by a tombolo, Leboeuf Bay, Gabriola Island, British Columbia (Steven Earle, "Physical Geology").*

In areas where coastal sediments are abundant and coastal relief is low (because there has been little or no recent coastal uplift), it is common for **barrier islands** to form (Figure 13.4.6). Barrier islands are elongated islands composed of sand that form offshore from the mainland, potentially reaching several kilometers wide and hundreds of kilometers long. They are common along the U.S. Gulf Coast from Texas to Florida, and along the U.S. Atlantic Coast from Florida to Massachusetts. The islands often form as the result of sediment moving offshore through river discharge, while wave action works to push the sediment back towards the shore. The resulting sediment buildup is then stretched into long barrier islands by longshore transport.

Figure 13.4.6 *Assateague Island on the Maryland coast, U.S. This barrier island is about 60 km long and only 1 km to 2 km wide. The open Atlantic Ocean is to the right and the lagoon is to the left. This part of Assateague Island has recently been eroded by a tropical storm, which pushed massive amounts of sand into the lagoon. (http://soundwaves.usgs.gov/2014/04/images/DelmarvaAssateague_aerial_ViewCV.jpg).*

Mature barrier islands contain a number of ecological zones. Beginning on the ocean side of the island there is a beach, consisting of the zones we discussed in section 13.1. Behind the beach lie dunes that are built up by sand transported by wind. The ocean side of the dunes are home to grasses and other plants which help stabilize the sand from erosion, and also help slow down the wind to allow sand to settle and accumulate. Beyond the dunes lies a more heavily vegetated barrier flat, covered by larger shrubs and trees that are tolerant to the high winds and salty conditions. As the land slopes down on the side of the island facing the mainland, the low-lying areas transition into a salt marsh or mud flat habitat, which is protected from wave action, but is influenced by tidal changes. The mud flats are colonized by grasses, which slow down the movement of water and lead to increased sediment deposition, building up the land in the marsh. Different species of grasses eventually dominate the different elevations of the salt marsh, depending on their tolerance for submersion in seawater. These salt marshes are very important habitats for many invertebrates, birds, and juvenile fish. Between the island and the mainland lies a lagoon, which usually contains brackish water from the mixing of fresh water runoff from the land and the seawater within a somewhat enclosed space. Barrier islands, although attractive locations for beach houses, are not permanent structures, and people should be wary of building on them. Over time, the erosion on the seaward side of the island, and the expansion of the marsh on the landward side, causes the island to slowly move towards the mainland, eventually closing off the lagoon. Maintaining dune grasses is one way to slow this movement, and as we will see in the next section, people have developed a number of other strategies to try to curtail the natural erosion of beaches.

13.5 Human Interference with Shorelines

The continued erosion and deposition of coastal sediments is a natural process, with features forming and disappearing as sea level and other conditions change. However, we have also come to enjoy and rely on many of these beaches and other coastal features for commerce, recreation, and living space. So from our perspective, we often see the transient nature of the coast as a threat to our activities, and as a result we have developed a number of ways to try and influence the erosion process, usually through **hard stabilization**, or the building of structures to stop the flow of sand. While some of these efforts have been successful, many others have actually exacerbated the problem, as we will see below.

Groins (or groynes) are barriers built perpendicular to the shore (Figure 13.5.1 *left*). Groins are built to interrupt longshore transport and trap sand upstream of the groin, which they do very well. But downstream of the groin the source of replacement sand is cut off, while sand continues to be removed, so erosion can become even more pronounced on that side of the groin. To prevent that erosion, another groin must be built downstream of the first one, which then creates its own erosion problems, leading to another groin, and so on. Eventually a beach may become covered in a series of groins, called a **groin field**, all trying to stabilize the natural flow of sand (Figure 13.5.1 *right*).

Figure 13.5.1 *Left: A groin on Bolinas Beach, California. Longshore transport would be moving from right to left, accumulating sand on the right of the groin (Beatrice Murch, https://www.flickr.com/photos/blmurch/952523971, CC BY-SA 2.0). Right: A groin field. Longshore transport would move from the bottom of the picture towards the top (https://pxhere.com/en/photo/1048378, Public Domain, CC0).*

Jetties are like longer groins, often built to protect the mouths of harbors to prevent them from filling with sand. Because they are longer they can trap more sand than groins, and they also can contribute to increased erosion on the downstream side (Figure 13.5.2). If too much sand accumulates upstream of the jetty it can spread past the jetty and into the mouth of the harbor, in which case the jetty may need to be extended.

***Figure 13.5.2** The jetties protecting Santa Cruz harbor, California. Sand has accumulated on the left (north) side of the harbor, and the beach is eroded on the right (south) side (Google Maps, Map Data: Google).*

Breakwaters are walls that are usually built parallel to the shore. Their purpose is not necessarily to interfere with sediment transport, but instead to protect the areas behind them from heavy wave action, so they are often deployed at the mouth of a harbor, or to protect the boats in a mooring field. But breakwaters do have an unintended impact on sediment distribution. Longshore transport continues to move sand along the beach, but once it gets behind the breakwater the lack of wave action interrupts the flow, and the sand settles and accumulates. The beach grows behind a breakwater, until eventually they may become connected (Figure 13.5.3). With the longshore transport interrupted, increased erosion can occur downstream of the breakwater.

***Figure 13.5.3** A series of breakwaters along the coast in Skagen, Denmark. In this case, sand has accumulated to the point that they now connect the breakwaters to land (Google Maps; Imagery: DigitalGlobe, Aerodata,International Surveys, TerraMetrics, Data SIO, NOAA, US Navy, NGA, GEBCO, Map Data: Google).*

Santa Monica Pier

The beach around the Santa Monica Pier in California provides a good example of the effects of breakwaters on a sandy shore. A breakwater was constructed in the early 1930s to protect the pier and the boats that moored near it. Following the construction, the once-straight beach became much wider behind the breakwater as sand accumulated in the absence of strong wave action (*below left*). Now that the breakwater is no longer in place, the bulge in the shoreline is gone, and the beach is much straighter once again (*below right*).

Left; aerial image of Santa Monica Pier and breakwater from 1936 (Courtesy of Santa Monica Public Library Image Archives/ Spence Air Photos). Right; Santa Monica Pier in 2011 (© JCS, CC BY-SA 3.0, via Wikimedia Commons).

Seawalls are constructed at the top of the surf zone, where the waves crash against the shore. The walls are designed as a barrier between the waves and the shore, to prevent the land from being eroded (Figure 13.5.4). They are often utilized in beachfront property to prevent the ground under a home from being undermined by the waves. However, as with the other forms of hard stabilization we have discussed, seawalls are not without their own environmental consequences. The sudden release of wave energy on a seawall can create turbulence, which undermines the sediment at the base of the wall and causes it to erode. Furthermore, on a softer, natural coastline some of the wave energy is absorbed or dissipated, but with a hard seawall most of the wave energy is reflected, leading to stronger longshore currents and faster erosion. In many places where seawalls have been built the beaches are getting steeper, and erosion rates have increased, with the potential for seawalls to collapse along with whatever they are supporting. Because of this, some coastal communities are phasing out seawall construction to try to return to more natural beach fronts.

Figure 13.5.4 *A sea wall at Horsey Gap, UK (Evelyn Simak [CC BY-SA 2.0], via Wikimedia Commons).*

13.6 Estuaries

Estuaries are partially enclosed bodies of water where the salt water is diluted by fresh water input from land, creating **brackish** water with a salinity somewhere between fresh water and normal seawater. Estuaries include many bays, inlets, and sounds, and are often subject to large temperature and salinity variations due to their enclosed nature and smaller size compared to the open ocean.

Estuaries can be classified geologically into four basic categories based on their method of origin. In all cases they are a result of rising sea level over the last 18,000 years, beginning with the end of the last ice age; a period that has seen a rise of about 130 m. The rise in sea level has flooded coastal areas that were previously above water, and prevented the estuaries from being filled in by all of the sediments that have been emptied into them.

The first type is a **coastal plain estuary**, or **drowned river valley**. These estuaries are formed as sea level rises and floods an existing river valley, mixing salt and fresh water to create the brackish conditions where the river meets the sea. These types of estuaries are common along the east coast of the United States, including major bodies such as the Chesapeake Bay, Delaware Bay, and Narragansett Bay (Figure 13.6.1). Coastal plain estuaries are usually shallow, and since there is a lot of sediment input from the rivers, there are often a number of depositional features associated with them such as spits and barrier islands.

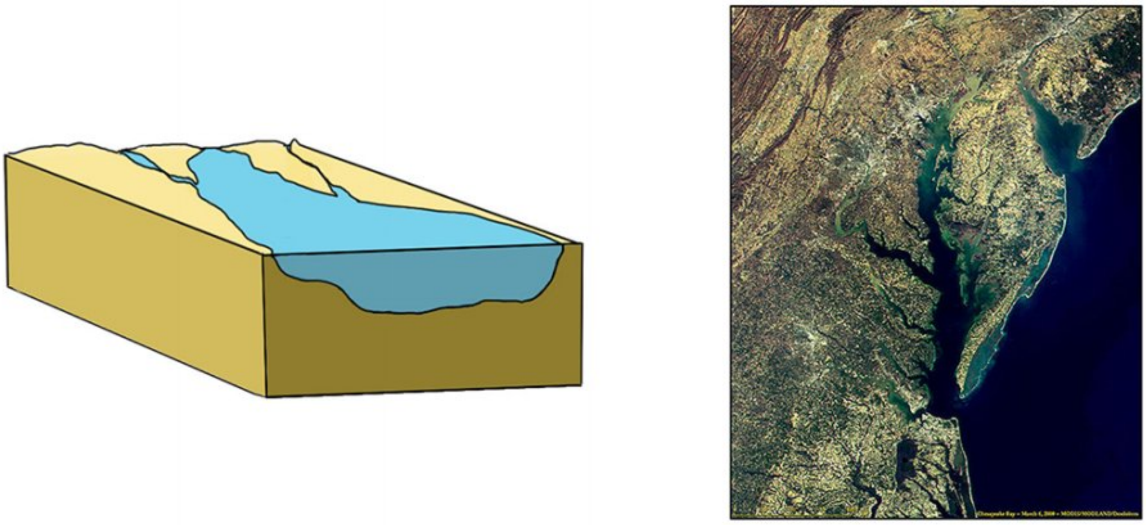


Figure 13.6.1 *A coastal plain estuary. Sea level has risen and flooded what was once a river valley. The satellite image shows Chesapeake Bay and Delaware Bay, two coastal plain estuaries (left: JR, right: NASA, Public Domain via Wikimedia Commons).*

The presence of sand bars, spits, and barrier islands can lead to **bar-built estuaries**, where a barrier is created between the mainland and the ocean. The water that remains inside the sand bar is cut off from complete mixing with the ocean, and receives freshwater input from the mainland, creating estuarine conditions (Figure 13.6.2).

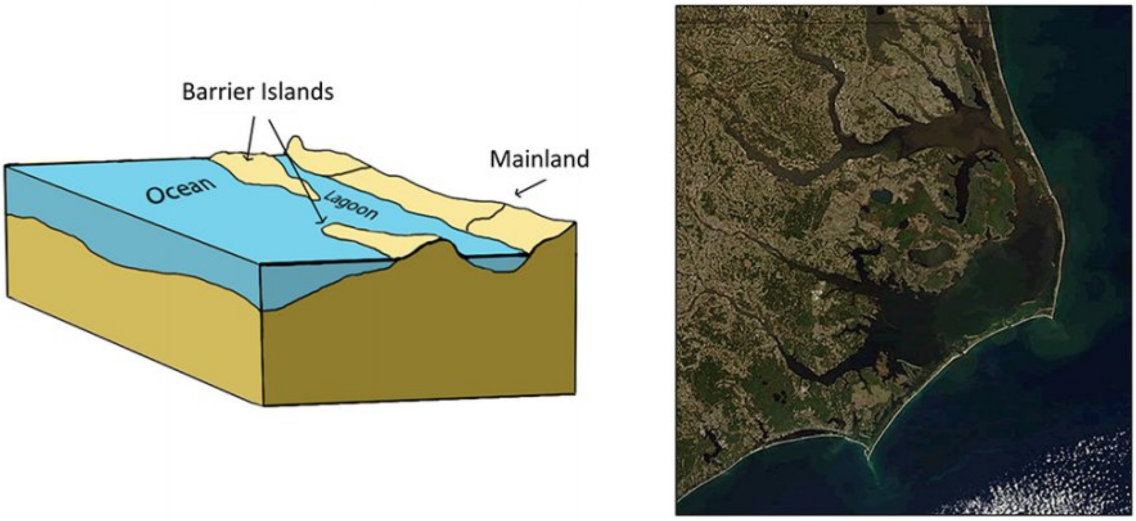


Figure 13.6.2 *A bar-built estuary. Sand bars and barrier islands have partially isolated a lagoon from the rest of the ocean. Freshwater input into the lagoon from the mainland creates brackish conditions in the estuary. At right is a satellite image of Pamlico Sound, North Carolina, a bar-built estuary surrounded by spits and barrier islands (left: JR, right: NASA, Public Domain via Wikimedia Commons).*

Fjords are estuaries formed in deep, U-shaped basins that were carved out by advancing glaciers. When the glaciers melted and retreated, sea level rose and filled these troughs, creating deep, steep-walled fjords (Figure 13.6.3). Fjords are common in Norway, Alaska, Canada, and New Zealand, where there are mountainous coastlines once covered by glaciers.

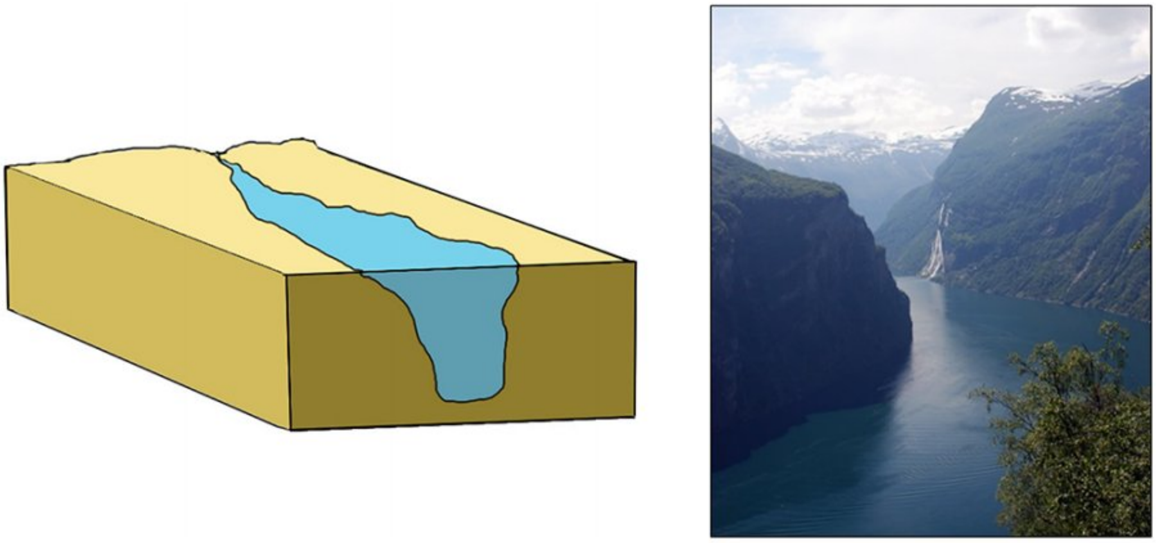


Figure 13.6.3 *A fjord is a deep estuary that was carved out by glacial movements. At right is Geirangerfjord, Norway (left: JR, right: Fgmedia, [CC-BY-SA-3.0], via Wikimedia Commons).*

Tectonic estuaries are the result of tectonic movements, where faulting causes some sections of the crust to subside, and those lower elevation sections then get flooded with seawater. San Francisco Bay is an example of a tectonic estuary (Figure 13.6.4).

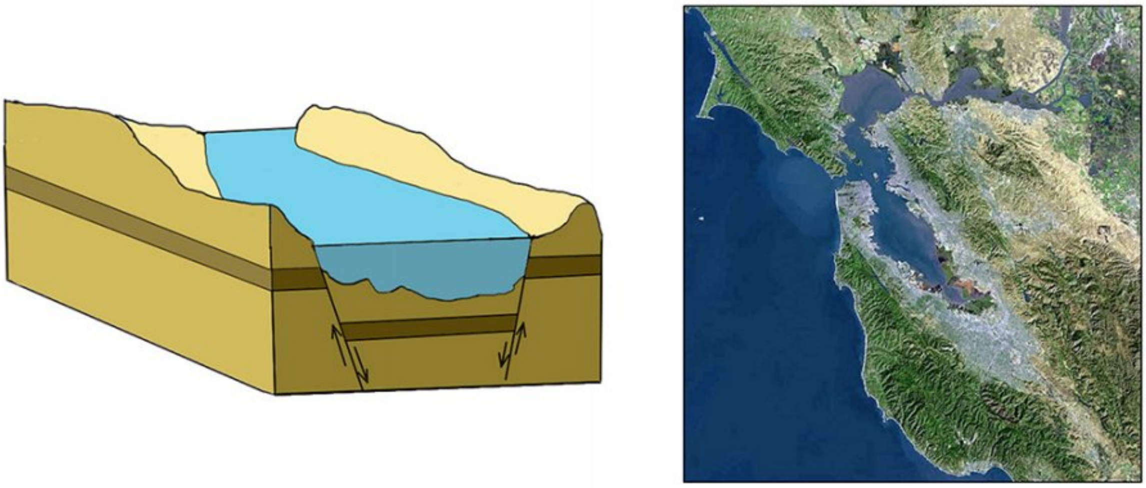


***Figure 13.6.4** A tectonic estuary, formed from the subsidence of crust along fault lines, and the subsequent filling by seawater. San Francisco Bay is a tectonic estuary, shown at right (left: JR, right: USGS, Public Domain, via Wikimedia Commons).*

Estuaries are also classified based on their salinity and mixing patterns. The amount of mixing of fresh and salt water in an estuary depends on the rate at which fresh water enters the head of the estuary from river input, and the amount of seawater that enters the estuary mouth as a result of tidal movements. The input of fresh water is reflected in the **flushing time** of the estuary. This refers to the time it would take for the in-flowing fresh water to completely replace all the fresh water currently in the estuary. Seawater input is measured by the **tidal volume**, or **tidal prism**, which is the average volume of sea water entering and leaving the estuary during each tidal cycle. In other words, it is the volume difference between high and low tides. The interaction between the flushing time, tidal volume, and the shape of the estuary will determine the extent and type of water mixing within the estuary.

In a **vertically mixed**, or **well-mixed** estuary there is complete mixing of fresh and salt water from the surface to the bottom. In a particular location the salinity is constant at all depths, but across the estuary the salinity is lowest at the head where the fresh water enters, and is highest at the mouth, where the seawater comes in. This type of salinity profile usually occurs in shallower estuaries, where the shallow depths allow complete mixing from the surface to the bottom.

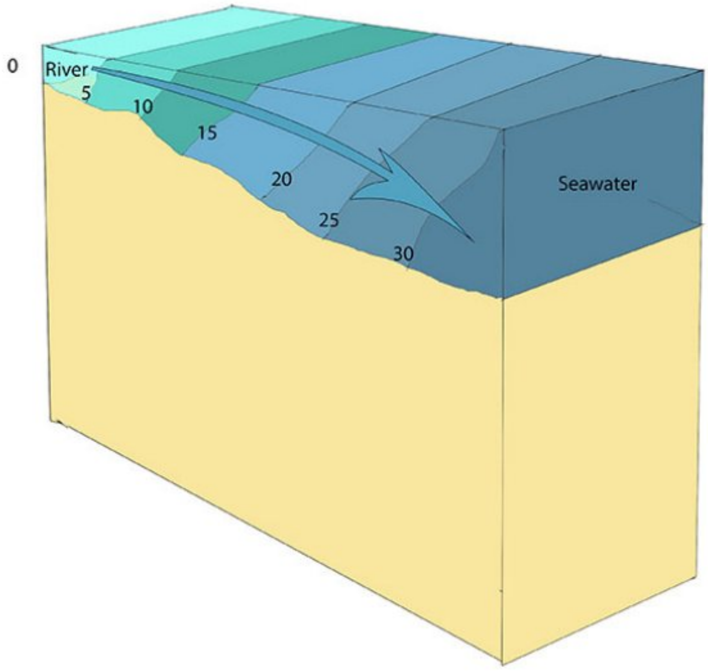


Figure 13.6.5 *A well-mixed estuary. The shallow basin allows nearly complete mixing or fresh and seawater from top to bottom. Salinities are in ppt (JR).*

Slightly stratified or **partially mixed** estuaries have similar salinity profiles to vertically mixed estuaries, where salinity increases from the head to the mouth, but there is also a slight increase in salinity with depth at any point. This usually occurs in deeper estuaries than those that are well-mixed, where waves and currents mix the surface water, but the mixing may not extend all the way to the bottom.

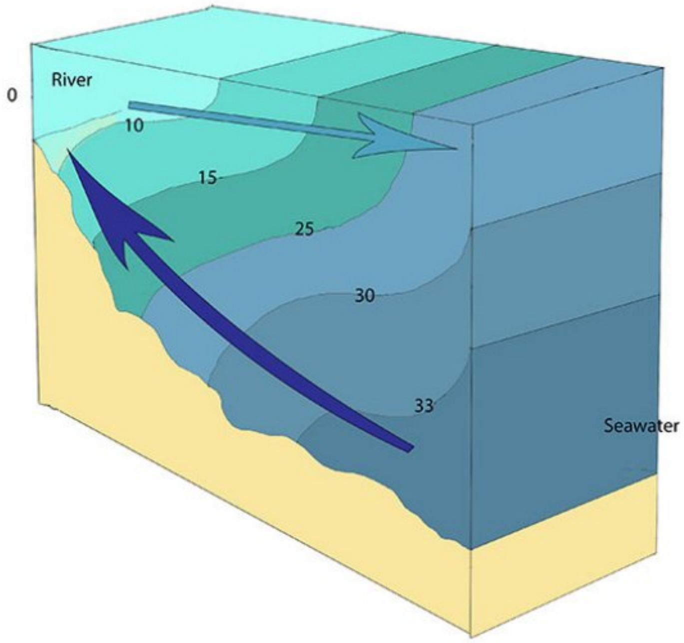


Figure 13.6.6 *A slightly-stratified estuary. Generally deeper than a well-mixed estuary, the inflow of seawater (dark blue arrow) and fresh water (light blue arrow) create an estuary where salinity increases with depth, and at the surface when moving from the head to the mouth of the estuary. Salinities are in ppt (JR).*

A **salt wedge** estuary occurs where the outflow of fresh water is strong enough to prevent the denser ocean water to enter through the surface, and where the estuary is deep enough that surface waves and turbulence have little mixing effect on the deeper water. Fresh water flows out along surface, salt water flows in at depth, creating a wedge shaped lens of seawater moving along the bottom. The surface water may remain mostly fresh throughout the estuary if there is no mixing, or it can become brackish depending on the level of mixing that occurs.

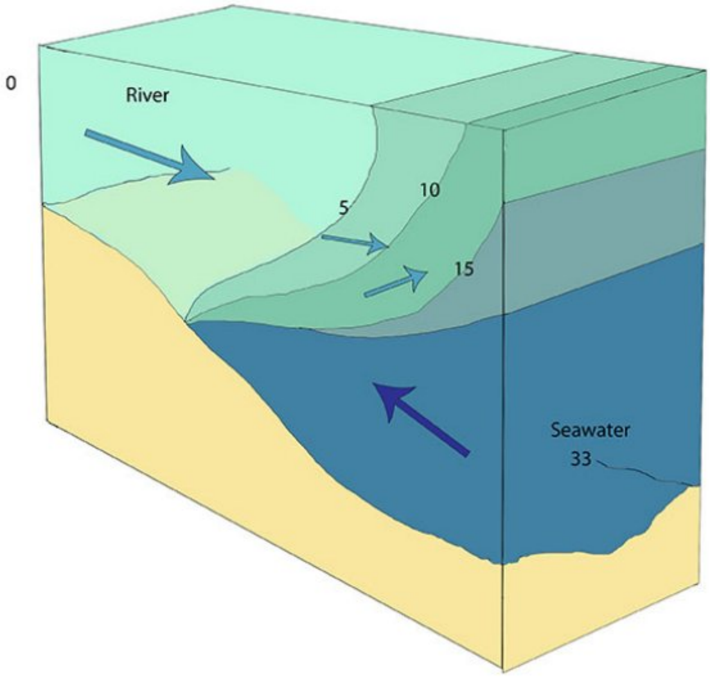


Figure 13.6.7 *A salt wedge estuary. Strong river outflow (light blue arrows) creates a layer of mostly fresh water that sits on top of a wedge of encroaching seawater along the bottom (dark blue arrow). Salinities are in ppt (JR).*

Highly stratified profiles are found in very deep estuaries, such as in fjords. Because of the depth, mixing of fresh and salt water only occurs near the surface, so in the upper layers salinity increases from the head to the mouth, but the deeper water is of standard ocean salinity.

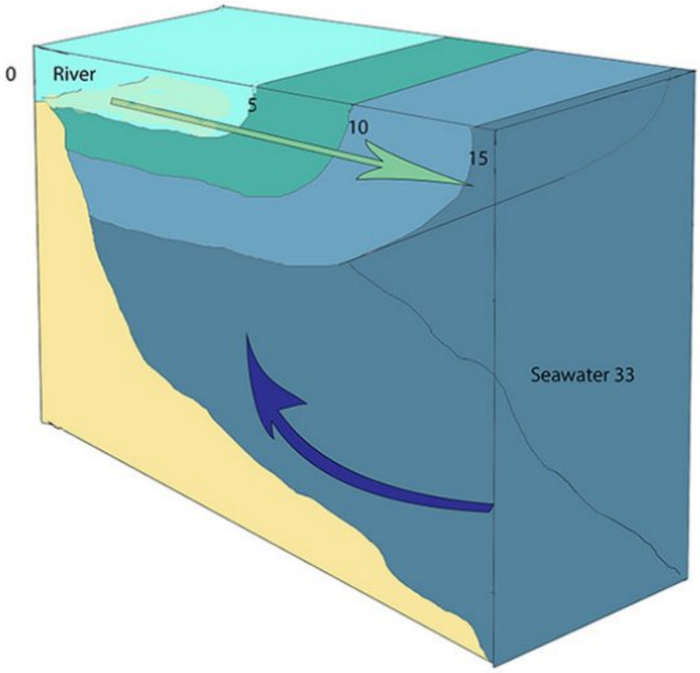


Figure 13.6.8 *A highly stratified estuary. Strong river outflow and a deep basin prevent mixing between surface and bottom water, creating an estuary that is vertically stratified. Salinities are represented in ppt (JR).*

Estuaries are very important commercially, as they are home to the majority of the world's metropolitan areas, they serve as ports for industrial activity, and a large percentage of the world's population lives near estuaries. Estuaries are also very important biologically, especially in their role as the breeding grounds for many species of fish, birds, and invertebrates.

13.7 Sea Level Change

*Modified from "Physical Geology" by Steven Earle**

Sea level change has been a feature on Earth for billions of years, and it has important implications for coastal processes, estuaries, and both erosional and depositional features. There are two main mechanisms of sea level change, eustatic and isostatic, as described below.

Eustatic sea level changes are global sea level changes related to changes in the volume of water in the ocean. These can be due to changes in the volume of glacial ice on land, thermal expansion of the water, or to changes in the shape of the seafloor caused by plate tectonic processes. For example, seafloor spreading widens an ocean basin, thus changing its volume and affecting sea level.

Over the past 20,000 years, there has been approximately 125 m of eustatic sea level rise due to glacial melting. Most of that took place between 15,000 and 7,500 years ago during the major melting phase of the North American and Eurasian Ice Sheets (Figure 13.7.1). At around 7,500 years ago, the rate of glacial melting and sea level rise decreased dramatically, and since that time, the average rate has been in the order of 0.7 mm/year.

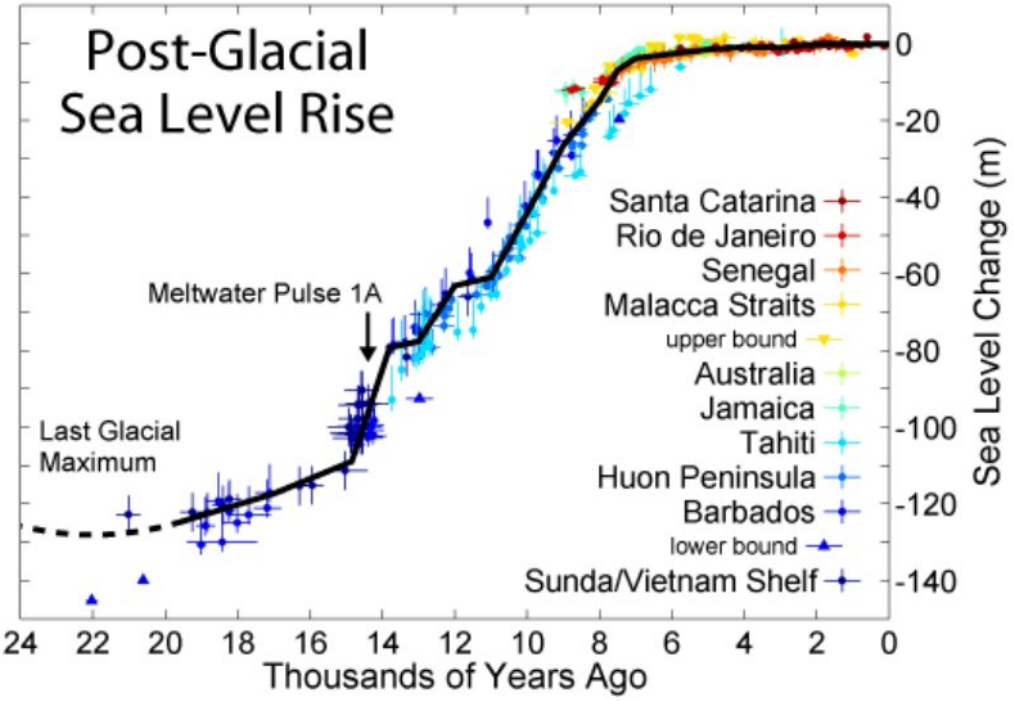
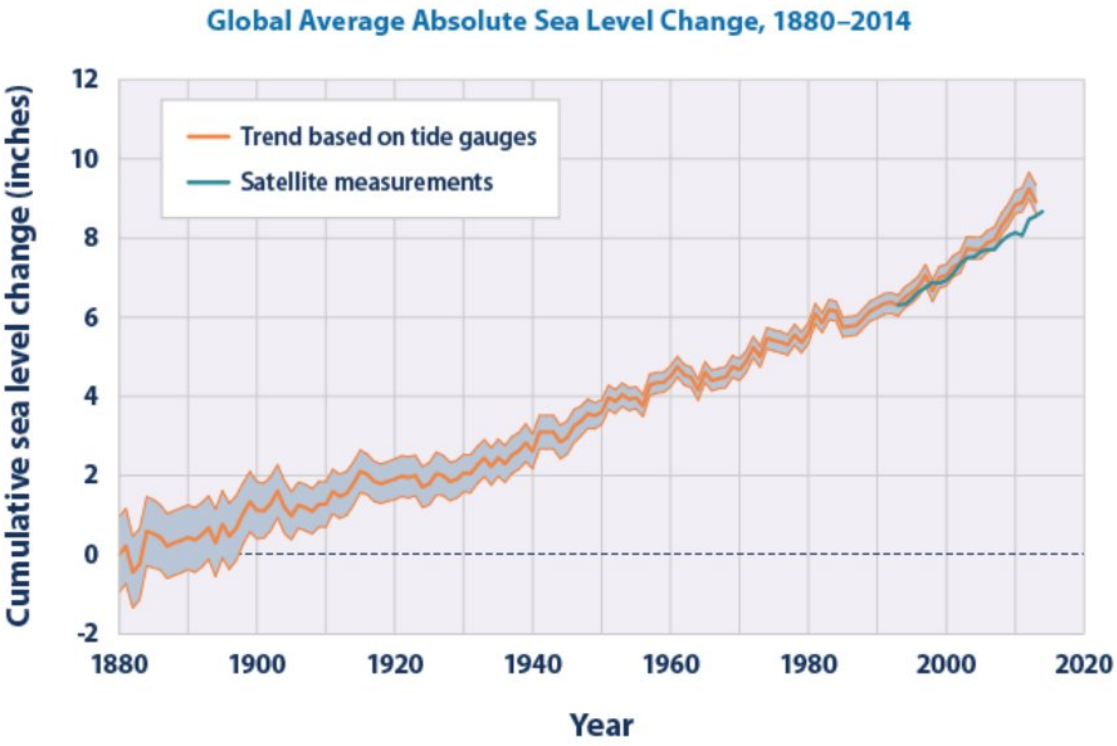


Figure 13.7.1 *Sea level rise resulting from the melting of glacial ice over the past 24,000 years (Robert A. Rhode, CC BY-SA 3.0, via Wikimedia Commons).*

Anthropogenic climate change led to accelerating sea level rise starting around 1870. Since that time, the average rate has been 1.1 mm/year, but it has been gradually increasing. Since 1992, the average rate has been 3.2 mm/year (Figure 13.7.2). Much of this is due to increased glacial melting as the global climate gets warmer (section 14.3), but a large part is due to **thermal expansion** of the water. As water warms, the molecules gain more kinetic energy and move faster and farther apart; the result is that the same amount of water now takes up more space. So even without the input of new water from melting ice, warming ocean temperatures will cause sea level to rise.



Data sources:

- CSIRO (Commonwealth Scientific and Industrial Research Organisation). 2015 update to data originally published in: Church, J.A., and N.J. White. 2011. Sea-level rise from the late 19th to the early 21st century. Surv. Geophys. 32:585–602. www.cmar.csiro.au/sealevel/sl_data_cmar.html.
- NOAA (National Oceanic and Atmospheric Administration). 2015. Laboratory for Satellite Altimetry: Sea level rise. Accessed June 2015. http://ibis.grdl.noaa.gov/SAT/SeaLevelRise/LSA_SLR_timeseries_global.php.

For more information, visit U.S. EPA's "Climate Change Indicators in the United States" at www.epa.gov/climatechange/indicators.

Figure 13.7.2 *Average absolute sea level change, which refers to the height of the ocean surface, regardless of whether nearby land is rising or falling. Satellite data are based solely on measured sea level, while the long-term tide gauge data include a small correction factor because the size and shape of the oceans are changing slowly over time (US EPA [Public domain], via Wikimedia Commons).*

Isostatic sea level changes are local changes caused by subsidence or uplift of the crust related either to changes in the amount of ice on the land, or to growth or erosion of mountains. Almost all of Canada and parts of the northern United States were covered in thick ice sheets at the peak of the last glaciation. Following the melting of this ice, there has been an isostatic rebound of continental crust in many areas. This ranges from several hundred meters of rebound in the central part of the Laurentide Ice Sheet (around Hudson Bay) to 100 m to 200 m in places such as Vancouver Island and the mainland coast of British Columbia. In other words, although global sea level was about 130 m lower during the last glaciation, the glaciated regions were depressed at least that much in most places, and more than that in places where the ice was thickest. Tectonic processes, such as the uplift of crust, can also cause localized changes in sea level.