ENVIRONMENTAL GEOLOGY FOR CBE



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Environmental Geology for CBE

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Licensing

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CHAPTER OVERVIEW

1: Introduction



This chapter provides a definition of what environmental geology is and lists the topics the text addresses.

1.1: Environmental Geology Defined

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1.1: Environmental Geology Defined

Environmental geology is about the interface between geological processes and the environment, and we choose to use a broad definition of “the environment”. This includes Earth's biosphere (all living things), the hydrosphere (all water including frozen water), the atmosphere (the layer of gas that surrounds Earth), and the geosphere/lithosphere (all loose sediment and rock). It also includes human activities that affect the geosphere/lithosphere, such as mining, energy resource extraction, and waste disposal: into the ground, into water and into the air. Summarized, it involves how we can practically apply the principles of geology in the solving of environmental problems created by man.

To understand environmental geology, you must first understand these earth systems. This course covers the following topics as it relates to these systems:

1. Earth's Interior
2. Plate Tectonics
3. Minerals
4. Rocks
5. Soils
6. Volcanoes
7. Earthquakes
8. Tsunamis
9. Earth’s Atmosphere
10. Carbon and Nitrogen Cycles
11. Weather
12. Climate
13. Water Resources

Then we add in the effects of humans and explore topics like:

1. Mass Wasting
2. Water Needs
3. Flooding
4. Drought
5. Energy Needs
6. Energy Resources
7. Waste Disposal
8. Water Pollution
9. Air Pollution
10. Climate Change
11. Sea Level Change

It isn’t difficult to see that Environmental Geology is more important now than it has ever been. This is partly because environmental issues in general are more important than ever due to the crisis of climate change and the rapidly expanding human population, but also because climate change is, to a large degree, a geological problem. We can understand its past by studying the geological record going back thousands, millions and billions of years and we can understand its present by applying geological methods to data collection and analysis. Other environmental concerns, many related to the topics listed above, are critical as well.

Most important of all, we can affect the future of all environmental issues by changing the way we do things, and through the decisions we make as we set policy.

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CHAPTER OVERVIEW

2: Physical Geology Overview



This chapter takes many of the topics addressed in an Introductory Geology course and presents them in a condensed format. Normally each of these topics would be their own chapter; this textbook only presents what is essential to understand the remaining topics in this textbook. Since the breadth of this subject is wide, often topics are simplified in order to gain the base-level understanding required for this course.

2.1: Earth’s Interior
2.2: Plate Tectonics
2.3: Minerals
2.4: Rocks

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2.1: Earth's Interior

As shown on Figure 2.1.1 the interior of the Earth is comprised of several concentric layers, starting with the crust at surface, down through the different parts of the mantle, and then into the outer and inner core.

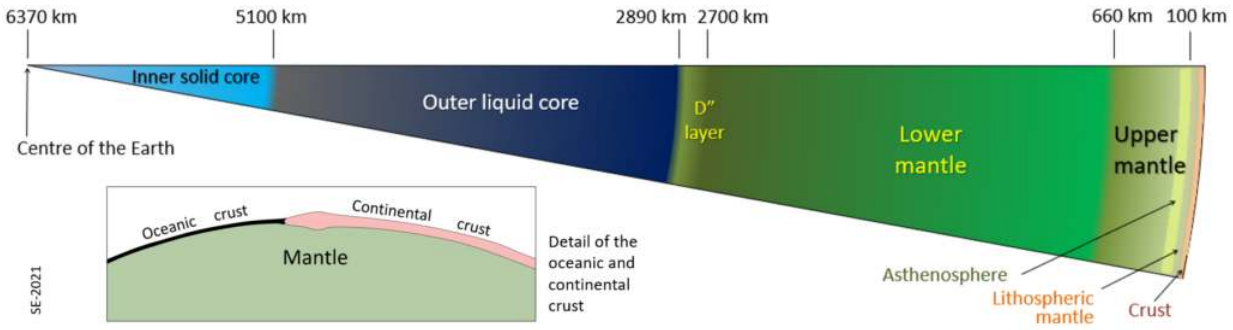


Figure 2.1.1: The Parts of the Earth's Interior

The **crust** is the Earth's thin, brittle, outer layer, and is shown in more detail in the inset of Figure 2.3.1. It makes up approximately 0.2% of the Earth's radius, and therefore is proportionally no thicker than the skin on an apple. There are two types of crust: continental (making up the land) and oceanic (found at the bottom of oceans). The continental crust is dominated by rocks formed as magma (molten rock below the surface) cools and forms rocks like granite. There are also lesser amounts of various types of rocks that form when lava cools (like you see in Hawaii), sedimentary rocks (like you see in the Grand Canyon), and metamorphic rocks (a rock type you will learn about soon). Overall, it has a composition high in silica (silicon and oxygen) which has a relatively low density and low in metals making it relatively "light". It is 30 to 40 km thick in most areas (thicker in mountainous areas, and thinner near to the edges of the continents). The oceanic crust is also made from rocks formed as magma or lava cools, but it is much thinner at 5 to 6 km thick in most areas. These rocks contain more metals than the continental crust, so they are denser.

The key takeaways about the crust are:

- The crust is the thin, brittle, outer layer of Earth.
- There are two types of crust.
- Continental crust is thick and "light" or less dense. Oceanic crust is thin and "heavy" or denser.

The crust rests on the **mantle**, which is made up of rocks that are high in metals. The upper part of the mantle is rigid or brittle, just like the crust. That rigid part of the mantle plus the crust is called the **lithosphere**. The temperature within the Earth increases with depth, from close to 0^0 C at surface to almost 5000^0 C in the center of the core, but that rate of increase isn't linear (Figure 2.1.2). The temperature rises quite rapidly within the lithosphere, but the rate slows within the lower mantle. At between about 100 and 250 km depth the temperature is very close to, or even slightly above, the melting temperature for mantle rock and so the mantle rock within that depth range is partly molten. This layer is known as the **asthenosphere** because the rock there is weaker (softer, or more plastic-like) than in the rest of the mantle.

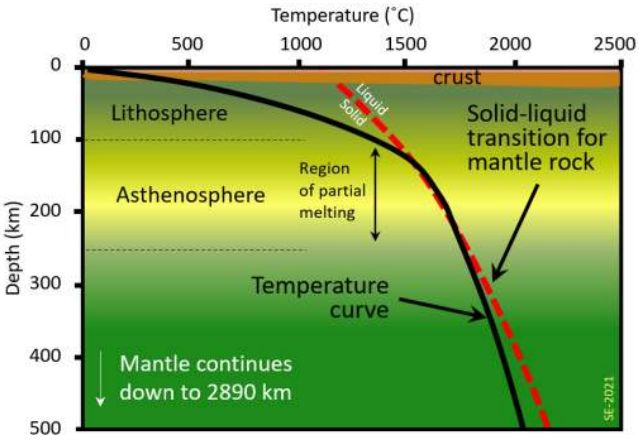


Figure 2.1.2: Temperature and Partial Melting in the Upper Part of the Mantle

The asthenosphere, due to heat transfer from the core, is slowly convecting. As we'll see in the next section, that convection is critical to the process of plate tectonics.

The key takeaways about the mantle are:

- The mantle is a thick middle part of the Earth's interior that is high in metals.
- The upper part of the mantle is solid, so we combine it with the solid crust and call this the lithosphere.
- Below the solid part of the mantle is a plasticy or waxy layer of the mantle we call the asthenosphere.
- Convection occurs in the asthenosphere which will be important later.

The Earth's **core** is mostly made of iron, with up to 10% nickel and a small proportion of other elements. The temperature at the core-mantle boundary is close to 4000^{o} C and that gradually increases to about 5000^{o} C at the Earth's center. In the outer part of the core that temperature is high enough for the iron-nickel alloy to be liquid, but the pressure is so extreme at greater depth that the inner core is solid. The transfer of heat from the core leads to convection in the outer core, and, because the core is metallic, that convection generates the Earth's magnetic field.

The key takeaways about the core are:

- The core is made of iron.
- The outer core is liquid, the inner core is solid.
- Since the core is so hot, the heat transfer causes convection in the outer core which generates the Earth's magnetic field.

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2.2: Plate Tectonics

Plates and Plate Motion

The lithosphere (the upper rigid mantle plus the crust) is divided into several pieces known as **plates** that can move around on the Earth's surface, all in different directions and at different rates. The behavior of these plates: their motions and their interactions with each other is known as plate tectonics, where the word "tectonics" refers to the deformation of rocks. The distributions of the plates are shown on the figure below; the seven major ones are as follows:

- North American Plate
- Eurasian Plate
- Pacific Plate
- African Plate
- South American Plate
- Indo-Australian Plate (includes Australia and India Plates)
- Antarctic Plate

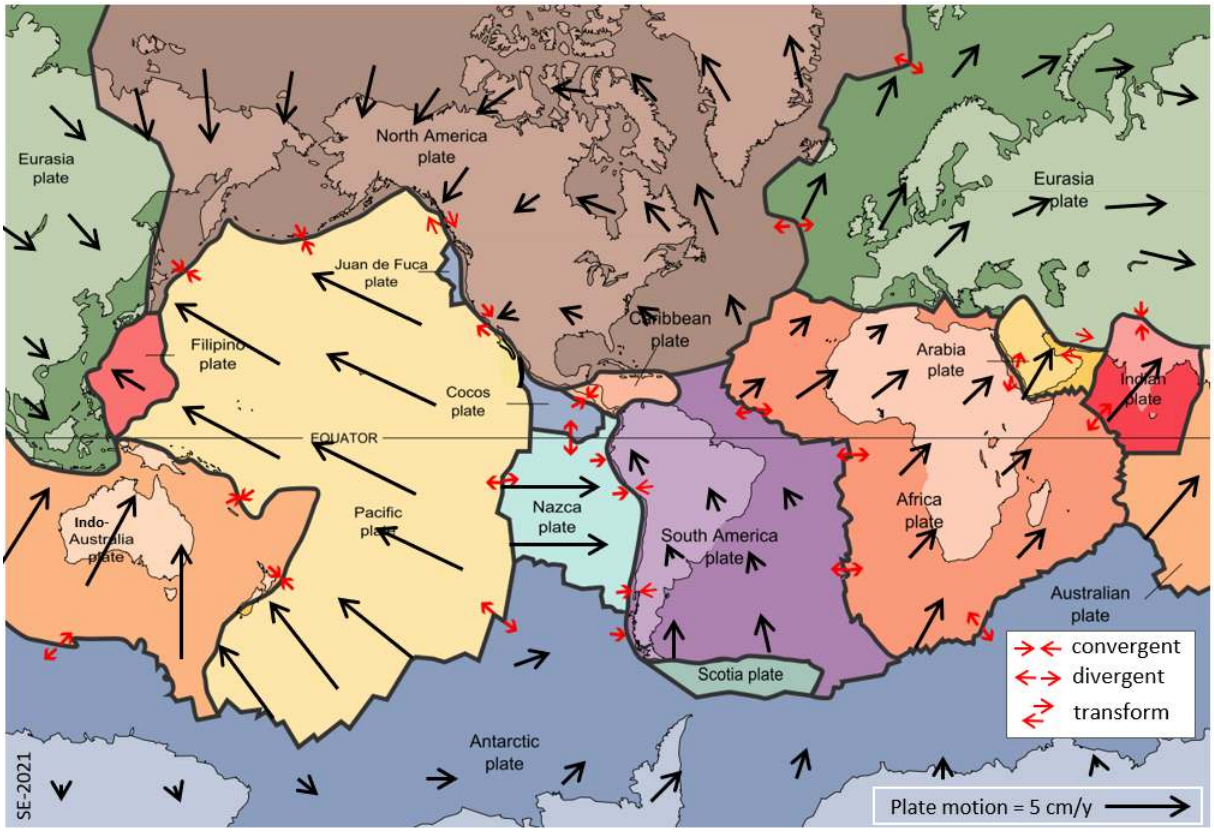


Figure 2.2.1: The Approximate Extents and Rates of Motion of the Earth's Tectonic Plates

Some of the minor plates include the Juan de Fuca, Cocos and Nazca Plates along the western edge of N. America, the Caribbean Plate, and the Scotia, Arabia and Filipino Plates. There are several other smaller plates not shown on this map.

The generalized plate motions are shown in the figure with black arrows. Plate motions range from roughly 1 to 10 cm/yr (larger arrows mean the plate is moving faster there). As can be seen on the map, parts of individual plates are moving in different directions and at different rates. That's not because the plates are squeezing and stretching (although that does happen near to plate boundaries) but because the plates are all moving in a rotational way, each around a different rotational axis. The North America Plate is moving counterclockwise around an axis in the southern hemisphere, so the rate of motion is greater in the far north than in the south, and it changes from "towards the northwest" in the east to "towards the southeast" in the west.

Plate Boundaries

At **plate boundaries** the interaction between plates can be: convergent (moving towards each other), divergent (moving away from each other), or transform (sliding past one another). A **convergent boundary** is illustrated on Figure 2.2.2. In this case a plate comprised of oceanic crust is moving towards one comprised of continental crust. Because oceanic crustal is denser than continental crust, the oceanic plate gets pushed down—or subducted—beneath the continental plate. That has some important implications, as shown. First, is that there is friction between the two plates, which results in periodic earthquakes, some of which can be very large. Second, is that the subducted oceanic crust introduces water into the mantle. This water mixes with the hot rocks of the asthenosphere which reduces their melting temperature (so more melting takes place) creating magma that moves towards surface. This magma can erupt at the surface as lava and form a volcano as seen in the figure.

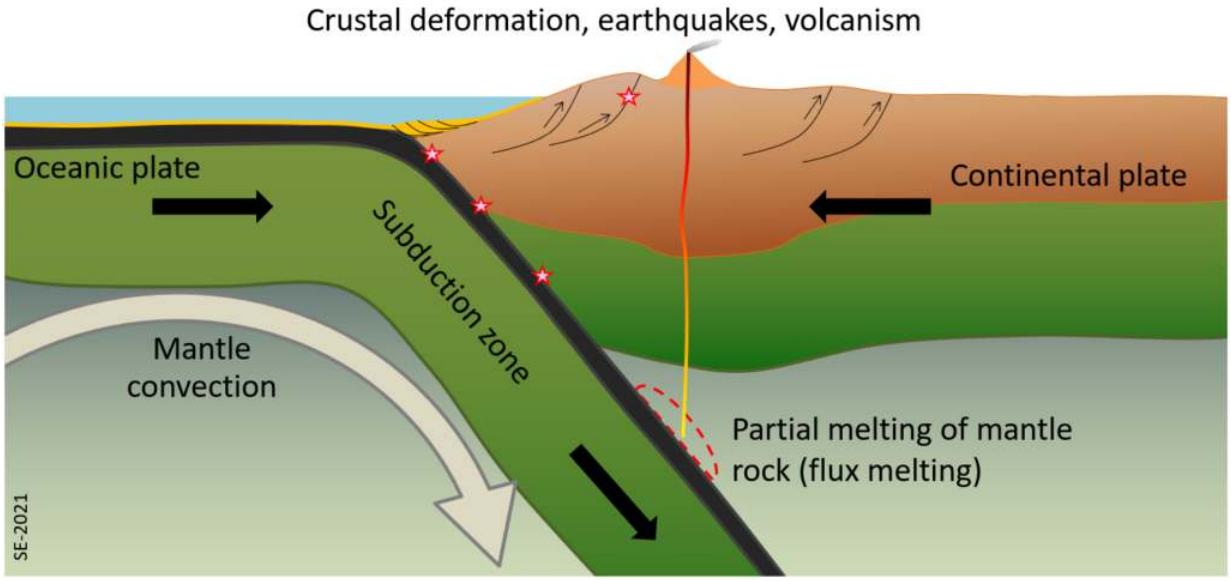


Figure 2.2.2: Depiction of Some of the Processes Taking Place at an Ocean-Continent Subduction Zone. The red stars represent where earthquakes may start.

As an oceanic plate converges with a continental plate, as shown in the figure above, it is possible that a continent or island will be moving along with that oceanic lithosphere and that the two areas of continental lithosphere will eventually collide. This scenario is illustrated in the figure below. In this situation the continental lithosphere cannot be subducted because it isn't sufficiently dense to be pushed down into the mantle. As the continents collide the sediments that had accumulated along their edges get pushed up to form fold-belt mountains and the older crustal rocks also get deformed and pushed up. The leading edge of the subducted oceanic lithosphere eventually breaks off and descends into the mantle.

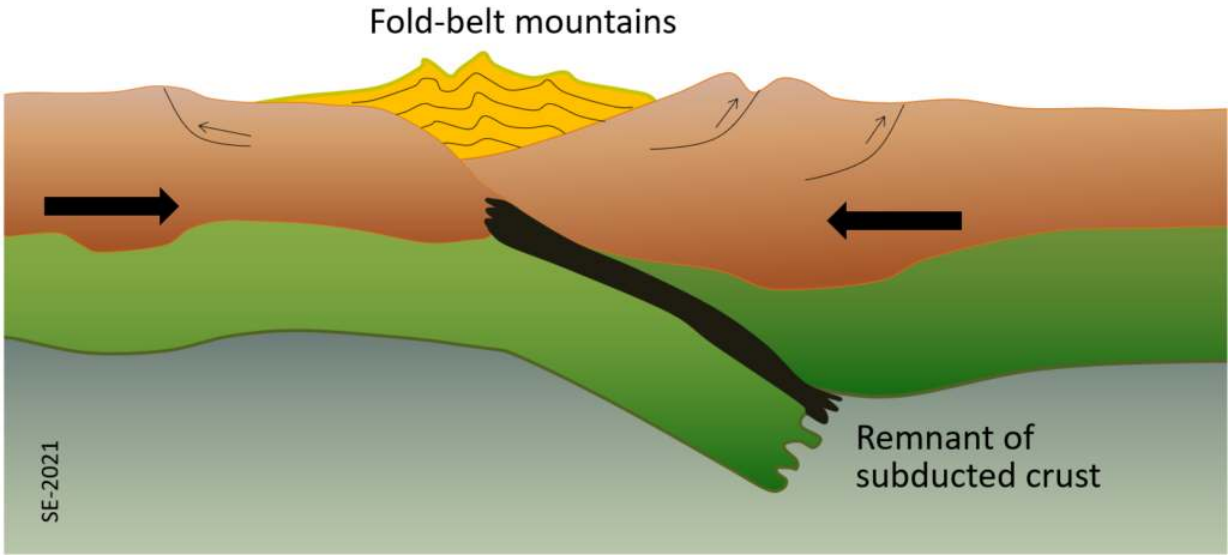


Figure 2.2.3: Depiction of Processes Taking Place at a Continent-Continent Convergence Zone

A **divergent boundary** exists where two plates are moving apart from each other, likely in response to convection in the mantle. This means that there is slow upward movement of mantle rock along the boundary. As the hot mantle rock moves upward it experiences reduced pressure which allows some of it (about 10%) to melt. This produces metal-rich magma that erupts at surface (in this case on the sea floor) as lava. New oceanic crust is made in this way.

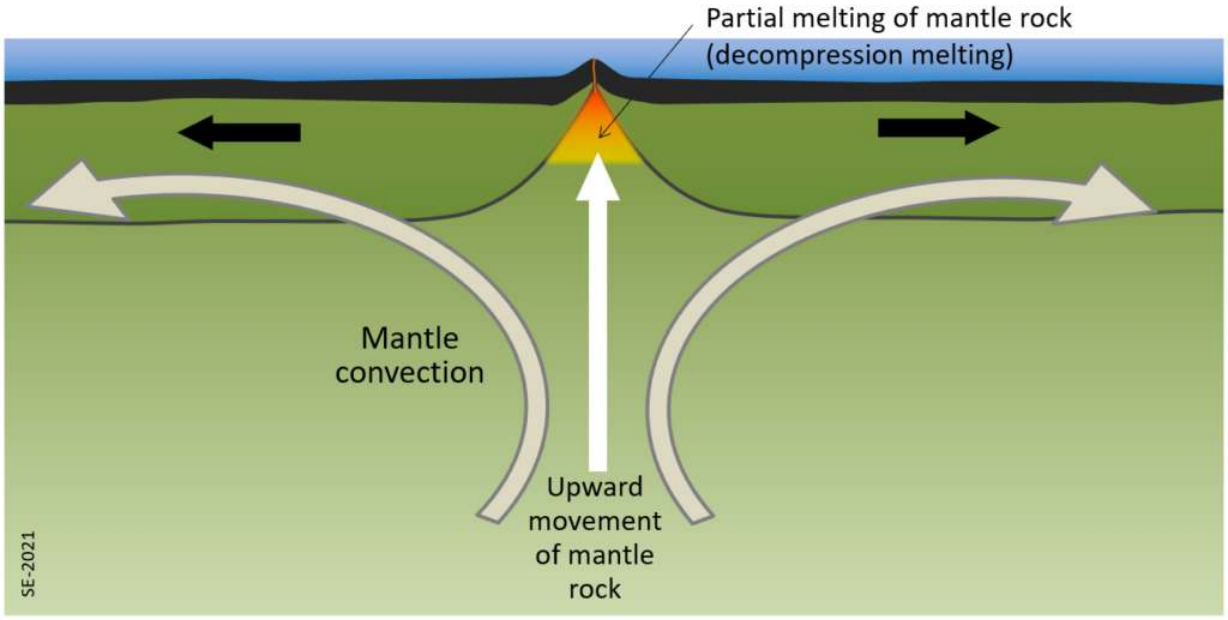


Figure 2.2.4: Depiction of Processes Taking Place at a Divergent Boundary Between Two Oceanic Plates

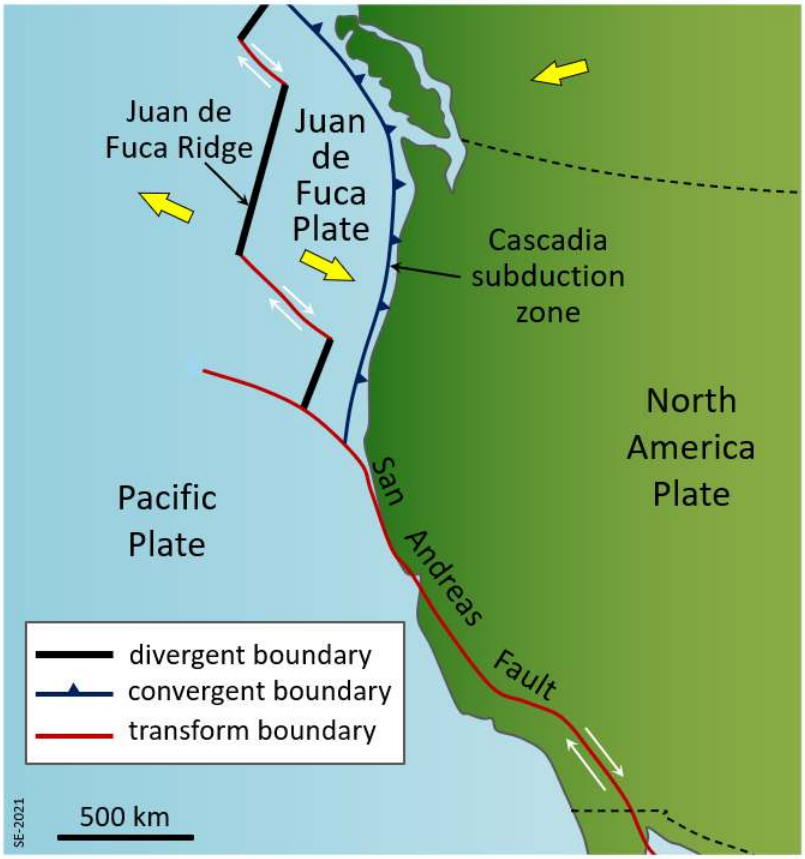


Figure 2.2.5: Three Different Types of Plate Boundaries in the Western US and Canada

Some plate boundaries are shown in plan view on Figure 2.2.5. The Juan de Fuca Ridge, where the Juan de Fuca and Pacific Plates are moving away from each other and new oceanic crust is being made, is an example of a divergent boundary. The Cascadia Subduction Zone is an example of a convergent boundary. Here the Juan de Fuca Plate is pushing down underneath the North America Plate, resulting in earthquakes and volcanoes.

The third type of plate boundary—a **transform boundary**—where two plates are moving side-by-side relative to each other, also exists in this region. An example is the San Andreas Fault, which forms the boundary between the North America and Pacific Plates through California. The relative motion of these two plates is shown with small white arrows. There have been large earthquakes along this boundary, and there are frequent smaller ones. It is important to note that this type of plate boundary produces earthquakes up to about an 8.0 on the Richter scale. The larger events (9.0 and greater) only occur with subduction.

Two smaller transform boundary segments are shown (as red lines) on the map, between the segments of the Juan de Fuca Ridge. In both cases the Juan de Fuca Plate is moving relative to the Pacific Plate, and there are frequent small earthquakes along these boundaries.

Hazards Associated With Plate Boundaries

The sections above address the geologic hazards related to plate tectonics, but it is worth looking at them again, in a more centralized section.

Volcanic Activity

Regarding plate boundaries specifically, there either needs to be a gap at the boundary the magma can exploit or melt needs to be generated somehow and rise to the surface, through the crust.

When two plates move away from one another at divergent boundaries, a space is created that must be filled. Molten material is created below this boundary due to **decompression melting** as seen in Figure 2.2.4. The material rises, fills the gap, and cools to form new crust. When this happens out in the ocean, new ocean floor is created. This does not affect humans as this is not where

we live. When this happens on land, it eventually pulls the continental crust apart enough an ocean forms, but in the meantime the crust thins, and bits of molten material rises to the surface and volcanoes form.

When two plates move toward one another at convergent boundaries, two things can happen. In the case where both plates are made of continental crust, land is pushed up and mountains form (Figure 2.2.3), but there is no volcanic activity. In the case where at least one of the plates is made of oceanic crust, the plate subducts and magma is generated (Figure 2.2.2) resulting in the formation of a chain of volcanoes.

When two plates slide past one another at transform boundaries there is no gap to fill, and molten material is not generated. Accordingly, there is no volcanic activity at these boundaries.

To summarize whether various plate boundaries are volcanically active:

- Divergent boundaries - yes
- Convergent boundaries without subduction - no
- Convergent boundaries with subduction - yes
- Transform boundaries - no

Earthquakes

Since **earthquakes** are generated on active faults, and active faults primarily exist at plate boundaries, this is where 90% of earthquakes occur. When looking at divergent boundaries, since the processes are happening in the uppermost part of the crust (Figure 2.2.4), the earthquakes generated tend to occur at shallow depths. At convergent boundaries, especially those with subduction, earthquakes occur at shallow and deep depths. This is because the stresses associated with those collisions are happening deeper into the Earth's interior (figures 2.2.2 and 2.2.3). This is also the type of plate boundary that generates the largest earthquakes (>9.0M). Transform boundary earthquakes are typically quite shallow and can be sizable (~8.0M) but do not reach the magnitude of the largest convergent boundary events.

To summarize earthquake activity by plate boundary type:

- Divergent boundaries - shallow; smaller in magnitude
- Convergent boundaries - shallow to deep; very large in magnitude
- Transform boundaries - shallow; large in magnitude (but not as large as convergent boundary events)

Mass Wasting

Mass wasting is discussed in detail in a future chapter. For now, you can think of mass wasting as synonymous with landslides. These events are driven by gravity, so for them to occur land must be uplifted above the surrounding area, so the land has somewhere to slide to. Divergent boundaries are unique because as you can see in Figure 2.2.4, a little ridge develops at the spreading center. This uplifted area is susceptible to mass wasting. You can see in figures 2.2.2 and 2.2.3, convergent boundaries produce mountains. These uplifted areas are prone to mass wasting. Transform boundaries that just produce pure sliding motion do not result in any uplift or down drop of land, so they are not particularly susceptible to mass wasting. However, it is common for bends in these boundaries to occur. If they bend in the "right" direction, the boundary can experience compression and mountains can uplift. In this case, mass wasting can occur.

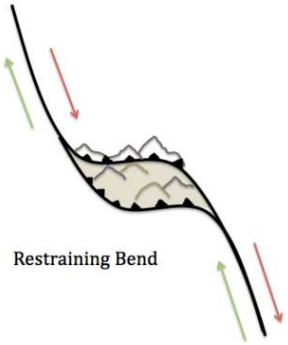


Figure 2.2.6: Depiction of a bend along a transform boundary. The red arrows on the plate on the right and green arrows on the plate on the left show the transform motion of the plates overall. Where the bend occurs, the green and red arrows point at one another showing where compression occurs and mountains form.

To summarize whether various boundaries are susceptible to mass wasting:

- Divergent boundaries - yes
- Convergent boundaries - yes
- Transform boundaries - sometimes

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2.3: Minerals

Minerals Defined

A **mineral** is a naturally occurring, inorganic solid, with a definite chemical composition and a characteristic crystalline structure. Naturally occurring, means that anything man has created, like beautiful cubic zirconia created in labs used to resemble diamonds, does not count as a mineral. To be an inorganic solid, the mineral must not be composed of the complex carbon molecules that are characteristic of life and must be in the solid state (no vapor or liquid). This means that water in its liquid form is not a mineral, while water as a solid (ice), would be (if it is not man-made). A definite chemical composition refers to the chemical formula of a mineral. For most minerals, this does not vary (ex. halite is NaCl - sodium chloride, or table salt), though some minerals have a range of compositions, since one element can substitute for another of similar size and charge (ex. olivine has varying amounts of magnesium and iron). The atoms within minerals are lined up in an orderly fashion, like a stack of soup cans at a store, so the characteristic crystal structure reflects the internal arrangements of atoms. Using halite (NaCl) as an example again, the sodium and chlorine are in a predictable cubic grid, which is what we expect with a mineral. Opal is made of silicon, oxygen, and water, but the location of the atoms and molecules are not regular or predictable, so it is not a mineral. Since this is the only criteria of a mineral that opal does not meet, we call it a mineraloid.



Figure 2.3.1: The white crystal in the back is quartz. It is made of pure silicon and oxygen. The crystal in the front is also quartz but is purple due to the addition of extra elements. We call this amethyst, but really it is just a variety of quartz.

Minerals are not only important for their many uses, but also as the building blocks of rocks - igneous, sedimentary, and metamorphic. Just like words are made up of letters, rocks are made up of minerals. There are several thousand minerals, but we only focus on the most common ones. A few common minerals to mention are:

- quartz
- amphibole
- olivine
- feldspar
- pyroxene
- clay minerals (group of minerals that are very small)
- mica
- calcite
- halite

If it has been a while since you have taken a chemistry course here are a few reminders of important concepts you will need for this section of the text.

- An atom is the basic building block of matter.
- An element is a type of atom like hydrogen, oxygen, or gold. They are all generically atoms, but they are specific elements.
- Molecules are made of multiple elements.
- An ion is an atom or molecule having a positive or negative charge.
- A cation is a positively charged ion.
- An anion is a negatively charged ion.

Types of Minerals

Silicates

Most of the minerals that make up the rocks of the Earth's crust are silicate minerals. These include minerals such as quartz, feldspar, mica, amphibole, pyroxene, olivine, and a great variety of clay minerals. The building block of all these minerals is the **silica tetrahedron**, a combination of four oxygen atoms and one silicon atom. In silicate minerals these tetrahedra are arranged and linked together in a variety of ways, from single units to complex frameworks.

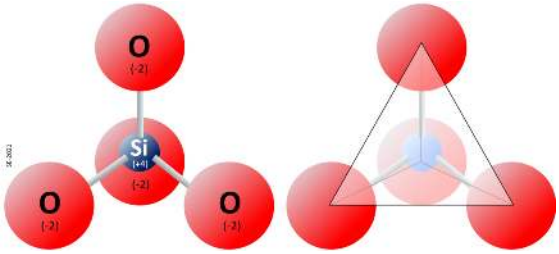


Figure 2.3.2: The Silica Tetrahedron – Building Block of All Silicate Minerals. Because the silicon has a charge of +4 and the four oxygens each have a charge of -2, the silica tetrahedron has a net charge of -4.

The simplest silicate structure, that of the mineral olivine, is composed of isolated tetrahedra bonded to iron and/or magnesium ions. In olivine the -4 charge of each silica tetrahedron is balanced by the addition of two iron or magnesium cations as they each have a +2 charge. Olivine can be either Mg_2SiO_4 or Fe_2SiO_4, or some combination of the two, which is written like this: $(Mg,Fe)_2SiO_4$, meaning that any proportions of Mg and Fe are possible.

Looking at the chart below, you can see other configurations are possible. For this course we are going to focus on sheet silicates and framework silicates.

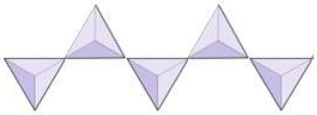
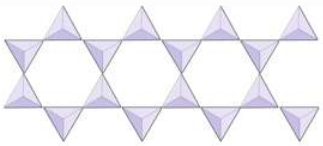
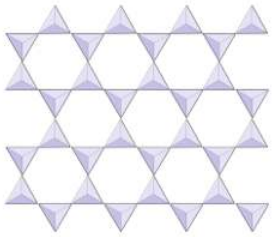
Tetrahedron configuration		Example minerals
	Isolated (nesosilicates)	Olivine, garnet, zircon, kyanite
	Single chains (inosilicates)	Pyroxenes, wollastonite
	Double chains (inosilicates)	Amphiboles
	Sheets (phyllosilicates)	Micas, clay minerals, serpentine, chlorite
3-dimensional structure	Framework (tectosilicates)	Feldspars, quartz

Figure 2.3.3: Silicate Mineral Configurations. The triangles represent silica tetrahedra.

In sheet silicates, the silica tetrahedra are arranged in continuous sheets. There is even more sharing of oxygen between adjacent tetrahedra, and hence fewer positive ions are needed to balance the charge. Bonding between sheets is relatively weak, so these

minerals tend to break into sheets. Clay minerals and micas (like biotite mica and muscovite mica pictured below) are very common sheet silicates. Clay minerals are interesting (and important to this class) because they do not like to allow water to pass through them and make infiltration difficult. At the same time when water is absorbed into clay minerals, it can hold a lot of water and associated ions.



Figure 2.3.4: Biotite Mica (left) and Muscovite Mica (right). Both are sheet silicates and split easily into thin layers along planes parallel to the sheets. Biotite is dark like the other iron- and/or magnesium-bearing silicates (e.g., olivine, pyroxene and amphibole), while muscovite is light colored. Each sample is about 3 cm across.

Silica tetrahedra are bonded in three-dimensional frameworks in both the feldspars and in quartz. Feldspars include aluminum, potassium, sodium and calcium in various combinations. Quartz is made solely of silicon and oxygen where the silica tetrahedra are bonded in a “perfect” three-dimensional framework. Each tetrahedron is bonded to four other tetrahedra (with oxygen shared at each corner of each tetrahedron), and as a result, the ratio of silicon to oxygen is 1:2 (quartz is SiO_2). Since the one silicon cation has a +4 charge and the two oxygen anions each have a -2 charge, the charge is balanced and there is no need for other ions to balance the charge.

Non-Silicate Minerals and Mineral Groups

While silicates dominate Earth's crust, there are other important minerals or mineral groups. Read through the table below. You do not need to memorize all of these groups and minerals, but you will want to use this table as a reference in the future.

Table 2.3.1: The Main Mineral Groups and Some Examples of Minerals in Each Group

Group	Definition	Examples
Oxides	minerals with oxygen as their anion, but they exclude those with oxygen complexes such as carbonate (CO_3), sulphate (SO_4), or silicate (SiO_2)	hematite (iron-oxide – Fe_2O_3), corundum (aluminum-oxide Al_2O_3), water-ice (H_2O)
Sulphides	minerals with the S^{-2} anion and are the most important ores of lead, zinc, copper and molybdenum	galena (lead-sulphide – PbS), pyrite (iron-sulphide or fool's gold – FeS_2), chalcopyrite (copper-iron-sulphide – $CuFeS_2$)
Carbonates	minerals in which the anion is the CO_3^{-2} complex	calcite (calcium-carbonate – $CaCO_3$), dolomite (calcium-magnesium-carbonate – $(Ca,Mg)CO_3$
Halides	minerals with anions that are the halogen elements (the minerals in the second last column on the right side of the Periodic Table) chlorine, fluorine, bromine etc.	fluorite (calcium-flouride – CaF_2), halite (sodium-chloride – NaCl)
Sulphates	minerals with the SO_4^{-2} anion	gypsum (calcium-sulphate – $CaSO_4 \cdot H_2O$), barite (barium-sulphate – $BaSO_4$) (Note that sulphates are different from sulphides. Sulphates have the SO_4^{-2} ion while sulphides have the S^{-2} ion)
Native elements	minerals include only one element (bonded to itself), such as gold, copper, sulphur or carbon (which could be graphite or diamond)	gold (Au), diamond (C), graphite (C), sulphur (S) , copper (Cu)

The common non-silicate minerals are:

- hematite
- pyrite
- calcite
- dolomite
- halite
- gypsum



Figure 2.3.5: These are samples of the mineral pyrite, also known as "fool's gold" as it looks like gold. Pyrite has a much lower density than gold (it is lighter) and is harder than gold (pure gold is very soft which is why it is mixed with other metals when used in jewelry).

Mineral Properties

When you identify a mineral, you use clues gathered from your observations of its physical properties. The properties are things like color, density, and how hard the mineral is. In a general geology course, you would explore about 10 properties of minerals. For our purposes, we will focus on just a few. Physical properties can vary within the same minerals, so you must be careful.

Color, the color of the mineral in its regular crystal form, is a property that often varies in each mineral. Quartz is a mineral that comes in many colors as shown in Figure 2.3.1. Purple-colored quartz is called amethyst, the white quartz is called milky quartz, and the clear quartz is called quartz crystal.

Specific gravity references a mineral's density and is the ratio of a mineral's weight to the weight of an equal volume of water. A mineral with a specific gravity of 3 would weigh three times as much as water. Most minerals have a specific gravity around 2.7. Some minerals like pyrite (fool's gold) shown in Figure 2.3.5 are noticeably dense with a specific gravity of 4.9-5.2. Gold's specific gravity is much higher at 19.3. Minerals with a high specific gravity will feel heavy. Those with a low specific gravity will feel light.

Hardness describes the resistance of a mineral to being scratched by another material and is controlled by the strength of the bonds between atoms. That other material could be a piece of metal or another mineral. If mineral A scratches mineral B, A is harder. If it does not, B is harder. In geology, hardness is based off a scale of 1 to 10 created by a mineralogist named Friedrich Mohs. Mohs' scale lists ten minerals from softest to hardest as follows.

- 1 - Talc
- 2 - Gypsum
- 3 - Calcite
- 4 - Flourite
- 5 - Apatite
- 6 - Feldspar
- 7 - Quartz
- 8 - Topaz
- 9 - Corundum
- 10 - Diamond



Figure 2.3.6: These are two different micas, biotite (dark) and muscovite (light), which are common rock-forming minerals. They show one plane of cleavage. The silica tetrahedra are bonded strongly along the flat sheets but weakly between sheets such that it tends to break along those flat planes. They show one plane of cleavage as they have one orientation of natural breakage.

Each mineral on the scale can scratch any mineral having a lower number. So, quartz can scratch minerals 1-6 but cannot scratch 8-10. The hardness of quartz is related to the fact that all the bonds between the silica tetrahedron that make it up are equally strong.



Figure 2.3.7: These are two different micas, biotite (dark) and muscovite (light), which are common rock-forming minerals. They show one plane of cleavage. The silica tetrahedra are bonded strongly along the flat sheets but weakly between sheets such that it tends to break along those flat planes. They show one plane of cleavage as they have one orientation of natural breakage.

One last property of minerals is **cleavage**. As minerals are broken (such as when they are hit with a hammer, for example), some may break along smooth flat planes known as cleavage. This happens because bonds within a mineral may not be of the same strength, so when a mineral breaks it does so along these weaker areas. This results in flat cleavage planes. Micas, as pictured in Figure 2.3.7, break into these flat sheets for this very reason. The strong bonds between silica tetrahedra occur along the sheets. The weaker bonds are what hold the sheets together. Some minerals do not contain zones of weakness because either all bonds are the same strength, or the weaker bonds are not aligned within a plane. In this case it will not have cleavage, but rather breaks in a random fashion. Quartz is a great example of this as all of the bonds between the silica tetrahedron that make it up are equally strong.

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2.4: Rocks

Rocks Defined

Rocks are aggregates of the crystals of one or more minerals. A rock can be made of quartz, feldspar, and mica, or a rock can just be made of many grains of quartz. There are three main types: igneous, sedimentary and metamorphic. They form in different ways, and they have specific properties that help us to distinguish them. Through geological processes the rocks on Earth can be transformed from one type to another, and this concept is illustrated using the rock cycle (see the figure below). The three types of rock are depicted within rectangles, some of the intermediate forms of rocky materials (magma, outcrop and loose sediments) are shown as ellipses, and the processes that are important in the transformations are shown with arrows. Those processes include:

- Uplift (such as mountain formation) that results in rock that was present at depth in the crust being brought to surface in an "outcrop" and exposed to weathering,
- Erosion and transportation of weathered products (e.g., sand, clay, and ions in solution) and then deposition as sediments (e.g., within rivers or the ocean),
- Burial of those sediments beneath other sediments, followed by compaction (squeezing) and cementation to make sedimentary rock,
- Further burial which results in heating and more squeezing and then mineral transformations to form metamorphic rock,
- Further heating or other changes in conditions that result in melting to form magma, and
- Movement of magma towards surface where it can cool slowly to make intrusive igneous rock, or to surface where it can cool quickly to make extrusive igneous (volcanic) rock.

The rock cycle can be disrupted at any point by a change in conditions brought about by uplift, or burial (blue and red arrows), or in rare cases by the nearby presence of magma. The rock cycle is something you should continually refer to as you read this section of the text. It is not usually understood in one reading, so keep referring to it.

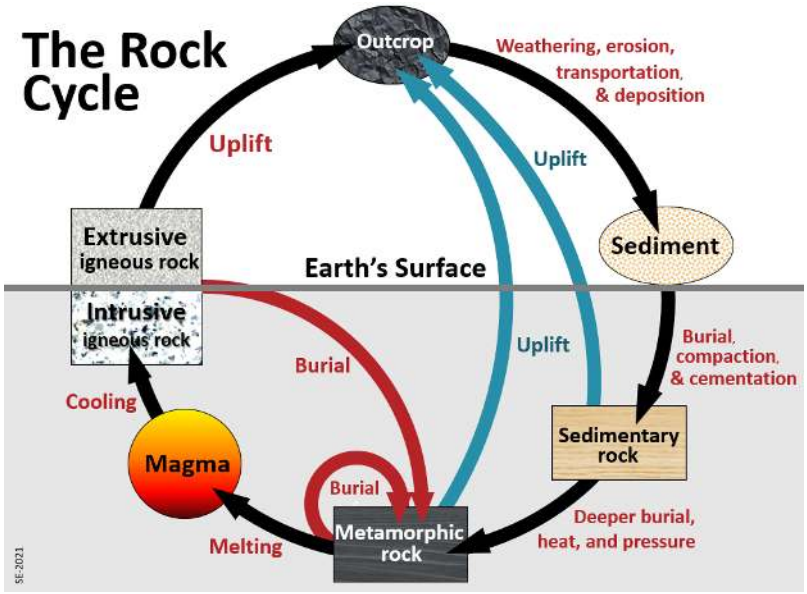


Figure 2.4.1: The Rock Cycle

Igneous Rocks

Igneous rocks form from the cooling of magma (molten rock at depth) slowly underground IN the crust, or from the cooling of lava (molten rock on the surface) quickly ON the crust. In general, the longer that cooling process takes (up to millions of years), the larger the crystals will be. Rocks formed from lava typically have mineral crystals that are less than 0.1 mm across (because they can cool in seconds or minutes). They are often called volcanic rocks as they often create volcanoes. They are also called extrusive rocks because they are formed on the exterior of the Earth. Rocks formed from magma have crystals that are typically larger than 1

mm across. They are called intrusive rocks because they are formed on the interior of the Earth. Classification of igneous rocks is based mainly on the texture (size of the grains) and rock composition.

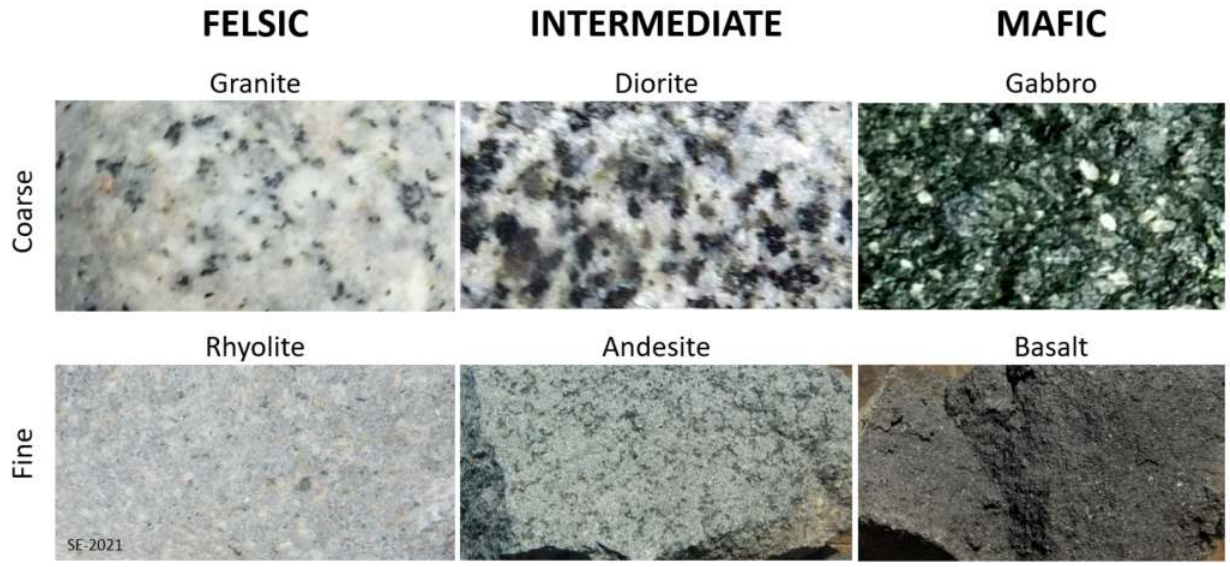


Figure 2.4.2: General Classification of Igneous Rocks

In the figure above, the two textural categories are fine and coarse. The fine-grained rocks have small grains and form from lava. The coarse-grained rocks have large grains and form from magma.

Three broad compositional classes of igneous rocks are shown in the figure above, namely felsic, intermediate, and mafic. These are determined by the amount of silica in the rock Since pure silica is white or clear, rocks with high silica tend to be lighter and those with low silica tend to be darker. Accordingly, since felsic rocks have ~70% silica, they are light in color as there is little room for the darker minerals. Mafic rocks have ~50% silica so they have plenty of room for darker minerals and are typically dark in color. Intermediate rocks are in between compositionally and are typically medium-dark (typically grey) in color. The three main types of coarse-grained (or intrusive) igneous rocks are granite, diorite and gabbro. The equivalent fine grained, or volcanic or extrusive rocks, are rhyolite, andesite and basalt. Igneous rocks with close to 100% dark minerals (not shown on the figure) are known as ultramafic; these are rare on the Earth's surface, but common in the mantle.

Mafic igneous rocks (e.g., basalt or gabbro) are denser than felsic igneous rocks. Basalt has a specific gravity of about 3 g/cm^3, while for granite the value is about 2.6 g/cm^3. This small difference becomes very important in the context of plate tectonics because it helps us understand why oceanic crust (made of basalt) subducts beneath continental crust (made of granite). In comparison, the ultramafic rock of the mantle has a density of about 3.3 g/cm^3.

Sedimentary Rocks

Sedimentary rocks form near to the Earth's surface following the accumulation of fragments of rocks and minerals that have been weathered (broken down) and eroded (removed) from outcrops (rocks sticking out of the ground), transported by gravity, rivers, waves, wind, or glacial ice, and then deposited as sediments. The sedimentary grains (e.g., grains of sand) are known as clasts, and the resulting sedimentary rocks are called clastic if they are composed mostly of such grains.



Figure 2.4.3: Cross-Bedded River-Deposited Sand on Vancouver Island. This is not sandstone because the deposit is soft and loose and can be scraped away with fingers. Instead, it is just a deposit of sediment that happens to be sand-sized.

Clasts can range in size from tiny (invisible) clay fragments to boulders the size of buildings. We classify clastic sedimentary rocks based on the clast sizes. The key piece of information to remember is that a grain of sand ranges in size from 1/16th mm to 2 mm, and that means from about 1/4 the size of the period at the end of this sentence, to about the size of this capital O. (That depends, of course, on the type of device that you are reading this on.) Very fine sand will feel gritty (not slippery) between your fingertips. Clasts smaller than 1/16th mm are classified as silt and clay, and those larger than 2 mm are classified as gravel. Gravel is sometimes broken down into granules, pebbles, cobbles, and boulders (in order of increasing size). Sand grains can be transported by rivers with medium flow, by strong winds, and by waves, and so sand deposits tend to accumulate in rivers and deserts and on beaches. Silt and clay can be transported in similar environments, but they tend not to be deposited unless the medium slows, so they will be deposited in lakes, and the ocean. Gravels can typically only be transported and deposited by fast-flowing water, and so they are commonly deposited in high-energy parts of streams. These sediments must then become buried beneath other layers of sediments and compressed and cemented before they can become sedimentary rock, as illustrated on Figure 2.4.1.

Three important types of clastic sedimentary rocks are illustrated below.



Figure 2.4.4 Examples of the Elastic Sedimentary Rocks Conglomerate, Sandstone and Mudstone. The pen is 15 cm long, and the coin in the mudstone photo is 2 cm across.

Sedimentary rocks can also form from the crystallization of ions that were transported in water as dissolved ions. These are known as chemical sedimentary rocks. For example, minerals form when water evaporates from an inland sea or lake because the ions get too concentrated to remain in the solution. Examples are rock salt (halite) and gypsum (which is used to make dry wall).

Sedimentary rocks can also form from materials associated with organisms. For example, marine organisms extract bicarbonate and calcium ions (HCO_3^- and Ca^{2+}) from ocean-water to make calcite shells ($CaCO_3$) which then accumulate on the sea floor (typically

in tropical areas around reefs) to form calcite mud and sand that later gets buried and becomes limestone. Other organisms make their shells out of silica, and those can accumulate on the sea floor to make the rock chert.

The final way sedimentary rocks can form is from the remains of plants, animals, and other biological materials that are compressed over time to form rock. These are called organic sedimentary rocks, and the most common example is coal which forms when the plant and animal materials decay in swampy or marshy environments.

Metamorphic Rocks

Metamorphic rocks form when pre-existing sedimentary or igneous rocks are heated and squeezed in such a way that one or more of the minerals present becomes unstable. The result might be that crystals of those minerals are converted into different minerals or into larger crystals of the same type.

One way to understand this process is to consider the sedimentary rock mudstone, which is mostly made up to clay minerals. Clays are low-temperature minerals; they are not stable at temperatures higher than about 150^{o} C. As a clay-rich rock is heated the clay minerals tend to break down and are converted into micas. At even higher temperatures those might be converted to minerals such as quartz, feldspar and amphibole. There is no melt involved as that would be an igneous process. This all happens as minerals recrystallize in the solid state.

Most metamorphism takes place at depth in the crust in areas that have experienced mountain-building (and so crustal thickening) and where there is compression due to plate convergence. That means that the rocks get heated (because of burial) and squeezed (because of the converging plates) at the same time. New minerals that form under these conditions are typically forced to grow perpendicular to the direction of that pressure, and so the metamorphic rock becomes foliated meaning that it takes on a fabric of aligned minerals or aligned bands of minerals.

Examples of foliated metamorphic rocks are shown below. Slate forms from mudstone at relatively low metamorphic temperatures and pressures, as clay minerals are turned into tiny (invisible) mica crystals. The alignment of these gives slate a layered look and the tendency to split into sheets. Schist forms at higher temperatures that allow the micas to become large enough to see. The mica crystals are generally parallel to each other, but the rock doesn't split into sheets so easily. Gneiss forms at temperatures thar are typically beyond the stability of micas, and so is characterized by minerals like quartz, amphibole and feldspar that have segregated into dark and light bands.



Figure 2.4.5 Examples of Foliated Metamorphic Rocks. (From left to right: slate, schist and gneiss.)

It is very important not to confuse foliation with bedding. The slate pictures above is not splitting along pre-existing bedding planes in the parent mudstone, and the layers in the gneiss have no relationship to what bedding (if any) might have existed in the starting rock.

Some other metamorphic rocks include quartzite and marble. These form from the metamorphosis of the sedimentary rocks sandstone and limestone respectively. They tend not to be foliated even if they did form under directional squeezing due to the minerals making them up. Quartzite, for example, is mostly made up of quartz crystals, and they tend not to take on a directional fabric.

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CHAPTER OVERVIEW

3: Weathering, Clay Formation, and Soil Formation



This chapter shows how some Earth materials (minerals and rocks) are broken down (weathered) to form sediment (loose material), clays (tiny material), and soil (loose material formed in place and not transported).

3.1: Weathering

3.2: Products of Weathering and Erosion

3.3: Clay Minerals

3.4: Soil Formation

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3.1: Weathering

Weathering Defined

Intrusive igneous rocks form at depths of several hundreds of meters to several tens of kilometers. Sediments are turned into sedimentary rocks only when they are buried by other sediments to depths more than several hundreds of meters and up to several kilometers. Most metamorphic rocks are formed at depths of kilometers to tens of kilometers. **Weathering**, the process by which rock breaks down, and subsequent soil formation cannot even begin until these rocks are uplifted through various processes of mountain building—most of which are related to plate tectonics—and the overlying material has been eroded away and the rock is exposed as outcrop.[1]

There are two types of weathering. **Mechanical weathering** which is the physical breakdown of rock into smaller pieces, and **chemical weathering** which is the chemical change of earth material into materials with a different composition resulting from exposure to the atmosphere.

Mechanical Weathering

Since mechanical weathering results in the decrease in size of the materials, the important agents of it are as follows:

a. the decrease in pressure that results from removal of overlying rock,
b. erosional forces related to gravity, water and wind,
c. freezing and thawing of water within cracks in the rock,
d. formation of salt crystals within pores in the rock, and
e. plant roots and burrowing animals.

When a mass of rock is exposed by weathering and by removal of the overlying rock there is a decrease in the confining pressure on the rock, and the rock expands. This unloading promotes cracking of the rock, known as **exfoliation**, as shown in granitic rock in the picture below.



Figure 3.1.1: Exfoliation Fractures in Granitic Rock Exposed at Yak Peak, Coquihalla Summit Recreation area, BC

Granitic rock tends to exfoliate parallel to the exposed surface because the rock is typically homogenous, and it may not have pre-determined planes along which to fracture. Sedimentary and metamorphic rocks, on the other hand tend to exfoliate along predetermined planes (Figure 3.1.2).



Figure 3.1.2: Exfoliation of Slate at a Road Cut in the Columbia Mountains West of Golden, BC

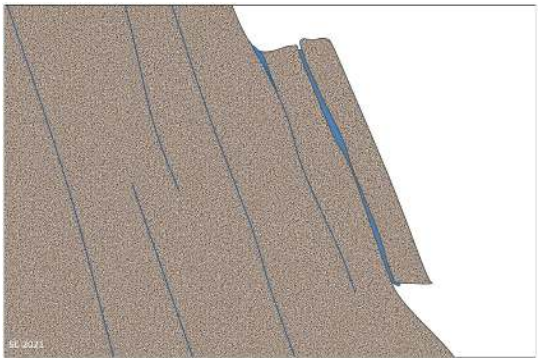


Figure 3.1.3: The Process of Frost-Wedging on a Steep Slope. Water gets into fractures and then freezes, expanding the fracture a little. When the water thaws it seeps a little further into the expanded crack. The process is repeated many times, and eventually a piece of rock will be wedged away.

Frost wedging is the process by which the water seeps into cracks in a rock, expands on freezing, and thus enlarges the cracks (Figure 3.1.3). The effectiveness of frost wedging is related to the frequency of freezing and thawing. Frost wedging is most effective in a climate where there are many days each year with temperatures close to freezing, so that it might freeze overnight and then thaw in the day.

When salty water seeps into rocks, and then the water evaporates on a sunny day, salt crystals grow within cracks and pores in the rock. The growth of these crystals exerts pressure on the rock and can push grains apart, causing the rock to weaken and break. There are many examples of this on rocky ocean shorelines worldwide, especially where sandstone outcrops are common (Figure 3.1.4).



Figure 3.1.4: Honeycomb Weathering of Sandstone on Gabriola Island, BC. The holes are caused by crystallization of salt within rock pores, and the seemingly regular pattern is related to the original roughness of the surface. It's a positive-feedback process because the holes collect salt water at high tide, and so the effect is accentuated around existing holes. This type of weathering is most pronounced on south-facing sunny exposures.

The effects of plants and animals are significant in mechanical weathering. Roots can force their way into even the tiniest cracks, and then they exert tremendous pressure on the rocks as they expand, widening the cracks and breaking the rock. Although animals do not normally burrow through solid rock, they can excavate and remove huge volumes of soil, and thus expose the rock to weathering by other mechanisms.

Chemical Weathering

Chemical weathering results from the chemical changes to some minerals that become unstable when they are exposed to surface conditions. The kinds of changes that take place are highly specific to the mineral and to the environmental conditions. Some minerals, like quartz, are virtually unaffected by chemical weathering, while others, like feldspar, are quite easily altered. In general, the degree of chemical weathering is greatest in warm and wet climates, and least in cold and dry climates. The important characteristics of surface conditions that lead to chemical weathering are the presence of water (in the air and on the ground surface), the abundance of oxygen, and the presence of carbon dioxide, which, when combined with water, produces weak carbonic acid.

Exposure to this weak acid causes feldspar to turn into the clay mineral kaolinite in a process called **hydrolysis**. Figure 3.1.5 shows two images of the same granitic rock, a recently broken fresh surface on the left, and a clay-altered weathered surface on the right.

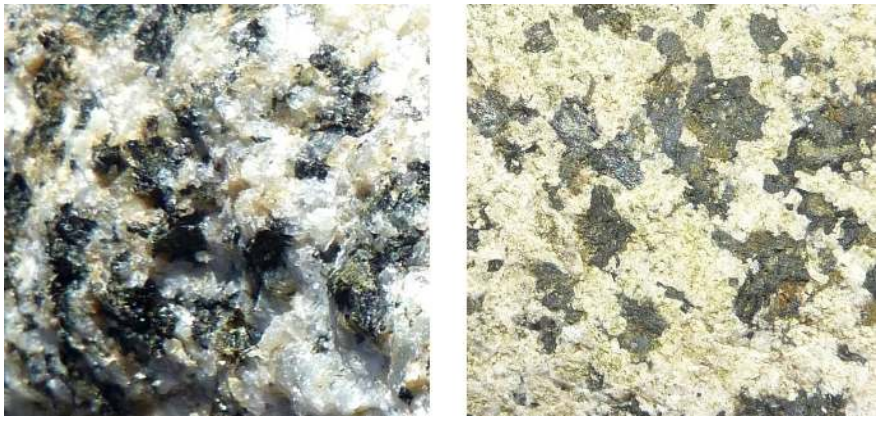


Figure 3.1.5: Un-weathered (left) and Weathered (right) Surfaces of the Same Piece of Granitic Rock. On the unweathered surfaces the feldspars are still fresh and glassy looking. On the weathered surface the feldspar has been altered to the chalky-looking clay mineral kaolinite.

Oxidation is another very important chemical weathering process. The oxidation of the iron in an iron-bearing silicate starts with the dissolution of the iron. The iron is dissolved due to the presence of the carbonic acid mentioned above. Figure 3.1.6 shows a

granitic rock in which some of the biotite and amphibole have been altered to form the iron oxide mineral limonite. Oxidation produces the red color you see here and in many of the rocks in Arizona, New Mexico, Utah, and Colorado.



Figure 3.1.6: A Granitic Rock Containing Biotite and Amphibole, Altered Near to the Rock's Surface to Limonite, A Mixture of Iron-Oxide Minerals.

Hydrolysis and oxidation both serve to create rocks that are softer and weaker than they were to begin with, and thus more susceptible to mechanical weathering.

The weathering reactions that we've discussed so far involved the transformation of one mineral to another mineral (e.g., feldspar to clay). Some weathering processes involve the complete dissolution of a mineral. Calcite, for example, will dissolve in weak acid, to produce calcium and bicarbonate ions.

Calcite is the major component of limestone (typically more than 95%), and under surface conditions limestone will dissolve to varying degrees (depending on which minerals it has other than calcite), as shown on Figure 3.1.7. Limestone also dissolves at relatively shallow depths underground, forming limestone caves.



Figure 3.1.7: A Limestone Outcrop on Quadra Island, BC. The limestone, which is primarily made up of the mineral calcite, has been dissolved to different degrees in different areas because of compositional differences. The buff-colored bands are either volcanic rock or chert, which are not soluble.

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1. To a geologist, an outcrop is an exposure of bedrock—the solid rock of the crust. ↵

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3.2: Products of Weathering and Erosion

The products of weathering and erosion are the unconsolidated materials that we find around us on slopes, beneath, beside and on top of glaciers, in stream valleys, on beaches, and in deserts. The nature of these materials—their composition, size, degree of sorting, and degree of rounding—is determined by the type of rock that is being weathered, the nature of the weathering, the erosion and transportation processes, and the climate.

Some examples of the products of weathering are shown in Figure 3.2.1. They range widely in size and shape depending on the processes involved in their transportation. When deposits like these are turned into sedimentary rocks, the textures of those rocks will vary significantly. Importantly, when we describe sedimentary rocks that formed millions of years in the past, we can use those properties to make inferences about the conditions that existed during their formation.



Figure 3.2.1: Products of Weathering and Erosion Formed Under Different Conditions.

It's worth considering here why the sand-sized sediments shown in Figure 3.2.1 are so strongly dominated by the mineral quartz, even though quartz makes up less than 20% of Earth's crust. The explanation is that quartz is highly resistant to the weathering that occur at Earth's surface. It is not affected by weak acids, or water or the presence of oxygen. This makes it unique among the minerals that are common in igneous rocks. Quartz is also very hard, and doesn't have cleavage, so it is resistant to mechanical erosion. The other products of erosion: clays and dissolved ions like calcium, iron, and magnesium can be washed out into the oceans to form sediments on the sea floor.

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3.3: Clay Minerals

Clay Minerals Defined

In Earth Science the word “clay” has two meanings. **Clay** is broadly defined as any unconsolidated material with a grain diameter less than 0.004 mm. That is about 1/100th as big as the period at the end of this sentence, so is not big enough to see with the naked eye. This could include finely ground up quartz, feldspar, or any other mineral. “Clay” also refers to the clay minerals, which are sheet silicates as previously discussed. Remember these form as silica tetrahedra are strongly bonded into sheets. The sheets are then stacked and held together by weaker bonds. Clay minerals typically only exist as very tiny crystals, so most true clays also conform to the fine-grained meaning of the word “clay”.

Most of the clay present in rocks at surface has formed as a result of weathering of other silicate minerals, primarily feldspars, micas, pyroxene and amphibole. The reactions involved are hydrolysis reactions as previously explained.

In one example, feldspar reacts with water and carbon dioxide to form kaolin (clay mineral) plus bicarbonate ions. The potassium and some of the silicon that were originally present in the feldspar, are removed in solution. The carbon dioxide comes from the atmosphere, and over geological time, this is type of reaction plays an important role in controlling the atmosphere’s composition and hence the greenhouse effect.

Clay minerals can also be formed when hot waters (known as hydrothermal solutions) circulate through a body of rock. As is the case for weathering, the hot solutions lead to alteration of pre-existing minerals. Hydrothermal solutions are often also associated with the formation of metal deposits (such as porphyry copper deposits) and the surrounding clay-mineral halos can be an important guide in the exploration for such deposits.

Unlike the primary silicate minerals that they form from, clay minerals are soft and easily eroded into tiny fragments and then transported. They accumulate mostly as sediments in low-energy deposition environments (e.g., deep ocean or in lakes), sediments that are eventually turned into shale.

Properties of Clay Minerals

It is worthwhile to understand some of the properties of clay minerals, as they have important implications for many aspects of environmental geology. They play a role in a great variety of processes, from soil chemistry to the causes and effects of earthquakes, to the permeability of rocks. Some of their important properties are as follows:

They are soft and weak, primarily because of the weak bonds between sheets and the resulting tendency for the sheets to slide past each other under stress. Talc is number 1 on the Mohs scale, and most other clay minerals are similarly soft. The weakness of clay minerals has implications for slope failure (as noted above) because clay bearing rocks also tend to be weak, and for earthquakes, because a plate boundary with clay-rich rocks is likely to slide smoothly, and so less likely to stick and cause large earthquakes.

Most clays are malleable when wet—also because of weak inter-layer bonds—and so can easily be formed into useful shapes for artistic, domestic, industrial and scientific purposes.

Clay minerals are crystals like other minerals, but they typically only form as very small crystals, so clay deposits are almost universally fine grained. Although a body of clay has significant porosity, the pores are extremely small and most of the water within them is close enough to a grain boundary to be held tightly by surface tension, making a clay deposit significantly impermeable. This has implications for groundwater flow and for waste disposal which will be discussed later in this text.

The tetrahedra that make up clay minerals have negatively charged ions (anions) on their outsides making the surfaces of the individual layers negatively charged, and therefore attractive to positively charged ions (cations) in solution. Most metals exist as cations and many organic pollutants have positive charges, and so clay minerals are efficient scavengers of environmental pollutants and can be used as barriers to prevent dispersal of contaminants and also in environmental rehabilitation projects. Different clays have different capacities to absorb cations (known as “cation exchange capacity”), and some of these are listed in the table below.[1] Smectite has a much higher cation exchange capacity than other clays because cations can get onto the sites in between the molecular layers within a crystal, as opposed to just the outside surfaces of the crystals.

Table 3.3.1 ***Surface Area and Cation Exchange Capacity of Some Clay Minerals***

**Meq/g is milli-equivalents per gram, or milli-moles. E.g., 10 meq/g of Cu = 0.29 g of Cu per g of clay*

–	**Effective Surface Area in m2/g**	–	**Cation Exchange Capacity**
Mineral	**Interlayer**	**External**	**Meq/g***
Kaolin	0	15	1 to 10
Chlorite	0	15	<10
Illite	5	15	10 to 40
Smectite	750	50	80 to 150

Clays, especially smectites, have a unique ability to absorb water molecules in interlayer sites, and thereby will expand or swell when wet. Some swelling clay is shown on Figure 3.3.1. The clay is present within a depression and was wet. On drying it shrank in the typical mudcrack pattern. Swelling clays have numerous important industrial and domestic uses, but they also have some serious geological implications. A swollen wet smectite is even weaker than a dry one and can weaken slopes significantly. Bodies of swollen clay can distort the materials around them and contribute to slope failure or problems for building or road foundations.



Figure 3.3.1: Smectite-Bearing Clay in the volcanic Krafla Area, Iceland. On drying the clay shrank and the decrease in volume was accommodated by cracking.

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1. The data in Table 3.3.1 are based on information in Wilson, M. (2004). Weathering of the primary rock-forming minerals, processes, products and rates. *Clay Mineralogy, 39*(3), 233-66. doi:10.1180/0009855043930133; and in Deer, W., Howie, R., and Zussman, J. (1991). *An introduction to the rock-forming minerals* (2nd ed). Longman. ↵

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3.4: Soil Formation

Soil Defined

Weathering is a key part of the process of soil formation, and soil is critical to our existence on Earth. In other words, we owe our existence to weathering, and we need to take care of our soil!

Many people refer to any loose material on Earth's surface as soil, but to geologists (and geology students) **soil** is the material that includes organic matter, lies within the top few tens of centimeters of the surface, and is important in sustaining plant growth. Most critically for definition purposes, soil is formed in place by weathering the underlying materials. Loose material that is formed as rock is weathered, transported, and deposited is called sediment. Soft sediments can be described using terms that are indicative of how they formed, such as glacial till, river-deposited sand and gravel, lake-deposited clay, and wind-blown silt.

Soil is a complex mixture of minerals (approximately 45%), organic matter (approximately 5%), and empty space (approximately 50%, filled to varying degrees with air and water). The mineral content of soils is variable, but is often dominated by clay minerals and quartz, along with minor amounts of feldspar and small fragments of rock. The types of weathering that take place within a region have a major influence on soil composition and texture. For example, in a warm climate, where chemical weathering dominates, soils tend to be richer in clay. Soil scientists describe soil texture in terms of the relative proportions of sand, silt, and clay, as shown in Figure 3.4.1. The sand and silt components in this diagram are dominated by quartz, with lesser amounts of feldspar and rock fragments, while the clay component is dominated by the clay minerals.

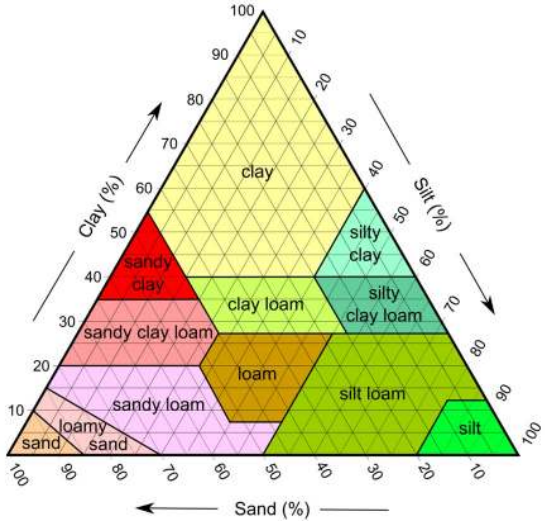


Figure 3.4.1: Variations in the Proportions of Clay-, Silt-, and Sand-Sized Fragments in Soils. This diagram applies only to the mineral component of soils, and the names are textural descriptions, not soil classes. The bottom of the Wikipedia article on Ternary plots explains exactly how to read this graph.

Soil Forming Factors

Soil forms through accumulation and decay of organic matter and through the mechanical and chemical weathering processes described previously. The factors that affect the nature of soil and the rate of its formation include climate (especially average temperature and precipitation amounts), organisms (especially the types and intensity of vegetation), relief (the slope of the surface and the direction it faces) the type of parent material, and the amount of time available. These are known by the acronym CLORPT, coined by Hans Jenny in 1941.[1]

Climate

Soils develop because of the weathering of materials on Earth's surface, including the mechanical breakup of rocks, and the chemical weathering of minerals. Soil forms most readily under temperate to tropical conditions (not cold) and where precipitation amounts are moderate (not dry, but not too wet). Chemical weathering reactions (especially the formation of clay minerals) and biochemical reactions proceed fastest under warm conditions, and plant growth is enhanced in warm climates. Too much water (e.g., in rainforests) can lead to the leaching of important chemical nutrients and hence to acidic soils. In humid and poorly drained

regions, swampy conditions may prevail, producing soil that is dominated by organic matter. Too little water (e.g., in deserts and semi-deserts), results in very limited weathering. Soils in dry regions also suffer from a lack of organic material (Figure 3.4.2).



Figure 3.4.2: Poorly Developed Soil on Wind-Blown Silt (Loess) in an Arid Part of Northeastern Washington State. The thickness shown is about 1 m, and only the upper 2 or 3 cm are actual “soil”.

Organic matter

Good soil is rich in organic matter, and that can only accumulate if there is sufficient plant growth in the area. There is only sparse vegetation growing in the area pictured in Figure 3.4.2, and the soil is poor.

Relief

Soil can only develop where surface materials remain in place. If erosion continually removes material at the surface, soil does not get a chance to form. Consequently, steep slopes tend to have little or no soil.

Parent Material

Soil **parent materials** can include all different types of bedrock and any type of unconsolidated sediments, such as glacial deposits and stream deposits. Quartz-rich parent material, such as granite, sandstone, or loose sand, leads to the development of sandy soils. Quartz-poor material, such as shale or basalt, generates soils with little sand, and in some cases with elevated clay levels.

Parent materials provide important nutrients to residual soils. For example, a minor constituent of granitic rocks is the calcium-phosphate mineral apatite ($Ca_5(PO_4)_3(F,Cl,OH)$), which is a source of the important soil nutrient phosphorus. Basaltic parent material tends to generate very fertile soils because it also provides phosphorus, along with significant amounts of iron, magnesium, and calcium. Soils in active volcanic regions tend to be generally quite fertile, partly because the fine-grained and glass-rich eruption products weather quickly and produce significant amounts of clay that hold trace elements.

Some unconsolidated materials, such as river-flood deposits, make for especially good soils because they also tend to be rich in clay minerals. Clay minerals have large surface areas with negative charges that are attractive to positively charged elements like calcium, magnesium, iron, and potassium—important nutrients for plant growth.

Time

Even under ideal conditions, soil takes thousands of years to develop. Virtually all of southern Canada and parts of the northern US were still glaciated up until 14,000 years ago. Glaciers still dominated the central and northern parts of Canada until around 10,000 years ago, and so, at that time, conditions were still not ideal for soil development even in the southern regions. Therefore, soils in Canada, and especially in central and northern Canada, are relatively young and not well developed.

The same applies to soils that are forming on newly created surfaces, such as recent deltas or sand bars, or in areas of mass wasting. Climate and parent material both exert a significant control on how long it takes for soil to develop.

Soil Formation

The process of soil formation is summarized in the figure below. The left-hand diagram shows the situation of the site within several years of the exposure of the rock surface (for example, following the melting of glaciers and the subsequent exposure of the rock). The rock is fractured and both mechanical and chemical weathering have started. Lichen and moss are present on the rock surface and small plants have started to grow in cracks and depressions in the outcrop where small amounts of sediment have accumulated.

The second diagram represents a time some hundreds to thousands of years later (longer in cold and dry climates). Both mechanical and chemical weathering of the rock are well advanced. The rock is softer and weaker than it was originally, and the weathering products have accumulated in between the remaining rock fragments. The C horizon soil (described below) has developed from the products of weathering (small rock fragments, sand, and clay) and organic matter is accumulating near to surface.

The third diagram is a few thousand to several thousand years later. The soil profile has started to evolve, mostly through chemical changes involving both downward and upward motion of ions in water, and transfer of water and chemicals by the roots of plants.

The last diagram, on the right, represents a time several thousands to tens of thousands of years later. The soil is now well developed. There has been significant weathering of minerals like feldspar and amphibole within the soil to produce clay minerals and there has also been upward and downward movement of chemicals (iron, manganese, potassium, sodium, calcium, magnesium, and aluminum). Along with all the living organisms (roots, worms, insects), there is a great deal of carbon stored in the soil (as organic matter, charcoal, carbon dioxide and methane). Depending on the type of parent material and the rate of soil formation in the local climate, the soil in this last diagram could be from several centimeters to over a meter thick.

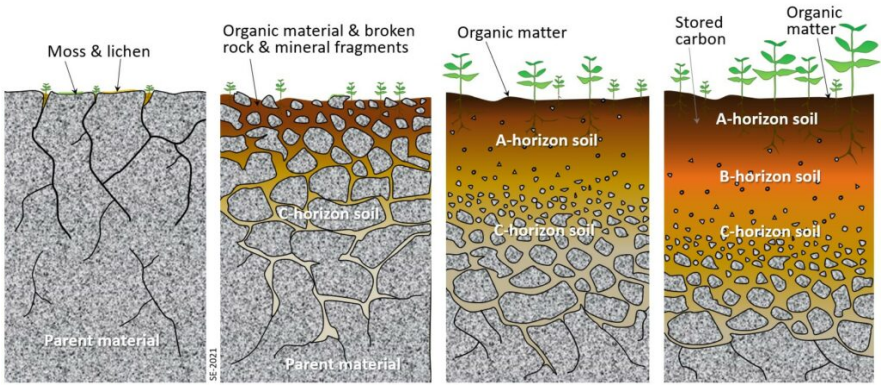


Figure 3.4.3: Steps in the Evolution of Soil

Soil Horizons

The process of soil formation generally involves the downward movement of clay, water, and dissolved ions, and a common result of that is the development of chemically and texturally different layers known as **soil horizons**. The typically developed soil horizons, as illustrated in Figure 3.4.4, are:

O – a layer of organic matter,
A – a layer of partially decayed organic matter mixed with mineral material
E – an eluviated (leached) layer from which some of the clay and iron have been removed to create a pale layer that may be sandier than the other layers
B – a layer of accumulation of clay, iron, and other elements from the overlying soil
C – a layer of incomplete weathering, which grades down into unaltered parent material

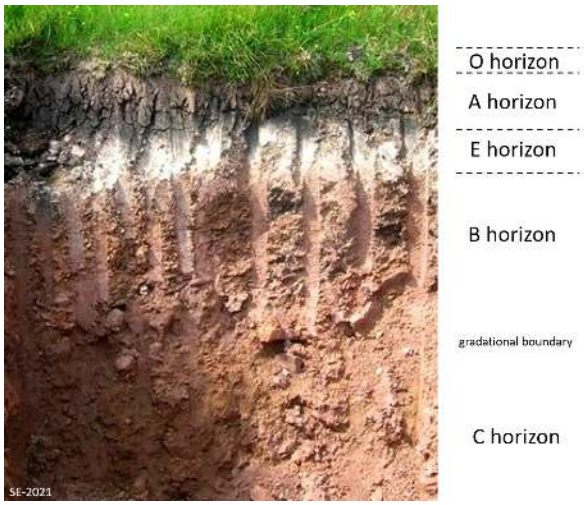


Figure 3.4.4: Soil Horizons from a Site in Northeastern Scotland.

Like all geological materials, soil is subject to erosion, although under natural conditions on gentle slopes, the rate of soil formation either balances or exceeds the rate of erosion. Human practices, especially those related to forestry and agriculture, have significantly upset this balance in many places.

Soils are held in place by vegetation. When vegetation is removed, either through cutting trees or routinely harvesting crops and tilling the soil, that protection is either temporarily or permanently lost.

The primary agents of the erosion of unprotected soil are water and wind. Water erosion is accentuated on sloped surfaces because fast-flowing water obviously has greater eroding power than slow-flowing or still water (Figure 3.4.5). Raindrops can disaggregate exposed soil particles, putting the finer material (e.g., clays) into suspension in the water. Sheet wash—unchanneled flow across a surface—carries suspended material away, and channels erode right through the soil layer, removing both fine and coarse material.

Soil Erosion

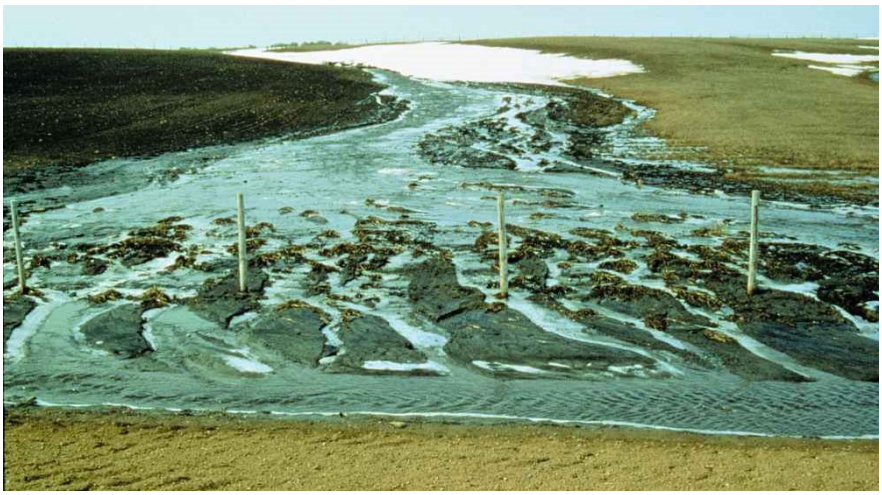


Figure 3.4.5: Soil Erosion by Rain, Sheet Wash and Channeled Runoff on a Field in Alberta, Canada

Wind erosion is exacerbated by the removal of trees that act as wind breaks and by agricultural practices that leave bare soil exposed (Figure 3.4.6).

Tillage is also a factor in soil erosion, especially on slopes, because each time the soil is lifted by a cultivator, it is moved a few centimeters down the slope.



Figure 3.4.6: Soil Erosion by Wind in Alberta

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1. Jenny, H. (1941). *Factors of soil formation—a system of quantitative pedology*. McGraw-Hill. ↵

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CHAPTER OVERVIEW

4: Volcanism



This chapter explores volcanism. The textbook already addressed how igneous rocks form and this chapter helps us see how rocks formed from magma cool below volcanoes and rocks formed from lava create the volcano or volcanic feature. As part of this the relationships volcanoes have with plate tectonics, magma compositions, eruption style/violence, types of volcanic features, and volcanic hazards are explored.

4.1: Plate Tectonic Settings of Volcanism

4.2: Magma Composition and Eruption Style

4.3: Types of Volcanism

4.4: Volcanic Hazards

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4.1: Plate Tectonic Settings of Volcanism

The relationships between volcanism and plate tectonics are summarized on Figure 4.1.1. Magma is formed at three main plate-tectonic settings: mantle plumes and divergent boundaries (melting as pressure is reduced when the rock rises), and convergent boundaries (subducting plate causing melt to generate).

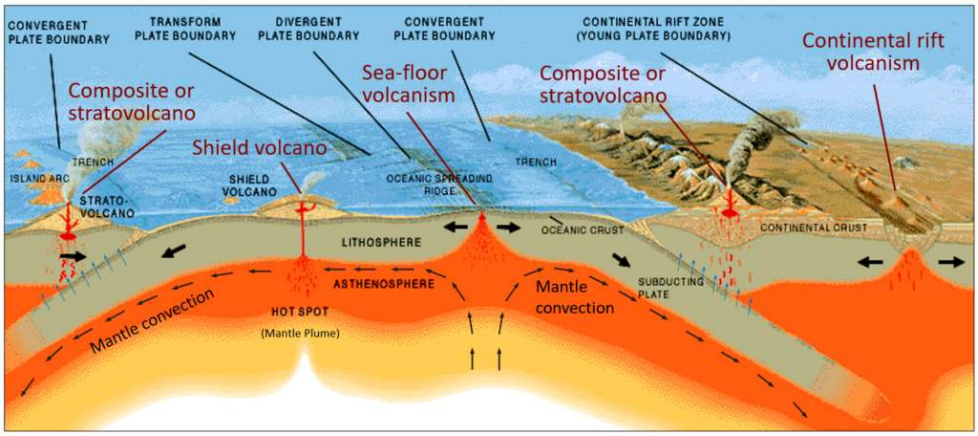


Figure 4.1.1: The Plate-Tectonic Settings of Common Types of Volcanism. Volcanoes form at subduction zones, either on ocean-ocean convergent boundaries (left) or ocean-continent convergent boundaries (right). Volcanoes also form above mantle plumes but can also form at divergent boundaries. Sea-floor volcanism can take place at divergent boundaries, mantle plumes and ocean-ocean-convergent boundaries.

It is important to really think about what types of boundaries do and do not produce volcanism.

- Convergent with subduction - yes
- Convergent with no subduction (continent to continent convergence) - no
- Divergent - yes
- Transform - no

Not all volcanic regions fit nicely into these three categories, and one of these exceptions is the volcanism in northwestern British Columbia (Figure 4.1.2). This area is not at a divergent or convergent boundary, and there is no evidence of an underlying mantle plume. The prevailing theory is that the crust of northwestern BC is being stressed by the northward movement of the Pacific Plate against the North America Plate, and that the resulting crustal fracturing provides a conduit for the flow of magma from the asthenospheric mantle.[1]

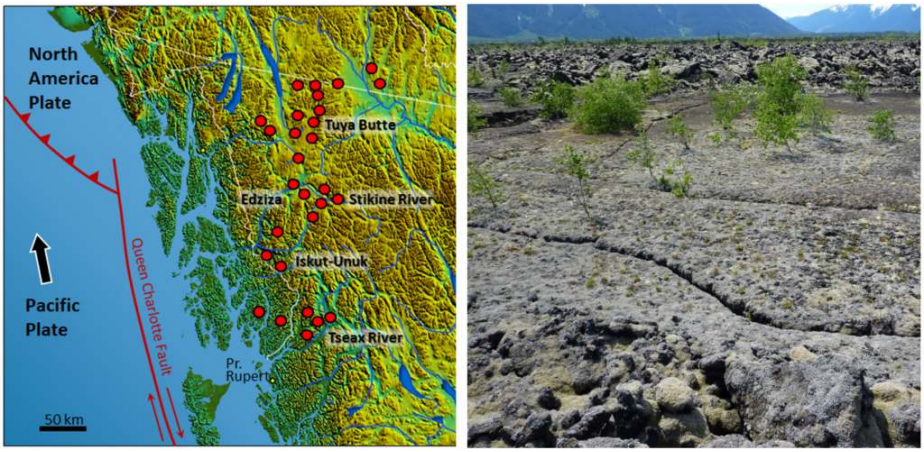


Figure 4.1.2: (Left) Volcanoes and Volcanic Fields in the Northern Cordillera Volcanic Province, BC.; and (Right) Volcanic Rock at the Tseax River Area (now Ksi Sii Aks), Northwestern BC

Media Attributions

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1. Edwards, B. & Russell, J. (2000). Distribution, nature, and origin of Neogene-Quaternary magmatism in the northern Cordilleran volcanic province, Canada. *Geological Society of America Bulletin*, *112*(8), 1280-1293. https://doi.org/10.1130/0016-7606(2000)112<1280:DNAOON>2.0.CO;2 ↵

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4.2: Magma Composition and Eruption Style

The types of magma produced in the differing volcanic settings can differ quite significantly. At divergent boundaries and oceanic mantle plumes, where there is little interaction with crustal materials, the magma tends to be consistently mafic (~50% silica with significant metals). At subduction zones, where the magma ascends through significant thicknesses of crust, interaction between the magma and the crustal rock—some of which is quite felsic (~70% silica with few metals)—results in magma that is relatively felsic.

In summary:

- Divergent boundaries - mafic
- Mantle plumes in ocean - mafic
- Convergent boundaries with subduction - felsic

From the perspective of volcanism there are some important differences between felsic and mafic magmas. First, felsic magmas tend to be more viscous and are therefore sticky because they have more silica, and more polymerization. Mafic magmas are less viscous and are therefore more "runny". Second, felsic magmas tend to have higher levels of **volatiles**—that is components that behave as gases during volcanic eruptions. The most abundant volatile in magma is water (H_2O), followed, typically, by carbon dioxide (CO_2) and then by sulphur dioxide (SO_2). The general relationship between the SiO_2 content of magma and the amount of volatiles is shown on Figure 4.2.1. Although there are many exceptions to this trend, mafic magmas typically have 1 to 3% volatiles, intermediate magmas have 3 to 4% volatiles and felsic magmas have 4 to 7% volatiles.

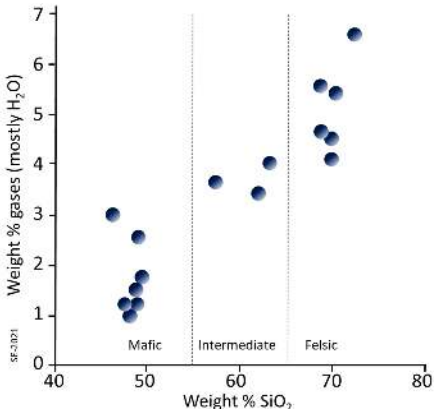


Figure 4.2.1: Variations in the Volatile Compositions of Magmas as a Function of Silica Content

Differences in viscosity and volatile level have significant implications for the nature of volcanic eruptions. When magma is deep beneath the surface and under high pressure from the surrounding rocks, the gases remain dissolved. As magma approaches the surface the pressure exerted on it decreases. Gas bubbles start to form, and the more gas there is in the magma the more bubbles will form.

As is typical in mafic magmas, if the gas content is low or the magma is runny enough for gases to rise up through it and escape to surface, the pressure will not become excessive. Assuming there is a way for it to get to surface, the magma will flow out relatively gently.

If the magma is felsic, and therefore too viscous for gases to escape easily, or if it has a particularly high gas content, it is likely to be under high pressure. Viscous magma doesn't flow easily, so even if there is a way for it to get out, it may not be able to flow out readily. Under these circumstances pressure will continue to build as more magma moves up from beneath. Eventually some part of the volcano will break and then that pent up pressure will lead to an explosive eruption.

In summary:

- felsic magmas have high viscosity, so they don't flow easily; they also tend to have a high gas content which gets trapped by the sticky nature of the magma; when the magma/lava erupts it is explosive
- mafic magmas have low viscosity, so they are very fluid; they also tend to have a low gas content; even the gas that is there easily escapes the fluid magma; when the magma/lava erupts it is gentle

Mantle plume magmas in the middle of plates and spreading-ridge magmas at divergent boundaries tend to be consistently mafic and so gentle eruptions are the norm. At subduction zones the average magma composition ranges from felsic to intermediate even within the same magma body, so different eruptions can have very different magma compositions. Eruption styles can be correspondingly variable but are generally violent.

In summary:

- Divergent boundaries - gentle eruptions
- Mantle plumes in ocean - gentle eruptions
- Convergent boundaries with subduction - violent eruptions

Looking back at Figure 4.2.1, the eruptions on the far right and far left of the image created at subduction zones would be violent. Those occurring at the hotspot or at the divergent boundary in the ocean would be gentle.

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- **Figure** 4.2.1**:** Steven Earle, CC BY 4.0, after Schmincke, H-U. (2004). *Volcanism.* Springer-Verlag, Heidelberg. https://link.springer.com/content/pd...42-18952-4.pdf

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4.3: Types of Volcanism

There are numerous types of volcanism; some of the more common ones are summarized in Table 4.3.1. You don't need to memorize these; this is just here to give context to our learning.

Table 4.3.1: Summary of Common Types of Volcanism

Type	Tectonic Setting	Size & Shape	Magma & Eruption Characteristics	Example
Cinder cone	Various. Some form on the flanks of other volcanoes	Small (10s to 100s of m) and steep (>30°)	Most are mafic and form from the gas-rich early stages of a shield- or rift-associated eruption	Eve Cone, northern BC
Composite volcano	Almost all are at subduction zones	Medium size (1000s of m) and moderate steepness (10 to 30°)	Magma composition varies from felsic to mafic, and from explosive to effusive	Mt. St. Helens and other Cascade Peaks Andes Mountains
Shield volcano	Most are at mantle plumes, some on spreading ridges	Large (up to several 1000 m high and 200 km across), not steep (typically 2 to 10°)	Magma is almost always mafic, and eruptions are typically effusive, although cinder cones are common on the flanks of shield volcanoes	Kilauea, Hawaii
Large igneous provinces	Associated with “super” mantle plumes	Enormous (up to millions of km2) and 100s of m thick	Magma is always mafic. Individual flows can be 10s of meters thick	Columbia River basalts
Sea-floor volcanism	Generally associated with spreading ridges but also mantle plumes	Most of the oceanic crust formed at spreading ridges	At normal eruption rates pillows form. At faster rates, lava flows develop.	Juan de Fuca ridge Mid Atlantic ridge
Kimberlite	Older parts of continents	The remnants are typically 10s to 100s of m across	Most appear to have had explosive eruptions forming cinder cones. The youngest one is over 10 ka, and all others are over 30 Ma.	Lac de Gras kimberlite field, NWT

The sizes and shapes of typical shield, composite and cinder-cone volcanoes are compared on Figure 4.3.1, although, to be fair, Mauna Loa is the largest shield volcano on Earth. Mauna Loa rises from the surrounding flat sea floor, and its full diameter is in the order of 200 km, with a diameter of about 100 km above sea level. Its elevation is 4169 m above sea level. Mt. St. Helens, a composite volcano, rises above the surrounding hills of the Cascade Range. It is about 6 km across at the base, and its height is 2550 m above sea level. Cinder cones are much smaller. On this drawing even a large cinder cone is just a dot.

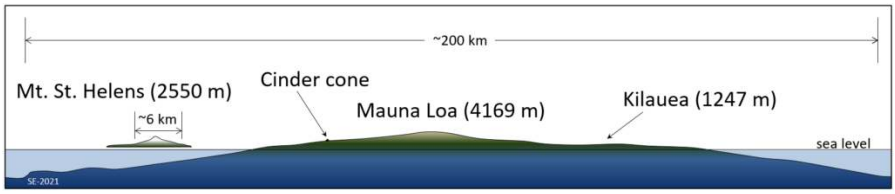


Figure 4.3.1: Profiles of a Shield Volcano (Mauna Loa and Kilauea), a Composite Volcano (Mt. St. Helens), and a Large Cinder Cone

Cinder Cones

Cinder cones, like Eve Cone in northern BC (Figure 4.3.2), are typically only a few hundred meters in diameter and few are more than 200 m high. Most are comprised of fragments of mafic volcanic rock that were blasted out during a high-gas-pressure early phase of an eruption that may have subsequently become gentle (lava flows). Most cinder cones were created during a single eruptive phase that might have lasted weeks or months. Because cinder cones are made up almost exclusively of loose fragments, they have very little strength and can be easily, and relatively quickly, eroded away. Since these are mafic in composition, they produce relatively gentle eruptions.



Figure 4.3.2: Eve Cone, Which Rises About 170 m Above the Surrounding Plateau, Formed Approximately 700 Years Ago.

Composite Volcanoes

Composite volcanoes, like Mt. St. Helens in Washington State (Figure 4.3.3), are almost all associated with subduction at convergent plate boundaries—either ocean-continent or ocean-ocean boundaries. At many such volcanoes magma is stored in a magma chamber in the upper part of the crust. For example, at Mt. St. Helens, there is evidence of a magma chamber that is approximately 1 kilometer in width and extends from about 6 to 14 km depth below surface (Figure 4.3.4). Since these are felsic or intermediate in composition, they produce relatively violent eruptions.



Figure 4.3.3: The North Side of Mt. St. Helens in South-Western Washington State, 2003. The large 1980 eruption reduced the height of the volcano by 400 m, and a sector collapse removed a large part of the northern flank. Between 1980 and 1986 the slow eruption of more lava led to construction of a dome inside the crater.

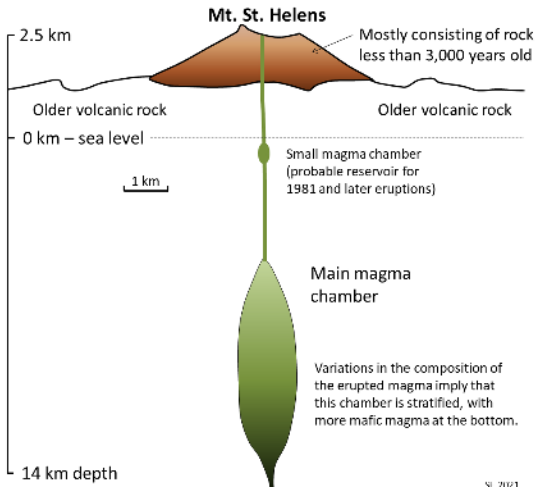


Figure 4.3.4: A Cross-Section Through the Upper Part of the Crust at Mt. St. Helens Showing the Zoned Magma Chamber.

The rock that makes up Mt. St. Helens ranges in composition from rhyolite (fine-grained and felsic) to basalt (fine-grained and mafic), and that implies that the types of past eruptions have varied widely in their character. As already noted, felsic magma doesn't flow easily and doesn't allow gases to escape easily. Under these circumstances pressure builds up until some part of the volcano gives way, and then an explosive eruption results. This type of eruption can also lead to rapid melting of ice and snow on a volcano, and that typically triggers large mudflows known as lahars. Hot, fast moving pyroclastic flows (fast-moving, high-density current of hot volcanic ash, gas, pumice, and rock fragments) and lahars are the two main causes of casualties in volcanic eruptions. Pyroclastic flows killed approximately 30,000 during the 1902 eruption of Mt. Pelée on the Caribbean Island of Martinique. Most were incinerated in their homes.

In contrast, mafic eruptions (and some intermediate eruptions), produce lava flows. If they are thick enough, they can cool in a columnar jointing pattern (Figure 4.3.5). Lava flows serve to both flatten the profile of the volcano (because the lava typically flows farther than the pyroclastic debris falls) and to protect it from erosion.

In a geological context, composite volcanoes tend to form relatively quickly and do not last very long. Mt. St. Helens, for example, is made up of rock that is all younger than 40,000 years; most of it is younger than 3,000 years. If its volcanic activity ceases, then it might erode within a few tens of thousands of years. This is largely because of the presence of pyroclastic eruptive material, which is quite weak because it is made up of fragments that are not well stuck together.

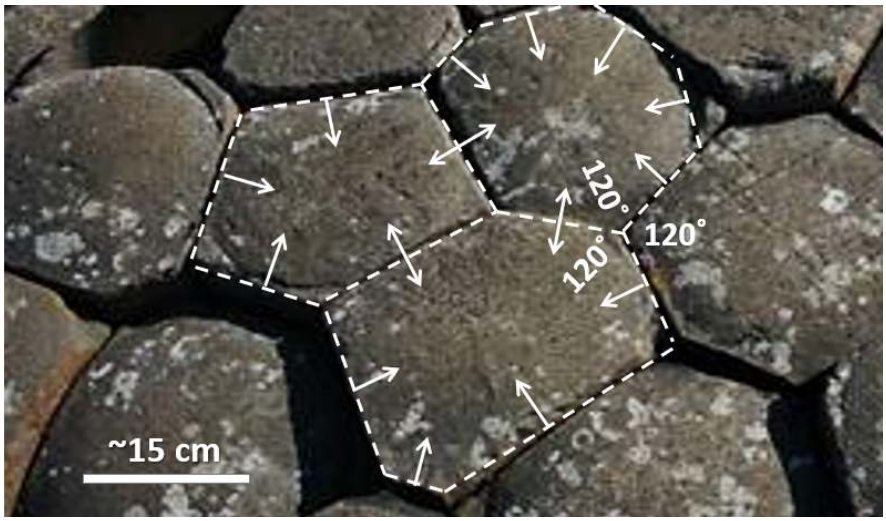


Figure 4.3.5

The Development of Columnar Jointing in Basalt, Here Seen from the Top Looking Down. As the rock cools it shrinks, and because it is very homogenous it shrinks in a systematic way. When the rock breaks it does so with approximately 120° angles between the fracture planes. The resulting columns tend to be 6-sided but 5- and 7-sided columns also form.

Shield Volcanoes

Most **shield volcanoes** are associated with mantle plumes, although some form at divergent boundaries, either on land or on the sea floor. Since these are mafic in composition, they produce relatively gentle eruptions. The best-known shield volcanoes are those that make up the Hawaiian Islands, and of these the only active ones are on the big island of Hawaii. Mauna Loa, the world's largest volcano and the world's largest mountain (by volume) last erupted in 1984. Kilauea, arguably the world's most active volcano, erupted almost continuously, from 1983 to 2018, and then started up again in late 2020. Loihi is an underwater volcano on the southeastern side of Hawaii. It is last known to have erupted in 1996 but may have erupted since then without being detected.

All the Hawaiian volcanoes are related to the mantle plume that currently lies beneath Mauna Loa, Kilauea and Loihi (Figure 4.3.6). In this area the Pacific Plate is moving northwest at a rate of about 7 cm/year, and this means that the earlier formed—and now extinct—volcanoes have now moved well away from the mantle plume. As shown on Figure 7.3.8, there is evidence of crustal magma chambers beneath all three active Hawaiian volcanoes.

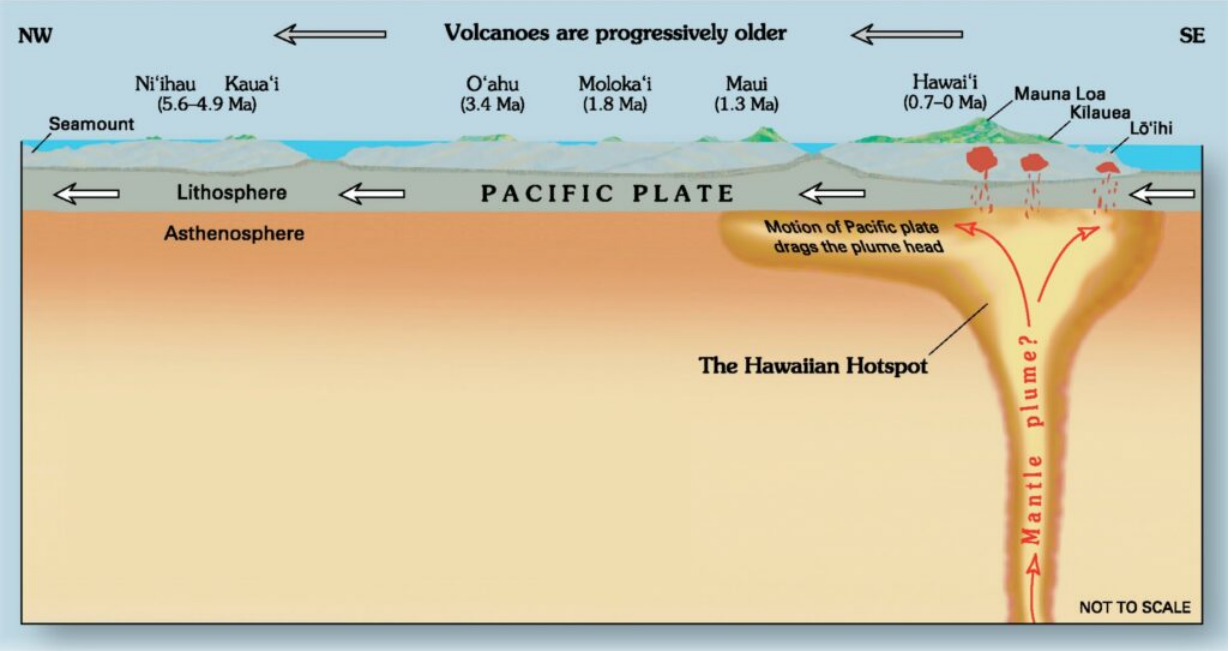


Figure 4.3.6 A Cross-Section Through the Crust and Upper Mantle in the Area of the Hawaii Mantle Plume

Large Igneous Provinces

While the Hawaii mantle plume has produced magma at a relatively slow rate for a very long time (at least 85 million years), other mantle plumes are less consistent, and some generate massive volumes of magma over relatively short time periods. Although their origin is still controversial, it is thought that the volcanism leading to large igneous provinces (LIP) is related to very high volume but relatively short duration bursts of magma from mantle plumes[1]. An example of an LIP is the Columbia River Basalt Group (CRGB), which extends across Washington, Oregon and Idaho (Figure 4.3.7). This volcanism, which covered an area of about 160,000 km^2 with basaltic rock up to several hundred meters thick, took place between 17 and 14 Ma.

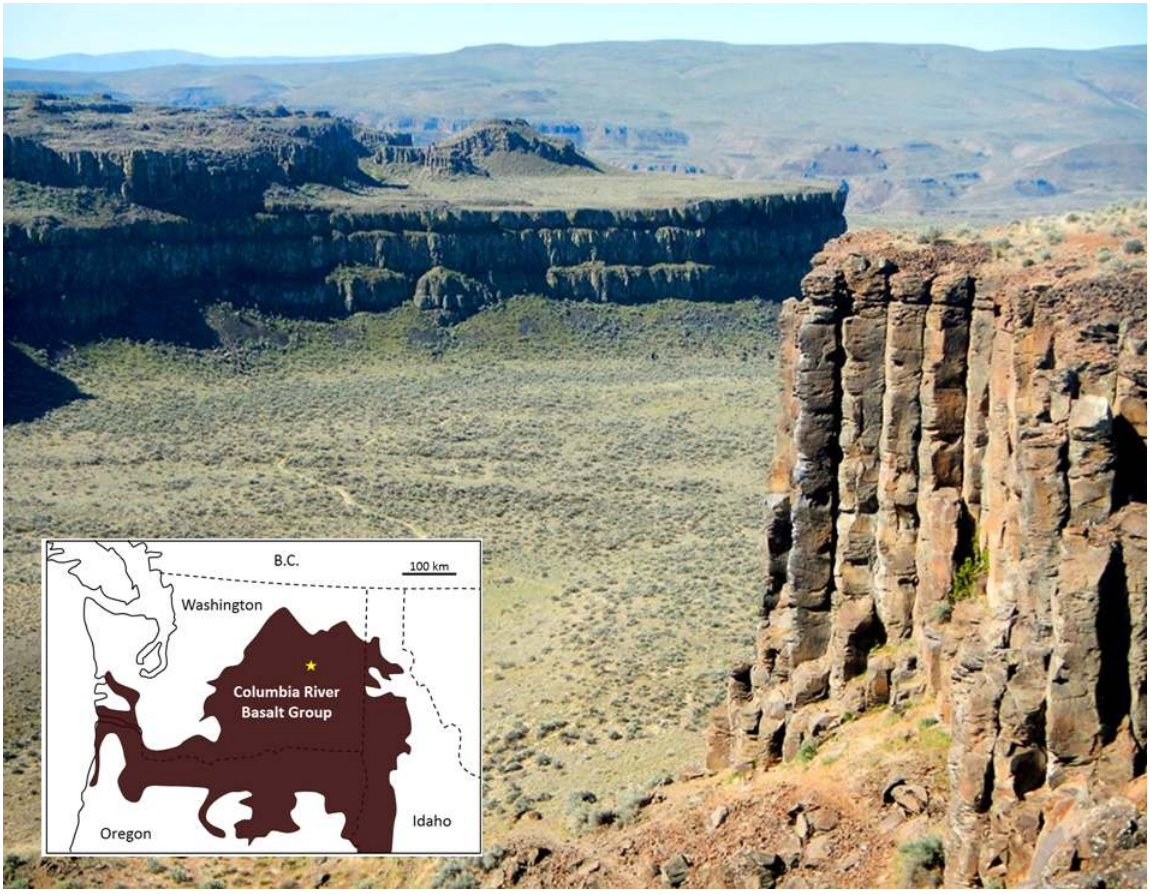


Figure 4.3.7: A Part of the Columbia River Basalt Group at Frenchman Coulee, Eastern Washington. All the flows visible here have formed large (up to 2 meters in diameter) columnar basalts. The inset map shows the extent of the 17 to 14 Ma Columbia River Basalts, with the approximate location of the photo shown as a star.

Some other LIP eruptions have been much bigger. The eruption of the Siberian Traps (also basalt), which happened at the end of the Permian period, at 250 Ma, is estimated to have been 40 times the volume of the CRBG, and is thought to have been responsible for the greatest extinction of all time.

The mantle plume that is assumed to be responsible for the CRBG is now situated beneath the Yellowstone area in Wyoming, where it is associated with felsic volcanism. Over the past 2 million years three very large explosive eruptions at Yellowstone have yielded approximately 900 km^3 of felsic magma, about 900 times the volume of the 1980 eruption of Mt. St. Helens, but only 5% of the volume of mafic magma in the CRBG.

Sea Floor Volcanism

Some LIP eruptions occur on the sea floor, the largest being the one that created the Ontong Java plateau in the western Pacific Ocean at around 122 Ma. But most seafloor volcanism originates at divergent boundaries and involves relatively low volume eruptions. Under these conditions, hot lava that oozes out in the cold seawater quickly cools on the outside and then behaves a little like toothpaste. The resulting blobs of lava are known as pillows, and they tend to form piles around a sea-floor lava vent (Figure 4.3.8). In terms of area, there is very likely more pillow basalt on the sea floor than any other type of rock on Earth.

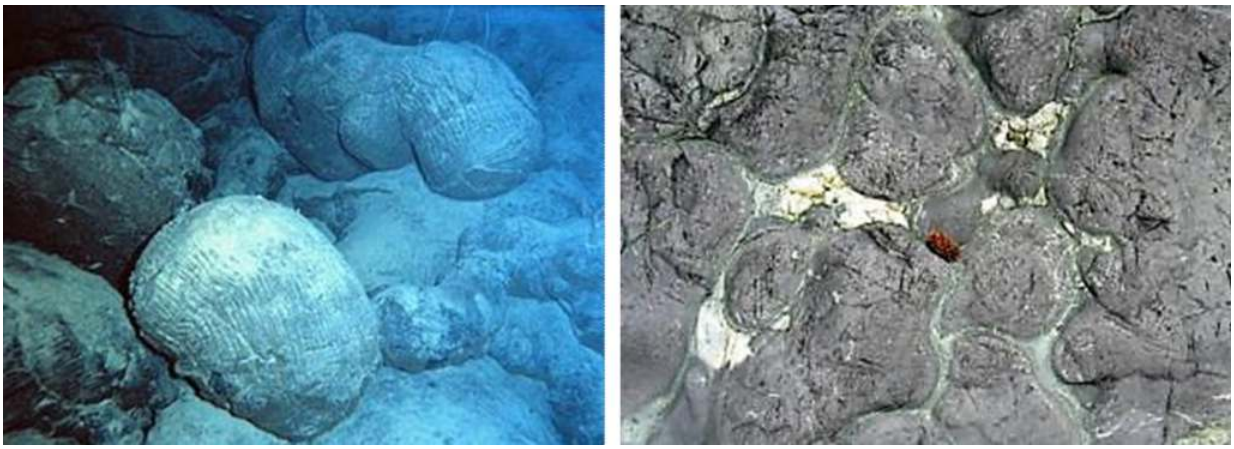


Figure 4.3.8: Modern Sea-Floor Pillows in the South Pacific. (Left: public domain image by NOAA, 1988, via Wikimedia Commons, https://commons.wikimedia.org/wiki/F...alt_crop_l.jpg; and Right: 40 to 50 Ma pillows on the shore of Vancouver Island, near to Sooke. The pillows are 30 to 40 cm in diameter.

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1. Bryan, S. & Ernst, R. (2007). Revised definition of large igneous provinces (LIPs). *Earth-Science Reviews*, *86*(1-4), 175-202. https://doi.org/10.1016/j.earscirev.2007.08.008 ↵

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4.4: Volcanic Hazards

Given the obvious dangers of living near active volcanoes, there must be some reason why humans like living around them. The main reason is that the soil tends to be fertile, and thus there is the potential to grow enough food to live. For example, some parts of the area around Mt. Merapi in Indonesia can support populations of 8 to 10 people per hectare. In comparison, the typical farm in the United States can feed just under 1 person per hectare (US Farm Bureau).

Volcanic soil is good for several reasons. One is that volcanic ash and rock fragments are rich in volcanic glass and under weathering conditions glass breaks down quickly to clay minerals so that productive soil can form within 200 to 300 years in favorable climates. Another is that the clays that form from volcanic parent materials are effective at holding onto nutrients such as phosphorous. A third is that volcanic lava or tephra are typically quite rich in some important plant nutrients, such as magnesium and sulphur.

There are two classes of volcanic hazards, direct and indirect. Direct hazards are those that can directly kill or injure people or destroy property or wildlife habitat. Indirect hazards are volcanism-induced environmental changes that lead to distress, famine or habitat destruction. Indirect hazards of volcanism have accounted for many times more deaths during historical times than direct hazards. Some of the more important types of volcanic hazards are summarized in the table below. Do not memorize this; it is here for your exploration and reference.

Table 4.4.1: A Summary of the Important Volcanic Hazards

Type	Description	Risk
Tephra emissions	Small particles of volcanic rock are emitted into the atmosphere	Respiration problems for some individuals. Short-term climate cooling and potential famine. Aircraft engines at risk.
Gas emissions	The emission of gases during an eruption, or other event	Short-term climate cooling leading to crop failure and famine. Poisoning is widespread in some cases.
Pyroclastic density current	A very hot (several 100°C) mixture of gases and volcanic tephra flows rapidly (up to 100s of km/h) down the side of a volcano	Extreme hazard. Virtually anything in the way will be destroyed.
Pyroclastic fall	Vertical fall of tephra in the area surrounding an eruption	Areas close to the eruption (km to 10s of km) can be covered in thick tephra. Roofs may collapse; structures may burn.
Lahar	A flow of mud and debris down a channel leading away from a volcano, triggered either by an eruption or a severe rain event	Anything within the channel will be severe risk. Lahar mud flows can move at 10s of km/h.
Sector collapse/ debris avalanche	The failure of part of a volcano, either due to an eruption or for some reason, leading to an avalanche of debris	Anything in the past of the debris avalanche will be at severe risk.
Lava flow	The flow of lava away from a volcanic vent	People and infrastructure are at risk, but lava flows tend to be slow (typically a few meters per hour on average) and relatively easy to avoid.

Volcanic Gas and Tephra Emissions

Large volumes of **tephra** (rock fragments, mostly pumice, and volcanic ash) and gases are emitted during major explosive eruptions at composite volcanoes, and a large volume of gas is also released during some high-volume effusive eruptions. One of the major implications of these emissions is cooling of the climate by up to 1˚ C for several months to a few years because the dust

particles and tiny droplets and particles of sulphur compounds block the sun. The last time this happened was in 1991 and 1992 following the large eruption of Mt. Pinatubo in the Philippines. 1˚ C may not seem like a lot, but that was the global average amount of cooling, and cooling was more severe in some regions and at some times.

Over an 8-month period in 1783 and 1784 a large effusive eruption took place at the Laki volcano in Iceland. Although there was relatively little volcanic ash involved, a massive amount of sulphur dioxide was released into the atmosphere, and a significant volume of hydrofluoric acid (HF). The sulphate aerosols that formed in the atmosphere led to dramatic cooling in the northern hemisphere. In Iceland poisoning from the HF resulted in the death of 80% of sheep, 50% of cattle, and the ensuing famine, along with HF poisoning, resulted in the over 10,000 human deaths, about 25% of the population. The Laki eruption also resulted in many deaths in Europe, although the total number isn't known, it is estimated that there were approximately 20,000 deaths in the United Kingdom because of very cold weather,[1] and it seems likely that other parts of northern Europe would have been similarly affected.

Volcanic ash can also have serious implications for aircraft because it can destroy jet engines. In 2010 the eruption of Iceland's Eyjafjallajökull volcano led to the closure of the European airspace for several days, and the cancellation of numerous trans-Atlantic flights.

Not all the environmental effects of volcanism are related to eruptions of magma. The craters of dormant volcanoes are commonly filled with water (such as Crater Lake in Oregon). Within Lake Nyos in west central Cameroun, gases emanating from the underlying magma chamber continually percolate upward into the muddy lake sediment and bottom waters. One August night in 1986 a landslide, an earthquake or a minor eruption disturbed the lake sediment and the water and released approximately 100 million cubic meters of carbon dioxide from the lake bottom. The CO_2 quickly bubbled up through the water and out into the air above the lake. The gas spilled over the lip of the crater and descended in a white cloud down into the valleys surrounding the crater. Over 1700 people and 3000 cattle were killed in their sleep.

Pyroclastic Density Currents

In a typical explosive eruption at a composite volcano the tephra and gases are hot enough to be buoyant in the air and they are forced high up into the atmosphere. As the eruption proceeds, and the ejected materials start to cool, parts become heavier than air and they can then flow downward along the flanks of the volcano (Figure 4.4.1). As they descend, they cool more and so flow faster, reaching speeds up to several hundred km/h. The temperature of this material can be as high as 1000˚ C. The most famous examples are the one that destroyed Pompeii in the year 79 AD, killing an estimated 18,000 and the one that destroyed the town of St. Pierre, Martinique in 1902, killing an estimated 30,000.



Figure 4.4.1: The eruption of Mt. Mayon, Philippines. in 1984. Although most of the eruption column is ascending into the atmosphere, there are pyroclastic density currents flowing down the sides of the volcano in several places.

Pyroclastic Falls

Most of the tephra from an explosive eruption ascends high into the atmosphere, and some of it is distributed around the Earth by high altitude winds. The larger components (larger than 0.1 mm) tend to fall relatively close to the volcano, and the amount produced by large eruptions can cause serious damage and casualties. The large 1991 eruption of Mt. Pinatubo in the Philippines resulted in the accumulation of tens of centimeters of ash in fields and on rooftops in the surrounding populated region.

Lahars

A **lahar** is any mudflow or debris flow that is related to a volcanic eruption or volcanic mountain. Most are caused by melting snow and ice during an eruption, as was the case with the lahar that destroyed the Columbian city of Armero in 1985 (Figure 4.4.2). Lahars can also happen when there is no volcanic eruption, and one of the reasons is that, as we've seen, composite volcanoes tend to be weak and easily eroded.



Figure 4.4.2: Part of the City of Armero Following the 1985 Lahar.

For several reasons, there are significant lahar risks from Washington State's Mt. Rainier:

- It is the tallest and largest of the Cascade Range volcanoes,
- It has numerous large glaciers and accumulates a great deal of snow in winter,
- It has a significant volume of rock that has been weakened by alteration,
- It has been active within the past 125 years, and
- There are several large communities close to the mountain and within the channels of known past lahars (Figure 4.4.3).

According to a US Geological Survey (USGS) publication[2], Mt. Rainier is a lahar risk because there is a likelihood of melting snow and ice during an eruption, and also because there is a risk of slope failure at any time, but especially if there is a large earthquake in the region, or if there is movement of magma within the volcano itself. The USGS, Pierce County Department of Emergency Management, and Washington State Emergency Management Division have established an array of motion sensors in the drainage channels around Mt. Rainier. The system is designed to detect the vibrations associated with a lahar and then to alert at risk residents so that they have time to get to higher ground.

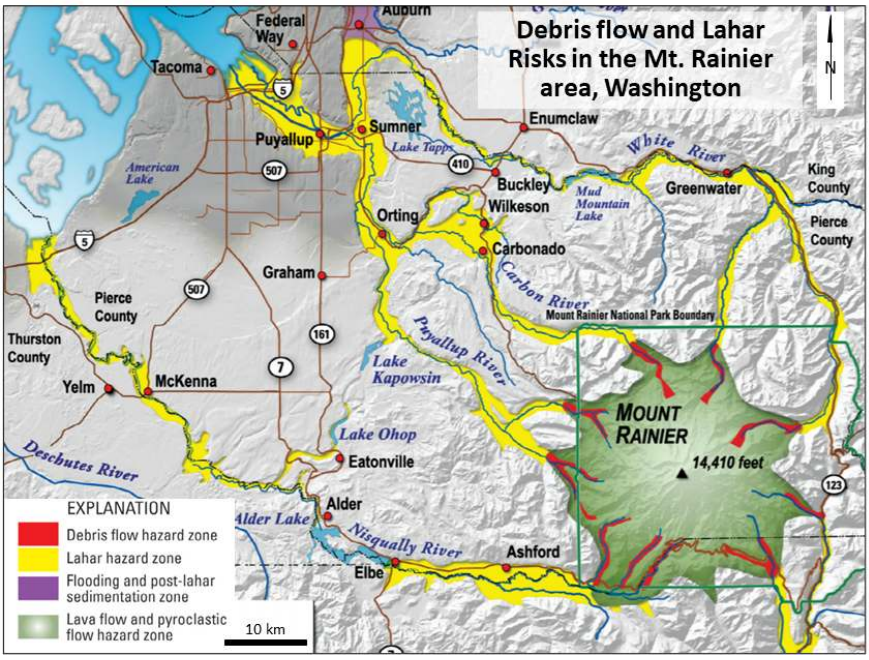


Figure 4.4.3: The Debris Flow and Lahar Risk Around Mt. Rainier in West-Central Washington.

Lava Flows

Lava flows at volcanoes like Kilauea do not advance very quickly, and in most cases, people can get out of the way. Of course, it is more difficult to move infrastructure, and so buildings and roads are typically the main casualties of lava flows.

That was the case with the massive Kilauea eruption in 2018 where lava flowed through a mostly rural area (Figure 4.4.4), resulting in 24 injuries, no deaths, $800 million in damages, and the loss of over 800 homes as a well as a geothermal energy plant. But the situation at Mount Nyiragongo in the Republic of the Congo in 2002 was quite different. There a similar-sized lava stream flowed through Goma, a city of 200,000 people, destroying thousands of buildings, and leaving about 120,000 people homeless. A total of 245 people died, most from carbon-dioxide asphyxiation.



Figure 4.4.4: Kilauea's Lower Puna Lava Flow on May 19th, 2018

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1. Witham, C. S., Oppenheimer, C. (2004). Mortality in England during the 1783–4 Laki Craters eruption. *Bulletin of Volcanology 67*, 15–26. https://doi.org/10.1007/s00445-004-0357-7 ↵
2. Driedger, C. & Scott, W. (2008). Living safely with a volcano in your back yard. U.S. *Geological Survey, Fact Sheet 2008-3062, p.4*. https://pubs.usgs.gov/fs/2008/3062/fs2008-3062.pdf ↵

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CHAPTER OVERVIEW

5: Earthquakes



This chapter describes what an earthquake is and where they tend to occur, shows how to determine the location and magnitude of earthquakes, addresses the affects of earthquakes, and explains the advancements (or lack of) made in earthquake forecasting.

5.1: What is an Earthquake?
5.2: Earthquakes and Plate Tectonics
5.3: Measuring Earthquakes
5.4: The Impacts of Earthquakes
5.5: Forecasting Earthquakes

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5.1: What is an Earthquake?

An earthquake is the shaking caused by the rupture (breaking) and subsequent displacement of rocks (one body of rock moving with respect to another) beneath the Earth's surface. Most earthquakes are a result of the stresses placed on rocks in areas where adjacent tectonic plates are moving in different directions.

A body of rock that is under stress becomes deformed, and that deformation is elastic, meaning that the stressed rock can spring back into its original position. When the rock can no longer withstand the deformation, it breaks, and the two sides slide past each other. Most earthquakes take place near to plate boundaries, but not necessarily right on a boundary, and not necessarily even on an existing or known fault.

The engineering principle of **elastic deformation** is illustrated below. The **stress**, or force, applied to a rock—typically because of ongoing plate movement—results in **strain** or deformation of the rock. Because most rock is strong (unlike loose sand for example), it can withstand a significant amount of deformation without breaking. But every rock has a deformation limit and will rupture (break) once pushed beyond that limit. At that point the rock breaks, there is displacement along the rupture surface, and the two bodies of rock that had been elastically deformed, rebound back to their original shape. The magnitude of the earthquake depends on the extent of the area that breaks (the area of the rupture surface) and the average amount of displacement (sliding).

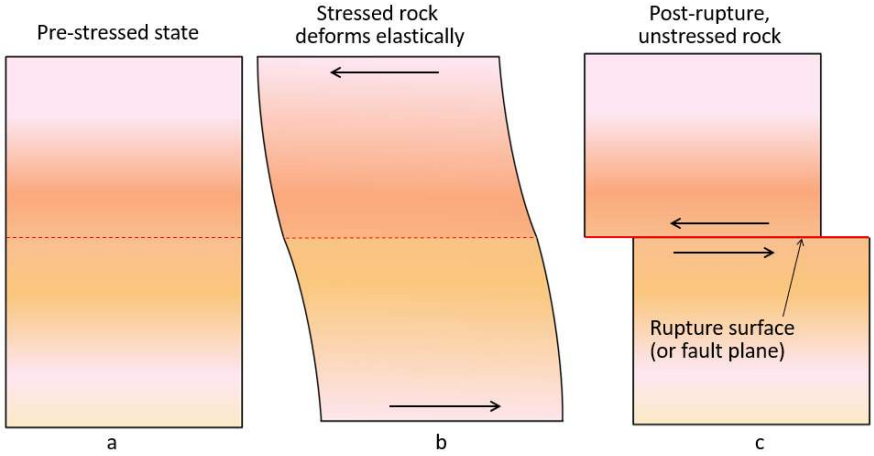


Figure 5.1.1: Depiction of the Concept of Elastic Deformation, Rupture and Elastic Rebound

You may have heard the term aftershock. An aftershock is an earthquake just like any other, but it is one that can be shown to have been triggered by stress transfer from a preceding earthquake. Within a few tens of seconds of the main 1989 Loma Prieta earthquake (near San Francisco, CA) there were hundreds of smaller aftershocks. Aftershocks can be of any magnitude. Most are smaller than the earthquake that triggered them, but they can be bigger, and they can be delayed for hours, weeks, years or even decades. They occur because the initial even reduces stress in one area but increases it in the nearby areas (Figure 5.1.2), which can then produce earthquake events.

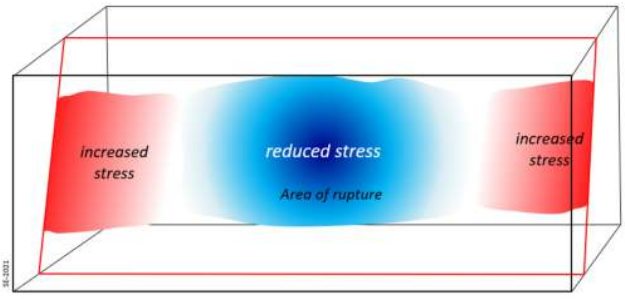


Figure 5.1.2: Depiction of Stress Changes Related to an Earthquake. Stress is decreased (blue) in the area of the rupture surface, but it may be increased (red) on adjacent parts of the fault.

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5.2: Earthquakes and Plate Tectonics

The distribution of earthquakes across the globe is shown in the figure below. It is relatively easy to see the relationships between earthquakes and the plate boundaries. Along divergent boundaries like the mid-Atlantic ridge (middle of Atlantic Ocean) and the East Pacific rise (in ocean west of South America) earthquakes are common but restricted to a narrow zone close to the ridge, and consistently less than 30 km depth (red dots). Shallow earthquakes are also common along transform faults, such as the San Andreas Fault. Earthquakes are very common along subduction zones, and their depth below surface increases inshore from the subduction zone (green and blue dots).

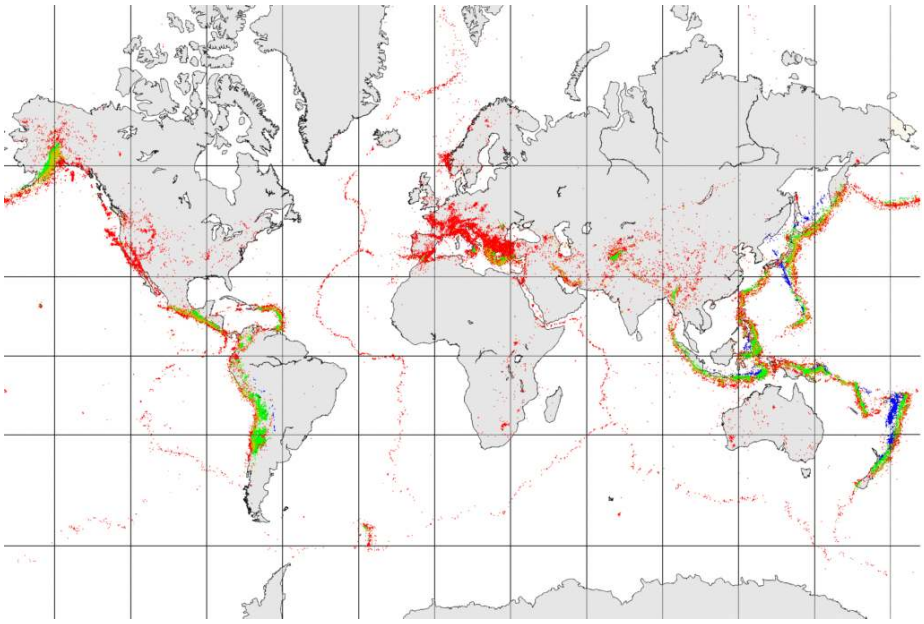


Figure 5.2.1: General Distribution of Global Earthquakes of Magnitude 4 and Greater During the Period from 2004 to 2011. Color coded by depth (red: 0-33 km, orange 33-70 km, green: 70-300 km, blue: 300-700 km)

Earthquakes also occur in a few **intraplate** locations, including the Rift Valley area of Africa (near the center of Africa), in the Tibet region of China and in the Lake Baikal area of Russia.

Earthquakes at Divergent and Transform Boundaries

Figure 5.2.2: provides a closer look at magnitude 4 and larger earthquakes in an area of divergent and transform boundaries in the mid-Atlantic region near to the equator. Here the segments of the mid-Atlantic ridge (divergent boundaries) are offset by some long transform faults, and there is side-by-side motion on those faults. Most of the earthquakes are located along the transform faults, rather than along the divergent boundaries, although there are clusters of earthquakes at some of the divergent-transform intersections. Some earthquakes do occur on divergent boundaries, but they tend to be small and infrequent because of the relatively high rock temperatures in the areas where spreading is taking place.

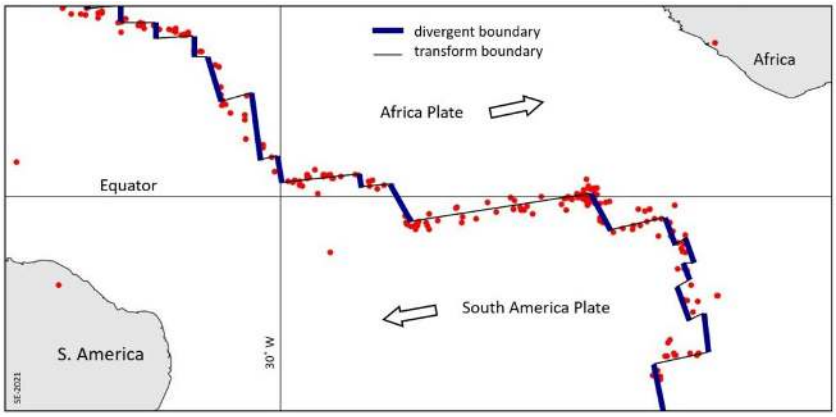


Figure 5.2.2: Distribution of Earthquakes of Magnitude 4 and Greater in the Area of the Mid-Atlantic Ridge Near to the Equator During the Period From 1990 to 1996. All are 0 to 33 km depth.

Earthquakes at Convergent Boundaries

The distribution and depths of earthquakes in the Caribbean and Central America area are shown on Figure 5.2.3. In this region the Cocos Plate is subducting beneath the North America and Caribbean Plates (an ocean-continent convergence), and the South and North America Plates are subducting beneath the Caribbean Plate (an ocean-ocean convergence). In both cases the earthquakes get deeper with distance from the trench.

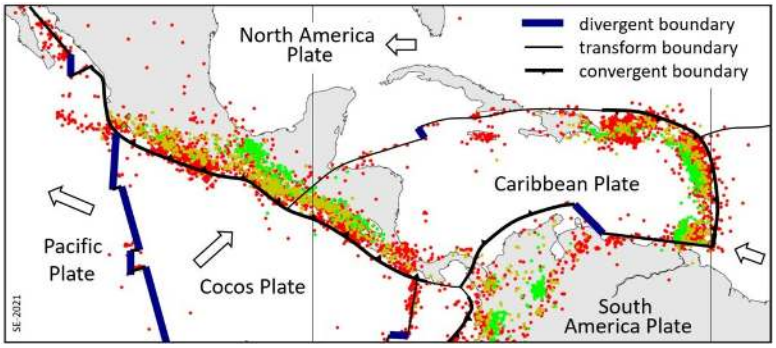


Figure 5.2.3: Distribution of Earthquakes of Magnitude 4 and Greater in the Central America Region from 1990 to 1996. (red: 0-33 km, orange 33-70 km, green: 70-300 km, blue: 300-700 km) (Spreading ridges are heavy blue lines, subduction zones are toothed lines, and transform faults are light lines.)

All the very large earthquakes—M9 or higher—take place at subduction boundaries because there is the potential for greater rupture zone width on a gently dipping subduction boundary than on a steep transform boundary. The largest earthquakes on transform boundaries, like what is most of California marked by the San Andreas fault, are in the order of M8.

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5.3: Measuring Earthquakes

There are two main ways to measure earthquakes. The first of these is an estimate of the energy released, and the value is referred to as **magnitude**. This is the number that is typically first released by the press when a big earthquake happens. It is often referred to as “Richter magnitude”, and it estimates the amount of energy released.

The other way of assessing the impact of an earthquake is to assess what people felt and how much damage was done. This is known as **intensity**. Intensity values are assigned to locations, rather than to the earthquake itself, and intensity can vary widely therefore, depending on the proximity to the earthquake and the type of ground underneath.

Earthquake Magnitude

Before we look more closely at magnitude, we need to review what we know about **body waves** (waves that travel through the Earth), and also look at **surface waves** (waves that travel along the Earth's surface). Body waves are of two types, P or primary or compression waves (like the compression of the coils of a spring), and S or secondary or shear waves (like the flick of a rope). An example of P and S seismic records is shown on Figure 5.3.1. The critical parameters for the measurement of Richter magnitude are labeled, including the time interval between the arrival of the P and S waves—which is used to determine the distance from the earthquake to the seismic station, and the amplitude of the S waves—which is used to estimate the magnitude.

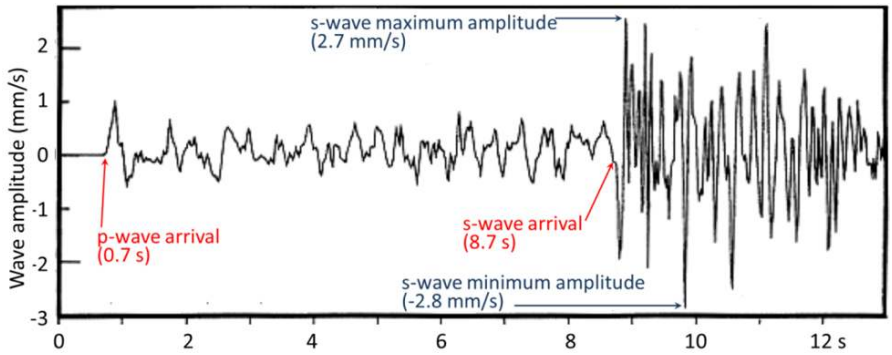


Figure 5.3.1: P and S Waves from a Small (M 4) Earthquake that Took Place Near to Vancouver Island in 1997.

When a body wave (P or S) reaches the Earth’s surface some of its energy is transformed into surface waves, of which there are two main types, as illustrated in Figure 5.3.2. Rayleigh waves are characterized by vertical motion of the ground surface, like waves on water, while Love waves are characterized by horizontal motion. Both Rayleigh and Love waves are about 90% as fast as S waves (so they arrive later at a seismic station). Surface waves typically have greater amplitudes than body waves, and they do more damage.

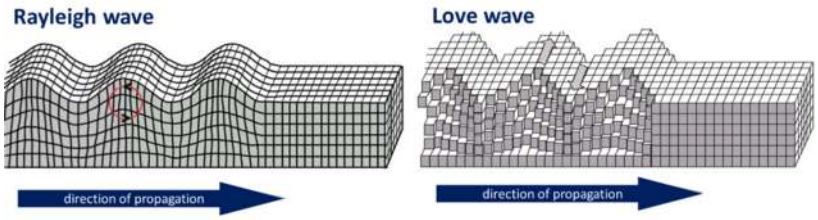


Figure 5.3.2: Depiction of Seismic Surface Waves

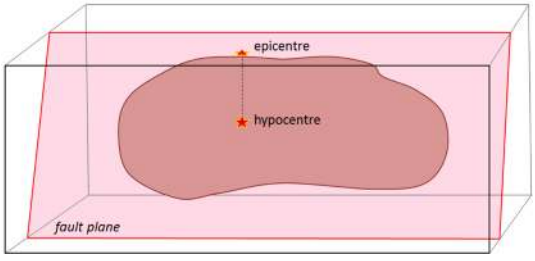


Figure 5.3.3: Definition of Epicenter and Hypocenter

Two other important terms from the perspective of describing earthquakes are **hypocenter** and **epicenter**. The hypocenter is the actual location of an individual earthquake shock at depth in the ground, and the epicenter is the point on the land surface directly above the hypocenter (Figure 5.3.3).

Because of the increasing size of cities in earthquake-prone areas (e.g., China, Japan, California and Turkey) and the increasing sophistication of infrastructure, it is becoming important to have very rapid warnings, and magnitude estimates of earthquakes that have already happened. This can be achieved by using P-wave data because P waves arrive first at seismic stations, in many cases several seconds ahead of the more damaging S waves and surface waves. Operators of electrical grids, pipelines, trains and other infrastructure can use the information to automatically shut systems down so that damage and casualties can be limited.

The magnitude scale is logarithmic, in fact the amount of energy released by an earthquake of magnitude 4 is 32 times higher than that released by one of magnitude 3, and this ratio applies to all intervals in the scale. If we assign an arbitrary energy level of 1 unit to a magnitude 1 earthquake the energy for quakes up to magnitude 8 will be as shown on the following list:

Magnitude	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Energy	1	32	1024	32,768	1,048,576	33.5 million	1.1 billion	34.6 billion

In any given year when there is a large earthquake on Earth (M 8 or 9) the amount of energy released by that one event will likely exceed the energy released by all smaller events combined.

Earthquake Intensity

The intensity of earthquake shaking at any location is determined by the magnitude of the earthquake and its distance, but also by the type of underlying rock or unconsolidated materials. If buildings are present, the size and type of building are also important.

Intensity scales were first used in the late 19th century, and then adapted in the early 20th century by Giuseppe Mercalli and modified later by others to form what we know call the Modified Mercalli Intensity scale (Figure 5.3.4). Intensity estimates are important because they allow us to characterize parts of any region into areas that are especially prone to strong shaking versus those that are not. The key factor in this regard is the nature of the underlying geological materials, and the weaker those are the more likely it is that there will be strong shaking. Areas underlain by strong solid bedrock tend to experience much less shaking that those underlain by unconsolidated river or lake sediments.

I Not felt	Not felt except by a very few under especially favorable conditions.
II Weak	Felt only by a few persons at rest, especially on upper floors of buildings.
III Weak	Felt quite noticeably by persons indoors, especially on upper floors of buildings. Many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibrations similar to the passing of a truck. Duration estimated.
IV Light	Felt indoors by many, outdoors by few during the day. At night, some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.
V Moderate	Felt by nearly everyone; many awakened. Some dishes, windows broken. Unstable objects overturned. Pendulum clocks may stop.
VI Strong	Felt by all, many frightened. Some heavy furniture moved; a few instances of fallen plaster. Damage slight.
VII Very Strong	Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable damage in poorly built or badly designed structures; some chimneys broken.
VIII Severe	Damage slight in specially designed structures; considerable damage in ordinary substantial buildings with partial collapse. Damage great in poorly built structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned.
IX Violent	Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb. Damage great in substantial buildings, with partial collapse. Buildings shifted off foundations.
X Extreme	Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations. Rails bent.
XI Extreme	Few, if any (masonry), structures remain standing. Bridges destroyed. Broad fissures in ground. Underground pipe lines completely out of service. Earth slumps and land slips in soft ground. Rails bent greatly.

Figure 5.3.4: The Modified Mercalli Intensity Scale

An example of this amplifying effect is provided by the 1985 M8 earthquake which struck the Pacific coast Michoacán region of western Mexico, about 350 km southwest of Mexico City. There was relatively little damage in the area around the epicenter, but there was tremendous damage and about 5000 deaths in heavily populated Mexico City. The key reason for this is that Mexico City was built largely on the unconsolidated and water-saturated sediment of former Lake Texcoco. These sediments resonate at a frequency of about 2 seconds, which was similar to the frequency of the body waves that reached the city.[1] For the same reason that a powerful opera singer can break a wine glass by singing the right note, the seismic shaking was amplified by the lake sediments. Survivors of the disaster recounted that the ground in some areas moved up and down by about 20 cm every 2 seconds for over 2 minutes. Damage was greatest to buildings between 5 and 15 stories tall, because they also resonated at around 2 seconds, and amplified the shaking.

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1. An earthquake creates seismic waves with a wide range of frequencies. The fast-vibrating shorter wavelength waves get absorbed by strong bedrock because strong rock has a fast natural vibration frequency. The slow-vibrating longer wavelength waves can travel a long way through the solid rocks of the crust (because they don't match its natural vibration frequency and are not absorbed), and these are the waves that reached Mexico City in 1985. Their slow frequencies matched the natural frequency of the sediments underneath the city. ↵

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5.4: The Impacts of Earthquakes



Figure 5.4.1: A Part of the Nimitz Freeway in Oakland California that Collapsed During the 1989 Loma Prieta Earthquake.

Some of the common impacts of earthquakes include structural damage to buildings, fires, damage to bridges and highways, slope failures, liquefaction and tsunami. The types of impacts will depend to a large degree on the type of area where the earthquake is located: whether it is predominantly urban or rural, densely or sparsely populated, highly developed or under-developed, and of course on the ability of the infrastructure to withstand shaking.

Ground Shaking

As we've seen from the example of the 1985 Mexico earthquake, the geological foundations on which structures are built can have a significant impact on earthquake shaking. In many cases the soft sediments amplify the seismic shaking, so it is very common to see much worse earthquake damage in areas underlain by soft sediments than in areas of solid rock. A good example of this is in the Oakland area near to San Francisco, where parts of a two-layer highway built on soft sediments collapsed during the 1989 Loma Prieta earthquake (Figure 5.4.1).

Building damage is also worse in areas of soft sediments, and multi-story buildings tend to be more seriously damaged than smaller ones. Buildings can be designed to withstand most earthquakes, and this practice is increasingly applied in earthquake-prone regions. Turkey is one such region, and even though Turkey had a relatively strong building code in the 1990s, adherence to the code was weak, as builders did whatever they could to save costs, including using inappropriate materials in concrete and reducing the amount of steel reinforcing. The result was that there were over 17,000 deaths in the M7.6 1999 Izmit earthquake (Figure 5.4.1). After two devastating earthquakes in 1999 Turkish authorities strengthened the building code, but the new code has only been applied in a few regions, and enforcement of the code is still weak, as revealed by the amount of damage from a M7.1 earthquake in eastern Turkey in 2011.



Figure 5.4.2: Buildings Damaged by the 1999 Earthquake in the Izmit Area, Turkey

Fire



Figure 5.4.3: Fires in San Francisco During the 1906 Earthquake

Fires are commonly associated with earthquakes because gas pipelines get ruptured and electrical lines get damaged when the ground shakes. Most of the damage in the great 1906 San Francisco earthquake was caused by massive fires in the downtown area of the city (Figure 5.4.3). Some 25,000 buildings were destroyed by those fires, which were fueled by broken gas pipes. Fighting the fires was difficult because water mains were also ruptured. The risk of fires can be reduced through P-wave early warning systems if utility operators can reduce pipeline pressure and close electrical circuits.

Slope Failure



Figure 5.4.4: The Las Colinas Debris Flow at Santa Tecla (A Suburb of the Capital San Salvador) Triggered by the January 2001 El Salvador Earthquake. This is just one of many hundreds of slope failures that resulted from that earthquake. Over 500 people died in the area affected by this slide.

Earthquakes are important triggers for failures on slopes that are already prone to weakness. An example is the Las Colinas slide in the city of Santa Tecla, El Salvador, which was triggered by a M7.6 offshore earthquake in January 2001 (Figure 5.4.4).

Liquefaction



Figure 5.4.5: Collapsed Apartment Buildings in the Niigata Area, Japan. The material beneath the buildings was liquefied to varying degrees by the 1964 Niigata earthquake.

Ground shaking during an earthquake can be enough to weaken rock and unconsolidated materials to the point of failure, but in many cases the shaking also contributes to a process known as **liquefaction**, in which an otherwise solid body of sediment gets transformed into a liquid mass that can flow. When water-saturated sediments are shaken the grains become rearranged to the point where they are no longer supporting one-another. Instead, the water between the grains is holding them apart and the material can flow. Liquefaction can lead to the collapse of buildings and other structures that might be otherwise undamaged. A good example is the collapse of apartment buildings during the 1964 Niigata earthquake (M7.6) in Japan (Figure 5.4.5). Liquefaction can also

contribute to slope failures and to fountains of sandy mud (sand “volcanoes”) in areas where there is loose saturated sand beneath a layer of more cohesive clay.

Liquefaction risk is greatest where the loose sediments are saturated with water, and this applies to near-shore areas along coastlines.

Tsunami

Earthquakes that take place beneath the ocean have the potential to generate **tsunamis** (very large waves) under certain conditions. The most likely situation for a significant tsunami is a large (M7 or greater) subduction-related earthquake. As shown on Figure 5.4.6, during the time between earthquakes the overriding plate gets slowly distorted by elastic deformation; it is squeezed laterally (Figure 5.4.1B) and it is pushed up. When an earthquake happens that deformed crust springs back, resulting in either rapid subsidence of the sea floor, rapid uplift of the seafloor, or both.

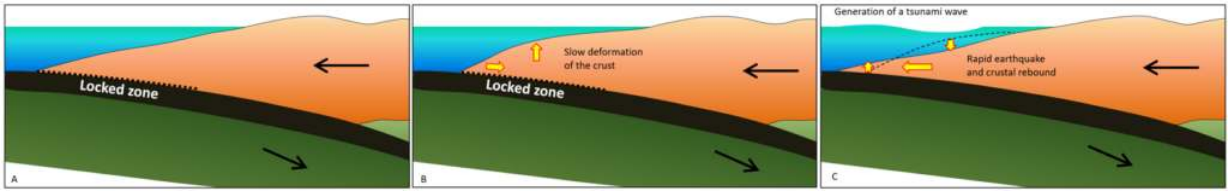


Figure 5.4.6: Elastic Deformation and Rebound of Overriding Plate at a Subduction Setting (B). The release of the locked zone during an earthquake (C) results in both uplift and subsidence on the sea floor, and this is transmitted to the water overhead, resulting in a tsunami.

Subduction earthquakes with magnitude less than 7 do not typically generate significant tsunami because the amount of vertical displacement of the sea floor is minimal. Seafloor transform earthquakes, even large ones (M7 to 8), don’t typically generate tsunami either, because the motion is mostly side-to-side, and not vertical. And, of course, earthquakes that take place entirely on land don’t generate tsunami.

Tsunami waves travel at velocities of several hundred km/h and easily make it to the far side of an ocean in about the same time as a passenger jet. The simulated one shown on Figure 5.4.7, is like that created by the January 1700 Cascadia earthquake off the coast of British Columbia, Washington, and Oregon, which was recorded in Japan 9 hours later.

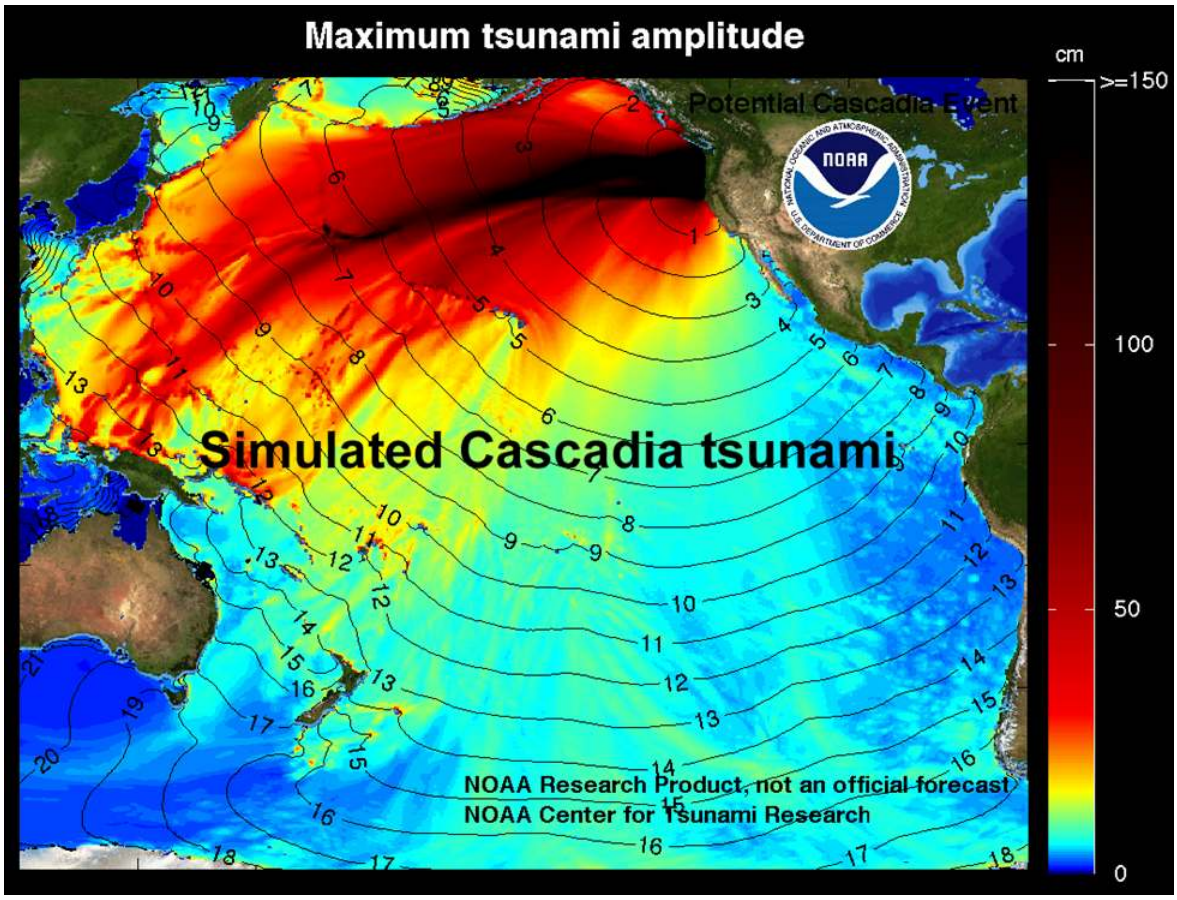


Figure 5.4.7: Model of the Tsunami from the 1700 Cascadia Earthquake (~M9) Showing Open-Ocean Wave Heights (Colors) and Travel Time Contours. Tsunami wave amplitudes typically increase dramatically in shallow water.

In many earthquake events the damage and loss of life from a tsunami is much greater than those from the earthquake shaking. This certainly applies to the massive (M9.1) 2004 Sumatra earthquake and tsunami, for which the death toll was well over 200,000. An example of the damage from that event is shown of Figure 5.4.8. In fact, there is no certainty about the proportion of deaths related to shaking and building collapse versus those from the tsunami because many of the buildings in coastal areas that might have collapsed in the shaking were soon destroyed by the waves.



Figure 5.4.8: Damage to a Community in Aceh, Indonesia from the Tsunami Associated with the 2004 Earthquake. The only building still standing is a large mosque.

Approximately 16,000 of the deaths from Japan's 2011 Tohoku earthquake were a result of drowning or in some other way related to the tsunami, while about 3000 are described as being related to the earthquake. Most of the damage to structures was also caused by the tsunami, including the devastating damage to the Fukushima Daiichi nuclear power station.[1]

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- **Figure** 5.4.8**:** Tsunami damage to a Community in Aceh, Indonesia**,** Public domain image, US Navy, https://nara.getarchive.net/media/a-...sumatra-86b33f

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1. International Atomic Energy Agency (IAEA) (2011). *Japanese Earthquake Update [Alert Log]. (19 March 2011, 4:30 UTC).* https://web.archive.org/web/20110607.../press/?p=1463 ↵

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5.5: Forecasting Earthquakes

It has long been a dream of seismologists, geologists and public safety officials to be able to accurately predict earthquakes on time scales (weeks, days or hours) that would be useful for minimizing danger to the public and damage to infrastructure. Many different avenues have been explored, such as warning foreshocks, changes in magnetic fields, seismic tremor, changing groundwater levels, strange animal behavior, observed earthquake periodicity, stress transfer considerations and a range of others. So far, none of the research into earthquake prediction has provided a reliable method. Although there are reports of successful earthquake predictions, they are rare, and many are surrounded by doubtful circumstances.

The problem with earthquake predictions, as with any other type of prediction, is that they must be accurate most of the time, not just some of the time. We have come to rely on weather predictions because they are generally (and increasingly) accurate. But if we try to predict earthquakes and are only accurate 10% of the time (and even that isn't likely with the current state of knowledge), the public will lose faith in the process very quickly, and then all the predictions will be ignored.

There was a great hope for earthquake predictions late in the 1980s, when attention was focused on part of the San Andreas fault at Parkfield, about 200 km south of San Francisco. Between 1881 and 1966 there were 5 earthquakes at Parkfield, most spaced at approximately 20-year intervals, all confined to the same 20 km-long segment of the fault and all very close to M6 (Figure 5.5.1). Both the 1934 and 1966 earthquakes were preceded by small foreshocks exactly 17 minutes before the main quake.

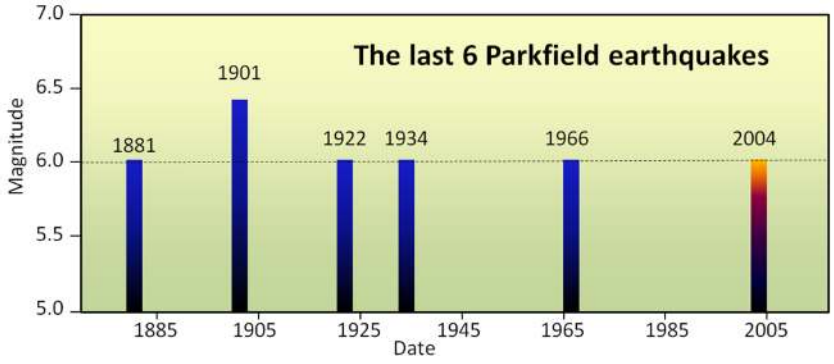


Figure 5.5.1: Earthquakes on the Parkfield Segment of the San Andreas Fault, 1881 to 2004.

The U.S. Geological Survey recognized this as an excellent opportunity to understand earthquakes and earthquake prediction, so they armed the Parkfield area with a huge array of geophysical instruments and waited for the next quake, which was expected to happen around 1987. Nothing happened! The "1987 Parkfield earthquake" finally struck in September 2004, about 17 years late. Fortunately, all the equipment was still there, but it was to no avail from the perspective of earthquake prediction. There were no significant precursors to the 2004 Parkfield earthquake in any of the parameters measured, including: seismicity, harmonic tremor, strain (rock deformation), magnetic field, the conductivity of the rock or creep, and there was no foreshock. In other words, even though every available technique was used to monitor it, the 2004 Parkfield earthquake came as a complete surprise, with no warning whatsoever.

The hope for earthquake prediction is not dead, but it was hit hard by the Parkfield experiment. The current focus in earthquake-prone regions is to provide forecasts of earthquake probabilities within a certain time period—typically a number of decades—and also to ensure that the population is educated about earthquake risks and that buildings and other infrastructure are as safe as can be. An example of this approach for the San Francisco Bay region of California is shown on Figure 5.5.2. Based on a wide range of information, including past earthquake history, accumulated stress from plate movement, and known stress transfer, seismologists and geologists have predicted the likelihood of a M6.7 or greater earthquake on each of 8 major faults that cut through the region. The greatest probabilities are on the San Andreas, Rogers Creek and Hayward faults. As shown on the diagram, there is a 72% chance that a major and damaging earthquake will take place somewhere in the region prior to 2043.

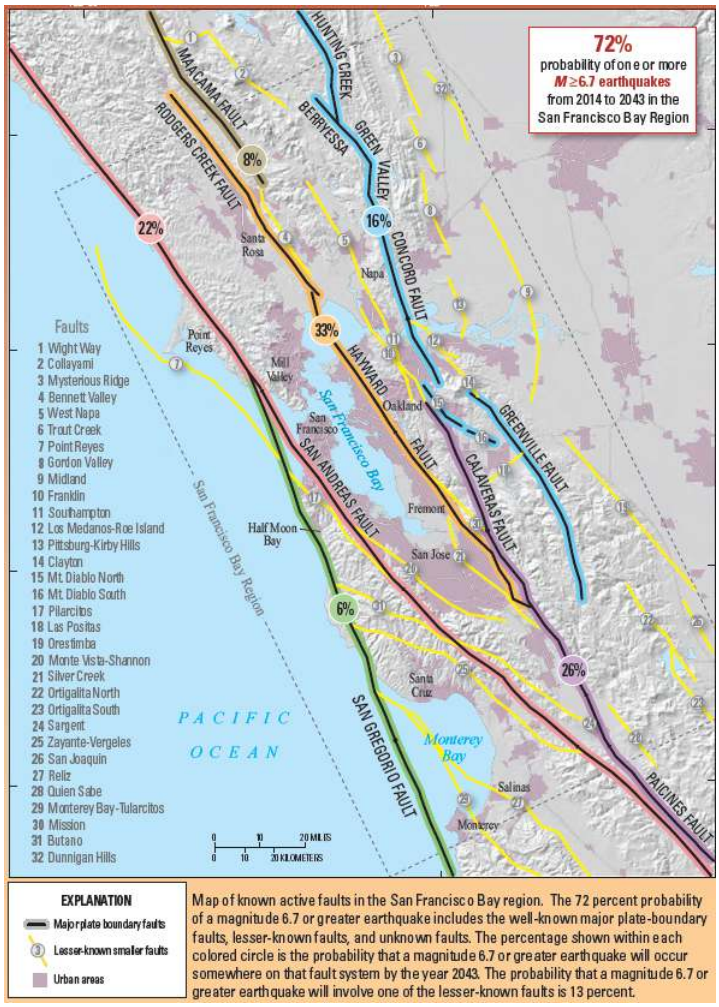


Figure 5.5.2: Probabilities of a M6.7 or Larger Earthquake on Various Faults in the San Francisco Bay Region of California, 2014 to 2043.

Japan established a nation-wide earthquake warning system in 2008, and the US Geological Survey started work on the ShakeAlert system for Washington, Oregon and California in 2016, and the systems are functional. Both systems are based on seismometers on land quickly picking up earthquakes near epicenters and warning nearby areas of the impending waves.

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1. Province of British Columbia. *Seismic Mitigation Program* (last updated May 11, 2021**)**. https://www2.gov.bc.ca/gov/content/e...ation#progress ↵

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CHAPTER OVERVIEW

6: Mass Wasting



This chapter defines what mass wasting is and then addresses what causes slopes to be stable and what factors contribute to slope failures. It also offers a way to classify mass wasting events and suggests ways in which humans intervene to reduce the likelihood of an event from occurring in a given area.

6.1: Factors that Control Slope Stability

6.2: Classification of Mass Wasting

6.3: Mitigating the Effects of Mass Wasting

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6.1: Factors that Control Slope Stability

Mass wasting, which is synonymous with “slope failure”, is the failure and down-slope movement of rock or unconsolidated materials in response to gravity. The term “landslide” is almost synonymous with mass wasting, but not quite because some people reserve “landslide” for relatively rapid slope failures, while others do not. Because of that ambiguity, we will avoid the use of “landslide” in this textbook. Instead, wherever possible, mass wasting events will be referred to by specific names that describe the type of material that failed and the type of motion that took place.

Mass wasting happens because the Earth’s surface is made up of sloped surfaces, and that has happened because tectonic processes have produced uplift. Erosion, driven by gravity, is the inevitable response to that uplift, and mass wasting is a type of erosion. Slope stability is ultimately determined by two factors: the angle of the slope, and the strength of the materials on it.

Figure 6.1.1 shows a block of rock situated on a rock slope. It is being pulled towards the Earth’s center (straight down) by gravity. We can split the vertical gravitational force into two components relative to the slope, one pushing the block down the slope (the shear force), and the other pushing it into the slope (the normal force). The shear force—which wants to push the block down the slope—most overcome the strength of the connection between the block and the slope, which may be quite weak if the block has split away from the main body of rock or may be very strong if the block is still a part of the rock. This is the shear strength, and in Figure 6.1.1a it is greater than the shear force, so the block should not move. In Figure 6.1.1b the slope is steeper, and the shear force is approximately equal to the shear strength. The block may or may not move under these circumstances. In Figure 6.1.1c the slope is steeper still, so the shear force is considerably greater than the shear strength, and the block will very likely move.

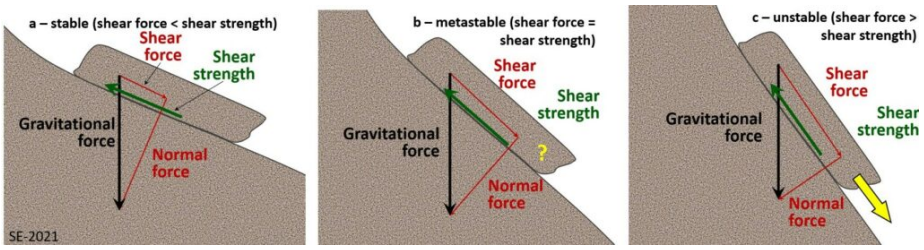


Figure 6.1.1: Differences in the Shear and Normal Components of the Gravitational Force on Slopes with Differing Steepness. The gravitational force is the same in all three cases. In “a” the shear force is substantially less than the shear strength, so the block should be stable. In “b” the shear force and shear strength are about equal, so the block may or may not move. In “c” the shear force is substantially greater than the shear strength, so the block is very likely to move.

The strength of the materials on slopes can vary widely. Solid rocks tend to be strong, but there is a very wide range of rock strength. If we consider just the strength of the rocks, and ignore issues like fracturing and layering, then most crystalline rocks—like granite, basalt or gneiss—are very strong, while some metamorphic rocks—like schist—are moderately strong. Sedimentary rocks have variable strength. Limestone is strong, some sandstone and conglomerate are moderately strong, while some types of sandstone and all mudstones are weak.

Fractures, metamorphic foliation or bedding can significantly reduce the strength of a body of rock, and, in the context of mass wasting, this is most critical if the planes of weakness are parallel to the slope and least critical if they are perpendicular to the slope. This is illustrated on Figure 6.1.2: . At locations A and B the bedding is nearly perpendicular to the slope and the situation is relatively stable. At location D the bedding is nearly parallel to the slope and the situation is quite unstable. At location C the bedding is nearly horizontal, and the stability is intermediate between the other two extremes.

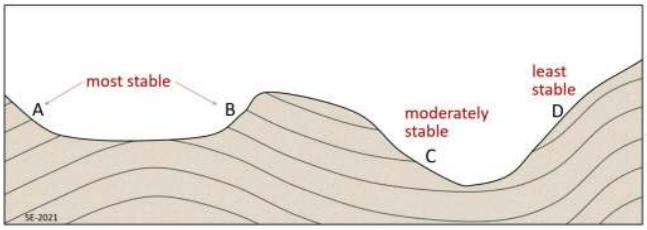


Figure 6.1.2: Cross-Section Through an Area with Topographic Relief That is Underlain by Folded Sedimentary Rocks. Relative stability of slopes as a function of the orientation of weaknesses (in this case bedding planes) relative to the slope orientations.

Unconsolidated sediments are generally weaker than sedimentary rocks because they are not cemented and, in most cases, have not been significantly compressed by overlying materials. Sand and silt tend to be particularly weak; clay is generally a little stronger (unless it is wet, see below), and sand mixed with clay can be stronger still. The deposits that make up the cliffs at Point Grey in Vancouver include sand, silt and clay overlain by sand. As shown on Figure 6.1.3 (left) the finer deposits are relatively strong (they maintain a steep slope), while the overlying sand is relatively weak, has maintained a shallower slope and has recently failed. Glacial till—typically a mixture of clay, silt, sand, gravel and larger clasts—that forms beneath tens to thousands of meters of glacial ice and is well compressed, can be as strong as some sedimentary rock (Figure 6.1.3 – right).



Figure 6.1.3: Left: Glacial Outwash Deposits at Pt. Grey, in Vancouver. The dark lower layer is comprised of sand, silt and clay. The light-colored upper layer is well-sorted sand. Right: Glacial Till at Quadra Island, BC. The till is strong enough to have formed a near-vertical slope.

Apart from the type of material on a slope, the amount of water it contains is the most important factor controlling its strength. This is especially true for unconsolidated materials, like those shown on Figure 6.1.3, but it also applies to bodies of rock. Granular sediments, like the sand at Pt. Grey, have lots of spaces between the grains. Those spaces may be completely dry (filled only with air), or moist, (often meaning that some spaces are water filled, some grains have a film of water around them and small amounts of water are present where grains are touching each other), or completely saturated (Figure 6.1.4). Unconsolidated sediments tend to be strongest when they are moist because the small amounts of water at the grain boundaries hold the grains together with surface tension. Dry sediments adhere together only by the friction between grains, and if they are well sorted or well rounded, or both, that adhesion is weak. Saturated sediments tend to be the weakest of all because the large amount of water pushes the grains apart reducing the mount friction between grains. This is especially true if the water is under pressure.

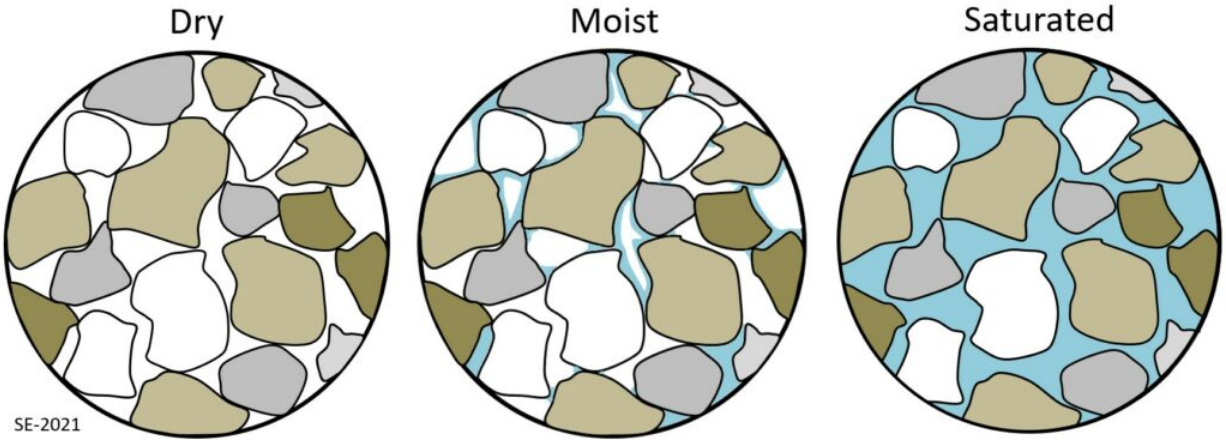


Figure 6.1.4: Depiction of Dry, Moist and Saturated Sand. Air-filled pores are white, water is blue.

Water will also reduce the strength of solid rock, especially if it has fractures or bedding planes, or clay-bearing zones. This effect is most significant when the water is under pressure, and that's why you'll often see holes drilled into rocks on road cuts.

Water also has a particular effect on clay-bearing materials. All clay minerals will absorb a little bit of water, and this reduces their strength. The smectite clays (such as the bentonite used in cat litter) can absorb a lot of water, and that water pushes the sheets apart

on a molecular level and makes the mineral swell. Smectite that has expanded in this way has almost no strength; it is extremely slippery.

And finally, water can significantly increase the mass of the material on a slope. This will increase the gravitational force pushing it down, but it will also increase the normal force pushing mass against the slope and that will increase the friction, so while adding water may make the material on the slope weaker and more prone to fail, the additional weight doesn't necessarily contribute to failure.

Mass Wasting Triggers

In the foregoing discussion we talked about the shear force and the shear strength of materials on slopes, and about factors that can reduce the shear strength. Shear force is primarily related to slope angle, and this does not change quickly. But shear strength can change quickly for a variety of reasons, and events that lead to a rapid reduction in shear strength are triggers for mass wasting.

An increase in water content is the most common mass wasting trigger because of the reduction in strength. This can result from rapid melting of snow or ice, by heavy rain, or by some type of event that changes the pattern of water flow on the surface. Rapid melting can be caused by a dramatic increase in temperature (e.g., in spring or early summer) or by a volcanic eruption. Changes in water flow patterns can be caused by earthquakes, or previous slope failures that dam up streams or human structures that interfere with runoff (e.g., building, roads or parking lots). An example of this is the deadly 2005 debris flow in North Vancouver (Figure 6.1.5). The 2005 failure took place in an area that had failed previously, and in a report written in 1980 it was recommended that steps be taken by the municipal authorities and the residents to address drainage issues. Little was done to improve the situation.[1]



Figure 6.1.5: Site of the Debris Flow in the Riverside Drive Area of North Vancouver in January, 2005. This debris flow happened during a rainy period but was likely triggered by excess runoff related to the roads at the top of this slope and by landscape features in the area surrounding the house visible here.

In some cases, a decrease in water content can lead to failure. This is most common with clean sand deposits (e.g., the upper layer in Figure 6.1.3, left), which lose strength when there is no more water around the grains.

Freezing and thawing can also trigger some forms of mass wasting, more specifically, the freezing can expand the crack between two parts of rock, and then thawing can release a block of rock that was attached to a slope by a film of ice, as illustrated on Figure 6.1.6.

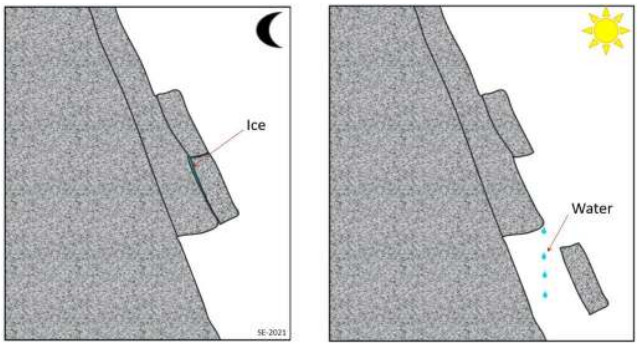


Figure 6.1.6: Illustration of the Process of Ice Wedging (left) and then Release of a Fragment Because of Melting

Shaking is another process that can weaken a body of rock or sediment. The most obvious source of shaking is an earthquake, but shaking from highway traffic, construction or mining will also do the job. Several deadly mass wasting events (including snow avalanches) were triggered by the M7.8 earthquake in Nepal in April 2015.

Saturation with water and then seismic shaking led to the occurrence of thousands of slope failures in the Sapporo area of Hokkaido, Japan in September 2018, as shown on Figure 6.1.7. The area was drenched with rain from tropical storm Jebi on September 4th, and then shaken by a M 6.6 earthquake on September 6th. That combination appears to have triggered thousands of debris flows of water-saturated volcanic materials on steep slopes. There were 41 deaths related to these slope failures.



Figure 6.1.7: Left: Slope Failures in the Sapporo Area of Japan Following a Typhoon (Sept. 4th, 2018); and right: Earthquake (Sept. 6th, 2018). (Before and after Landsat 8 images: left: July 2017, right: September 2018).

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- **Figure** 6.1.7**:** Public domain image from Dauphin, L. (2018). Landslides in Hikkaido. NASA Earth Observatory, https://earthobservatory.nasa.gov/im...es-in-hokkaido

1. Riverside Drive Landslide, from Natural hazards learning resources at EOAS, UBC, https://blogs.ubc.ca/eoashazards/riv...ive-landslide/ ↵

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6.2: Classification of Mass Wasting

Overview of Classification

It is important to classify slope failures so that we can understand what caused them, learn how to mitigate their effects, and communicate clearly. The three criteria used to describe slope failures are:

- The type of material that failed (typically either bedrock or unconsolidated sediment),
- The mechanism of the failure (how the material moved), and
- The rate at which it moved.

The type of motion is the most important characteristic of a slope failure, and there are three different types of motion: if the material drops through the air, vertically or nearly vertically, it's known as a fall, if the material moves as a mass (without internal motion within the mass), it's a slide, and if the material has internal motion, like a fluid, it's a flow. Unfortunately, it's not normally that simple. Many slope failures involve two of these types of motion, some involve all three, and in many cases it's not that easy to tell how the material moved. The types of slope failure that we'll cover here are summarized in Table 6.1.1.

Table 6.2.1: Classification of Slope Failures Based on Type of Material and Type of Motion

Failure Type	Type of Material	Type of Motion	Rate of Motion
Rock fall	Rock fragments	Vertical or near-vertical fall (plus bouncing in many cases)	Very fast (>10s m/s)
Rock slide	A large rock body	Motion as a unit along a planar surface (translational sliding)	Typically very slow (mm/y to cm/y), but some can be faster
Rock avalanche	A rock body that slides and then breaks into small fragments	Flow At high speeds the mass of rock fragments is suspended on a cushion of air.	Very fast (>10s m/s)
Creep or solifluction	Soil or other overburden, in some cases mixed with ice	Flow (although sliding motion may also occur)	Very slow (mm/y to cm/y)
Slump	Thick deposits (m to 10s of m) of unconsolidated sediment	Motion as a unit along a curved surface (rotational sliding)	Slow (cm/y to m/y)
Mud flow	Loose sediment with a significant component of silt and clay	Flow (a mixture of sediment and water moves down a channel)	Moderate to fast (cm/s to m/s)
Debris flow	Sand, gravel and larger fragments	Flow (similar to a mud flow, but typically faster)	Fast (m/s)

Rock Fall

Rock fall describes the abrupt movement of rock which become detached from steep slopes or cliffs. Rock fragments can break off relatively easily from steep bedrock slopes, most commonly due to frost-wedging in areas where there are many freeze-thaw cycles per year. If you've ever hiked along a steep mountain trail on a cool morning you might have heard the occasional fall of rock fragments onto a talus slope as the sun melts the ice, releasing rock fragments that had been wedged out the night before.

A typical talus slope, near to Keremeos in southern BC, is shown on Figure 6.2.1. In December 2014 a large block of rock split away from a cliff in this same area. It broke into smaller pieces, which fell and tumbled down the slope and crashed into the road, smashing the concrete barriers and gouging out large parts of the pavement.



Figure 6.2.1 Left: A Talus Slope Near to Keremeos, BC, Formed by Rock Fall from the Cliffs Above. Right: The Results of a Rock Fall onto a Highway West of Keremeos in December 2014.

Rock Slide

A **rock slide** is the sliding motion of rock along a sloping surface. In most cases the movement is parallel to a fracture, bedding plane or metamorphic foliation plane, and it can range from very slow to moderately fast. The word sackung describes the very slow motion of a block of rock (mm/y to cm/y) on a steep slope. A good example is the Downie Slide north of Revelstoke BC, which is illustrated on Figure 6.2.2. In this case a massive body of rock is very slowly sliding down a steep slope along a plane of weakness that is parallel to the slope.[1]

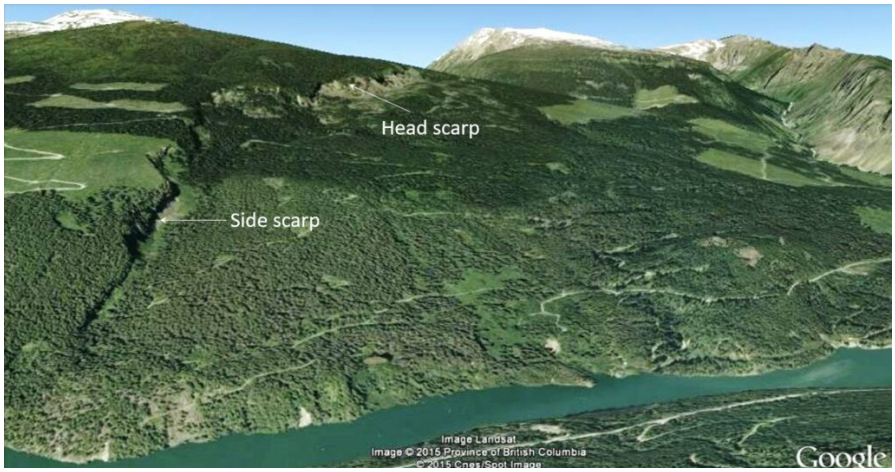


Figure 6.2.2: The Downie Slide, A Sackung, on the Shore of the Lake Revelstoke Reservoir (Above the Revelstoke Dam). The head scarp is visible at the top and a side-scarp along the left-had side.

A rock slide is typically a “translational slide”, meaning that the part of the rock that is moving down the slope without rotating—it is translating. Please don’t confuse “translational” with “transitional”. As we’ll see below, a “rotational slide” (or slump) is when the material (typically unconsolidated sediments) moves as a single rotating unit along a curved surface.

Rock Avalanche

If a rock slide starts moving quickly the rock is likely to break into many small pieces, and at that point it can become a **rock avalanche**, in which the large and small fragments of rock move in a fluid manner supported by cushion of air within and beneath the moving mass. The 2010 slide at Mt Meager (west of Lillooet), is a rock avalanche (Figure 6.2.3).[2]



Figure 6.2.3: The 2010 Mt. Meager Rock Avalanche, Showing Where the Slide Originated (top center of image). It then raced down a steep narrow valley, into the valley of Meager Creek, and then out into the wider valley of the Lillooet River at the bottom of the image.

Creep

The very slow—mm/y to cm/y—movement of soil or other unconsolidated material on a slope is known as **creep**. Creep, which normally only affects the upper several centimeters of loose material, is typically a type of very slow flow, but in some cases sliding may take place. Creep can be facilitated by freezing and thawing, because particles get lifted perpendicular to the surface by the growth of ice crystals within the soil and are then let down vertically by gravity when the ice melts. The same effect can be produced by frequent wetting and drying of the soil.

Creep is most noticeable on moderate to steep slopes where trees, fence posts or gravestones are consistently leaning in a downhill direction (Figure 6.2.4). In the case of trees, they try to correct their lean by growing upright, and this leads to a curved lower trunk known as a “pistol butt” (or “j-shaped tree trunk”). Creep can take place on nearly flat surfaces.



Figure 6.2.4: A Hillside with Pistol-Butt Trees as Evidence of Persistent Creep

Slump

Slump is a type of slide (movement as a mass), that takes place within thick unconsolidated deposits (typically greater than 10 m). Slumps involve movement along a curved surface, with downward motion near to the top and outward motion towards the bottom (Figure 6.2.5:). They are typically caused by an excess of water within the materials on a steep slope.

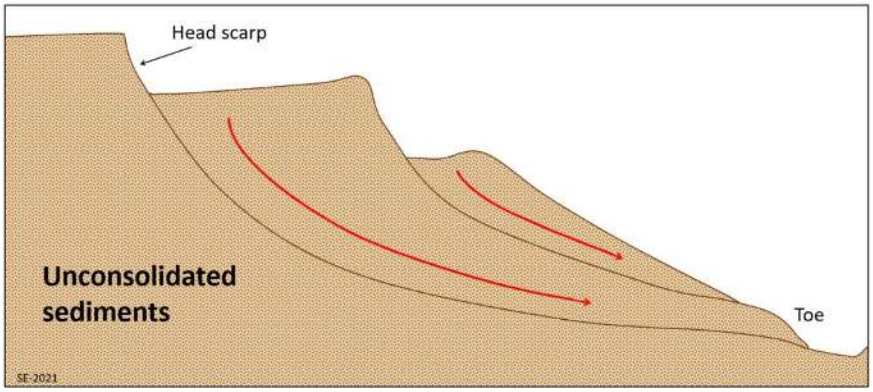


Figure 6.2.5: A Depiction of the Motion of Unconsolidated Sediments in an Area of Slumping

An example of a slump in the Lethbridge area, Alberta, is shown on Figure 6.2.6. This feature has likely been active for many decades and moves a little more whenever there are heavy spring rains and significant snow-melt runoff. The toe of the slump is failing because it has been eroded by the small stream at the bottom.



Figure 6.2.6: A Slump Along the Banks of a Small Coulee Near to Lethbridge, Alberta. The main head-scarp is clearly visible at the top, and a second smaller one is visible about one-quarter of the way down. The toe of the slump is being eroded by the seasonal stream that created the coulee.

Mud Flows and Debris Flows

When a mass of sediment becomes completely saturated with water, to the extent that the grains are pushed apart, the mass will lose strength and flow, even on a gentle slope. This can happen during rapid spring snow melt or heavy rains and is also relatively common during volcanic eruptions because of the rapid melting of snow and ice. If the material involved is primarily sand-sized and smaller it is known as a **mud flow**, such as the one shown on Figure 6.2.7. If the material involved is a mixture of sizes, including gravel-sized and larger, it is known as a **debris flow**. Because it takes more gravitational energy to move larger particles, a debris flow typically forms in an area with a steeper slope and more water than does a mudflow. A typical debris flow is shown on Figure 6.2.8. This event took place in November 2006 in response to very heavy rainfall. There was enough energy to move large boulders and to knock over large trees.



Figure 6.2.7: A Slump (left) and an Associated Mudflow (center), Near to Lethbridge, Alberta.

https://geo.libretexts.org/@go/page/33121



Figure 6.2.8: Effects of a Debris Flow Within a Steep Stream Channel Near to Buttle Lake, BC., November 2006

As already noted, to understand a slope failure we need to be able to determine what type of material moved, what type (or types) of motion were involved, and how quickly it moved. The type of motion is the most important of these, and so Figure 6.2.9 is provided here to help you clearly understand how things moved in different types of slope failure.

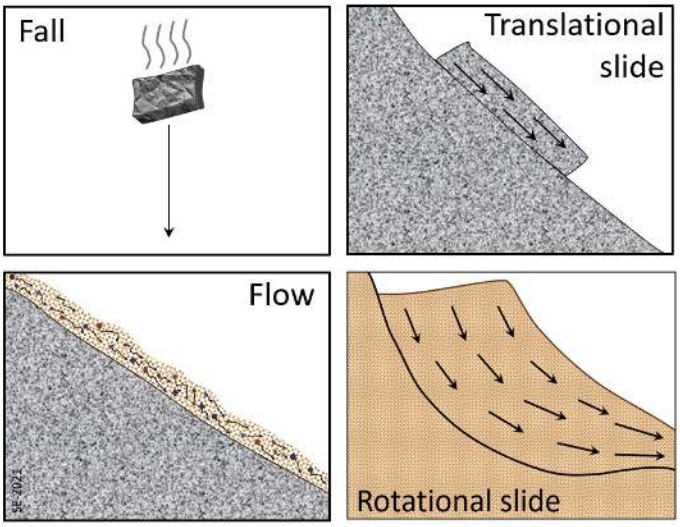


Figure 6.2.9: Types of Slope-Failure Motion. A fall is typically a rock fall. A flow can be creep, mudflow, debris flow, or rock avalanche. A translational slide is typically a rock slide. A rotational slide is typically a slump.

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1. Kalenchuk, K. S., Hutchinson, D. J., Diederichs, M. S., and Moore, D. (2012). Downie Slide, British Columbia, Canada. In Clague, J. J. & D. Stead (Eds.), *Landslides: Types, Mechanisms and Modeling* (p. 345-358). Cambridge University Press. ↵
2. Guthrie, R. et al., (2012). The 6 August 2010 Mount Meager rock slide-debris flow, Coast Mountains, British Columbia: characteristics, dynamics, and implications for hazard and risk assessment. *Natural Hazards Earth System Science*, *12*(5), 1277–1294, https://doi.org/10.5194/nhess-12-1277-2012. ↵

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6.3: Mitigating the Effects of Mass Wasting

We cannot prevent mass wasting, but in many situations, there are actions that we can take to delay it from happening. Where we cannot delay it, there are things we can do to mitigate its damaging effects on people and infrastructure. Where we can neither delay nor mitigate mass wasting, we should have the sense to stay out of the way.

Preventing and Delaying Mass Wasting

It is comforting to think that we can prevent mass wasting by mechanical means, such as the bolts in a road cut or by draining water out of a slope, or by building physical barriers. What we must remember is that the works of man are weak and pathetic things compared to the works of nature. The rock bolts in road cuts will start to corrode within a few years, and within a few decades many of them will lose strength. Unless they are replaced, they will no longer be supporting that slope. Drainage holes eventually get plugged up with sediment and chemical precipitates, and, unless they are periodically unplugged (which is difficult) their effectiveness will be reduced. Eventually, unless new holes are drilled, the drainage will be so compromised that the slide will start to move again.

The important point is that our efforts to “prevent” mass wasting are only as good as our resolve to maintain those preventative measures. We may have created systems to ensure that others will carry out that maintenance in future decades or even future centuries, but there is nothing to ensure that it will be done.

We must be careful to avoid doing things that could make mass wasting more likely. The most common anthropogenic cause of mass wasting is road construction, and this applies both to remote gravel roads built for resource extraction and to large highways. Road construction is a potential problem for two reasons. First, to create a flat road surface on a slope inevitably involves creating a cut bank that is steeper than the original slope and might also involve creating a filled bank that is both steeper and weaker than the original slope (Figure 6.3.1). Second, roadways typically cut across natural drainage features, and unless great care is taken to reroute the runoff water, and to prevent it from pooling, oversaturation of materials can result.

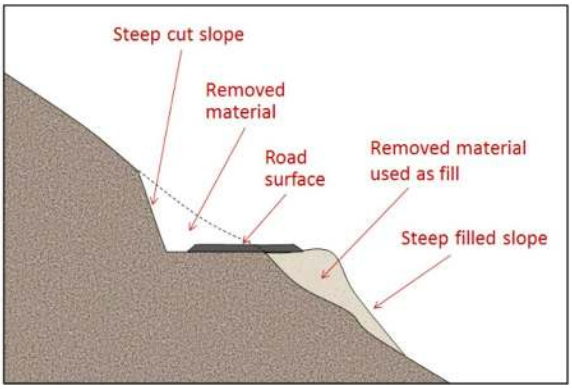


Figure 6.3.1: An Example of a Road Constructed by Cutting into a Steep Slope, and the Use of the Cut Material as Fill

Apart from water issues, builders of roads and other infrastructure on bedrock slopes have to be acutely aware of the geology, and especially of any weaknesses in the rock related to bedding, fracturing or foliation. If possible, we should aim to avoid certain areas and build somewhere else—rather than try to stitch the slope back together with rock bolts.

It is commonly believed that construction of buildings on the tops of steep slopes can contribute to the instability of the slope. This may be true, but probably not because of the weight of the building. A typical house isn’t likely to be heavier than the hole in the ground that was made to build it. A more likely contributor to instability of the slope around a building is the effect that it has on drainage.

Monitoring Mass Wasting

In some areas it is necessary to establish warning systems so that we know if conditions have changed at a known slide area, or if a rapid failure, such as a debris flow, is on its way. Some areas are monitored 24-7 with optical devices. A simple mechanical device for monitoring a slide is shown on Figure 6.3.2.



Figure 6.3.2: Part of a motion-monitoring device at the Checkerboard Slide near to Revelstoke, BC. The other end of the cable is attached to a block of rock that is unstable. Any incremental motion of that block will move the cable, and this will be detectable on this device. (Author photo, CC BY 4.0)



Figure 6.3.3: Mount Rainier, from Auburn, Washington

Mt. Rainier in Washington State has the potential to produce massive mud flows or debris flows (technically lahars) with or without a volcanic eruption, and over 100,000 people in the Tacoma, Puyallup and Sumner areas are in harm's way because they currently reside on deposits from past lahars (Figure 6.3.3). In 1998 a network of acoustic monitors was established around Mt. Rainier. The monitors are embedded in the ground adjacent to expected lahar paths. They provide warnings to emergency officials, and when a lahar is detected the residents of the area will have anywhere from 40 minutes to 3 hours to get to safe ground.[1]

It is critical to monitor the weather conditions and stream flows to assess changes to the risk of slope failure. Changing weather conditions can be failure triggers, especially in the following ways:

- extreme rain events saturate and weaken surficial materials (and even bedrock),
- extreme rain events lead to stream flooding and so to eroded banks, contributing to failures,
- sudden warming events can trigger rapid snow melt, increasing the amount of water in surface materials and streams, and
- persistent drought will dry out sandy materials making them more prone to failure.

Mitigating the Impacts of Mass Wasting

In situations where we can't predict, prevent, or delay mass wasting hazards, there are some effective measures that can be taken to minimize the associated risk. For example, many highways in temperate mountainous regions have avalanche shelters like that

shown on Figure 6.3.4. In some parts of the world similar features have been built to shelter infrastructure from other types of mass wasting.



Figure 6.3.4: A Snow Avalanche Shelter on the Coquihalla Highway. The expected path of the avalanche is the steep un-treed slope above.

Finally, in situations where we can't do any of these things, we simply have to have the common sense to stay away.

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- **Figure** 6.3.4**:** Photo by Steven Earle, CC BY 4.0

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1. Monitoring Lahars at Mt. Ranier, US Geological Survey, https://www.usgs.gov/volcanoes/mount...-mount-rainier ↵
2. Moore, D. P. (1976). *The Rubble Creek landslide Garibaldi, British Columbia* (Thesis, University of British Columbia). https://open.library.ubc.ca/collecti...tems/1.0052710 ↵

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CHAPTER OVERVIEW

7: Earth's Atmosphere, Carbon and Nitrogen Cycles, and Weather and Climate



Photo by NOAA on Unsplash

This chapter addresses several topics that are related in one way or another to each other. The atmosphere is used to store and transfer carbon and nitrogen to other Earth materials. Much of what happens in the atmosphere affects both climate and weather. To understand future topics like air pollution and climate change, the concepts presented here are important.

7.1: Atmospheric Composition

7.2: Layers of the Atmosphere

7.3: Carbon and Nitrogen

7.4: Weather vs. Climate

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7.1: Atmospheric Composition

We know quite a lot about the atmosphere which is a thin layer of gases that protects life on Earth. It has taken decades, if not centuries, of careful observation and insightful theory that is based on solid physical and chemical laws.



Figure 7.1.1: Clouds over the Arctic Ocean at sunrise. Credit: W. Brune

The atmosphere consists mostly of dry air composed mostly of nitrogen (78%), oxygen (21%), and argon (0.9%), and highly variable amounts of water vapor (from parts per million in air to a few percent). Now we will consider gases and particles in the atmosphere at trace levels. The most abundant of the trace gases in the global atmosphere is carbon dioxide (~400 parts per million, or 400 x 10^{-6}), but there are thousands of trace gases with fractions much less than a few parts per million. These trace gases and particles are as important to atmospheric structure and weather as are nitrogen, oxygen, and water vapor and they also play a huge role in human and ecological health and global climate.

The major gases that comprise today's atmosphere are in Table 7.1.1.

Table 7.1.1: Major Constituents in Earth's Present Atmosphere

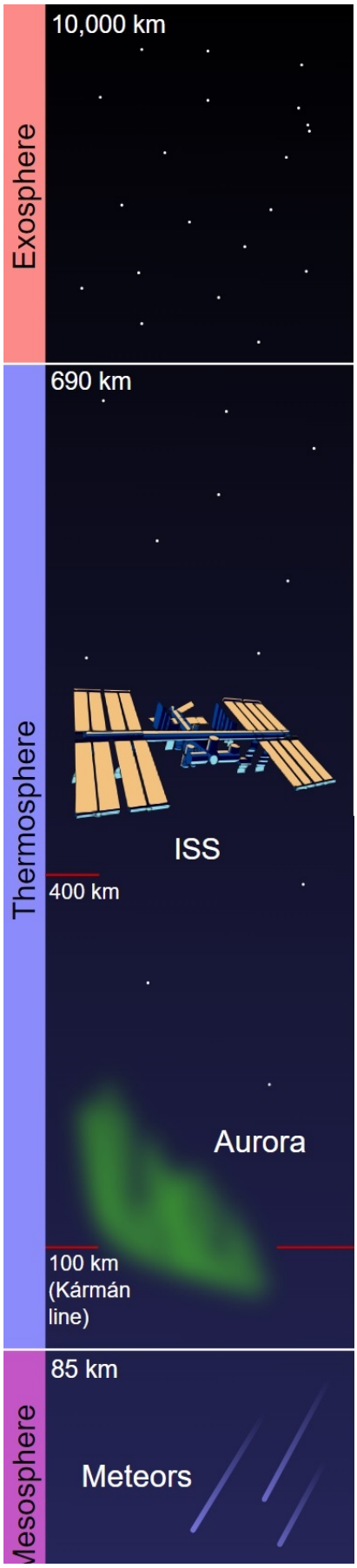
Constituent	Percent of Total Gas in Atmosphere	Role in the Atmosphere
nitrogen (N_2)	78%	transparent; provides heat capacity and momentum; exchanged with biomass; decomposed in combustion
oxygen (O_2)	21%	transparent except for in extreme ultraviolet; provides some heat capacity and momentum; exchanged with life; source of important reactive gases like ozone
argon (Ar)	0.9%	no role
carbon dioxide (CO_2)	<1%	transparent in visible; absorbs infrared light (i.e., contributes to global warming); exchanged with life; product of combustion
neon (Ne)	<1%	no role, but makes colorful glowing signs
water vapor (H_2O)	varies <1 to 5%	gas transparent in visible; absorbs infrared light (i.e., contributes to global warming); exists as vapor, liquid, and solid; exchanged with life; product of combustion
aerosol particles	<1%	essential for cloud formation; interact with visible and infrared light; exchanged with surfaces and life
methane (CH_4)	<1%	transparent in visible; absorbs in infrared (i.e. contributes to global warming); exchanged with life; source of CO_2 and H_2O
ozone (O_3)	<1%	transparent in visible; absorbs in UV and infrared; reactive and source of more reactive gases
particles	<1%	absorbs and scatters light; acts as CCN and IN (see below)

Key features of the gases include their compressibility (i.e., ability to expand or shrink in volume), and their heat capacity. Water vapor has the additional important feature of existing in the vapor, liquid, and solid phases in the atmosphere and on Earth's surface. The most important properties of small particles include their ability to dissolve in water to be Cloud Condensation Nuclei (CCN) or to maintain a lattice structure similar to ice in order to be Ice Nuclei (IN), as well as their ability to absorb and scatter sunlight. These properties depend completely on the particle size and composition.

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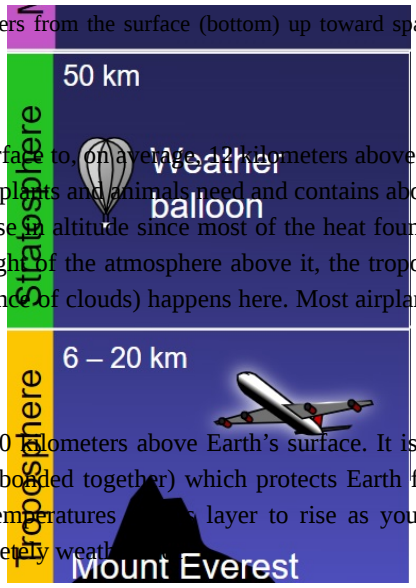
7.2: Layers of the Atmosphere

The Earth’s atmosphere is broken down into five layers. From the Earth's surface up toward space, they are the troposphere, stratosphere, mesosphere, thermosphere, and exosphere.



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Figure 7.2.1: Depiction of Earth's five layers from the surface (bottom) up toward space (top). Credit: NOAA & Mysid, Public domain, via Wikimedia Commons



Troposphere

Earth's **troposphere** extends from Earth's surface to, on average, 12 kilometers above the surface. Its height is higher at the equator and lower at Earth's poles. It holds all the air plants and animals need and contains about 99 percent of all water vapor and aerosols. Temperatures usually decrease as you increase in altitude since most of the heat found in this layer is generated by the transfer of energy from Earth's surface. Due to the weight of the atmosphere above it, the troposphere is most the dense layer. Additionally, most of Earth's weather (including the existence of clouds) happens here. Most airplanes fly in this layer though they do cross over into the next layer up.

Stratosphere

Earth's **stratosphere** is located from 12 to 50 kilometers above Earth's surface. It is most famous for containing the ozone layer (composed of a gas made of three oxygens bonded together) which protects Earth from the radiation produced by the Sun. The Sun's ultraviolet radiation is what causes temperatures in this layer to rise as you increase in altitude. At the lowest, coldest altitudes, some clouds form so it is not completely weather

Mesosphere

Earth's **mesosphere** is located from 50 to 80 kilometers above Earth's surface. Just like the troposphere, this layer gets colder as you increase in altitude and is the coldest place found in the atmosphere. This layer protects Earth as all but the largest meteors burn up here. There are essentially no clouds or water vapor.

Thermosphere

Earth's **thermosphere** is located from 80 to 700 kilometers above Earth's surface. Temperatures increase with altitude due to the lack of matter found here. Since temperature just measures the activity of molecules, temperatures must be low if there aren't very many around. There are essentially no clouds or water vapor. As a point of interest, the International Space Station orbits in the thermosphere.

Exosphere

Earth's **exosphere** is located from 700 to 10,000 kilometers above Earth's surface. It is the highest layer and there is even less matter here. Because of this, the layer doesn't behave like a gas, and particles escape into space. Most of Earth's satellites orbit in this layer.

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7.3: Carbon and Nitrogen

The Natural Carbon Cycle

Due to the importance of carbon dioxide (CO_2) as a greenhouse gas, the carbon cycle is a crucial part of the climate system. Since carbon exchanges with the biosphere, life processes need to be considered in climate science. The **carbon cycle** is part of broader cycles, which include other biologically important chemical elements such as nitrogen and oxygen.

Carbon exchanges relatively rapidly between three large reservoirs: the ocean, the land, and the atmosphere. Of those, the ocean contains the most carbon, about 40 times more than the atmosphere and 10 times more than land. A key feature of the ocean is it takes up more carbon from the atmosphere than it gives up.

Carbon dioxide from the atmosphere dissolves in ocean water, especially the surface where it is in contact with the atmosphere. Some of the carbon dioxide remains as dissolved gas in the water. A lot of it is converted into other things. Photosynthesis by phytoplankton (tiny plants in the ocean) in the sunlit surface waters turns the carbon into organic matter. Many marine organisms use the carbon to make a mineral called calcite as they build shells. Chemical processes use the carbon to create a rock made of calcite called limestone. All these processes use up the carbon dissolved in the water. The carbon tied up in shells or rock can remain there for millions or even hundreds of millions of years. This allows more carbon dioxide to enter the water from the atmosphere. It is important to note that some organisms introduce carbon back into the water as they respire (breathe).

The second biggest of the three rapidly exchanging carbon reservoirs is the land. On land carbon is stored in living vegetation, in soils, and in permafrost (ground that remains frozen for two or more years).

Photosynthesis by land plants removes carbon from the atmosphere and turns it into organic matter. Organic matter cycles through the land food web as animals eat plants ane one another. The carbon eventually gets into the soil as animal and plant materials die and decompose. Carbon gets released back into the atmosphere as animals (including humans) respire (breathe). Land carbon uptake and release does not depend strongly on atmospheric CO_2 concentrations. They depend more on water availability which promotes plant growth and temperature which affects respiration rates.

The atmospheric carbon reservoir is small (40 times smaller than the ocean and 4 times smaller than the land). However, the atmosphere is crucial in linking land and ocean through rapid exchanges as described above.

The Natural Nitrogen Cycle

The **nitrogen cycle** tracks how nitrogen is converted into various forms as it circulates within Earth's oceans, land, and atmosphere. Since almost 80% of Earth's atmosphere is composed of nitrogen, the atmosphere is the largest source. The problem is it is not always accessible to biological processes which need it for survival. The conversion of nitrogen is carried out through biological and physical processes include fixation, ammonification, nitrification, and denitrification.

Nitrogen Fixation

The conversion of nitrogen gas (N2) into nitrates and nitrites (forms of nitrogen that can be used by plants) through atmospheric, industrial, and biological processes is called **nitrogen fixation**. Atmospheric nitrogen must be processed, or "fixed", into a usable form to be taken up by plants. One way nitrogen is introduced into the soil is through lightning strikes which create nitrogen dioxide which dissolves in water and converts to a useable form of nitrogen by plants.

Most fixation is done by bacteria known as diazotrophs. These bacteria combine nitrogen gas with hydrogen gas to produce ammonia (a gas), which contains nitrogen that can eventually be used by plants as described below. Most biological nitrogen fixation occurs by the activity of bacteria as well. In one example nitrogen-fixing bacteria such as Rhizobium live in the root nodules of legumes (such as peas, alfalfa, and locust trees). Here they form a mutually beneficial relationship with the plant, producing ammonia in exchange for carbohydrates. Because of this relationship, legumes will often increase the nitrogen content of nitrogen-poor soils. Today, about 30% of the total fixed nitrogen is produced industrially using a process which uses high temperatures and pressures to convert nitrogen gas and a hydrogen source (natural gas or petroleum) into ammonia.

While the process of creating ammonia is important, it must be converted to nitrates or nitrites (describe below) because ammonia gas is toxic to plants.

Ammonification

When a plant or animal dies or an animal expels waste, the initial form of nitrogen is organic. Bacteria or fungi convert the organic nitrogen within the remains back into ammonium (nitrogen containing ion in solution), using a process called **ammonification**. The nitrogen will eventually be available for plants to use as described below.

Nitrification

Soil-living bacteria and other bacteria convert ammonia (gas) or ammonium (ion in solution) to nitrate (a form of nitrogen that can be used by plants) in a process called **nitrification**. First, one set of bacteria converts it to nitrites. Then another set converts the nitrites to nitrates.

Denitrification

Denitrification is the reduction of nitrates back into nitrogen gas, completing the nitrogen cycle. This process is performed by bacterial species under anaerobic (lacking available oxygen) conditions experienced in waterlogged soils. When oxygen is not available during respiration, the nitrate fills its normal role, and in the process, produces nitrogen gas as a byproduct. This nitrogen is no longer available to plants unless it goes through the nitrogen fixation process again.

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7.4: Weather vs. Climate

Climate is the average of the weather for a region over time. There is a common confusion that arises when people use the word climate. Often, even if they think they are discussing climate, the conversation will begin with a discussion of the current weather. It might go something like this:

"It was really hot today! Must be global warming…"

Weather

And, indeed, it might be. However, what they are describing is the weather. **Weather** is the summation of current atmospheric conditions at any given moment. And, to measure it, we use things like thermometers, barometers, and other devices. This information is collected and is used to develop models that can be used for predictive purposes. From these, you get your 1-10-day forecasts. These forecasts of the weather are entirely based on probabilities. A 20% chance of rain just means that, under current weather conditions (or those predicted), it tends to rain 20% of the time. These conditions are a part of a region's climate story, but they are still defined as weather. While they use recent historical data, they are intended to describe the condition of the atmosphere at a moment in time…perhaps three days from now.

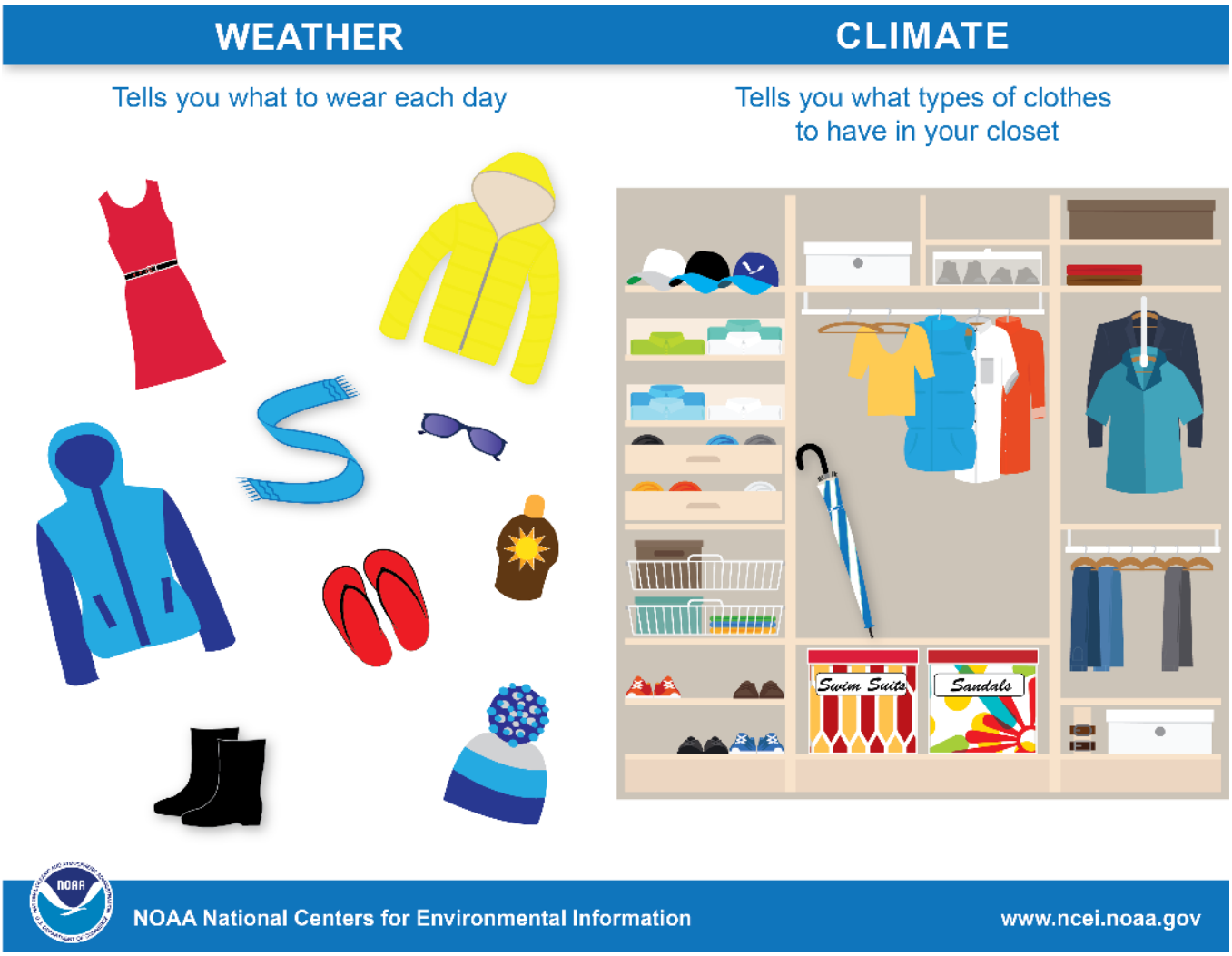


Figure 7.4.1: Illustration of weather versus climate. Do you own only shorts and sleeveless shirts? Or do you wear a wide variety of clothing throughout the year? The composition of your wardrobe describes climate. What you pick out for the day describes the weather. (Source: NOAA, NCEI National Centers for Environmental Information)

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Climate

Climate, on the other hand, is the average of these daily conditions over time. At its most basic and familiar level, climate can be described based upon seasons. Some places on Earth experience four of them (winter through autumn), others experience two (rainy and dry). These short-term climatic conditions are based upon a large array of variables. These include latitude, topography, proximity to the sea, time of year, and so forth. Looking at changes in climate over the course of the year at a given location on the planet provides a short-term picture unique to that location. Climate can also be described on a global average basis. Under these conditions, we can follow long-term changes in temperature and associated variables (greenhouse gases, ice loss, evapotranspiration, *etc.*) that provide a broader picture of global climate and how it is changing.

Classification of Climate

We use words like sunny, hot, rainy, cold, freezing, windy, etc. to describe weather on a given day. But how do we describe climate since it is the long-term average of weather? The Koppen-Geiger Climate Classification System is used to define different climate categories. Watch the video from 1:49-3:35 and 5:30-5:46. Note the following:

- what the five climate categories are with brief summaries
- why categories are subdivided
- what the first letter indicates
- what the second letter indicates
- what the third letter indicates



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CHAPTER OVERVIEW

8: Water, Flooding, and Drought



This chapter addresses the basics behind where water is naturally stored on Earth, namely streams and the ground. It also talks about what happens when streams get full - it floods. Understanding what natural flooding entails helps to understand how humans increase the size and frequency of flood events. And finally, related to water is also the concept of drought - or a lack of water. This also happens naturally but can be exasperated by human activity.

8.1: The Hydrologic Cycle
8.2: Streams and Stream Flow
8.3: Groundwater
8.4: Natural Effects on Water Quality
8.5: Flooding
8.6: Drought

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8.1: The Hydrologic Cycle

Water is constantly on the move. It is evaporated by solar energy from the oceans, lakes, streams, the surface of the land, and from plants (**transpiration**) (Figure 8.1.1). It is moved through the atmosphere by winds and condenses to form clouds of water droplets or ice crystals. In response to the pull of gravity it comes back down as rain or snow and then flows through streams, into lakes, and eventually back to the ocean. Water on the surface and in streams and lakes infiltrates the ground to become **groundwater**. Groundwater slowly moves through the surface materials and underlying bedrock. Some groundwater returns to streams and lakes, and some goes directly back to the oceans.

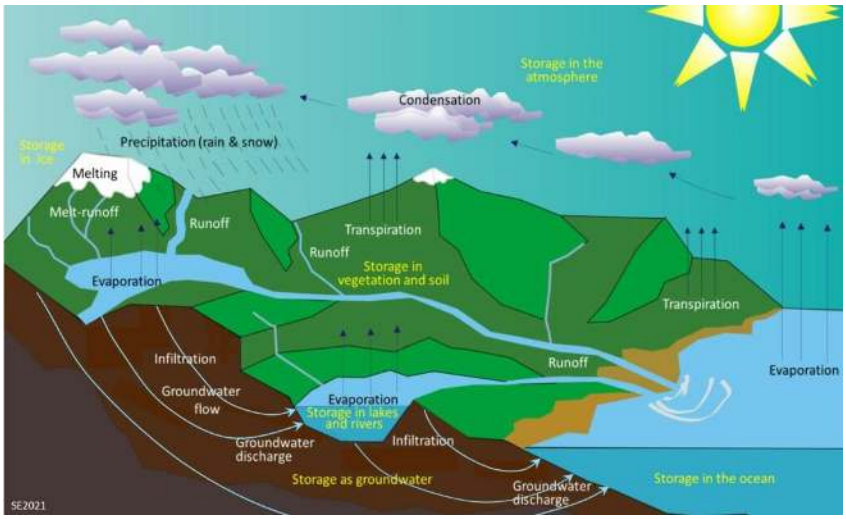


Figure 8.1.1: The Various Components of the Hydrologic Cycle. Black or white text indicates the movement or transfer of water from one reservoir to another. Yellow text indicates the storage of water.



Figure 8.1.2: Representation of the Volumes of Earth's Water Reservoirs. The 1-liter jug is filled with salty sea water (97%). The ice-cube is glacial ice (2%). The 2 teaspoons represent groundwater (1%), and the three drops represent all the fresh water in lakes, streams, and wetlands, plus all of the water in the atmosphere.

Even while it is moving around, water is stored in various reservoirs. The largest, by far, is the ocean, accounting for 97% of the total water volume at Earth's surface. That water is salty. The remaining 3% is fresh water. Two-thirds of our fresh water is stored in ice and one-third is stored in the ground. The remaining fresh water—about 0.03% of the total—is stored in lakes, streams,

vegetation, and the atmosphere. To put that in perspective, imagine putting all of Earth's water into a 1-liter jug (Figure 8.1.2). We start with sea water, by almost filling the jug with 970 mL of water and 2 tablespoons of salt. Then we add one regular-sized (roughly 20 mL) ice cube (representing glacial ice) and two teaspoons (roughly 10 mL) of groundwater. All the fresh water that we see around us in lakes and streams and up in the sky can be represented by adding just three more drops from an eyedropper (about 0.33 mL).

The volumes of the reservoirs are listed in Table 8.1.1, along with the average residence time of water in each reservoir. A molecule of water that falls into or flows into the ocean will stay there for an average of about 3,100 years. During that time, it might get moved all around the Earth via surface currents, and even to the deep ocean by thermohaline circulation. It will eventually be returned to the atmosphere via evaporation. A molecule of water that gets frozen into snow and then falls on a glacier, stays there for as long as 16,000 years on average (although some deep Antarctic ice is over a million years old) before it flows out as meltwater or calves into the ocean.

Groundwater stays in aquifers for an average of 300 years, although some very deep groundwater is hundreds of thousands or even millions of years old. In freshwater lakes with flows in and out via rivers, the average residence time is 1 to 100 years, while in salt lakes, from which the only exit is likely to be by evaporation, the average residence time is up to 1000 years. Moisture in the soil typically stays there for less than a year. It is cycled out via plants, or seeps down to become groundwater. Water remains in a river for an average of 12 to 20 days before flowing into a lake or the ocean. Water is held in the atmosphere there for an average of only 8 days.

Table 8.1.1: ***The Volumes and Average Residence Times of the Earth's Various Water Reservoirs***

Reservoir	Volume (thousands of km^3)	% of total	Average residence time (of a water molecule)
Ocean	1,370,000	97.1	3,100 years (1.1 million days)
Glaciers	29,000	2.05	16,000 years (5.8 million days)
Groundwater	12,000	0.85	300 years (110,000 days)
Freshwater lakes	125	0.009	1 to 100 years (365 to 36,500 days)
Salt lakes	104	0.008	10 to 1000 years (3,650 to 365,000 days)
Soil moisture	67	0.005	280 days
Rivers	1.2	0.00009	12 to 20 days
Atmosphere	13	0.0009	8 days

Although the proportion of Earth's water that is in the atmosphere is tiny, the actual volume is significant. At any given time, there is the equivalent of approximately 13,000 cubic kilometers (km^3) of water in the atmosphere in the form of water vapor and water droplets in clouds. Water is evapotranspired from vegetation and evaporated from the oceans and lakes at a rate of 1,580 km^3 per day, and just about the same volume falls as rain and snow every day—over both the oceans and land. The precipitation that falls on land goes back to the ocean in the form of stream flow (117 km^3/day) and groundwater flow (6 km^3/day). Most of the rest of this chapter is about that 123 km^3/day of stream and groundwater flow.

Surface water exists within lakes and ponds, as snow and ice, and within flowing streams. If we want to use surface water as a resource, we generally must restrict ourselves to streams, and we must be careful to leave enough of the stream water for the ecosystems (and other people) that depend on it. It is true that we can extract water from lakes, and many municipalities do that, but that can only be done to the extent that the lake is part of a stream system, and we cannot take more water from the lake than is being added by streams. If we do that on a long-term basis (more than 1 year) the lake level will start to drop and before too long the lake will not be viable as a water source.

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8.2: Streams and Stream Flow

A **stream** is a body of flowing surface water of any size, ranging from a tiny trickle to a mighty river. The basic anatomy of a stream is such that the stream channel marks the area where water normally flows. On either side of the stream channel is the **floodplain** (Figure 8.2.1). When the stream cannot hold all its water due to flooding, this area is covered by fast flowing water which usually carries a significant amount of sediment. When flooding ends, the floodplain is covered by a layer of sediment deposited when the water velocity slows, and the stream drops what it was carrying.

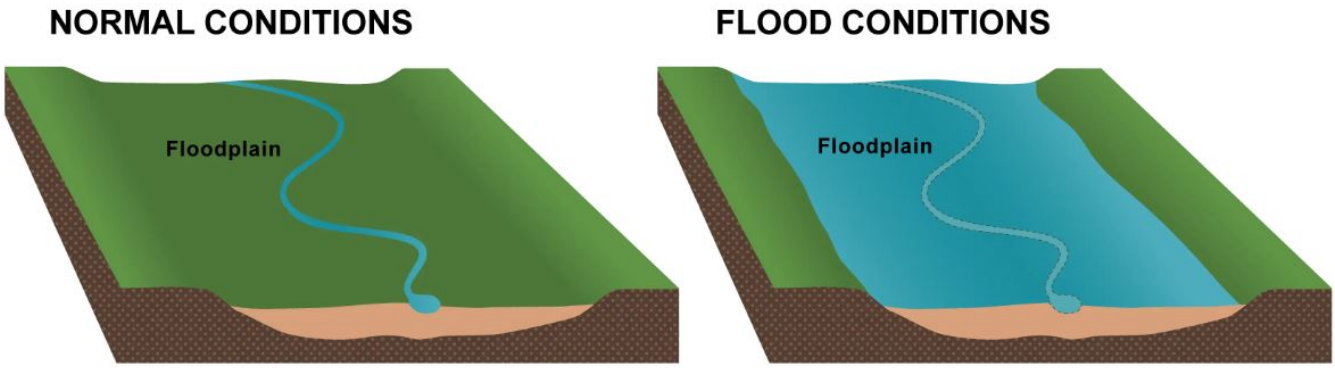


Figure 8.2.1: The stream channel has water in it in both images. The image on the left shows the stream flowing within its channel. The image on the right shows what happens when the stream floods as water covers the floodplain.

The area from which the water flows to form a stream is its **drainage basin**. Some of the precipitation (rain or snow) that falls within a drainage basin is returned to the atmosphere via evaporation or transpiration. The rest either flows across the surface and into a stream, or infiltrates to become groundwater and then slowly flows towards a stream (although it is possible that some of that groundwater will cross into an adjacent drainage basin via groundwater flow). An example of a drainage basin is shown in Figure 8.2.2.

The area in tan is the drainage basin as all precipitation which falls into this area will either infiltrate into the ground or make it to the Ashnola River using the **tributaries**, or smaller feeder streams, indicated with thin black lines. It is assumed the area is surrounded by high spots, or **drainage divides**, which separate this drainage basin from others nearby that feed water into other rivers.

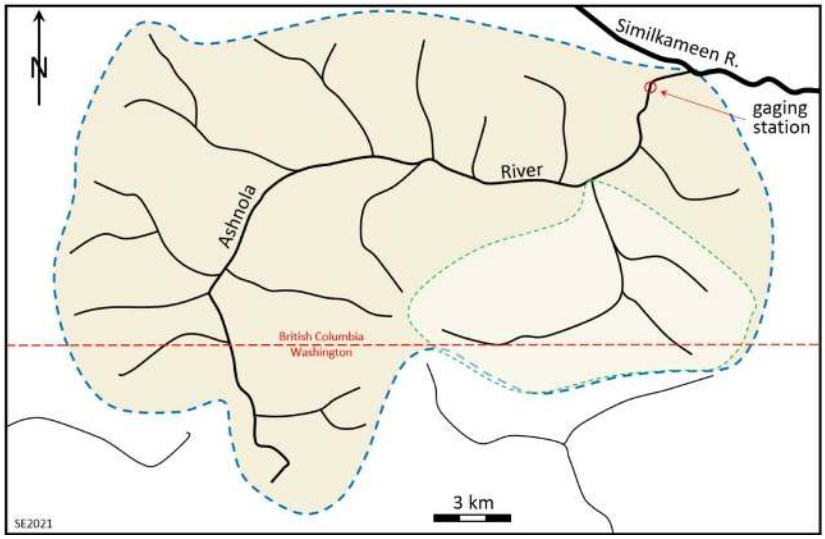


Figure 8.2.2: Ashnola River drainage basin on the US and Canadian border. The dashed blue line shows the extent of the drainage basin. The dashed green line is the drainage basin of one of its tributaries.

Figure 8.2.3: shows part of the Ashnola River drainage basin. You can see the steep slope immediately ahead followed by a more gently sloped area where water is pooling.



Figure 8.2.3: Part of the Drainage Basin of the Ashnola River

The gradient, or steepness, of a stream can be tracked along its length using a hydrograph (Figure 8.2.4). The upper and lower parts of the Ashnola River have quite steep gradients (in the order of 50 m/km, more in some areas) while the middle part and the part within the valley of the Similkameen River, are relatively flat (6 m/km, or less). The shape of the valley has been controlled first by tectonic uplift (related to plate convergence), then by pre-glacial stream erosion and mass wasting, then by several episodes of glacial erosion, and finally by post-glacial stream erosion and more mass wasting. The lowest elevation of the Ashnola River is 440 meters at the Similkameen River, and that is its base level. The Ashnola River cannot erode below that level unless the Similkameen River erodes deeper into its flood plain (the area that is inundated during a flood).

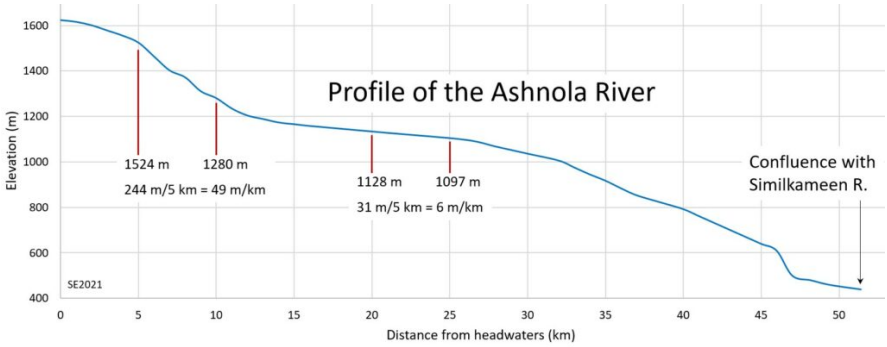


Figure 8.2.4: Topographic Profile of the Ashnola River Showing the Gradients at Two Locations

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8.3: Groundwater

Groundwater is the water stored in the open spaces within unconsolidated sediment and the underlying bedrock. This is freshwater, though it can be affected by the sediment and rock it is stored in. Sediment and rocks near the surface are under less pressure than those at depth and therefore tend to have more open space. For this reason, and because it's expensive to drill deep wells, most of the groundwater that is accessed by individual users is from within the first 100 meters of the surface. Some municipal, agricultural, and industrial groundwater users get their water from greater depth, but deeper groundwater tends to be of lower quality than shallow groundwater, so there is a practical limit as to how deep we can go.

Porosity is the percentage of open space within an unconsolidated sediment or a rock. It is the spaces between grains in a sediment or sedimentary rock and spaces that developed after or during rock formation due to fracture or with the formation of gas bubbles in lava rock. Porosity is expressed as a percentage calculated as the volume of open space in a rock compared with the total volume of rock. Typical porosities for several different geological materials are shown in Figure 8.3.1. Unconsolidated sediments tend to have higher porosity than consolidated ones because they have no cement, and most have not been strongly compressed. Finer-grained materials (e.g., silt and clay) tend to have greater porosity—some as high as 70%—than coarser materials like gravel.

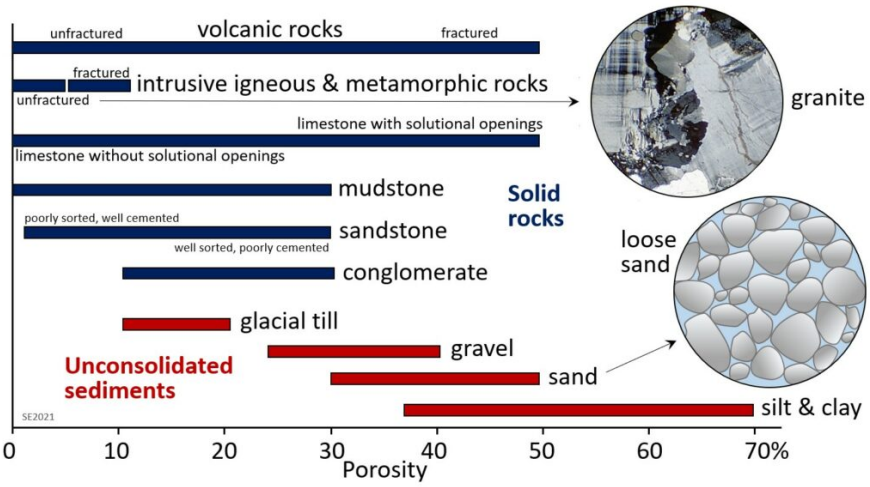


Figure 8.3.1: Variations in Porosity of Unconsolidated Materials (in red) and Rocks (in blue)

Porosity relates to how much water can be stored in geological materials. Almost all rocks have some porosity and therefore contain groundwater. Groundwater is present under your feet and everywhere on the planet. Considering that sedimentary rocks and unconsolidated sediments cover about 75% of the continental crust with an average thickness of a few hundred meters, and that they are likely to have around 20% porosity on average, it is easy to see that a huge volume of water is stored in the ground.

While porosity is a measure of open space, **permeability** is related to the sizes of those spaces and how they are shaped and interconnected, and so determines how easy it is for water to flow through the material. Larger pores mean there is less friction between flowing water and the sides of the pores. Smaller pores mean more friction along pore walls, and more twists and turns for the water to have to flow-through. Permeability controls how quickly water can flow through the rock or unconsolidated sediment and how easy it will be to extract the water for our purposes. Permeability is the most important variable in controlling groundwater flow rate and the quality of an aquifer as a source of water. Permeability can be expressed in a range of different units; in this book we will use meters per second, which is also termed the hydraulic conductivity (K, m/s).

As shown on Figure 8.3.2: there is a wide range of permeabilities in geological materials from hydraulic conductivities of 10^{-12} meters per second (0.000000000001 m/s) to approaching 1 m/s. Unconsolidated materials are generally more permeable than the corresponding rocks (compare sand with sandstone, for example), and the coarser materials are generally more permeable than the finer ones. The least permeable rocks are unfractured intrusive igneous and metamorphic rocks, followed by unfractured mudstone, sandstone, and limestone. The permeability of sandstone can vary widely depending on the rock's degree of sorting and cementation. Volcanic rocks can be highly permeable—especially if they are fractured—as can limestone that has been dissolved along fractures and bedding planes to create solutional openings.

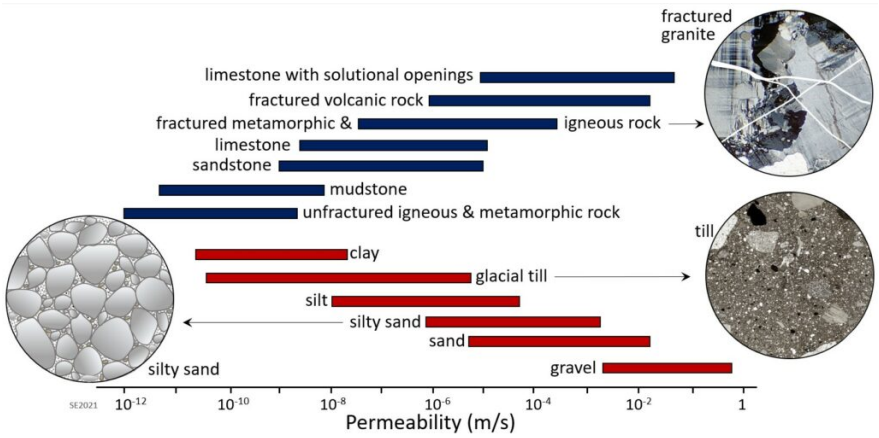


Figure 8.3.2: Variations in Permeability of Unconsolidated Materials (in red) and Rocks (in blue)

Surface water and groundwater are both active parts of the hydrologic cycle that moves water from where it has been deposited on the land surface as rain or snow, back to the ocean. The water within a watershed is all linked.

There is ongoing exchange of water between surface water (streams, lakes etc.) and the groundwater. Figure 8.3.3 shows how groundwater is stored below the surface. As water infiltrates into the ground, it fills the pore spaces. The line marked with "**Water table**" separates the area called the **saturated zone** where the pore spaces are filled with water (below the line) and the area called the **unsaturated zone** where the pore spaces are not filled with water (above the line). The water table goes up as more water infiltrates into this area, saturating more of the ground, and moves down when water is lost in various ways addressed later in this section.

Notice in Figure 8.3.3 (top), the level of the stream is higher than the water table off to the sides, so water is moving into the surrounding materials from the stream, and by water percolating downward from surface.

At a different time of year, when the water table is higher, water may flow from the surrounding materials into the stream, supplementing the stream flow (Figure 8.3.3, bottom).

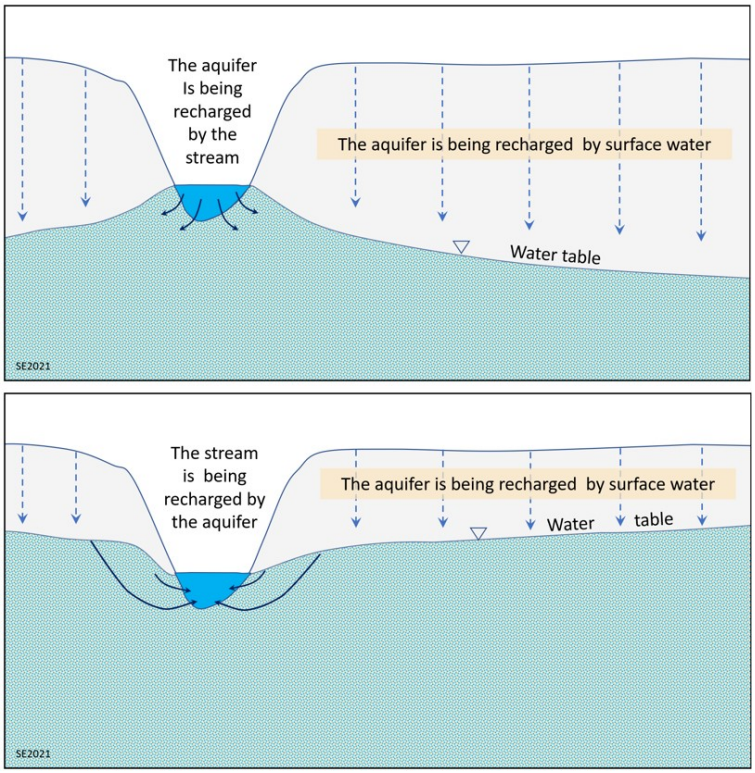


Figure 8.3.3: Examples of the Transfer of Water From Surface Reservoirs to Groundwater (top) and from Groundwater to Surface Water (bottom)

The porosities and permeabilities of different geological materials help us to define their water storage and water supply capabilities so that we can identify which materials might be useful as a groundwater source, and which might not. An **aquifer** is a body of sediment or rock that has sufficiently high permeability that we can easily extract water for our use using a well. An **aquitard** (or confining layer) is a body that has too little permeability to be useful. This concept is illustrated on Figure 8.3.4 which shows an aquifer at the top (labeled "Unconfined aquifer"). The level of the water in well A is at the same height as the water table at that location.

The **unconfined aquifer** is underlain by a layer of relatively impermeable material, here labeled a "Confining layer" which could also be called an aquitard. This is underlain by another permeable layer which is labeled as a "**Confined aquifer**". Water can enter the confined aquifer only in the area where it is exposed (upper left) and because that is at a relatively high elevation the groundwater at depth in this aquifer is under pressure. The red-dashed line defines the pressure at any point in this aquifer, and that is equivalent to the height to which water would rise in a well at that location. This is called the potentiometric surface. A well drilled at B is known as artesian because the water rises above the upper surface of the confined aquifer. The well at C is also artesian, but because the potentiometric surface is above the ground surface at that location this is a flowing artesian well. There could be more than one confined aquifer in a region. In that case, each would have its own potentiometric surface.

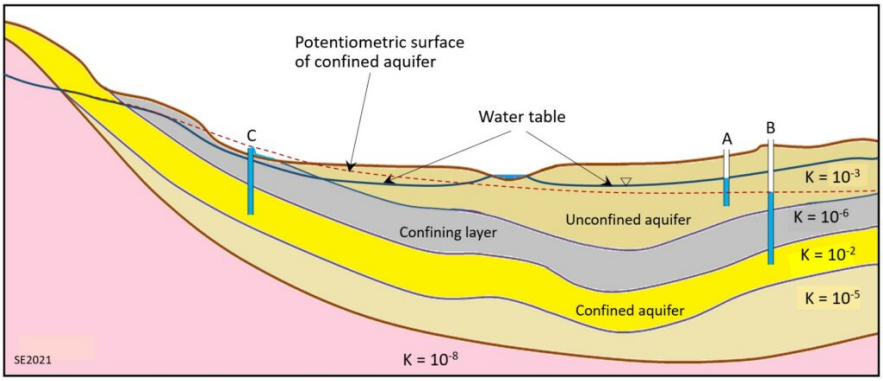


Figure 8.3.4: Aquifers and Confining Layers (Aquitards), the Water Table and a Potentiometric Surface, a Water Table Well (A), and Two Artesian Confined Aquifer Wells (B and C)

It is important to note that the distinction between an aquifer and an aquitard is subjective. As shown on Figure 8.3.5, a groundwater user with only a modest need for water may consider a body with low permeability to be an aquifer, while someone with a need for a lot of water might consider that same body to be an aquitard.

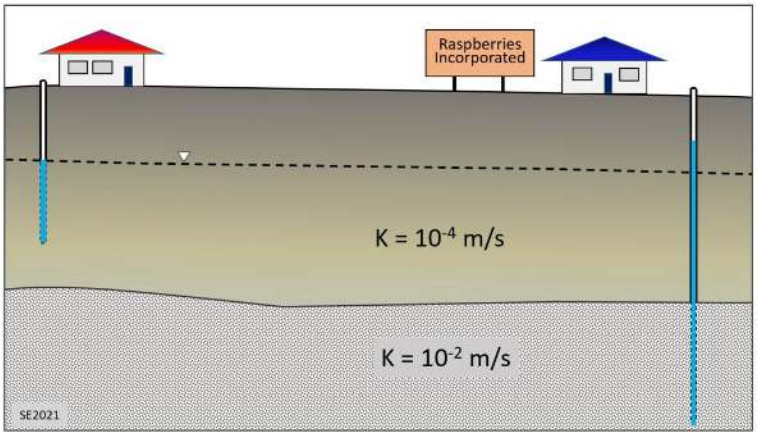


Figure 8.3.5: The upper layer is an aquifer to the water user on the left, who has only minimal water needs, but the upper layer is an aquitard (or confining layer) for the water user on the right, who has significant water needs.

Groundwater flows from areas of high hydraulic head (high water table or potentiometric surface) to areas of lower hydraulic head. This is shown on Figure 8.3.6, which also illustrates the concept of a groundwater divide (red-dashed lines), where the slope of the water table changes directions. Precipitation on the ground surface leads to recharge of the groundwater system. Water doesn't flow across a groundwater divide, which is why it is also termed a no-flow boundary. Groundwater flow lines always cross hydraulic head contour lines (also known as equipotential lines) at right angles.

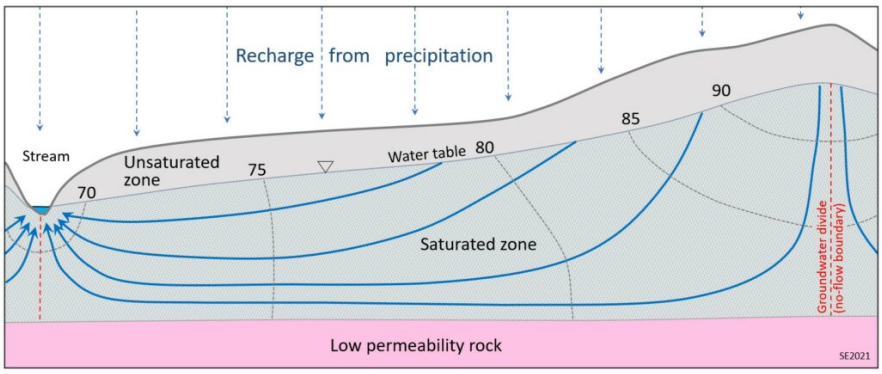


Figure 8.3.6: Possible Groundwater Flow Paths (Blue Lines) in an Unconfined Aquifer. The dashed grey lines are hydraulic head contours (equipotential lines), and the numbers 70 to 90 represent the hydraulic heads (in meters) along those lines and at the locations shown.

It is critical to understand that—except in limestone karst (cave) regions—groundwater does not flow in underground streams, nor does it form underground lakes. In almost all cases, groundwater flows very slowly through the pores in granular sediments, or through the fractures in solid rock. Flow velocities of several centimeters per day are possible in permeable sediments with significant hydraulic gradients. But in many cases, permeabilities are lower than the ones used in the examples above, and gradients are much lower. It is not uncommon for groundwater to flow at velocities of a few centimeters per year, or even just a few millimeters per year.

Problems With Wells

Cone of Depression

When a well is pumped at a rate that is faster than rate at which water can flow into it (as governed by the permeability of the aquifer) the water level in the well will drop and a cone of depression will develop around the well. This is illustrated for well A in Figure 8.3.7. (Wells B and C are not being pumped currently.)

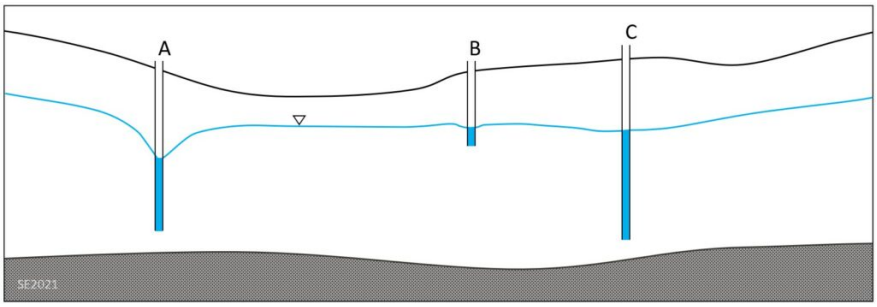


Figure 8.3.7

Subsidence

is the lowering of the ground surface due to the removal of groundwater. When water is removed, the weight of the overlying geologic materials causes the materials to compress, reducing the amount of pore space. This space is permanently lost resulting in a lowered surface. One excellent example occurred in the San Joaquin Valley in California and is depicted in Figure 8.3.8. The ground lowered 9 meters (30 feet) in 52 years.



Subsidence

Figure 8.3.8: Land surface subsided ~9 m from 1925 to 1977 due to compaction related to groundwater removal. Signs on the telephone pole indicate the former elevations of the land surface in 1925 and 1955.

Saltwater Intrusion

Many important aquifers are in coastal areas, but aquifers close to a coast are at risk from intrusion by salt water which is called **saltwater intrusion**. As illustrated on Figure 8.3.9, groundwater beneath the ocean is salty, while that beneath the land is fresh. Because fresh water is less dense than salt water the fresh groundwater in near-shore areas exists in a lens that is approximately 40 times as deep as the height of the water table above the ocean surface. A well drilled within this lens (A) will produce fresh water, but one that penetrates the salty groundwater (B) will produce salt water. In the scenario shown, well A is at risk of producing salt water if it is overused, as that will draw the water table down, and bring the fresh-salt interface up.

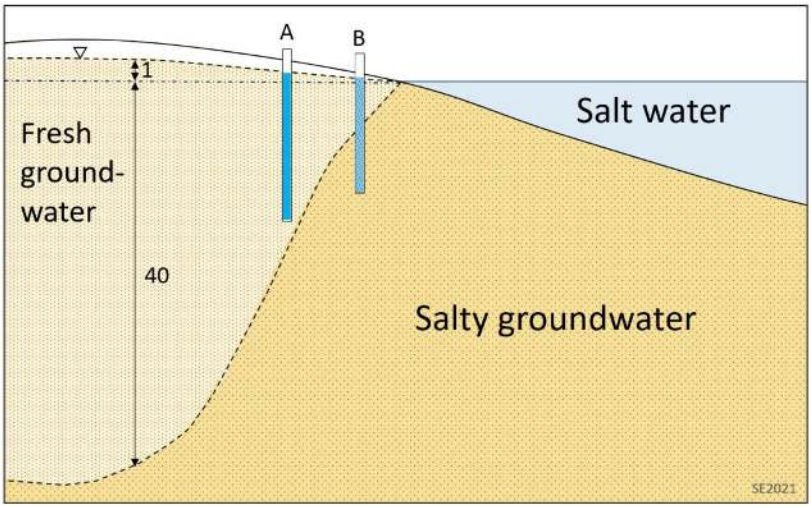


Figure 8.3.9: Depiction of the fresh water–salt water interface in near-shore areas

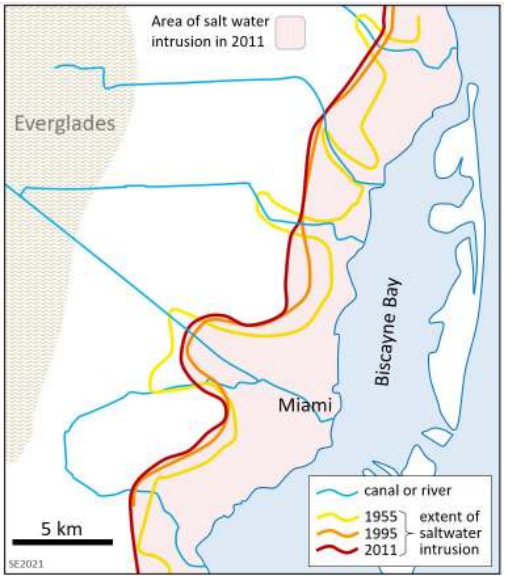


Figure 8.3.10: The areal extent of salt water intrusion in the Biscayne Aquifer, Florida

A significant salt water intrusion problem exists in the eastern part of Florida around Miami (Figure 8.3.10). The area is prone to intrusion for several reasons. First, it has very subdued topography; much of southern Florida is only a few meters above sea level. Second, the main near-surface aquifer in the region—the Biscayne Aquifer—includes limestone units with significant porosity and permeability related to dissolution that took place when the unit was above surface. In addition to those natural factors, there are also several anthropogenic factors that contribute to salt intrusion. The region is densely populated and most of the public water supply is extracted from wells in the Biscayne Aquifer. Starting in the 19th century large areas of the nearby Everglade wetlands were drained to create land for agriculture and urban expansion. The consequent drop in the water level allowed sea water to flow inland. Furthermore, draining the wetlands was largely accomplished by building canals, and those canals have allowed sea water to extend well inland and then seep into the underlying aquifer.

The extent of salt water intrusion along Biscayne Bay is illustrated on Figure 8.3.10. As of 2011 about 1200 km^2 were affected. Salt extended further inland in some areas in 1955—particularly along canals—but steps have been taken in recent decades to restrict the inland flow of salt water in the canals and so some of those areas have recovered.

Groundwater and Drainage Basins

Groundwater is the basis for water movement in a drainage basin. It is literally the base. Any water that cannot flow out of the drainage basin while still under the ground will end up flowing into low spots on the landscape, contributing to the flow in streams and lakes. Those flows are supplemented by surface runoff.

What we need to recognize is that pumping any amount of groundwater takes away from surface water somewhere in the drainage basin (unless we later rehabilitate that water and return it to the environment). It's OK to use groundwater, but we need to recognize that groundwater and surface water are really all the same thing, and so we need to be careful not to use so much that we negatively affect other users, including ecosystems.

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Reference

Nile Creek-Qualicum Bay restoration and enhancement: Reconnecting coastal cutthroat trout and salmon to their habitat. (2011).Trout Unlimited Canada. https://tucanada.org/project/nile-cr...d-enhancement/

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8.4: Natural Effects on Water Quality

For water to be useful, it must be of suitable quality. There are a range of factors that affect the quality of potential water resources.

Fresh water on the surface (in streams or lakes) has limited opportunity to react with the surrounding materials, and so its natural chemical composition (excluding human-sourced contamination) is not typically a factor in terms of its quality. Groundwater, on the other hand, is in close contact with the rock or sediment through which it is moving and there is plenty of opportunity for the water chemistry to be changed by interaction with minerals. Several factors affect how much the interaction of the water and mineral materials changes the composition of the water. The amount of time the groundwater is in contact with the materials plays a large role. The longer the water sits there, the more the materials can dissolve and contaminate the water. The depth of the groundwater is typically related to how old the water is as older groundwater is typically found at deeper depths. Consequently, deeper water tends to be more contaminated. And finally, the materials the water sits in plays a role. Some geologic materials dissolve quite easily, while others do not.

When geologists describe water quality, different terms may be used. Total Dissolved Solids (TDS) is a measure of the dissolved combined content of all inorganic and organic substances present in a liquid. It is often measured in parts per million (ppm) or milligrams per liter (mg/L). Concentrations of some of the common naturally occurring chemicals in water are summarized in this section. Tolerances are often dependent upon use where water for farming, water used by households, and drinking water need to be increasingly pure in that order.

Concentrations of Major Constituents

Figure 8.4.1 shows the concentrations of the major constituents in groundwater from different parts of a sandstone aquifer on Vancouver Island and in surface waters from the same region. These values could be somewhat representative of aquifers in other locations, as these seven constituents are the dominant components of most groundwaters. Bicarbonate (HCO_3^-), sodium (Na^+) and chloride (Cl^-) are present at the highest concentrations in these waters—all between 70 and 120 mg/L—followed by sulphate (SO_4^{-2}) and calcium (Ca^{+2}) at around 20 mg/L. If we were to add up all these numbers the total would be close to 350 mg/L, which means that if we evaporated a liter of this water, we would be left with 0.35 g of salts, or a little less than 1/10th of a teaspoon. Water with over 1000 mg/L of dissolved solids is unlikely to be good to drink. Sea water has approximately 35,000 mg/L of dissolved solids (about 7 teaspoons), mostly as sodium and chloride.

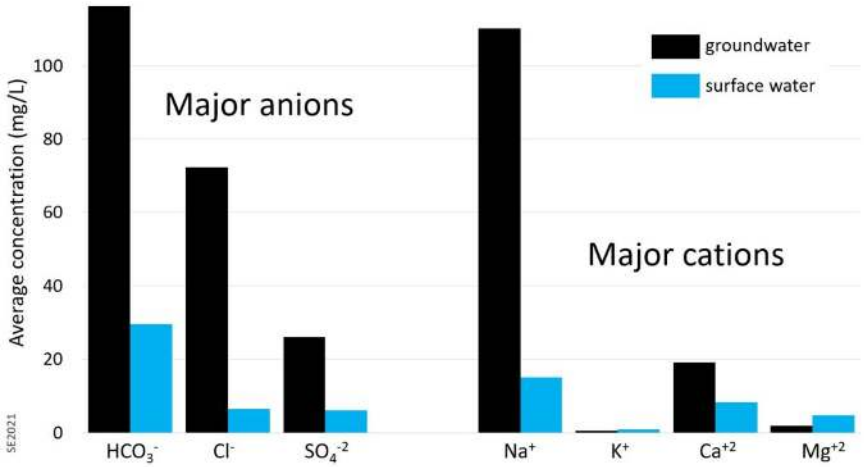


Figure 8.4.1: The average concentrations of the major components of groundwater from a sandstone aquifer, and surface water in the Vancouver Island area, BC

Concentrations in surface waters (streams and lakes) from the same areas of Vancouver Island are much lower (20% as high on average), although K and Mg are a little higher in the surface waters than the groundwaters. One liter of this water contains about 70 mg of the salts of these elements.

Concentrations of some of the important minor constituents in water samples from the same area are shown on Figure 8.4.2. The most abundant of these elements is silicon (Si), followed by iron (Fe) and fluoride (F). Note that this graph has a logarithmic scale;

the average concentration of Fe is less than 1/10th that of Si, and Al is about 1/100th that of Si. The total contribution of all these elements is equivalent to 6 mg in a liter of water.

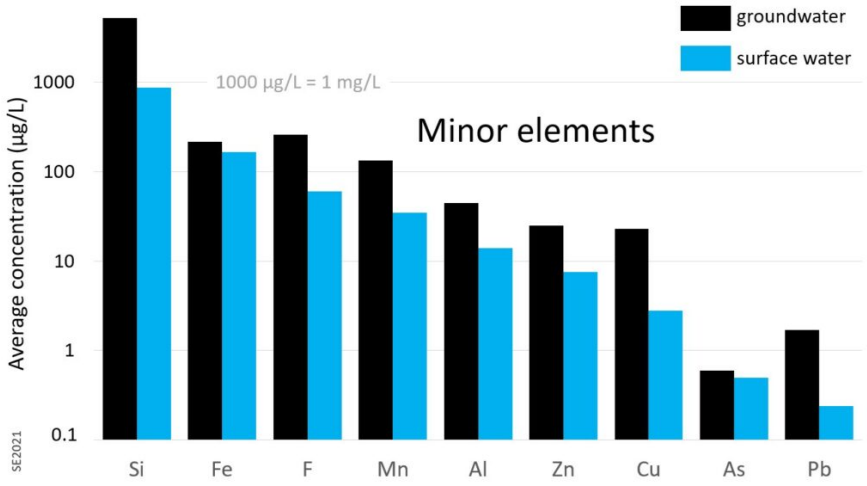


Figure 8.4.2: The Average Concentrations of Some of the Minor Components of Groundwater from a Sandstone Aquifer, and Surface Water in the Vancouver Island Area, BC. On average, the surface waters represented here have minor element concentrations that are about 1/5th as high as the groundwaters.

pH

Hydrogen ion concentration of water is expressed in pH units. Most waters have pH within the range 6 to 8, where anything less than 7 is acidic. It is not uncommon for surface waters to have pH levels of less than 6, especially in areas where the water is draining over rock with even low levels of pyrite (FeS_2). A low pH is not necessarily a concern, but because most metals are more soluble at lower pH, acidic water tends to have higher concentrations of heavy metals such as copper and zinc. Acidic water can also be a problem in buildings because it will contribute to corrosion of metal pipes. It's also quite common for surface water to have a pH well above 7, especially in areas underlain by limestone. Groundwater can also be acidic or basic (pH greater than 7). As discussed below in the section on fluoride, while a high pH is not typically a problem itself, it can be associated with other issues.

Hardness

One of the most common issues with groundwater is hardness, which is a measure of the combined concentrations of calcium and magnesium. Water is considered "hard" if it has hardness above 80 mg/L (Ca plus Mg expressed as $CaCO_3$ equivalent) and this is common with waters that are derived from sandy aquifers or from limestone aquifers. Hard water inhibits the activity of soaps and detergents, so makes washing of clothes or dishes less effective than it is with soft water. Water softeners are widely used to treat hard water. These are effective in removing most of the Ca and Mg, but do so by replacing them with Na. Excess Na consumption is a health risk to many people, so drinking or cooking with softened water is not recommended.[1]

Iron

Like most other elements, iron can exist in more than one oxidation state; the two most common are Fe^{2+} (ferrous iron) and Fe^{3+} (ferric iron). Ferrous iron is quite soluble, while ferric iron is virtually insoluble, except at very low pH. While the ground and surface waters shown on Figure 8.4.2 have iron concentrations of around 0.2 mg/L, ferrous iron is present at up to 10 mg/L in some deep groundwater.[2] When water of this type comes to surface the iron is quickly oxidized to the ferric state, and it precipitates as iron oxide and iron hydroxide minerals. An illustration of the effects this process is provided on Figure 8.4.3:. Rusty stains like this are also common in kitchen and bathroom fixtures in places where the water source is rich in iron.



Figure 8.4.3: Rusty Stains Associated With the Discharge of Iron-Bearing Groundwater from a Sandstone Aquifer on Vancouver Island

Fluoride

Fluoride is beneficial for dental health at low levels, but too much fluoride can lead to discoloration and malformation of teeth, and excessive fluoride over decades can lead to crippling skeletal problems. Almost all surface water and most groundwater has less than 0.5 mg/L (<500 µg/L) fluoride, but some groundwater has over 1.5 mg/L, which is the international maximum acceptable concentration (MAC) for fluoride. Fluoride solubility is low in water that has significant calcium concentrations and relatively low pH.

If groundwater has an elevated fluoride level, it's not likely because the aquifer materials (rock or sediments) have particularly high fluoride levels. Instead, there are water-rock interactions that make fluoride more soluble than it is under normal conditions, allowing fluoride levels to become elevated, even where there is relatively little fluorine in the surrounding material. That process is called base-exchange softening, and it is like what happens inside a water softener. The higher the pH, the more "exchanging" occurs resulting in more flouride in the water.

Arsenic

In most ground and surface waters arsenic (As) concentrations are typically below 5 µg/L, and so are below the international MAC of 10 µg/L, but in some situations arsenic levels can get much higher.

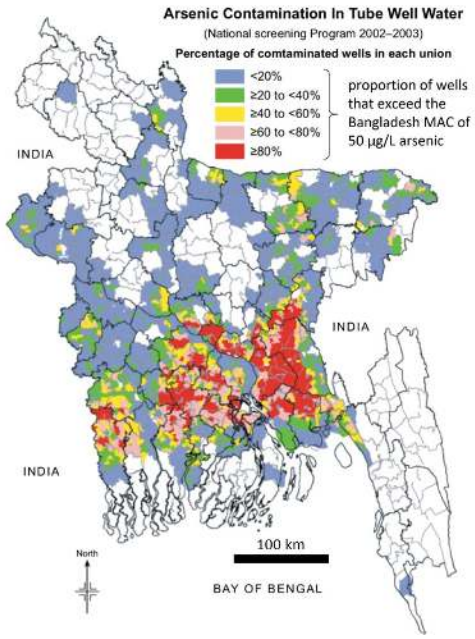


Figure 8.4.4: Areas of Significant Groundwater Arsenic Contamination in Bangladesh

In the floodplain of the Ganges and Brahmaputra Rivers in Bangladesh over 100 million residents extract groundwater from small "tube wells" (wells with diameters of less than about 10 cm). About 8 million such wells were installed in Bangladesh between 1960 and 1990, many with assistance from UNICEF. Prior to that time most rural Bangladeshi's relied on surface water sources, many of which were contaminated by bacteria and viruses. Gastrointestinal illnesses from these water sources were major health threats. The sediments surrounding groundwater wells are often sufficient to filter out many bacterial and viral contaminants, and thus provision of clean groundwater was celebrated as a major public health success.

However, in the mid-1990s it was discovered that many of the tube wells in Bangladesh have As levels above 50 µg/L (Figure 8.4.4), and as many as 20 million Bangladeshi's are at risk of As poisoning (outcomes include cancer, diabetes, thickening of the skin, liver disease and digestive problems).

Turbidity

Turbidity is a measure of the amount of solid matter—clay and silt plus fine-grained organic matter—suspended in water. Turbid water may look cloudy, although at relatively low turbidity levels—which can still be dangerous—turbidity isn't detectable without an instrument. Turbidity isn't an issue because the suspended particles themselves are a health risk, but because they inhibit the effectiveness of disinfection processes. In turbid water biological pathogens attached onto clay mineral grains are effectively protected from chlorine or ozone disinfection, or they can literally be hidden from ultraviolet radiation.

Groundwater is rarely turbid because of its inherent self-filtering by the aquifer, but surface water is often turbid, especially in regions with steep terrain (Figure 8.4.5) or following a storm or a debris flow. Most turbidity results from natural processes, but it can be exacerbated by human activities, especially farming, logging and construction.



Figure 8.4.5: Turbid Waters of a Glacier-Sourced Stream in the Canadian Rockies

Although it may not seem like a serious issue, elevated turbidity is one of the most common reasons for the declaration of boil-water advisories. Water suppliers that rely on surface water need to monitor turbidity carefully and continuously and to ensure that their filtration measures are effective. In order to avoid this problem, some water suppliers maintain a surface water supply for most of the year but have backup groundwater wells that they can draw upon when the turbidity of the surface water is too high.

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- **Figure** 8.4.5**:** Steven Earle, CC BY 4.0

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1. Health Canada. (2019). Guidelines for Canadian drinking water quality—Summary table. Water and Air Quality Bureau, Healthy Environments and Consumer Safety Branch. https://www.canada.ca/content/dam/hc..._recom-eng.pdf ↵
2. Hem, J. (1985). *Study and interpretation of the chemical characteristics of natural water* (3rd ed.). U. S. Geological Survey Water Supply Paper 2254. https://pubs.usgs.gov/wsp/wsp2254/pdf/wsp2254a.pdf ↵

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8.5: Flooding

Why Floods Occur

Floods happen because there is more water flowing in a stream than the normal channel can contain, but it's not that simple. The most common cause of stream flooding is heavy precipitation, and an example of that is shown on Figure 8.5.1. This is a doppler radar image for an area southwest of Oklahoma City. It shows the degree of radar energy reflected from water droplets in the lower atmosphere. The small pink area may be experiencing rainfall rates of greater than 400 mm/h (which is very heavy rain), while the red areas may be experiencing > 40 mm/h of rain. Streams in that region would have responded with significant discharge rates, and there might have been some localized flooding.

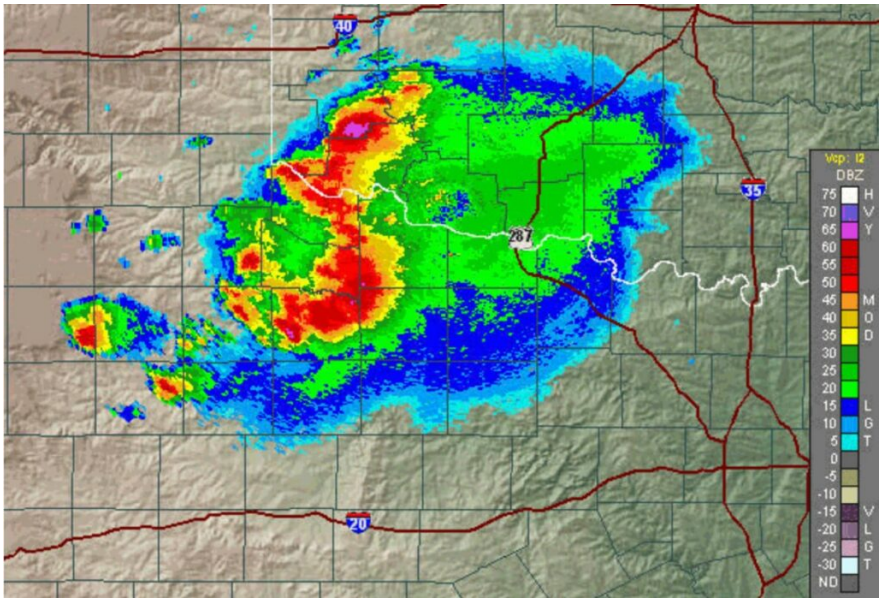


Figure 8.5.1: Doppler Radar Image for an Area southwest of Oklahoma City, OK. The numbers in the legend are in decibels, representing the amount energy returned to the radar station.

Stream discharge rates can also increase dramatically because of the rapid melting of snow and even glacial ice. Rain can contribute to snowmelt, so in many cases flooding results from a combination of these two processes.

The water flowing in a stream and its tributaries comes from two main sources: **overland flow** (water flowing over the surface of the ground during and following heavy rain or very rapid snow melt), and discharge from groundwater (groundwater at the surface that is added into streams). This second factor only affects the stream if the water table is close to the surface to begin with. In areas with deep water tables, this is not a consideration.

When there is heavy rainfall within a drainage basin some of the water can be expected to flow over the surface, but most of it infiltrates into the ground to become groundwater. This raises the water table, and therefore increases the rate of discharge into the stream. Those two main components contribute to a significant increase in the stream discharge that lasts for several days, and that discharge gradually decreases over time—rapidly at first as the overland flow rate slows, and slowly as the water table subsides and the rate of groundwater discharge into the stream decreases.

Flooding can also happen because of slope failure. If a stream channel is blocked because of slope failure the area upstream may flood, or if a significant amount of water accumulates behind a slope-failure dam, and then the dam fails, the area downstream may flood.

When a stream channel is filled with water to near its capacity, it is said to be at the "bank-full stage". In the case of streams with wide flood plains the cross-sectional area available for flow will increase dramatically as soon as the stream overtops its bank and starts to flood, and even though there is more water moving than at bank-full stage, the velocity will decrease. As the velocity decreases some of the suspended sediments will be deposited. The coarser material will be deposited close to the normal bank top,

forming a natural levee. Finer sediments will be deposited slowly, across the flood plain, over the days in which flood waters remain there, and especially when the flow velocity drops even more.

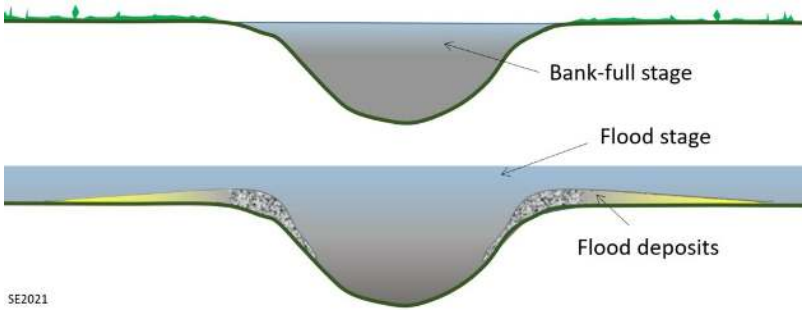


Figure 8.5.2: A Depiction of a Stream at Bank-Full Stage and at Flood Stage

The natural levees formed by flooding can provide some protection against future flooding, but they can also prevent flood waters from flowing back into the stream, so prolonging the time over which some areas remain flooded.

Flood Recurrence Interval

Providing that we have enough stream discharge data from previous years it is possible to estimate the probability that a flood of a certain size will happen at some time in the future. Flood probability is determined by calculating the **flood recurrence interval** (Ri), the estimated average time between events of a particular discharge, for any given stream. This type of information is useful for planners that must make decisions about approving proposals for infrastructure projects (buildings, roads etc.) within flood plains, and also for anyone that wants to live near to a river.

Emergency measures organizations use calculations of Ri to report past, current or predicted floods using terms like “100-year flood”. That means that the flood was, or is expected to be, as big as the largest flood in the past 100 years. Another way to think about it is a "100-year flood" occurs on average once every 100 years. This does not mean it happens every 100 years. You could have a 100-year flood two years in a row, and then not again for a long period of time. These floods are larger than "50-year floods" which occur on average, once every 50 years. They are smaller as they occur more often. "10-year floods" are even smaller than that and occur even more often.

Although we can determine a flood probability, we can’t predict when there is going to be a big flood, nor how big it will be, so to minimize damage and casualties we need to be prepared. Some of the ways of doing that are as follows:

- Mapping flood plains and not building within them,
- Building dams where necessary,
- Monitoring the winter snowpack, the weather, and stream discharges,
- Creating emergency plans, and
- Educating the public.

Another important point to remember is that estimation of flood probabilities based on past data relies on the premise that the climate conditions and land-use patterns that produced the historical record are still relevant in the future. As we know, weather can be unpredictable. Furthermore, land use changes may have changed the way water runs off the surface, and that could also change the probability of future large floods.

Examples of Major Flood Events

In late August of 2017, Category 4 Hurricane Harvey made landfall near to Corpus Christi, Texas, and then slowly moved east, remaining almost stationary over the Houston region for several days. In that time more than 1000 mm of rain fell over a large area. There was widespread flooding (Figure 8.5.3), more than 100 people died, and the amount of damage is estimated to have been $125 billion, mostly in the form of damages to buildings. In terms of the aggregate rainfall amount measured, Harvey was the wettest tropical storm ever to affect the United States.



Figure 8.5.3: Flooding in Pt. Arthur Texas Caused by Hurricane Harvey, August 31st, 2017

The annual number of tropical storms in the Atlantic basin has been increasing in recent decades, mostly because of increased ocean water temperatures as the climate has warmed. The higher water and air temperatures also mean that more water is transferred from the ocean to the atmosphere as a tropical storm evolves, and so we can look forward to a future with more very wet systems like Harvey to cause flooding.

Serious flooding in Canada in June of 2013 was initiated by rapid snow melt in the Rocky Mountains and was worsened by heavy rains due to an anomalous flow of moist air from the Pacific. Rainfall amounts exceeded 200 mm in 36 hours at Canmore, and 325 mm in 48 hours at High River. The discharges of several rivers in the area, reached levels that were 5 to 10 times higher than normal for the late June. Large parts of Calgary and surrounding areas were flooded, and 5 people died (see Figure 8.5.4). The cost of the 2013 flood is estimated to have been approximately $5 billion, making it the most expensive flood event in Canadian history.



Figure 8.5.4: Flooding in Calgary (June 21, left) and Okotoks (June 20, right) During the 2013 Southern Alberta Flood

The Himalayan region is a common source of snow-melt flooding in China, India, Pakistan, Bangladesh, and other countries in the region, but there have also been many slope-failure related floods in the mountains. In July 2000, a slope-failure in China dammed up the Satluj River, forming a temporary lake. By July 31st the water level in the lake had risen enough to flow over and then quickly erode the dam, releasing a massive flood that is said to have increased the water level of the river by 20 meters. Over 150 lives were lost, 250 houses destroyed, and 20 km of road and 7 bridges washed out. As many as 1000 irrigation, sewerage, flood protection, power installations and water supply systems were damaged.[1]

Anthropogenic Effects on Flooding

Natural landscapes provide a natural defense against flooding. Plants such as grasses, bushes, and trees keep soil in place which absorbs excess rainfall and allows it to infiltrate into the ground. Mature root systems can also help manage excess water as the roots absorb it. Natural stream systems with developed flood plains and wetlands all serve as places for water to go and be distributed from. Human activities can disrupt these systems, increasing the likelihood and severity of floods.

The development of urban and rural areas hinders these natural systems and increase the frequency and magnitude of flood events. Wetlands are meant to store excess water, but we often drain them or pave over them for building purposes. Water that should be stored there ends up in the stream channels. Levees, meant to keep water in the stream channel and away from the surrounding floodplains, ultimately result in increased flooding downstream. They also result in elevated river levels such that when a levee does fail, massive flooding can result, destroying the structures it was meant to protect. When Hurricane Katrina struck New Orleans in 2005, levee failures flooded the city, killing hundreds of people.

Large agricultural operations can deplete soil of the nutrients which results in reducing its quality. Plants then struggle to survive and die off. Since plants play a key role in protecting areas against flooding, the magnitude and frequency of flood events can increase. Deforestation can remove the large trees which act to keep soil in place. Without them, nutrient rich soil washes away and leaves dry soil in its place which is not suitable for absorbing heavy rainfall. This increases the amount of water that washes into streams, which causes flooding.

Flood Reduction and Control

There are several ways to reduce the risks associated with flooding, including limiting the potential for flooding in the first place, controlling where floodwaters go, and taking steps to limit the amount of damage that floods cause.

One of the best ways to reduce the risk of flooding is to do just the opposite of what we do most of the time in urban areas, namely constructing endless highways, roads and parking lots, and countless buildings. Paved surfaces and roofs do not absorb water effectively, so relatively little of it infiltrates into the ground to become groundwater; instead, most runs off the surface. The runoff coefficients for a range of different surface types are illustrated on Figure 8.5.5. The runoff coefficient is an estimate of the proportion of rain from a significant storm that will flow over a surface to become runoff, rather than infiltrating into the ground.

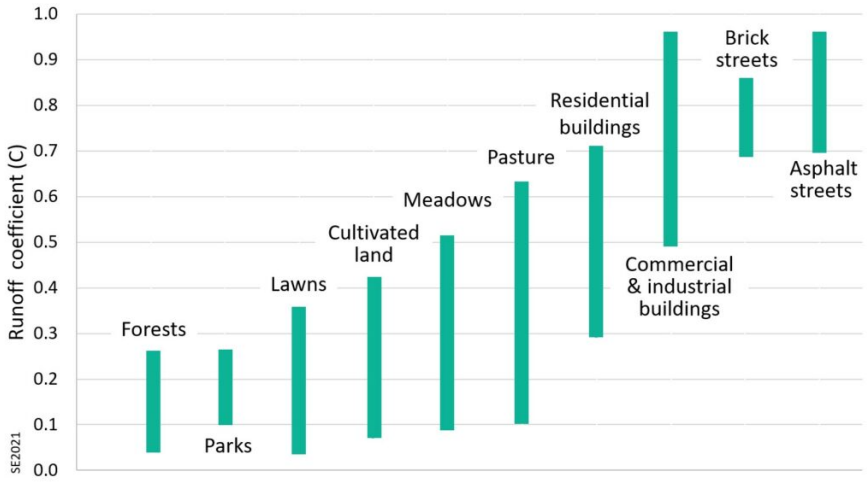


Figure 8.5.5: Runoff Coefficients for Various Types of Surfaces

Only a small proportion of the rain that falls in parks or forests—5 to 25% of it—becomes surface flow; the rest—75 to 95% of it—infiltrates into the ground and becomes part of the groundwater, and then moves very slowly towards surface drainages, thus delaying and reducing the ultimate size of a flood. For cultivated land, meadows and pasture, 10 to 65% of the precipitation runs across the surface, directly into streams and lakes, while 35 and 90% of the water infiltrates. For roads and streets 70 to 95% flows over the surface, or through ditches and storm sewers directly into surface water bodies, while only 5 to 30% infiltrates. Obviously, increasing the amount of infrastructure (roads, parking lots, buildings) in an area, increases the amount of water that will flow quickly into drainage systems and so will amplify the potential for flooding. On the other hand, conserving forests in their natural state, and creating parks that have minimal infrastructure will reduce the potential for flooding.

Some ways to reduce the flooding potential impact of existing urban regions include reducing the area covered by hard surfaces, making hard surfaces (e.g., roads) more permeable, replacing roads and parking lots with parks and community garden plots, constructing ponds or wetlands to capture runoff, and creating dips and hollows (swales) in landscaped areas to slow the rate of flow and increase the rate of infiltration.

We can control floodwaters by building dams, dykes and channels. The High Aswan Dam in Egypt is a good example of that, although there are significant downsides to the construction of large dams. A dyke or levee is a berm built along one or both sides of a river to prevent flood waters from spilling out onto the floodplain. An artificial channel can be constructed separate from the normal channel to carry a portion of the flow of a river during flood events.

The Mississippi-Missouri-Ohio river system is the largest in North America, with a drainage basin that covers more than 40% of the US and even a small part of Canada. It has great historical significance and has been a critical transportation corridor for over two centuries. The Mississippi is one of the most controlled rivers in the world. There are 64 major dams on the Mississippi, Missouri and Ohio Rivers, and hundreds of others on their tributaries. There are over 5600 km of dykes (a.k.a., levees) along the sides of the rivers, and thousands of other structures that have been built to make the water go where it is wanted, or to keep the shipping channels open. Wing dykes, for example are constructed within the river channel at an angle to the shore and are designed to keep most of the water flowing in the central part of the channel so as to limit the extent to which that part fills with sediment (Figure 8.5.6). Despite all of the engineering works on the Mississippi system (or in some cases because of them), the tendency for flooding has increased over the past century. According to Pinter et al. (2008),[2] although climate change has made flooding more likely over that time, “the largest and most pervasive contributors to increased flooding on the Mississippi River system were wing dikes and related navigational structures, followed by progressive levee construction. In the area of the 2008 Upper Mississippi flood, for example, about 2 m of the flood crest is linked to navigational and flood-control engineering. Systemwide, large increases in flood levels were documented at locations and at times of wing-dike and levee construction.”



Figure 8.5.6: Wing Dykes on the Mississippi River

Wing dykes were constructed to enhance navigation on the Mississippi system (not to reduce flooding), but Pinter et al. found that they resulted in increases in water levels in upstream areas because the wing dykes acted like dams. Levees were constructed to control flooding, but Pinter et al. found that they led to increased flooding downstream because they resulted in a loss of water storage in flood plains.

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- **Figure** 8.5.6**:** River Training Structures from US Army Corps of Engineers, public domain, https://www.army.mil/article/70627/r...for_navigation

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1. Gupta, V. & Sah, M. (2008). Impact of the Trans-Himalayan Landslide Lake Outburst Flood (LLOF) in the Satluj catchment, Himachal Pradesh, India. *Natural Hazards 45*, 379–390. https://doi.org/10.1007/s11069-007-9174-6 ↵
2. Pinter, N. et al. (2008). Flood trends and river engineering on the Mississippi River system. *Geophysical Research Letters, 35*(23). https://doi.org/10.1029/2008GL035987 ↵

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8.6: Drought

Drought Conditions

The word **drought** can mean different things to different people. To someone living in a city, it can mean there is a shortage of water for bathing, doing dishes, etc. from their provider and they are being asked to conserve. To a farmer, it means there has been less rainfall than is normal which is affecting the crops under cultivation. This can occur over a very short cycle (just a few weeks) if the moisture deficiency comes during certain periods of the growing cycle. To a meteorologist, a drought is a prolonged period when precipitation is less than normal. To a hydro geologist, a drought is an extended period of decreased rainfall and diminished stream flow.

Generically, drought is a period of reduced rainfall and/or snowfall that results in water-related problems. While precipitation (rainfall or snowfall) at a particular location varies from year to year, the average amount is constant over a period of years. This relates to the difference between weather which describes conditions at a point in time versus climate which is an average of those conditions. In the United States' southwestern deserts, the average precipitation is only a few inches per year. In contrast, the average yearly precipitation in some places in the southeast is over 50 inches. But, even if the total amount of rainfall for a year is average, rainfall shortages can occur during a period when moisture is critically needed for plant growth, such as in the early summer causing drought conditions.

The beginning of a drought can be difficult to determine, and weeks, months, or years may pass before people know that a drought is occurring. Droughts can persist for a decade or more, and the end can occur as gradually as it began. The first evidence of drought usually is seen in records of rainfall though this does not necessarily result in drought conditions. Some rain returns to the air as water vapor when water evaporates from water surfaces and from moist soil. Plant roots draw some of the moisture from the soil and return it to the air through a process called transpiration. When evaporation and transpiration rates are large, soils can lose moisture and dry conditions can develop. But if the weather is cool and cloudy, these rates may be small enough to offset the lack of precipitation and a drought may be less severe or may not develop at all.

Rainfall in any form will provide some drought relief. A light shower provides cooling, and revitalizes vegetation, but during the growing season, most of the rain that falls will be quickly evaporated or used by plants. The impact is short term. A thunderstorm will provide some of the same benefits as the light shower but can also be very damaging. Since thunderstorms produce large amounts of precipitation in a short period of time, most of the rain runs off into streams so it never soaks into the ground. If we are lucky, the rain falls upstream of a lake which captures the water and increases the available water supply.

Soaking rains, often produced by tropical storms, are best to alleviate drought. Water that enters the soil recharges ground water, which in turn sustains vegetation and feeds streams during periods when it is not raining. A single soaking rain will provide lasting relief from drought conditions, but multiple events over several months are usually required to break a drought and return conditions to within the normal range.

Even when a drought has been broken it may not be truly over. The benefits of substantial rainfall such as from a tropical storm may last for months, but a return to normal rainfall patterns and amounts is necessary for conditions in streams, reservoirs, and ground water to also return to normal.

Anthropogenic Effects on Droughts

Humans affect drought conditions in two major ways. First, especially in the current day, humans consume large amounts of water. Whether it is for household use, industrial use, or for agricultural use, water is often used at rates higher than what is naturally replaced. This leads to drought conditions as the amount required by a community is not available. This is particularly problematic for communities established in arid or semi-arid areas like southern California.

Second, according to a study from NASA's Goddard Institute for Space Studies (GISS) in New York City, human-generated greenhouse gases and atmospheric particles were affecting global drought risk as far back as the early 20th century. This is part of the global climate change crisis whereby industrialization affects temperatures as well as rainfall amounts. It should be noted that droughts do naturally occur. The amount of influence humans have had on drought conditions is a complex topic as there are many factors that contribute to changes in patterns.

How Drought Impacts Earth and Humans

Drought affects Earth and humans in many ways. When little or no rain falls, soils can dry out and plants die. When rainfall is less than normal for several weeks, months, or years, the flow of streams and rivers declines, water levels in lakes and reservoirs fall, and the depth to water in wells increases. If dry weather persists and water-supply problems develop, the dry period can become a drought.

The topic of well water depth is an important one as wells are used to access groundwater which is in turn used to provide a large portion of the Nation's population with drinking water, it provides business and industries water for their purposes and is used extensively for irrigation. The water level in the aquifer that supplies a well does not always stay the same. Droughts affect the height of the underground water levels as water continues to be pumped out and there is not enough water to recharge it. This obviously happens during drought due to the extreme deficit of rain.

Drought also affects humans through the destruction of crops and farms. The best modern-day example of this occurred during the 1930's. The US experienced what is referred to as the "Dust Bowl". During that time, most of the United States was much drier than normal. In California, the drought extended from 1928 to 1937. In Missouri, the drought lasted from 1930 to 1941. That extended dry period allowed wind to produced dust storms that destroyed crops and farms.

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CHAPTER OVERVIEW

9: Energy Resources



This chapter presents the the energy needs of humans adjacent to how we have satisfied these needs in the past with fossil fuels, and the shift in energy production using renewable sources like solar energy instead. Information presented earlier in the text about Earth's materials (like minerals and rocks) and processes (like those occurring in the atmosphere) helps in understanding this topic.

9.1: Our Energy Needs
9.2: Fossil Fuels
9.3: Solar and Wind
9.4: Hydroelectric Power
9.5: Wave and Tidal Energy
9.6: Geothermal Energy
9.7: Nuclear Energy

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9.1: Our Energy Needs

According to the U.S. Energy Information Administration (EIA) there are five main energy use sectors. The residential sector includes homes. The commercial sector includes offices, malls, stores, schools, hospitals, hotels, warehouses, restaurants, and places of worship and public assembly. The industrial sector includes facilities and equipment used for manufacturing, agriculture, mining, and construction. The transportation sector includes vehicles that transport people or goods, such as cars, trucks, buses, motorcycles, trains, aircraft, boats, barges, and ships. The electric power sector, whose primary business is to generate and sell electricity and, in some cases, heat, to the other energy use sectors.

Energy is produced by **non-renewable sources**, namely fossil fuels such as oil, coal, and natural gas. They are referred to as non-renewable as once they are extracted from Earth materials and consumed, they are gone. Energy is also produced by renewable sources such as wind farms and solar panels which work if wind blows and the sun shines.

It is evident we need to keep working on all options explored in this chapter. That includes rapidly expanding solar and wind, and then ensuring that we have enough other forms of energy to fill in the gaps. Other strategies that are important to continue to meet our energy needs are:

a. using much less energy by driving less and flying less, living in smaller homes that are more energy-efficient, and buying much less of the manufactured stuff that we don't need.
b. considering when electricity is used. As shown on Figure 9.1.1, energy demand varies significantly from season to season and from hour to hour within any day. In warm climates like California the electricity demand is lower in the winter than in the summer (mostly because of air conditioning). It is lowest in the middle of the night (1 am to 6 am) and highest in the evening (6 pm to 10 pm). There is also an afternoon low, but only in winter. In colder climates, where heating is needed through the winter, and where air conditioning is not widely used, the demand is typically higher in the cold part of the year. Electricity providers must be very nimble to make sure that they can meet the demand at any time, but not generate more than what is needed as the excess energy is not stored. In the example shown for northern California, the demand ranges from a low of 7,900 MW on a Saturday afternoon in February, to a high of 15,400 MW on a Monday evening in July. Based only on this limited data, we can see that Pacific Gas and Electric (PG&E) has to be able to produce at least 16,000 MW for this market, but typically needs to produce less than 13,000 MW, and often less than 10,000 MW. If the demand curve could be smoothed out PG&E (and other utilities) could get by with less generating capacity overall and especially less peaking capacity, much of which is currently met with fossil fuel sources. Utilities can lower the peaks by charging more in the evenings (as PG&E does), and electricity users can play an important role by reducing their demand at peak times. For example, they could cook evening meals before 6 pm or turn the a/c off between 7 and 9 and spend time outdoors on summer evenings, or not charge electric cars until after 10 pm. For most people, these types of changes would not represent a reduction in quality of life, just a change in habits.

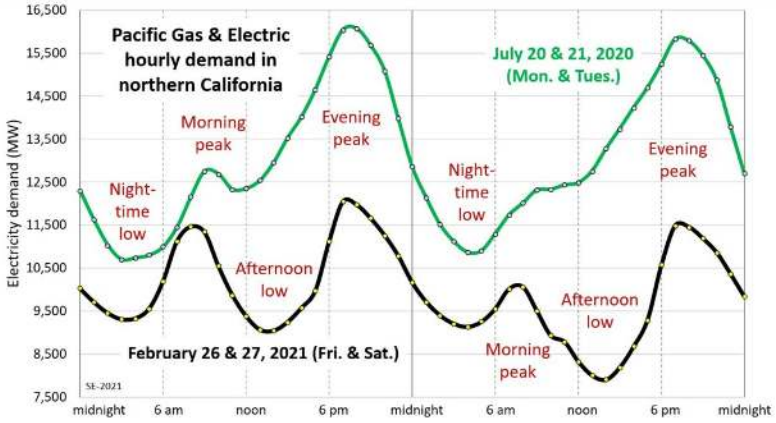


Figure 9.1.1: Electricity Demand for Pacific Gas and Electric Customers on Two Days in July 2020 and Two Days in February 2021

c. Another way to even out demand and maximize the benefit of sources such as solar and wind, is to store energy for short periods. An example of this is the Hornsdale wind farm in Southern Australia. When electricity production exceeds demand

the energy is stored in a 100 MWh Li-ion battery (the world's largest). That stored energy is used when demand exceeds production. Some of the presently available energy-storage options are listed in Table 9.1.1. It should be noted that these options can provide for storage of energy for a few hours to a few days, and so can help to smooth out daily changes in demand, but that they do not have the capacity for longer-term storage to smooth out seasonal changes in demand. While the options in Table 9.1.1 are described as "utility-scale", lithium-ion batteries can be used for household-scale energy storage to help individuals avoid peak-time electricity rates, and even smooth the curve a little. The Tesla Powerwall has software that allows the user to store energy during low-tariff periods and discharge energy during high-tariff periods, and therefore provides an opportunity to save money and help reduce utility peaks.

Table 9.1.1: Utility-scale energy storage options
Data from the Environmental and Energy Study Institute (EESI)

Type of Storage	Efficiency	Lifetime or Number of Cycles	Limitations
Pumped hydro	70-85%	Many decades	Topography and land needed
Compressed air	40-70%	A few decades	Low efficiency
Molten salt	80-90%	A few decades	Heat source needed
Li-ion battery	85-95%	1,000-10,000 cycles	Expensive at present, limited cycles
Flow battery	60-85%	12,000-14,000 cycles	
Hydrogen	25-45%	A few decades	Low efficiency

d. sharing electricity over wide areas. This way, for example, solar electricity produced in the afternoon in western and central North America could be used to help supply the peak evening demands of eastern North America. This type of sharing would involve the construction of super grids with efficient high voltage direct current transmission (which suffer energy losses of less than 2% per 1000 km). One example of this type of connection is the Québec–New England transmission line which has a capacity of 2250 MW and brings hydro power from northern Québec to the eastern USA. Another is the Pacific DC Intertie that brings 3100 MW of power from the Pacific Northwest to southern California.

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9.2: Fossil Fuels

Creation of Fossil Fuels

There are several types of **fossil fuels** (coal, natural gas, oil), each of which are used to generate energy. They all involve the storage of organic matter in sediments or sedimentary rocks as the carbon originates from CO_2 taken out of the atmosphere millions of years ago during photosynthesis. That process, driven by solar energy, involves reduction (the opposite of oxidation) of the carbon, resulting in it being combined with hydrogen instead of oxygen. The resulting "organic matter" is made up of complex and varied carbohydrate molecules.

Most of the organic matter produced in this way is oxidized back to CO_2 relatively quickly once the organism dies (within weeks to decades in most cases), but any of it that gets isolated from the oxygen of the atmosphere, for example deep in the ocean or in a stagnant bog, may last long enough to be buried by sediments and, if so, may be preserved for tens to hundreds of millions of years. Under natural conditions, that means it will be stored until those rocks are eventually exposed at surface and weathered.

Coal

Coal, the first fossil fuel to be widely used, forms mostly on land in swampy areas adjacent to rivers and deltas in areas with humid tropical to temperate climates. The vigorous growth of vegetation leads to an abundance of organic matter that accumulates within the stagnant water of swamps, ponds and lakes with little circulation, and thus does not decay and oxidize. This situation, where the dead organic matter is submerged in oxygen-poor water, must be maintained for centuries to millennia for enough material to accumulate to form a thick layer (Figure 9.2.1a). At some point the swamp deposit is covered with more sediment—typically because a river changes its course or overtops its bank (Figure 9.2.1b). As more sediments are added the organic matter starts to become compressed and heated. Low grade lignite coal will form at depths between a few 100 m and 1500 m and temperatures up to about 50˚ C (Figure 9.2.1c). At between 1000 to 5000 m and temperatures up to 150˚ C m bituminous coal will form (Figure 9.2.1 d). At depths beyond 5000 m and temperatures over 150˚ C anthracite coal will form.

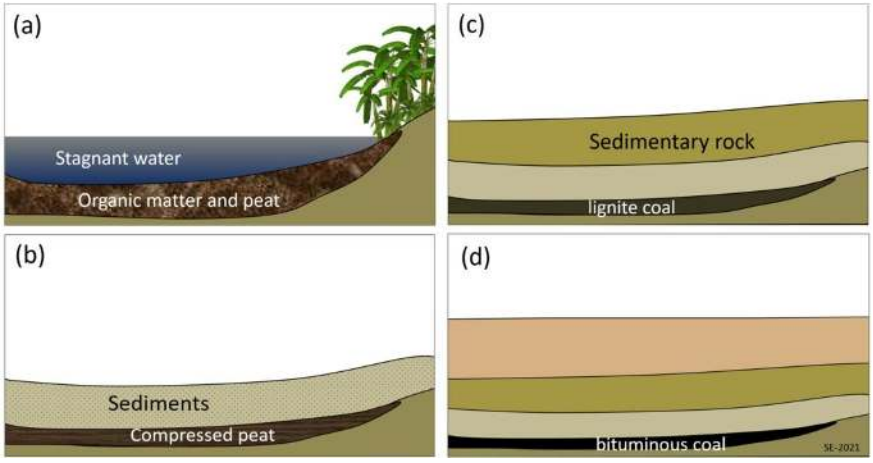


Figure 9.2.1: Formation of Coal. (a) Accumulation of organic matter within a swampy area, (b) the organic matter is covered and compressed by deposition of a new layer of clastic sediments, (c) with greater burial lignite coal is formed, and (d) at even greater depths bituminous (and eventually anthracite) coal are formed.

During the process of converting organic matter to coal some methane (i.e., natural gas) is produced and it is stored within the pores of the coal. When coal is mined methane is released into the mine where it can become a serious explosion hazard. Modern coal-mining machines have methane detectors on them and will stop operating if the methane levels are dangerous. It is possible to extract the methane from coal beds without mining the coal and the gas recovered in this way is known as coal bed methane.

Oil and Gas

While almost all coal is formed on land from terrestrial vegetation, most oil and gas is derived primarily from marine microorganisms that accumulate within sea-floor sediments. In areas where marine productivity is high dead organic matter is

delivered to the seafloor fast enough that at least some of it escapes being oxidized. This material accumulates in the muddy sediments and then those get buried to significant depth beneath other sediments.

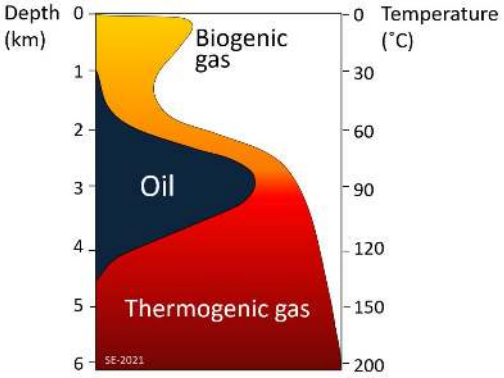


Figure 9.2.2: The Depth and Temperature Limits for Biogenic Gas, Oil, and Thermogenic Gas

As the depth of burial increases so does the temperature—due to the geothermal gradient—and gradually the organic matter within the sediments gets converted to hydrocarbons (Figure 9.2.2). The first stage is the biological production (involving anaerobic bacteria) of methane (i.e., natural gas). Most of this escapes back to surface, but some is trapped in methane hydrates near to the sea floor. At depths beyond about 2 km, and at temperatures ranging from 60 to 120˚ C, the organic matter is converted by chemical processes to oil. This depth and temperature range is known as the oil window. Beyond 120˚ C most of the organic matter is chemically converted to methane (i.e., natural gas).

The rock within which the formation of gas and oil takes place is known to petroleum geologists as the source rock. This rock is typically rich in organic matter, and a good example would be a black shale. Both liquid oil and gaseous methane are lighter than water, so as liquids and gases are formed, they tend to move slowly towards surface, out of the source rock and into reservoir rocks. Reservoir rocks are typically relatively porous and permeable rocks such as sandstone or fractured limestone, because that allows migration of the fluids from the source rocks and facilitates recovery of the oil or gas. In some cases, the liquids and gases make it all the way to surface, where they are oxidized and the carbon is returned naturally to the atmosphere, but in others they are contained by overlying impermeable rocks (a.k.a. “cap rock”, e.g., mudrock) in situations where anticlines, faults, stratigraphy changes and reefs or salt domes create traps (Figure 9.2.3).

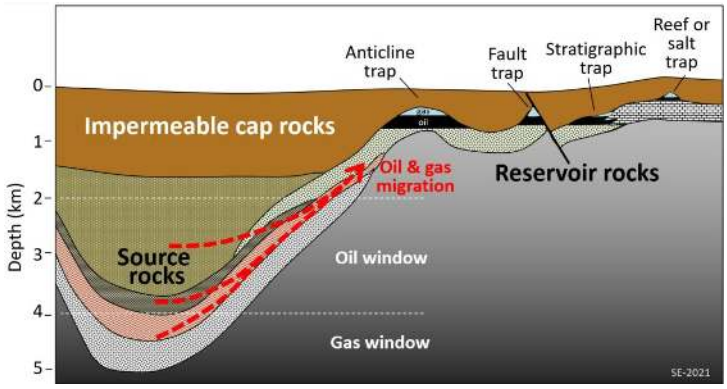


Figure 9.2.3: Migration of Oil and Gas from Source Rocks into Traps in Reservoir Rocks

The liquids and gases that are trapped within reservoirs will become separated into layers based on their density, with gas rising to the top, then oil, and water underneath. The proportions of oil and gas will depend primarily on the temperature in the source rocks. Some petroleum fields, such as many of those in Alberta, are dominated by oil, while others, notably those in northeastern BC, are dominated by gas.

In general petroleum fields are not visible from surface, and their discovery involves the search for structures in the sub-surface that have the potential to form traps. Seismic surveys are the most used tool for early-stage petroleum exploration, as they can reveal important information about the stratigraphy and structural geology of sub-surface sedimentary rocks. An example from the Gulf of Mexico south of Texas is shown on Figure 9.2.4. In this area a thick evaporite deposit (“salt”) has formed domes because

salt is lighter than other sediments and tends to rise slowly towards surface, and this has created traps. The sequence of deformed rocks is capped with a layer of undeformed rock.

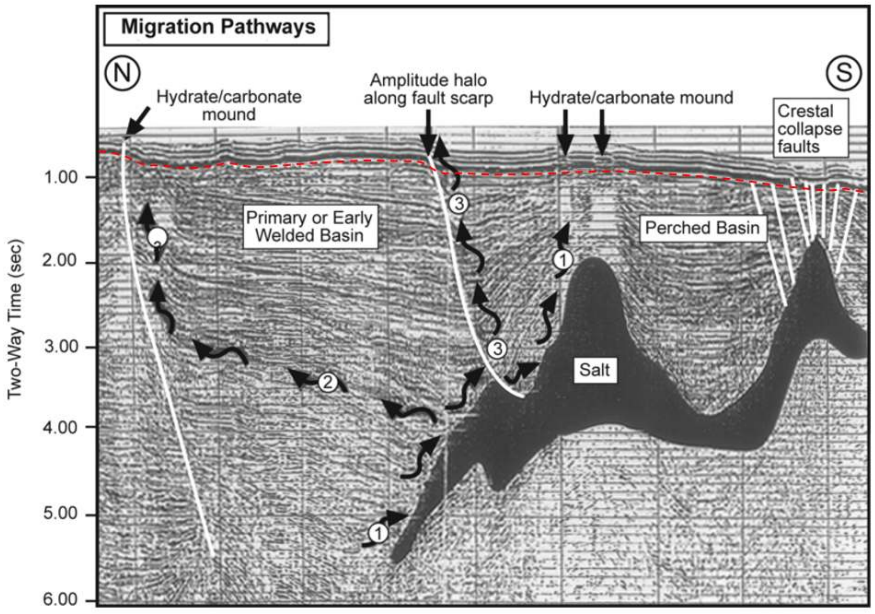


Figure 9.2.4: Seismic Section Through the East Breaks Field in the Gulf of Mexico. The dashed red line marks the approximate boundary between deformed rocks underneath and younger undeformed rocks lying horizontally on top. The wiggly arrows are interpreted migration paths.

The type of oil and gas reservoirs illustrated in Figure 9.2.3 and Figure 9.2.4 are described as conventional reserves. Some unconventional types of oil and gas include oil sands, shale gas and coal-bed methane.

Oil sands are important because the reserves in Alberta, Canada are so large (the largest single reserve of oil in the world), but they are very controversial from an environmental and social perspective. They are “unconventional” because the oil is exposed at surface and is highly viscous because of microbial changes that have taken place at surface. The hydrocarbons that form this reserve originated in deeply buried Paleozoic rocks adjacent to the Rocky Mountains and migrated up and towards the east (Figure 9.2.5).

The controversy comes with the environmental cost of their extraction. Since the oil is so viscous, it requires heat energy to make it sufficiently liquid to process. This energy comes from gas; approximately 25 m^3 of gas is used to produce 0.16 m^3 (~one barrel) of oil. (That’s bad, but not quite as bad as it sounds, as the energy equivalent of the required gas is about 20% of the energy embodied in the produced oil.) The other environmental cost of oil sands production is the devastation of vast areas of land where strip-mining is taking place, and the unavoidable release of contaminants into the groundwater and rivers of the region.

At present most oil sand recovery is achieved by mining the sand and processing it on site. Exploitation of oil sand that is not exposed at surface depends on in situ processes, an example being the injection of steam into the oil-sand layer to reduce the viscosity of the oil so that it can be pumped to surface.

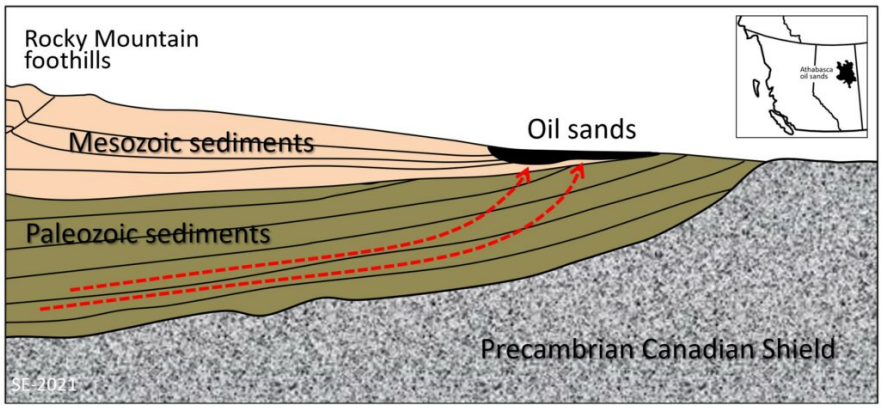


Figure 9.2.5: Schematic Cross-Section of Northern Alberta Showing the Source Rocks and Location of the Athabasca Oil Sands

Shale gas is gas that is trapped within rock that is too impermeable for the gas to escape under normal conditions and can only be extracted by fracturing the reservoir rock using water and chemicals under extremely high pressure. This procedure is known as hydraulic fracturing or fracking. Fracking is controversial because of the volume of water used, and because the fracking companies are not required to disclose the nature of the chemicals used. Although fracking is typically done at significant depths there is always the risk that overlying water-supply aquifers could be contaminated. Fracking also induces low-level earthquakes, which do have the potential to cause damage.

The Future of Fossil Fuels

It is important for us to understand the origins and exploitation of fossil fuels, but it is equally important to recognize that the Earth can no longer sustain the current rate of fossil fuel use.

At the United Nations Framework Convention on Climate Change meeting in Paris in 2016 the countries of the world agreed to a goal of limiting anthropogenic (human-caused) warming to 1.5° C above pre-industrial levels.[1] In order to achieve that goal, the Intergovernmental Panel on Climate Change (IPCC) has stated that we must decrease anthropogenic CO_2 emissions (and therefore fossil fuel use) by 45% below 2010 levels by 2030, and that we must reach net-zero CO_2 emissions by 2050.[2] If we wish to limit warming to 2.0° C above pre-industrial levels, we must decrease anthropogenic CO_2 emissions by 25% below 2010 levels by 2030, and that we must reach net-zero CO_2 emissions by 2070.

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1. Every country in the world has signed the Paris Agreement, and so every person in the world needs to be on board with reaching its goals. Seven countries: Eritrea, Iran, Iraq, Libya, South Sudan, Turkey and Yemen have signed, but have not ratified the agreement. In 2019 the United States announced its withdrawal from the Paris Agreement, but that decision was reversed in February 2021. ↵
2. IPCC. (2018). Summary for policymakers. In Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (Eds.), *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5° C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.* World Meteorological Organization. https://www.ipcc.ch/site/assets/uplo..._report_LR.pdf ↵

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9.3: Solar and Wind

Solar Energy

We use **solar energy** to grow food of course, and for some industrial processes (like concentrating lithium brines), and to passively heat buildings, but early in the 21st century the most important and fastest growing use of solar energy is for generating electricity. Solar energy is abundant. The amount of sunlight energy received on Earth is approximately 10,000 times the amount of energy consumed by humans in 2005.[1] As shown on Figure 9.3.1, solar potential is greatest in sub-tropical regions, but it is also significantly affected by weather conditions, and is highest in drier climates. That is why the dry central region of southern Canada, for example, has much greater solar potential than the wetter and cloudier west coast, even at the same latitude.

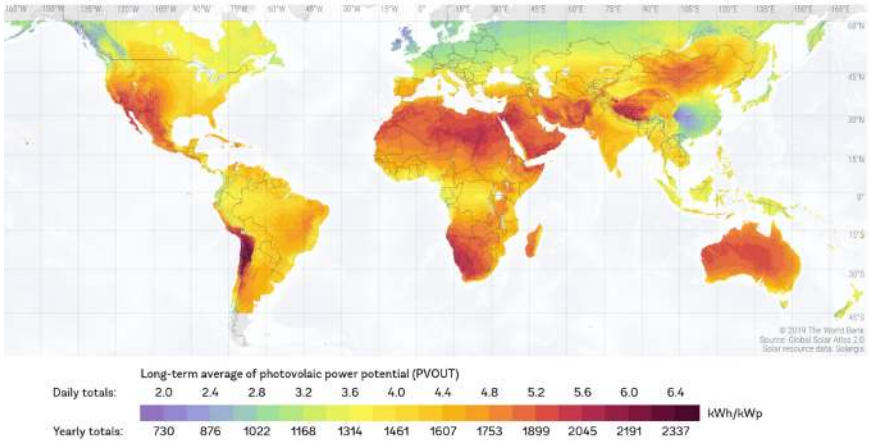


Figure 9.3.1: Global Solar Energy Potential

There are two main ways to generate electricity from the sun. One is through heat, the other through photovoltaic cells. The Crescent Dunes facility in Nevada is an example of solar heat electricity generation (Figure 9.3.2). This facility has 10,347 movable mirrors that reflect sunlight onto a tower in the center of the complex. The highly concentrated sunlight is used to heat molten salt that powers a steam turbine to generate electricity. The hot molten salt retains enough heat to continue producing electricity for 9 hours after sundown, and therefore the plant can operate through the high electricity-demand period in the evenings. The Crescent Dunes station operated from 2016 to 2019 but is currently shut down because of technical issues with the molten salt container.[2] Solar thermal energy has the disadvantage of relatively high capital and operating costs, such that the electricity production cost at most existing plants is currently higher than for some other sources, including photo-voltaic solar. But it has the advantage of short-term energy storage, which allows for energy production into the evening when it's need most and that could outweigh higher production cost in areas where there are time-of-day premiums on the value of electricity.

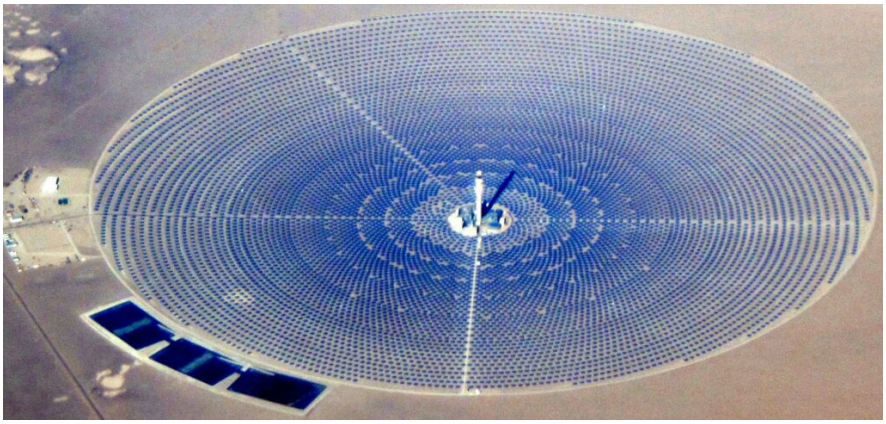


Figure 9.3.2: Crescent Dunes Thermal Solar Plant Near to Tonopah, Nevada

Photo voltaic solar (or PV) is based on the use of cells that convert sunlight directly to electricity. Solar PV is easily scalable, from several modules on a single roof (Figure 9.3.3) to thousands of modules at a utility-scale facility (Figure 9.3.4). The efficiency of

solar PV technology has increased significantly over the past several decades. Commercially available modules have evolved from about 10% efficiency in the 1970s to about 20% efficiency in the early 2020s. Experimental solar cells are now operating at about 40% efficiency—meaning that 40% of the sun's energy that strikes them is converted into electricity. While efficiency has gone up over that period, costs have come down dramatically. According to the International Energy Agency the average cost of solar PV modules has dropped from over $100/watt in 1975, to $10/W in 1987, to $1/W in 2015, and to $0.2/W in 2020.[3]



Figure 9.3.3: Installing Solar Modules on a Roof



Figure 9.3.4: A Commercial Solar PV Installation in Greece

Solar PV modules (and thermal solar) do not generate electricity all of the time, certainly not when the sun is down, and not that well under cloudy conditions. In areas with a reasonably good solar resource the capacity of solar modules is about 20% of the rated wattage. In other words, 100 modules rated at 250 watts (25 kW) should produce electricity at an average rate of 5 kW or should generate 43,800 kWh of energy over the course of a year, which is about enough to power 4 houses in North America, more than that in Europe.

According to the International Renewable Energy Agency solar represented 23% of the world's renewable energy supply in 2019, and that proportion is growing. The increasing efficiency and decreasing cost of solar PV modules has made it a viable option for a large part of the energy supply in a world without fossil fuels. The US National Renewable Energy Lab has estimated that a national grid with 55% solar and wind sources—both of which are intermittent—could be viable if the remaining power sources can be ramped up and down to even out the supply. Energy storage (such as pumped hydro or batteries) could also help to make this a reality.

A typical solar PV module, like those shown on Figure 9.3.3, contains about 76% glass (by weight), 10% plastic, 8% aluminum (in the frame), 5% silicon and 1% other metals (as wires and connectors). It takes energy to make these components and assemble them, but the amount of embodied energy is small compared with the amount of energy that can be produced by the module. The energy output of a solar module depends significantly on the region and the setting in which it is installed, but a modern well situated solar module should recover its energy costs in approximately one year,[4] and the module should last for at least 25 years.

Furthermore, many parts of a solar module are easily recyclable (or re-usable) including the glass and the metal frame. The silicon in the cells can also be melted for re-use. Even though the modules can be recycled, a significant increase in the use of solar-PV energy (which is what we need) will require more mining to supply the raw materials.

Wind Energy

Wind is a product of solar energy and gravity because air masses move in response to differences in air density created by solar heating. **Wind energy** has been used for centuries to turn windmills and to power sailing vessels, but it's only in the past few decades that wind has been used to generate electricity. As shown on Figure 9.3.5, wind is geographically variable as an energy resource. Average wind speeds are higher on the oceans than on land, and consistently higher in flat areas compared with mountainous areas. In North America the best wind resources are in eastern coast offshore, especially north from Virginia, and in western coast offshore areas, from California north, within the Great Lakes and Hudson Bay, and within the plains in both the US and Canada. Mountain ridges also have consistently strong winds.

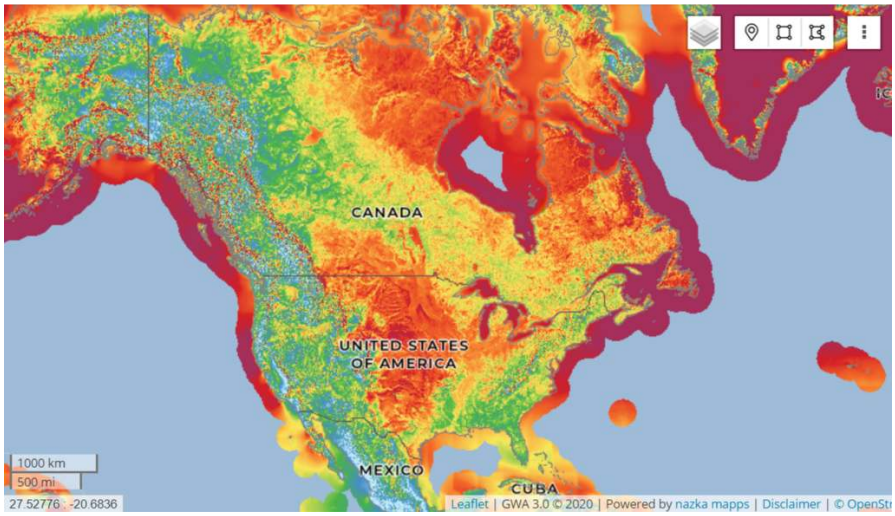


Figure 9.3.5: Typical Wind Speeds at 100 m Elevation Within and Around North America

Most utility-scale wind turbines are of the horizontal axis type, mounted on a tall tower. Over the past 30 years the power potential of wind turbines has increased by a factor of nearly 30 times (Figure 9.3.5) and the towers have become very tall. Of course, a 10 MW wind turbine doesn't generate power at 10 MW all the time. The typical capacity factors for land-based turbines are in the order of 30%, while offshore turbines are higher, at around 40%. The tall 10 MW and higher turbines being installed in offshore locations in the mid-2020s are likely to have even higher capacity factors because wind consistency increases with elevation. Most existing offshore turbines are embedded in the sea floor in areas with water depths of less than 50 m. Floating turbines have been developed for use in areas with deeper water. A single 10 MW offshore turbine operating at 50% capacity can generate enough electricity to power about 4,000 homes in North America.

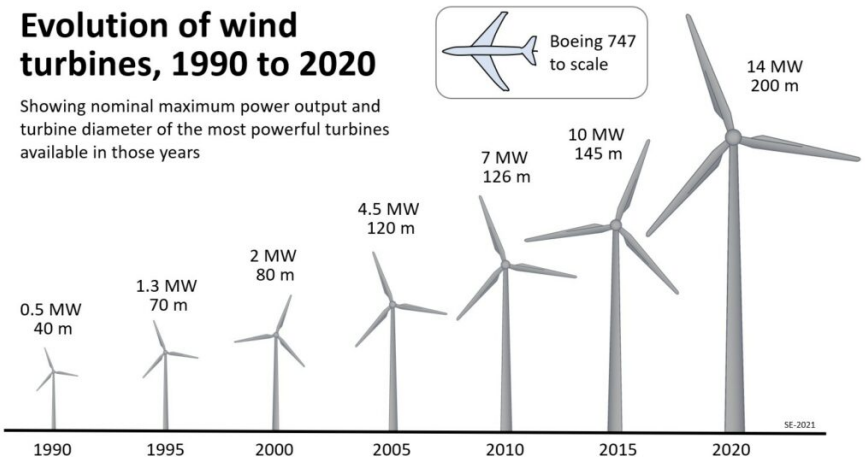


Figure 9.3.6: Highest Rated Wind Turbines Available at Various Times Between 1990 and 2020

According to the International Renewable Energy Agency wind energy makes up about 25% of installed renewable energy. Based on data from 2019, China and the US have the highest installed wind generation capacity, but Denmark has the highest proportion of wind-generated electricity, at 48%, followed by Ireland (33%), Portugal (27%), Germany (26%), the UK (22% – see Figure 9.3.6) and Spain (20%).[5]



Figure 9.3.7: An Offshore Wind Farm Under Construction in the UK in 2011. These turbines are rated at 3.5 MW.

Modern wind turbines are large and complex, and their manufacture and installation require a lot of materials and energy. For example, a typical 3 MW turbine, similar to the ones on Figure 9.3.7, includes about 1100 tons of concrete for the base on the sea floor (or on land), 276 tons of steel, for the base the tower and the nacelle (the housing that holds the generating mechanism, and to which the blades are attached), 2.6 tons of copper and 2.3 tons of aluminum, and 20 tons of fiberglass and epoxy resin for the blades.[6] As for solar modules, the energy payback of a turbine will depend on the features of the location selected, but it is typically less than one year, compared with an expected lifetime of at least 20 years. Much of this material can be recycled when the turbine is decommissioned.

Every year thousands of birds (and bats) are killed by wind turbines, although the rate of bird-kill is decreasing because the newer larger turbines spin slower than older models, and because a range of strategies are being developed to decrease the risk. To put this in perspective, millions of birds are killed each year by power lines, moving vehicles and tall buildings, and the total number from all these sources of mortality is dwarfed by the number killed by domestic cats.

Solar and wind power are currently the cheapest forms of electricity generation according to the US Energy Information Administration. The average leveled cost of solar is $0.30 per kWh, while that for onshore wind is $0.37 per kWh. All other forms of electricity generation are more expensive, including gas, coal, hydro and nuclear.[7] While most other energy forms are likely to become more expensive in coming years, solar and wind are likely to get cheaper because of technological improvements and economies of scale.

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1. Smil, V. (2005). Energy at the crossroads (presentation). OECD Global Science Forum Conference on Scientific Challenges for Energy Research. http://vaclavsmil.com/wp-content/upl...-2006-oecd.pdf ↵
2. Wikipedia contributors. (2021, November 7). Crescent dunes solar energy project. *Wikipedia*, https://en.Wikipedia.org/w/index.php...did=1054066143 ↵
3. IEA. (n.d.). Evolution of solar PV module cost by data source, 1970-2020 (last updated June 30, 2020). International Energy Agency. https://www.iea.org/data-and-statist...urce-1970-2020 ↵
4. Louwen, A., van Sark, W., Faaij, A. et al. (2016). Re-assessment of net energy production and greenhouse gas emissions avoidance after 40 years of photovoltaics development. *Nature Communications 7*(13728). https://doi.org/10.1038/ncomms13728 ↵
5. US Department of Energy. (2019). Approximate wind energy penetration in leading wind markets in 2019, by select country. Statista. https://www.statista.com/statistics/...on-by-country/ ↵
6. Crawford, R. (2009). Life cycle energy and greenhouse gas emissions analysis of wind turbines and the effect of size on energy yield. *Renewable and Sustainable Energy Reviews, 13(9)*, 2653-2660. https://doi.org/10.1016/j.rser.2009.07.008 ↵
7. US Energy Information Administration. (2021). Levelized costs of new generation resources in the *Annual Energy Outlook 2021*. https://www.eia.gov/outlooks/aeo/pdf...generation.pdf ↵

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9.4: Hydroelectric Power

Hydroelectric power is a product of solar energy because water, evaporated by the sun, falls onto land at elevation, and then flows down to the ocean. If we interrupt that flow, we can use its potential energy to generate electricity. Hydroelectric power is particularly effective in areas where there has been tectonic uplift to create mountains, and where there is abundant precipitation in the form or rain or snow.

There are two main types of hydroelectric facilities, those that involve construction of dams, and those that involve diversion of part of the water of a stream into a canal and/or a pipe. We'll refer to the first type as "dam and reservoir hydro", and to the second type as "run-of-river hydro".

Hydroelectricity is a very mature industry that goes back to the late 19th century. It currently represents 47% of the installed global renewable energy capacity (and 6.5% of all energy capacity), but the rate of growth is now very close to 0%. Although there have been many enhancements to the technology in the past 100 years, it's not likely that we will see significant technological advances in the future, and while there are many rivers that have hydro potential, the public appetite for changing how rivers flow, just to generate electricity, is waning.

Dam and Reservoir Hydroelectric Power

Most large hydro projects involve construction of a dam across a river and the creation of a reservoir behind that dam. The difference in elevation between the surface of the reservoir and that of the river below the dam is the hydraulic head, and the amount of energy that can be generated is proportional to that difference and to the rate at which water can flow through the turbines. An example is the Revelstoke Dam on the Columbia River in British Columbia (Figure 9.4.1). The Revelstoke Dam is 175 m high. It has created a reservoir (Lake Revelstoke) that is 130 km long and has flooded just over 100 km^2 of land. The electricity production capacity at Revelstoke Dam is 2,480 MW.

The significant value of a dam and reservoir is that a lot of water is stored (except under long-term drought conditions), and that water can be used to generate electricity according to the demand. The rate of flow through the turbines can be slowed (or even stopped) during the night (or over the summer) when demand is low and increased in the daytime (or during the winter) when the demand is higher. This type of production flexibility is especially valuable in areas where there is a significant proportion of non-dispatchable electricity generation from sources like solar and wind.

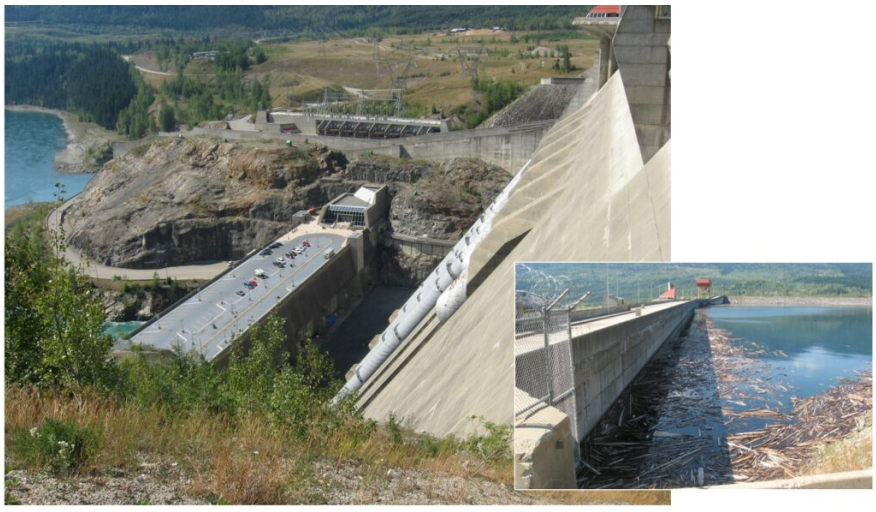


Figure 9.4.1: The Revelstoke Dam on the Columbia River, British Columbia. Water flows through the large pipes (penstocks) to turbines that are within the structure in the center, and then out into the river below. The inset shows part of the reservoir (Lake Revelstoke) on the upper side of the dam.

Two significant disadvantages of dam and reservoir hydro are that they block passage of migratory fish, and that they result in the flooding of large areas of land that was useful for other purposes or for nature. It's true that fish ladders can be constructed, but they are not typically successful in the case of a high dam like the one at Revelstoke. Flooding of land is inevitable when dams are constructed, and the implications of that include:

- loss of human habitat (e.g., construction of the Three Gorges Dam in China, the world's single largest hydro project, resulted in relocation of 1.24 million residents from 13 cities, 140 towns and 1350 villages),
- loss of farmland (which is a big issue for the Site C dam under construction in British Columbia),
- loss of natural terrestrial and aquatic (river) habitat,
- increased risk of slope failure and bank erosion,
- potential for release of mercury naturally present in soils[1], and
- potential for release of carbon dioxide from breakdown of organic matter (this is most likely to be an issue in tropical areas and where the reservoir is shallow).

Run-of-River Hydro

A run-of-river hydro installation is illustrated on Figure 9.4.2. Sechelt Creek flows into a coastal inlet about 60 km northwest of Vancouver. The three parts of the project are the head pond, at an elevation of 360 m, where a weir has been built to ensure that the upper end of the penstock is always submerged. Water flows from there through a 4-km long 1.2 m diameter steel pipe (penstock) to the powerhouse, where it is used to turn either one or both of two 8 MW turbine generators. This project did not involve flooding any land (the head pond is entirely within the river's normal channel) and it has not disrupted the passage or habitat of migratory fish. (A waterfall just upstream from the powerhouse has always prevented ocean fish from migrating to the middle and upper parts of Sechelt Creek.)



Figure 9.4.2: Components of a Run of River Hydro Project at Sechelt Creek, British Columbia. Left: the weir and head pond (at 360 m elevation); center: part of the penstock; right: one of two 8 MW turbines at 10 m elevation.

Water is not stored in a reservoir in the case of run-of-river hydro, instead the generation of electricity is dependent on the discharge of water at any one time. Over the course of a year the discharge of a stream like Sechelt Creek can vary significantly from season to season and even from day to day.

Two examples of river discharge variations are provided on Figure 9.4.3. The Qualicum River is situated in a coastal area of Vancouver Island where although the surrounding mountains are frozen and snow-covered over the winter, the lowland areas tend to remain unfrozen, and rain is common. The hydrograph is dominated by rainfall in the fall, winter and early spring months, and very little precipitation from June through later September. The Stikine River drains a region in northern BC in a mountainous area that remains frozen through the winter and there is almost no melting between December and April. The hydrograph is characterized by very low flows during the cold months, and very strong snowmelt and rain-driven flows in the spring, summer and early fall.

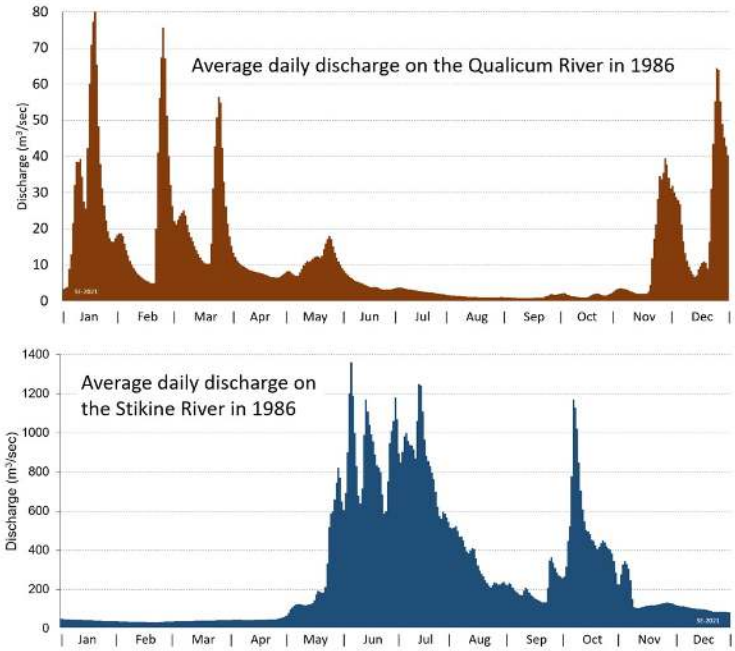


Figure 9.4.3: 1986 Variations in Daily Discharge on the Qualicum River (Vancouver Island) and the Stikine River (Northern Interior, BC)

The significant differences in the flow patterns of the Qualicum and Stikine Rivers illustrates the importance of understanding supply and demand when it comes to run-of-river generation. Sechelt Creek has a hydrograph similar to that of the Qualicum River, and so it can typically generate electricity at peak power in the period from November through June but produces little or no power over the summer months. This fits well with the electrical power demand in British Columbia, which is greatest in winter, but a river like the Stikine would not be very suitable for run-of-river generation in British Columbia because it has relatively little flow in the winter months.

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1. Small amounts of mercury are naturally present in an oxidized form in soil. When an area is flooded the resulting less-oxidizing conditions at the bottom of the reservoir promote the conversion of some of that mercury to a soluble form which then gets into the water and is dispersed downstream. This mercury has health implications for aquatic species, and also for those who depend on aquatic species (especially fish) as a food source. ↵

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9.5: Wave and Tidal Energy

Waves are generated by wind blowing over water, so this form of energy originates from the sun. On the other hand, tides are related to rotation in the sun-Moon-Earth system and from the resulting variations in the gravitational force on Earth. That energy comes from the original angular momentum (spin) of the solar-system and the galaxy, and can possibly be traced right back to the Big Bang.[1]

Wave Energy

At most exposed coastal locations there will be some wave action, even if there is little or no wind at that time. In general, wave energy is greatest in the areas of greatest wind energy. While waves are driven by the wind, they tend to be somewhat more reliable than the wind as a source of energy.

Several different wave energy devices have been designed and tested over the past several decades. They include shore-based systems, sea-floor tethered systems, and anchored floating systems that bend as waves pass. Some of these are illustrated on Figure 9.5.1. All of them have cylinders that are compressed and then relaxed every time a wave goes by, and the pressure created by that is converted into electricity.

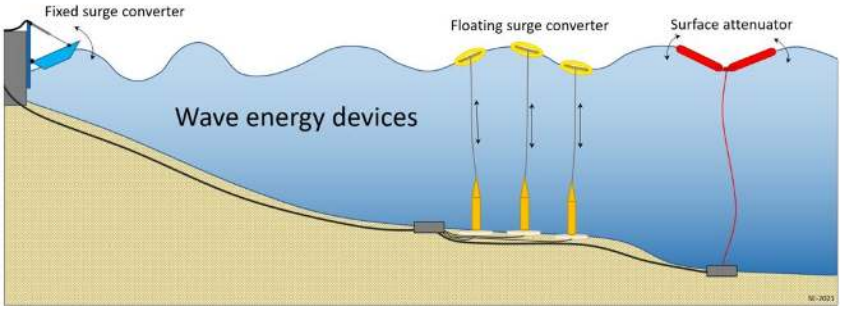


Figure 9.5.1: Three Different Wave Energy Systems

Although all three of these types of systems have been demonstrated in the past, at present (spring 2021) the only operating and grid-connected wave energy installations are of the fixed-surge type, and those are small, with power ratings in the kilowatts, not megawatts.

Tidal Energy

The **tides** are generated by variations in the geometry of the sun-Earth-Moon system and the effect that those have on the level of the surface of the ocean. In most areas there are two high tides and two low tides every day (known as semidiurnal tides), although a few regions have only one high and one low per day (diurnal tides). The range between high and low tides is highly variable from place to place. The world's highest tide range are in the order of 16 m difference between low and high tides in the Bay of Fundy between Nova Scotia and New Brunswick. On the other hand, many regions have tidal ranges of less than 1 m. Some examples of differing tidal ranges are shown on Figure 9.5.2.

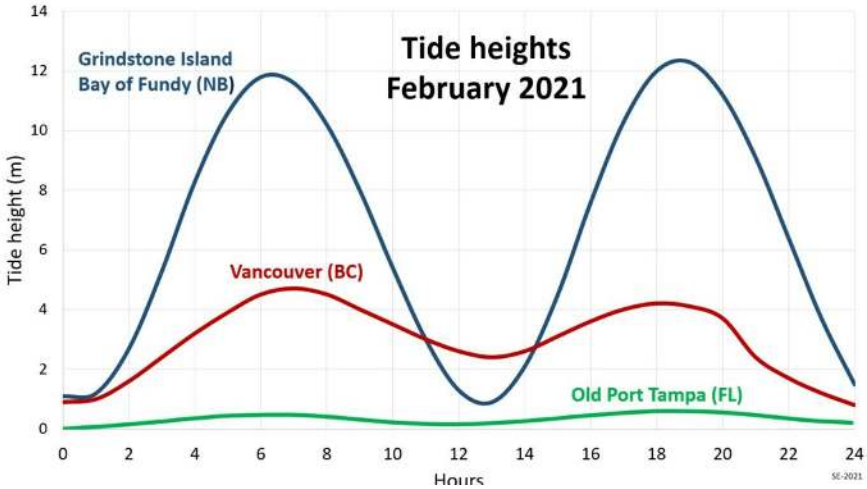


Figure 9.5.2: Typical Tidal Ranges at Three Stations, Old Port Tampa (Florida), Vancouver, British Columbia, and Grindstone Island, New Brunswick, February 2021

There are several ways to convert tidal energy into electrical energy, but the two most explored methods include the construction of a barrage (a dam) across a tidal estuary, and the installation of underwater turbines within channels that have significant tidal flow. The barrage method has been proven to be effective, but it can have serious environmental implications because a barrage results in changes to water-level fluctuations, salinity and turbidity in tidal flat areas, most of which are of great ecological importance. A tidal barrage is shown on Figure 9.5.3. The barrage acts like a dam, and the flow of both incoming and outgoing tides can be converted to electricity using turbines installed within the structure. There are three significant operating barrage tidal installations at present, including Sihwa Lake (South Korea, 254 MW, operating since 2011), La Rance River (France, 240 MW, operating since 1966) and Annapolis Royal (Nova Scotia, 20 MW, operated from to 1984 to 2019). Others have been proposed, but as of 2021, none is under construction.



Figure 9.5.3: Part of the Sihwa Lake Tidal Barrage in South Korea, completed in 2011 and Rated at 254 MW



Figure 9.5.4: A Single-Rotor Seaflow Tidal Stream Generator, With the Turbine in the Raised Position

The other main type of tidal system is a tidal stream turbine that is typically installed in a location with strong tidal currents. An example is shown on Figure 9.5.4. Most such devices are either embedded in, or resting on, the sea floor, although some are buoyant and are anchored to the sea floor. Based on information available in 2021, only one tidal stream is currently in operation, and that is the MeyGen project on the north coast of Scotland, which has four 1.5 MW sea-floor turbines connected to the grid, with more turbines reportedly to be under construction.

The potential for tidal energy is huge, but the engineering and environmental challenges are significant, and the high capital cost has been a barrier to implementation of many planned projects.

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1. Commissariat, T. (2011). Was the universe born spinning? Cosmology Research Update. *Physics World*. https://physicsworld.com/a/was-the-u...born-spinning/ ↵

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9.6: Geothermal Energy

Geothermal energy is heat that originates within the Earth—which includes heat left over from the original formation of the Earth and heat produced by radioactive decay—and is either naturally present at surface or is accessed at depth by drilling. We can harness this energy where there is higher than average heat flow from depth, and this is most common in areas near to active volcanoes. About 50% of all geothermal energy use is for heating buildings and other infrastructure, about 33% for hot pools and spas (Figure 9.6.1), while only about 17% is used to generate electricity. In many cases the left-over heat from electrical generation facilities is used for district heating or for swimming and bathing facilities.



Figure 9.6.1: The Geothermal Pool at Fludir, Iceland

A geo-exchange system (a.k.a. geothermal heat pump, or ground-source heat pump) is not based on geothermal energy at all. Instead, geo-exchange relies on the relatively constant temperature of the ground at depths between about 1 and 5 m, and that temperature is maintained by energy from the sun. Geo-exchange is used for either heating or cooling, or both.

In the context of generating electricity, geothermal heat is used to boil water or some other fluid to power a turbine. In the case of very hot sources, water piped to surface from depth will spontaneously convert to steam because of the reduction in pressure. If the water from depth is less than about 180° C it won't spontaneously boil but can be used in a binary cycle system to heat a working fluid, such as pentene or toluene, that will boil at a lower temperature than water.

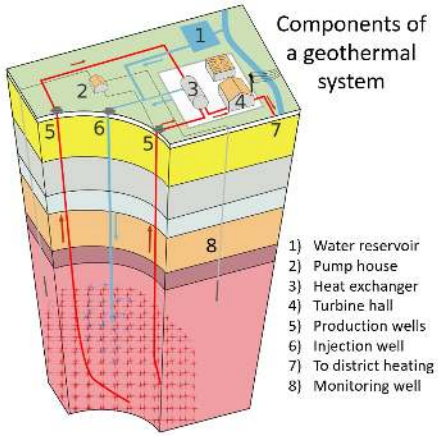


Figure 9.6.2: The Components of a Typical Binary Cycle Geothermal System

The components of a typical geothermal system are illustrated on Figure 9.6.2. The heat at depth (hundreds to a few thousand meters) is accessed via deep production wells. Water from within that rock (5) is pumped to surface and its heat is used to boil the working fluid to power the turbines (4). The original water is returned to the ground via an injection well (6) along with any additional surface water needed to maintain volume (1). Most geothermal plants have numerous production wells (dozens in some cases). It is common for wells to be cycled on and off to allow for recovery of the heat reservoir around them.

The Krafla power station in northern Iceland (Figure 9.6.3) is a 60 MW flash steam system (the hot water from depth boils at surface). It is situated in a very active volcanic region on the mid-Atlantic spreading ridge. An eruption episode that lasted from 1975 to 1984 almost led to cancellation of the project while it was under construction.



Figure 9.6.3: The Krafla Geothermal Plant in Iceland

The contribution of geothermal to total electricity production is important in some countries, especially in Iceland, where 30% of electricity is generated by geothermal (with most of the rest coming from hydro), and the Philippines, at 27%, and El Salvador at 25%. In Costa Rica, Kenya and Nicaragua and New Zealand geothermal makes up 14, 11, 10 and 10% of electrical energy.[1] These are all countries with active volcanoes and hence significantly high heat flow.

In the past 10 years global geothermal energy capacity has grown by an average of 3.75% per year. That is significant growth, although lower than for wind and solar, both of which have grown by an average of 20% per year in this century. But the potential for sustained growth is limited by the limited geothermal resource, and by the high capital cost of geothermal facilities.

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1. International Renewable Energy Agency, https://www.irena.org/ ↵

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9.7: Nuclear Energy

Nuclear energy is the energy that is stored in the nuclei of atoms; it comes in two types. Fission energy is released when large atoms like uranium split apart into smaller atoms. This is constantly taking place within the Earth—and it is part of the source of geothermal energy—and all around us, but the rate is very slow. We can build devices that increase that rate enough to generate heat in a controlled way, but there are some downsides to the technology.

Fusion energy is released when small atoms like hydrogen are fused together to make larger atoms which is what is what is happening inside the sun. We can reproduce nuclear fusion here on Earth in in the form of a hydrogen bomb, but that technology doesn't allow for a controlled rate of energy release. Over the past several decades governments of several countries have spent tens of billions on research into controllable nuclear fusion. The existence of the fusion energy industry is likely several decades away.

Nuclear Fission

Nuclear fission has been used for generating electricity since the late 1950s and there are currently around 440 fission reactors operating in 30 countries, producing about 10% of the world's electricity. In a few countries, including France, Slovakia and Ukraine nuclear fission makes up more than 50% of electricity generation[1].

While naturally occurring uranium in rock splits apart only very slowly, the rate of fission is accelerated many thousands of times in a fission reactor because the uranium is highly concentrated, and the fuel is packed close enough together so that the neutrons released by one fission event will almost immediately trigger another fission in a nuclear chain reaction. An important point is that the chain reaction process must be carefully controlled by substances called moderators and, in the event of some irregularity, the reaction can be slowed relatively quickly by inserting control rods that inhibit the chain reaction process. It is important to realize that although a fission reactor can be dramatically slowed by inserting the control rods, the massive reactor core will remain very hot for several days. This residual heat has been the cause of several nuclear accidents. A diagram of a type of fission reactor is provided on Figure 9.7.1, and the important components are described.

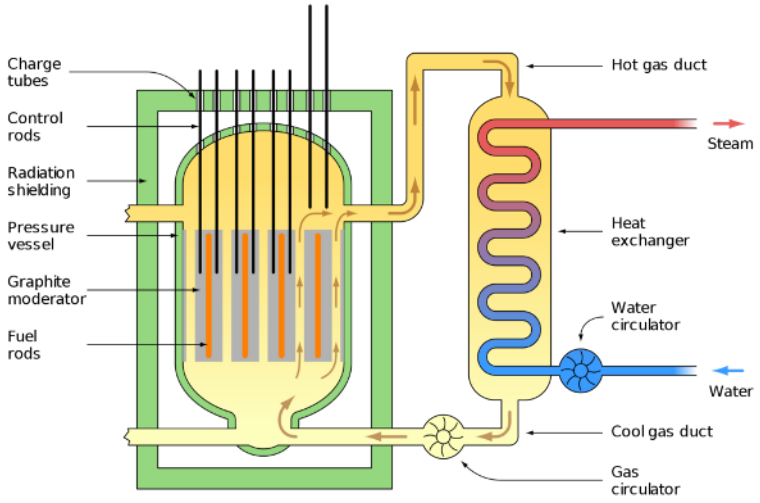


Figure 9.7.1: The Components of a Gas-Cooled Nuclear Fission Reactor. The uranium fuel elements are shown in orange. The graphite moderator, which keeps the reaction from getting out of control, is grey. The control rods that can be used to dramatically slow the chain reaction are black. Heat generated by the fission in the fuel is heats a gas which is circulated through a heat exchanger to boil water that is then used to run a steam turbine.

Modern nuclear reactors have many levels of protection against irregular operating conditions and against more significant failure and out-of-control behavior. While that might give us some comfort, there have been some major failures in the nuclear power industry, at least one of which has had significant human and environmental implications.

Nuclear Power Plant Failures

Three significant nuclear plant failures—Three Mile Island (Pennsylvania), Chernobyl (Ukraine) and Fukushima (Japan)—have shaped the public's perception of the safety of the nuclear industry and have also informed the industry's efforts to make nuclear reactors as safe as possible.

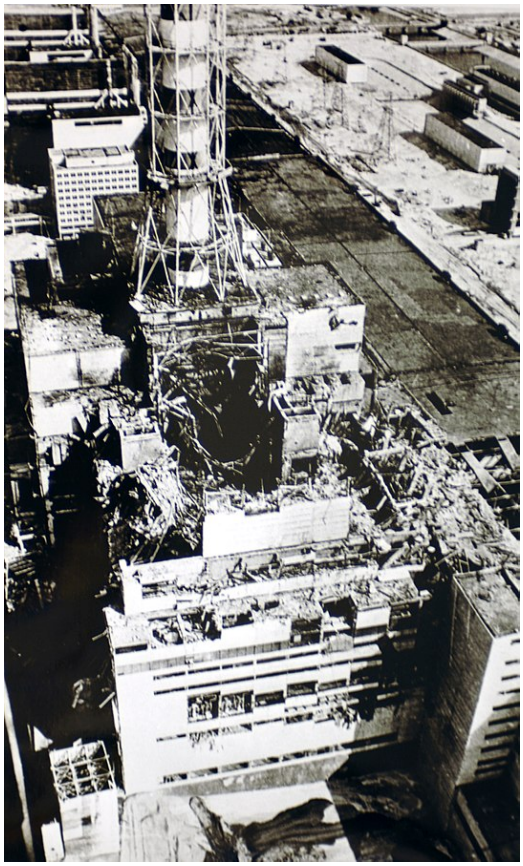


Figure 9.7.2: The Chernobyl Nuclear Fission Reactor Following the Accident in 1986

The Three Mile Island accident in March 1979 involved an operator error, the failure of a cooling system valve and the failure of the system that was meant to warn the operators of the valve's malfunction. This led to a loss of coolant within the reactor vessel and resulted in partial melting of the nuclear fuel. There were high levels of radioactivity within the plant, and some radioactive materials were released into the environment via steam. Health officials eventually concluded that there were no deaths or significant illnesses that could be attributed to the accident, however that conclusion was controversial at the time, and remains so in the minds of many people.

The Chernobyl accident of April 1986 also involved an operator error and a system failure that resulted in the reactor power level increasing when it should have been decreasing (Figure 9.7.2). This led to a steam explosion that ruptured the reactor core and triggered an open-air reactor fire that continued for 9 days, releasing airborne radioactive material into the environment. A total of 28 plant workers and firefighters died within several days of the accident.[2] A 2006 United Nations report concluded that as many as 4000 cancer deaths are likely to occur amongst 5 million residents in the contaminated region around the plant over the 80 years following the accident, and that this represents a 0.3% increase over expected cancer deaths for that region.[3]

The Fukushima accident of March 2011 was the direct result of a magnitude 9 earthquake and a subsequent tsunami. Although none of the reactors was damaged by the earthquake, they were automatically shut down when the earthquake struck and therefore could not provide power to the cooling systems. Six external power supply systems failed because of the earthquake and although an emergency diesel power plant continued to supply power to cooling pumps, this was destroyed 50 minutes later by the 15-meter-high tsunami that overtopped protective barriers and inundated the plant. The result was that there was no cooling available for the still-hot reactors, three of which suffered melting within the reactor cores. No deaths have been attributed to the Fukushima

accident, and although it is estimated that approximately 130 deaths may eventually occur because of elevated cancer rates, that number is small compared with the number of expected cancer deaths from other causes.

Refueling of Reactors and Waste Storage

In a typical reactor the fuel elements will last for 18 months to a few years. Some types of reactors can be refueled while still operating, but most must be shut down for periods of up to several weeks. The spent fuel is removed and replaced with fresh fuel. The highly radioactive spent fuel is stored in swimming-pool sized tanks at the reactor site for about 5 years, and then is transferred to dry storage facilities, which are also on-site in most cases. On-surface storage of nuclear waste is not a viable option because the materials remain radioactive for thousands of years and represent both a health risk and security risk (from the perspective of nuclear proliferation). Several countries, including Canada and the United States, have conducted research into the deep underground storage of nuclear waste, but as of 2021, only Finland has an operating long-term storage facility.

Although the waste from nuclear fission is a serious problem, the volumes are not huge. The amount of radioactive waste produced for a person who used nuclear energy for their lifetime supply of electricity is about 3 kg. Nuclear fuel is quite heavy, so that amount would likely fit within a coffee cup.

Nuclear Fusion

Nuclear fusion can be achieved when hydrogen nuclei are forced close enough together to allow them to fuse together. The advantage of nuclear fusion for electricity generation is that its fuel (hydrogen) is abundantly available, and it doesn't produce significant amounts of toxic or radioactive waste. Nuclear fusion has the potential to produce energy from fuel that is virtually inexhaustible, without producing a significant amount of waste, but the process of achieving it is extremely complex, requires large amounts of energy to initiate the process, and extremely high temperatures (in the order of 100,000,000° C). These conditions, and the existence of lots of fast-moving neutrons, have possible implications for the mechanism that are still poorly understood.

While nuclear fusion could provide abundant energy without significant waste products or climate implications, its development has been and will continue to be extremely expensive, and its realization is still decades away.

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1. World Nuclear Association, https://www.world-nuclear.org/ ↵
2. Wikipedia contributors. (2021, November 14). Chernobyl disaster. *Wikipedia* (accessed November 15, 2021), https://en.Wikipedia.org/wiki/Cherno...iate_aftermath ↵
3. *The Chernobyl Forum: 2003–2005. (2006). Chernobyl's legacy, health, environmental and socio-economic impacts* (second revised version). World Health Organization. https://www.who.int/publications/m/i...on-and-ukraine ↵

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CHAPTER OVERVIEW

10: Waste Disposal



This chapter aims to first describe the types of waste produced. Once that is established, understanding how to dispose of that waste is addressed. Information presented earlier in the text about Earth's materials (like clays) and processes (like those involving groundwater) helps in understanding this topic.

10.1: Waste Production
10.2: Dumps and Landfills

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10.1: Waste Production

Amounts of Waste Produced

Waste production varies significantly from country to country, and from place to place within a country, both in terms of volume and type. As shown on Figure 10.1.1, Americans and Canadians are the most wasteful people on the planet, followed closely by Australians (and New Zealanders), South Africans, and Europeans. Each American produced an average of over 900 kg of waste in 2018, or about 2.5 kg/day. In contrast Indians produced just over 100 kg in 2018 (or about 290 g/day), and it is likely that less of it was plastic, metal or complex electronic waste than is the case in North America.

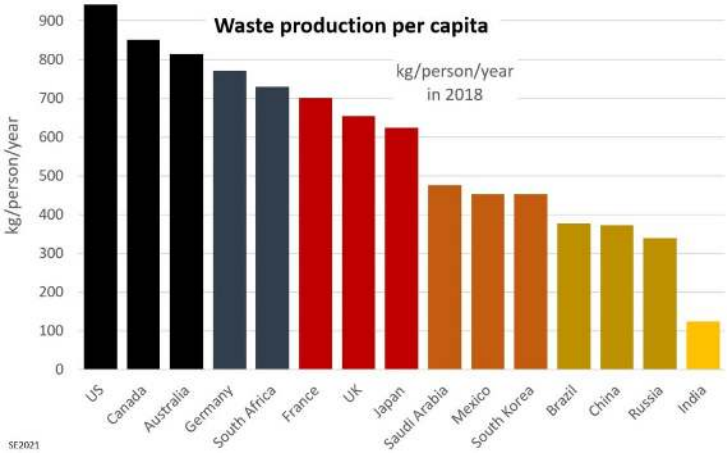


Figure 10.1.1: Production of Landfill Waste per Person per Year in Selected Countries

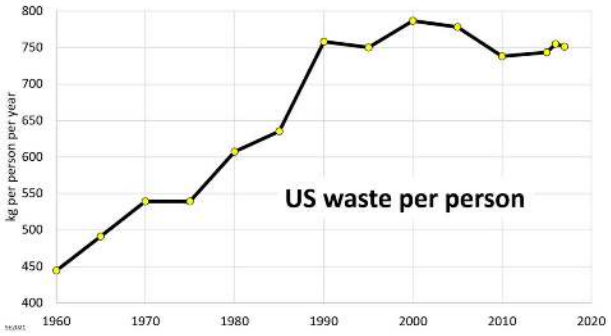


Figure 10.1.2: Per-Capita Rate of Waste Production in the United States, 1960 to 2017

Waste production per person in the United States has increased significantly over the past several decades, but the rate of increase has slowed since 1990, and the trend appears to have been slightly downward since 2000 (Figure 10.1.2). We'll see later why that is happening; it's not because we are consuming less stuff!

Types of Waste Produced

Approximately every five years the municipal government of the Victoria region, British Columbia, carries out a painstaking audit of what gets brought to the regional landfill, separating what comes from households, commercial operations, institutions, and building sites and dividing the waste from each stream into about 90 different types, and then carefully weighing each pile of waste. Some of the results from the audit completed in 2016[1] are shown on Figure 10.1.3, which represents household wastes (comprising 38% of the material brought to the landfill). Residents of the Victoria area produce less waste than most Canadians, averaging 357 kg per person per year.



Figure 10.1.3: Proportions of Household Waste Delivered to the Victoria (BC) Landfill in 2016

Review the graph above and notice the different types of waste.

The Victoria landfill also accepts waste from commercial, industrial and institutional entities, and from construction and demolition companies. The proportions for those two types of sources are summarized on Figure 10.1.4.

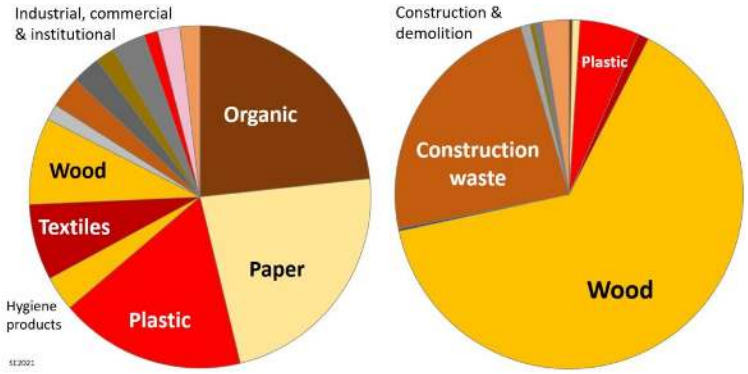


Figure 10.1.4: Proportions of Industrial, Commercial and Institutional, and Construction and Demolition Waste Delivered to the Victoria Landfill in 2016. Colors are the same as in Figure 10.1.3.

The waste stream from the industrial, commercial and institutional sector (which represents 41% of the landfill's intake) is not very different than that from the household sector, except that the proportion of food is lower and that of paper, plastic and wood are a little higher. The waste stream from the construction and demolition sector (16% of the total intake) is understandably different, with a great deal more wood waste, and general "construction waste", which is dominated by shingles and other roofing, and insulation.

Waste Reduction by Diversion

In the 1960s and 1970s only about 7% of waste in the US was diverted (recycled) away from the regular waste stream (Figure 10.1.5), but the rate of diversion climbed steeply from 1980 to 2010, which explains why our rate of production of landfill waste (Figure 10.1.2) is leveling off. The rate of diversion appears to have nearly plateaued at around 35%. The important, and rather alarming point here, is that although the amount of waste that is being sent to landfills has plateaued since 1990, the amount of stuff that gets thrown out is still increasing, because more is being sent for recycling. We can take some comfort in the fact that most of the waste sent to recycling is not ending up in landfills.

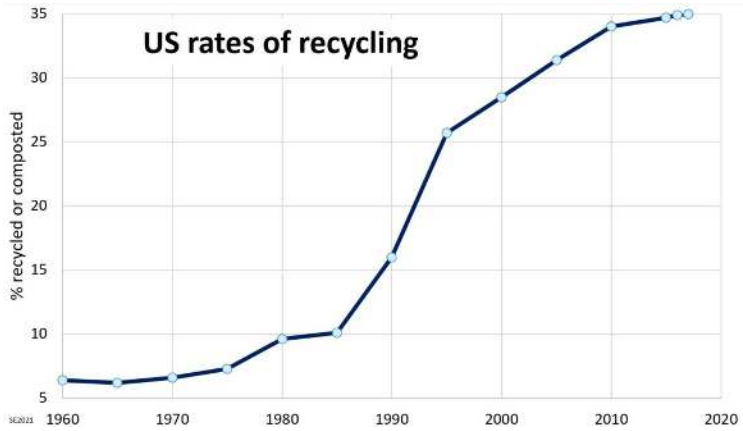


Figure 10.1.5: Trend in the Rate of Recycling in the United States, 1960 to 2017

From the preceding description it is evident that there are several ways to reduce the amount of waste going to our landfills. The first and most obvious is to divert organic matter (through household composting and curbside green-bin programs). If Victoria is a representative example, 29% of household waste can be diverted from landfills in this way. This is happening in Victoria, and in many other cities and towns across Canada, but is not as common in the US, though it is gaining in popularity in places like California as of 2024. The second is to improve paper recycling. Soiled paper (with food residue for example) can by composted, while most other paper can be recycled and turned into other products. Based on the analysis done in Victoria, it should be possible to divert 80% of paper from the landfill, and that represents 12% of the waste stream. Plastic is the third major category in Victoria, and since just under half of this is recyclable, it represents a potential of about 8% diversion. Very little of the material in the hygiene category (14.7%) can be recycled or diverted from the landfill, although some could be avoided with changes in behavior (e.g., re-usable diapers). Most of the textile items (7%) might have been reusable through donation, while others might be recyclable in some jurisdictions. Of the remaining items, some are readily recyclable, including wood (4%), glass (3%) and metal (3%).

If we add up the percentages of categories that could be diverted from landfills (based on the information from Victoria), we get a value that is close to 60% (29+12+7+4+3+3 = 58). There are many ways that we could improve on that by changing the way we do things.

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10.2: Dumps and Landfills

Dumps

A **dump** is a place where waste is discarded. There is little or no control over what is dumped, and by whom, and there are no mechanisms or procedures in place to ensure that the waste doesn't contaminate the surrounding land, water and air. Waste in a dump is available to scavengers to consume or carry away, it can be scattered by the wind, or it can be washed away by water. Water that flows through the waste and becomes contaminated can drain off-site or seep into the ground. Gases generated by the waste are free to diffuse into the atmosphere. Dumps are often set on fire and may burn for years. Although many dumps still exist, it is no longer permissible to create new ones in most countries.

Landfills

In contrast, a **landfill** is an engineered structure with barriers to contain the waste, mechanisms to capture and treat liquid and gaseous waste byproducts, and procedures in place to monitor the surrounding water and air. The important components of a typical landfill are illustrated on Figure 10.2.1.

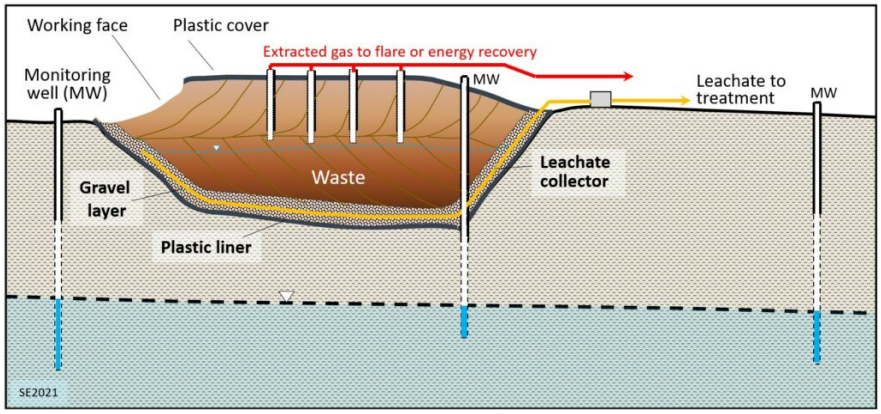


Figure 10.2.1: Features of a Modern Engineered Landfill. The dashed blue line shows the possible level of the water table within the landfill.

The key feature of an engineered landfill is the impermeable barrier at the base (Figure 10.2.2). In most cases this is a heavy plastic liner (0.5 to 1.5 mm thick) with welded seams, although a thick compacted clay layer may achieve the same purpose. The impermeable layer is intended to contain all fluids within the landfill so that there is no risk (or at least a very low risk) that landfill liquids will be dispersed into the groundwater underneath or into the surrounding surface water.



Figure 10.2.2: A Plastic Landfill Liner (Visible in the Lower Right). The rubber tires are waste and have been placed to protect the liner from damage from landfill materials and machinery.

The liner is normally covered with a layer of permeable fill (sand and gravel) within which pipes are installed to extract water (leachate) that has come in contact with the waste. That extracted leachate water may be sent to a dedicated processing plant, or to a sewage treatment plant, so that it can be detoxified prior to being released into the environment.

In a “completed” part of a landfill the waste is typically covered with another plastic membrane (or clay layer) to reduce the amount of water that can get in, and to prevent gases from escaping. The “working face” of the landfill is not covered in this way, but in most cases will be covered with a few centimeters of soil or some other material at the end of each day to prevent dispersal of the waste and access by birds, rodents and insects. An important part of the process at the working face is compaction of the waste, which is accomplished with heavy machines with studded metal wheels (Figure 10.2.3). That compaction allows for more waste to be stored within a specific volume. It also reduces the risk that there will be pockets of explosive gas within the waste.



Figure 10.2.3: A Compactor in Use to Redistribute and Compress Landfill Waste

As discussed below, the natural decomposition of landfill components results in generation of gases (mostly CO_2 and CH_4), and landfills are currently responsible for about 5% of global greenhouse gas emissions.[1] The key purpose of the landfill cover membrane is to contain these gases, so they are not released to the atmosphere. Another role is to contain all volatile emissions so that a landfill doesn’t smell as bad as it might otherwise.



Figure 10.2.4: A Landfill Gas Wellhead. The vertical grey pipe penetrates the cover membrane and extends down into the waste. The flexible orange pipe connects to the gas collection system.

Landfill gases cannot be allowed to build up indefinitely, so they must be released in a controlled way through gas wells installed within the area of the covered waste, and extending down to a depth just above the level of the landfill water table (Figure 10.2.4). The extracted gas is then either flared to convert methane to carbon dioxide ($CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$) or is used to generate electricity.

Monitoring wells are constructed around, and sometimes within, a landfill to sample the groundwater and determine if any leachate is escaping. There may be several dozen such wells around a typical landfill. They are sampled regularly (e.g., quarterly, or at least annually) and the water is analyzed for a range of constituents that might be expected in leachate. The monitoring protocol might also include collecting water samples from nearby streams, and air samples from around the landfill.
When a landfill is filled it can be covered with a thick layer of soil and adapted for other uses such as parks and playing fields (Figure 10.2.5).



Figure 10.2.5: Longhill Park, Bracknell, UK (the site of a Former Landfill)

Landfill Siting Criteria

Most jurisdictions have clear policies on siting landfills. Some of the siting criteria are as follows:

- A specified distance from an airport (or at least 3.5 km if bird-control measures are in effect),[3]
- A specified distance from a school or residential area,
- A specified distance from a fault that has been active in the Holocene (11,650 y), or from a known risk of slope failure, or from an area with karst terrain,
- A specified distance from a producing well and at least 1.5 m above the water table,
- A specified distance from a surface water body (stream, pond, marsh, lake, ocean),
- A specified distance from a park or archaeological site,
- Not within an existing topographic depression or on a river flood plain, and
- Not in an area at risk of tsunami, or within 1.5 m (vertical) of highest sea level.

Some other criteria that are important are the proximity to the source of the waste, the permeability of the material that underlies the site, and the proximity of material that can be used as cover.

Despite all the measures taken to prevent it, there is always a risk that leachate will leak into the surroundings, and into surface water and groundwater. The buffer to the nearest body of surface water allows time for a surface leak to be detected before it gets there. The buffer to the nearest well allows for the longer period of time that it might take to detect dispersal within an aquifer. The stipulation that the deepest part of a landfill must be a specified distance above the water table all but eliminates the construction of landfills in very wet regions where the water table may be within a few meters of surface, because most landfills are constructed by excavating to a depth of at least several meters. Landfills must not be sited within existing topographic depressions or gullies (even dry ones) because those, along with river floodplains, are at risk of flooding under extreme conditions.

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1. Stocker, T.F. et al. (2013). Technical summary. In Stocker, T.F et al. (Eds.), *Climate change 2013: The physical science basis.* Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change IPCC (p. 159–254). Cambridge University Press. ↵
2. Ministry of the Environment. (2016). *Landfill criteria for municipal solid waste*. BC Ministry of the Environment (accessed April 2021). https://www2.gov.bc.ca/assets/gov/en...l_criteria.pdf ↵
3. Bird control measures include covering the waste as effectively as possible at the end of each working day, minimizing bird nesting and roosting habitat around the landfill, using sounds to scare birds away, and employing raptors (e.g., falcons or hawks) to intimidate birds such as gulls). ↵

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CHAPTER OVERVIEW

11: Water and Air Pollution



This chapter takes many of the topics addressed in this book like burning of fossil fuels and the handling of waste, and explores how they pollute Earth's water and/or atmosphere.

11.1: Anthropogenic Effects on Water Quality

11.2: Groundwater Quality

11.3: Air Pollution

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11.1: Anthropogenic Effects on Water Quality

Types of Water Pollution

Human activities are common causes of water pollution problems, and, in this regard, the most important activities are agriculture, industry, landfills, sewage, and anything that can lead to elevated turbidity. Anthropogenic sources are divided into two types, **nonpoint sources** where the effect is distributed over a large area such as agriculture or logging, and **point sources**, like factories, landfills or mines, where the effect is localized to a specific site.

Nonpoint Sources

Agriculture

By a wide margin, agriculture represents the greatest threat to water quality. Agriculture is everywhere, and it occupies more land than all other uses combined. There is currently 30% more agricultural land than forested land. Modern agriculture, while very efficient in terms of production per input dollar, is also intensively dependent on the use of chemicals (fertilizers and pesticides) and a significant proportion of the chemicals applied either run off the surface into streams and lakes, or seep into aquifers.

A two-decade study by the US Geological Survey has shown that the water in over 50% of wells tested in agricultural regions has detectable amounts of pesticides, that the issue is also prevalent in urban areas (because of pesticide use on golf courses and lawns) and that it was worse during the period from 2002 to 2011 than it was from 1993 to 2001 (Figure 11.1.1). Although the figure doesn't show levels of pesticides in these wells, another study has shown that over 1000 wells in Florida have been closed because of pesticide levels above acceptable limits.[1]

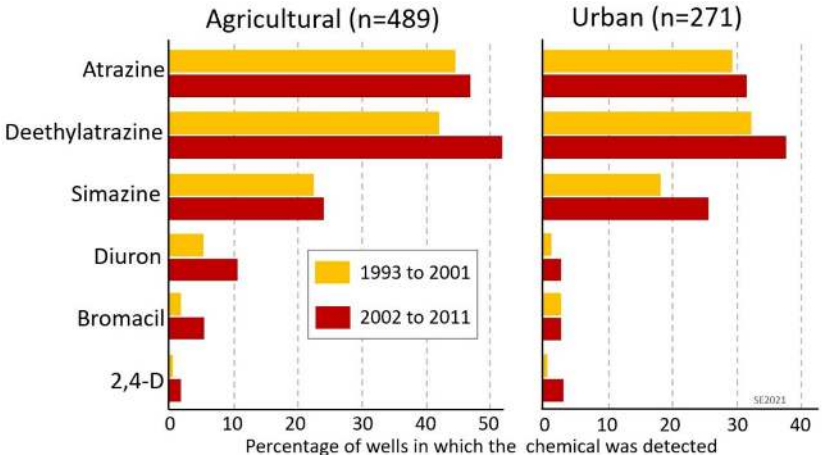


Figure 11.1.1: Pesticide Incidence in Groundwater in the United States, 1993 to 2011

Large amounts of nitrogen, phosphorous and potassium fertilizers are applied to fields all over the world. These nutrients help the crops to grow, but if more fertilizer is applied that is really needed, then the excess will end up making its way into the environment. Nitrogen from fertilizers can volatilize into the air, to come down within rainfall somewhere else. Nitrogen, phosphorous and potassium can run off fields into surface water bodies. They can also infiltrate down into the soil and move downwards out of reach of the plant roots where they are added to the groundwater. That groundwater may discharge to a surface water body. In lakes and streams these excess nutrients help algae to thrive, and that can create significant problems for aquatic life and human water supplies and is also an issue for anyone who likes to be in or near the water.

Lake Erie has long been the poster child for algal blooms related to excess nutrients, as is illustrated in a satellite image from 2011 (Figure 11.1.2). Erie is the shallowest of the Great Lakes (average depth is only 19 meters, compared with 147 meters for Lake Superior) and so has the greatest potential to warm up in the summer. The Erie drainage basin is also the most heavily populated of the Great Lakes (home to 12.4 million people) and the lake is surrounded by farmland and cities and industry, with very little remaining forest. The western part of Lake Erie has a springtime phosphorous level of over 12 µg/L, whereas Lakes Superior and Huron are in the range of 2 to 3 µg/L, and Lake Ontario is just over 6 µg/L.[2]



Figure 11.1.2: Algal Growth in Lake Erie in 2011

Agriculture is a major source of the phosphorous that leads to excess algal growth in Lake Erie, but not the only one. Other important sources include municipal sewage effluent, industrial effluent, urban storm water runoff, and atmospheric deposition.[3]

Runoff from fields is not only laced with excess nutrients and pesticides, but is also rich in suspended matter that contributes to the turbidity of surface water, degrading aquatic ecosystems, and potentially endangering human water supplies (Figure 11.1.3). The risk of turbid runoff is greatest when fields have been left unprotected by vegetation following harvesting or tillage.



Figure 11.1.3: Turbid Runoff from a Field in Iowa Following a Rainstorm

Nearly 80% of global farmland is dedicated to livestock, either for grazing or for growing animal feed (although livestock farming accounts for only 18% of the caloric output from farming)[4] and farm animals produce manure—lots of it. Manure from all livestock is rich in nitrogen, potassium and phosphorous, and so contributes to the surface water algae problem described above, and to elevated levels of nitrogen in groundwater.

In addition to nitrates and other nutrients, animal manure also contains bacteria, and while most of those bacteria are harmless to humans, some present a serious risk.

Walkerton Ontario, a town of about 5000 residents situated 150 km northwest of Toronto, has a water supply system sourced by wells in a fractured bedrock aquifer. One of those wells was shallow, drawing water from a depth of only 6 m. A heavy rainstorm in early May 2000 soaked a pasture that had been fertilized with cattle manure a few weeks earlier. Some of that water was introduced into the Walkerton water system from that well, situated 80 meters away from the pasture. In the following week 2300 residents became ill with gastroenteritis from the bacterium Escherichia coli in the water supply, and seven people died. Although Walkerton's Public Utility Commission did routine tests for bacterial contamination, the testing protocols were not always followed

nor were they as frequent as prescribed, monitoring records were falsified, and the utility's chlorination system was set to a level below that stipulated by the Ontario Clean Water Agency. A public inquiry concluded that much of the blame for the Walkerton disaster can be traced back to provincial government cuts to funding for programs that had been established to protect citizens and ensure safe water supplies.[7] The Walkerton disaster spurred increased efforts to protect groundwater across Canada.

Logging

Logging, like agriculture, is a nonpoint source of pollution because it is carried out over wide areas, and it involves the application of fertilizers and pesticides and the removal of vegetation. But logging differs because it is often carried out on steep slopes—in the remaining forested areas that are too rugged for farming or urbanization—(Figure 11.1.4) and so the issue with erosion and turbid runoff is exacerbated. Most logging also operations also involve the construction of temporary roads on steep terrain. Road construction amplifies the risk of slope failure and that increases the likelihood of damage to surface water habitat and supplies.



Figure 11.1.4: A Clear Cut in the Coquille River Basin of Southwestern Oregon

Point Sources

Point sources of pollution include mines, petroleum extraction operations, plants for extracting and refining ores and petroleum, chemical works, manufacturing plants, sewage treatment systems, landfills and underground storage tanks (USTs) at filling stations.

Throughout the history of industrialization, owners and operators all these types of facilities have failed catastrophically and repeatedly to protect the environment, water supplies, ecosystems and the lives and health of workers and innocent people. One of the most notorious examples was in the city of Niagara Falls, New York. In the 1920s the city set aside an abandoned canal—Love Canal—as a dump site for municipal waste. In 1942 the Hooker Chemical Company was given permission to dispose of chemical by-products from the manufacture of dyes, perfumes and rubber goods into the dump. From then until 1952 Hooker dumped nearly 20,000 tons of chemical wastes at the site, most of it in 200-liter metal drums, which they eventually covered up with clay. In 1952 they sold the site (which they had purchased from the city in 1947), along with the liability for the dumped chemicals, to the Niagara Falls Board of Education. A 400-student elementary school was built on top of the old dump, and it was in use from 1955 to 1978. Soon after construction of the school, toxic chemicals started coming to surface, parts of the clay cover collapsed, and some of the metal drums were exposed at surface.[8] During heavy storms contaminated surface water ran off the site and into the Niagara River (and then over the falls). Contaminated groundwater also migrated offsite and into the basements of neighboring homes. The Love Canal site was eventually cleaned up, and the school and surrounding homes abandoned, but there are lingering health issues amongst those who lived in the area.

There are industrial sites like Love Canal all over the world and their contamination legacies will be with us for decades, even centuries. Increasingly however, corporations and individuals are being held to account for assuming they can dump whatever waste they need to get rid of onto the ground and into water and the air.

But it isn't just large operations that are problematic. In virtually every village, town and neighborhood in North America (and elsewhere as well) there are abandoned sites surrounded by chain link fences and dotted with the plastic pipes of monitoring wells. Many of these are the remains of gas stations with underground storage tanks (USTs) that had leaked so badly that the operation was forced to close. If you think you haven't seen one, you probably just haven't realized what they are. Some UST sites have been cleaned up and rehabilitated. The one illustrated on Figure 11.1.5 has been vacant for over 20 years, possibly because the value of the land is less than the cost of removing the contamination and making the site usable for some other purpose.



Figure 11.1.5: The Site of a Filling Station with Leaking Underground Storage Tanks. The white pipes are groundwater monitoring wells.

A leaking fuel UST is at least three problems in one (Figure 11.1.6). Some components of the fuel are volatile, and so will form a vapor phase that rises to surface and may enter nearby buildings. Most fuels used for vehicles like cars, trucks and planes are lighter than water and so will float along the surface of the saturated zone (the water table). Some components of the fuel are soluble in water and so will mix with groundwater and be dispersed in that way. Some components of the fuel may be heavier than water so will sink through the saturated zone. The aquifer water will eventually come to surface somewhere and will bring some of those dissolved and heavy constituents with it.

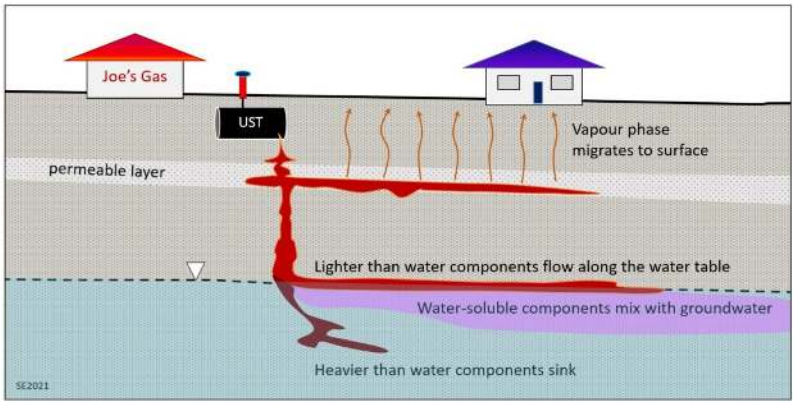


Figure 11.1.6: Illustration of the Fate of Petroleum That Has Leaked from a UST

Media Attributions

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- **Figure** 11.1.2**:** Excess Nutrients Flowing in Lake Erie, satellite image from N.A.S.A., public domain; inset photo is public domain from U.S. Geological Survey, https://www.usgs.gov/media/images/ex...s-algal-blooms
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1. Mateo-Sagasta, J., Marjani Zadeh, S., Turral, H. (2018). *More people, more food, worse water? - A Global Review of Water Pollution from Agriculture*. International Water Management Institute (IWMI), Colombo, Sri Lanka; Food and Agriculture Organization (FAO), Rome, Italy, http://www.fao.org/3/CA0146EN/ca0146en.pdf ↵
2. Environment and Climate Change Canada. (2020). Canadian environmental sustainability indicators: Phosphorus levels in the offshore waters of the Great Lakes (accessed March, 2021). https://www.canada.ca/content/dam/ec...ters-gl-en.pdf ↵
3. Environment and Climate Change Canada. (2020) Phosphorus loading to Lake Erie (accessed March 2021). https://www.canada.ca/en/environment...lake-erie.html ↵
4. Ritchie, H. (2019). Half of the world's habitable land is used for agriculture. Our World in Data. https://ourworldindata.org/global-la...or-agriculture ↵
5. Liebscher, H., Hii, B. & McNaughton, D. (1992). Nitrates and pesticides in the Abbotsford Aquifer, southwestern British Columbia. Environment Canada, Inland Waters Directorate. ↵
6. Cox, S., Liebscher, H. (1999) Groundwater quality data from the Abbotsford-Sumas Aquifer of southwestern British Columbia and northwestern Washington State, February 1997. U.S. Geological Survey, Open File Report 99-244. https://doi.org/10.3133/ofr99244 ↵
7. O'Connor, D. R. (2002). Report of the Walkerton Inquiry: The Events of May 2000 and Related Issues, Part One. Ontario Ministry of the Attorney General. http://www.archives.gov.on.ca/en/e_r...ton/index.html ↵
8. Colten, C. E., Skinner, P. N. (1996). The road to Love Canal: Managing industrial waste before EPA. University of Texas Press. ↵

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11.2: Groundwater Quality

Contamination of Groundwater

One of the good things about groundwater as a source of water is that it is not as easily contaminated as surface water is. But there are two caveats to that: one is that groundwater can become naturally contaminated because of its very close connection to the materials of its aquifer, and the second is that once contaminated by human activities on surface, groundwater is very difficult to clean up.

Natural Contamination of Groundwater

Groundwater moves slowly through an aquifer, and unlike the surface water of a stream, it has a lot of contact with the surrounding rock or sediment. In most aquifers, the geological materials that make up the aquifer are relatively inert or are made up of minerals that dissolve very slowly into the groundwater. Over time, however, all groundwater gradually has more and more material dissolved within it as it remains in contact with the aquifer. In some areas, that rock or sediment includes some minerals that could potentially contaminate the water with elements that might make the water less than ideal for human consumption or agricultural use. Examples include copper, arsenic, mercury, fluorine, sodium, and boron. In some cases, contamination may occur because the aquifer material has particularly high levels of the element in question. In other cases, the aquifer material is just normal rock or sediment, but some feature of the water or the aquifer allows the contaminant to build up to significant levels.

An example of natural contamination takes place in the bedrock aquifers of the east coast of Vancouver Island and the adjacent Gulf Islands. The aquifer is the Cretaceous (90 Ma to 65 Ma) Nanaimo Group, which is made up of sandstone, mudstone, and conglomerate (Figure 11.2.1).



Figure 11.2.1 Cretaceous Nanaimo Group sandstone exposed in a Nanaimo parking lot.

The rocks of the Nanaimo Group are not particularly enriched in any trace elements, but the sandstone that makes up much of the group has relatively high levels of clay (for a sandstone). This clay is good at adsorbing[1] some elements from the water and desorbing others, and in the process, its pH goes up (it becomes alkaline). At high pH levels (some as high as 9 in groundwater in the Nanaimo Group), the element fluorine that is naturally present in the rock (as it is in almost any rock) has an increased tendency to dissolve in the water. In some areas, groundwater in the Nanaimo Group has fluorine levels that are well above recommended levels for drinking water. The World Health Organization (WHO) maximum acceptable concentration (MAC) for fluorine is 1.5 milligrams per liter (milligrams per liter). Between 5% and 10% of the domestic wells around Nanaimo and adjacent Gabriola Island have more than that, some as much as 10 milligrams per liter. A small amount of fluorine in the human diet is considered important for maintaining dental health, but high levels can lead to malformation and discoloration of teeth, and long-term exposure can lead to other more serious health effects such as skeletal problems.

Nanaimo Group groundwater can also have elevated levels of boron, again related to pH and adsorption from clay minerals. While boron at the levels found there is not toxic to humans, there is enough boron in some wells to be toxic to plants, and the water cannot be used for irrigation.

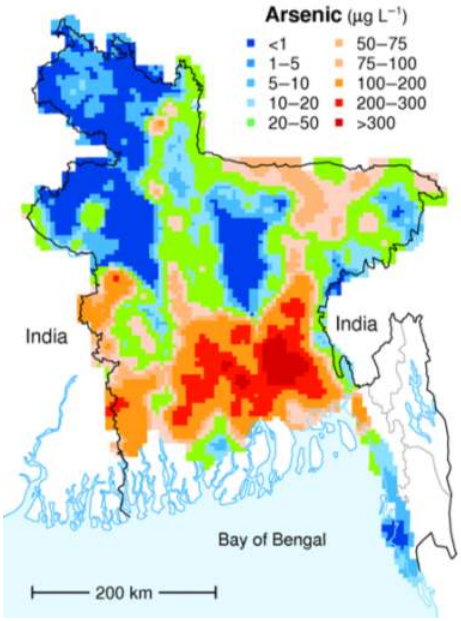


Figure 11.2.2 The distribution of arsenic in groundwater in Bangladesh. The WHO recommended safe level for arsenic is 10 µg/L. All the green, orange, and red areas on the map exceed that limit.

Rural residents in the densely populated country of Bangladesh used to rely mostly on surface supplies for their drinking water, and many of these were subject to bacterial contamination. Infant mortality rates were among the highest in the world and other illnesses such as diarrhea, dysentery, typhoid, cholera, and hepatitis were common. In the 1970s, international agencies, including UNICEF, started a program of drilling wells to access abundant groundwater supplies at depths of 20 meters to 100 meters. Eventually over 8 million such wells were drilled. Infant mortality and illness rates dropped dramatically, but it was later discovered that the water from a high proportion of these wells has arsenic above safe levels (Figure 11.2.2).

Most of the wells in the affected areas are drilled into relatively recent sediments of the vast delta of the Ganges and Brahmaputra Rivers. While these sediments are not particularly enriched in arsenic, they have enough organic matter in them to use up any oxygen present. This leads to water with a naturally low oxidation potential (anoxic conditions); arsenic is highly soluble under these conditions, and so any arsenic present in the sediments easily gets dissolved into the groundwater. Arsenic poisoning leads to headaches, confusion, and diarrhea, and eventually to vomiting, stomach pain, and convulsions. If not treated, the final outcomes are heart disease, stroke, cancer, diabetes, coma, and death. There are ways to treat arsenic-rich groundwater, but it is a challenge in Bangladesh to implement the simple and effective technology that is available.

Anthropogenic Contamination of Groundwater

Groundwater can become contaminated by pollution at the surface (or at depth), and there are many different anthropogenic (human-caused) sources of contamination.

The vulnerability of aquifers to pollution depends on several factors, including the depth to the water table, the permeability of the material between the surface and the aquifer, the permeability of the aquifer, the slope of the surface, and the amount of precipitation. Confined aquifers tend to be much less vulnerable than unconfined ones, and deeper aquifers are less vulnerable than shallow ones. Steeper slopes mean that surface water tends to run off rather than infiltrate (and this can reduce the possibility of contamination). Contamination risk is also less in dry areas than in areas with heavy rainfall.

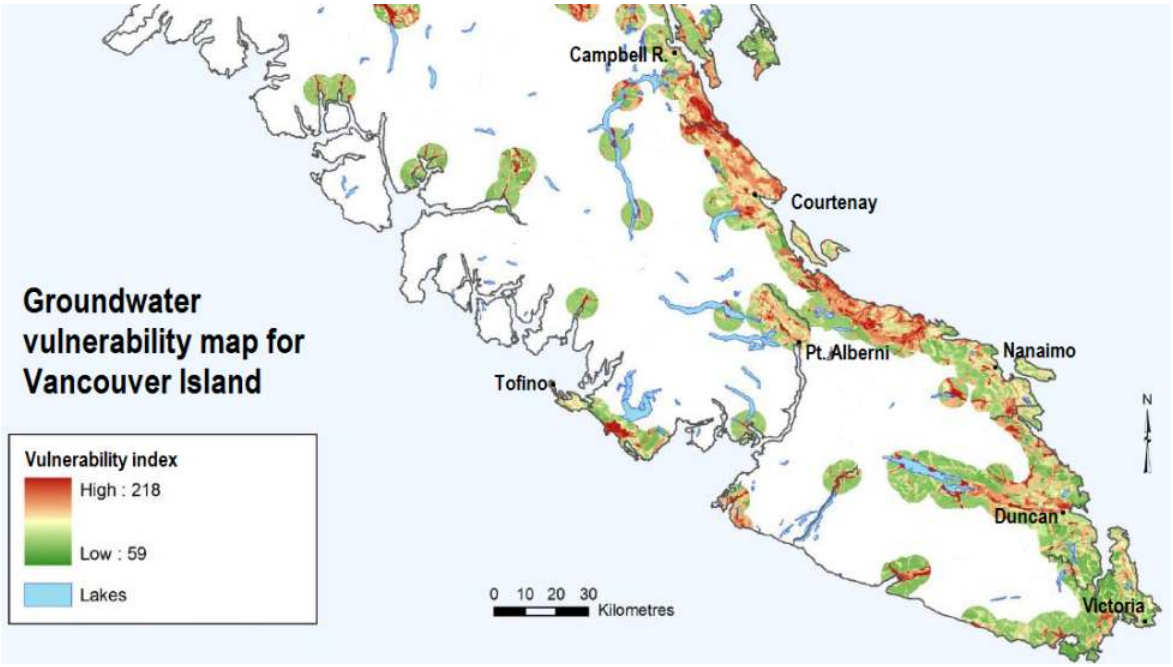


Figure 11.2.3 The vulnerability to anthropogenic contamination of aquifers on southern Vancouver Island. Much of the island is not mapped (shown as white) because of a lack of aquifer information in areas without wells.

Studies of groundwater vulnerability have been completed for various regions of British Columbia. A groundwater vulnerability map for southern Vancouver Island is shown in Figure 11.2.3. The yellow to red areas are considered to have high vulnerability to pollution from surface sources, and most of these are where the aquifers are unconfined in quite permeable unconsolidated sediments of either glacial or fluvial origin, where the water table is relatively shallow, and the terrain is relatively flat.

The important sources of anthropogenic groundwater contamination include the following:

- Chemicals and animal waste related to agriculture, and chemicals applied to golf courses and domestic gardens
- Landfills
- Industrial operations
- Mines, quarries, and other rock excavations
- Leaking fuel storage tanks (especially those at gas stations)
- Septic systems
- Runoff from roads (e.g., winter salting) or chemical spills of materials being transported

Agriculture

Intensive agricultural operations and golf courses can have a significant impact on the environment, especially where chemicals and other materials are used to enhance growth or control pests. An example of agricultural contamination is in the Abbotsford area of the Fraser Valley, where nitrate levels above the 44 milligrams per liter maximum acceptable level (expressed as nitrate) in the Abbotsford-Sumas aquifer have been observed since the 1950s; however, the problem became much worse as agriculture intensity increased in the 1980s. By 2004, groundwater with nitrate levels more than 44 milligrams per liter was reported over an area of about 75 kilometers square around Abbotsford, and the problem extended across the border into the Sumas area of Washington State.

This region is intensively used for berry crops (especially raspberries and blueberries) and large poultry operations, as well as lesser amounts of grazing and forage crops. Chicken manure is typically stored in fields adjacent to chicken barns and may release nitrogen to the environment from runoff water, and from releases of ammonia gas. Over decades, both chemical fertilizers and chicken manure and other manures have been applied to the berry crops to provide extra nitrogen to help maximize berry growth. If the fertilizer added is more than what the plants need or is poorly timed compared to when it is needed, then the extra nitrogen may be leached into the groundwater below. Berry crops are irrigated over the summer to help the crops grow. Summer irrigation and winter rainfall may carry excess nitrate from the near surface to the aquifer below.

Since the 1990s, agricultural practices have been tightened up to reduce the rate of groundwater contamination, but it will take decades for nitrate levels to drop in the Abbotsford-Sumas aquifer. Agriculture and Agri-Food Canada and many others are conducting research on better irrigation and nitrate management techniques to reduce the amount of nitrogen that leaches to groundwater.

Landfills

In the past, domestic and commercial refuse was commonly trucked to a "dump" (typically a hole in the ground), and when the hole was filled, it was covered with soil and forgotten. In situations like this, rain and melting snow can easily pass through the soil used to cover the refuse. This water passes into the waste itself, and the resulting landfill leachate that flows from the bottom of the landfill can seriously contaminate the surrounding groundwater and surface water. In the past few decades, regulations around refuse disposal have been significantly strengthened, and important steps have been taken to reduce the amount of landfill waste by diverting recyclable and compostable materials to other locations.

A modern engineered landfill has an impermeable liner (typically heavy plastic, although engineered clay liners or natural clay may be adequate in some cases), a plumbing system for draining leachate (the rainwater that flows through the refuse and becomes contaminated), and a network of monitoring wells both within and around the landfill (Figure 11.2.4). Once part or all a landfill site is full, it is sealed over with a plastic cover, and a system is put in place to extract landfill gas (typically a mixture of carbon dioxide and methane). That gas can be sent to a nearby location where it is burned to create heat or used to generate electricity. The leachate must be treated, and that can be done in a normal sewage treatment plant.

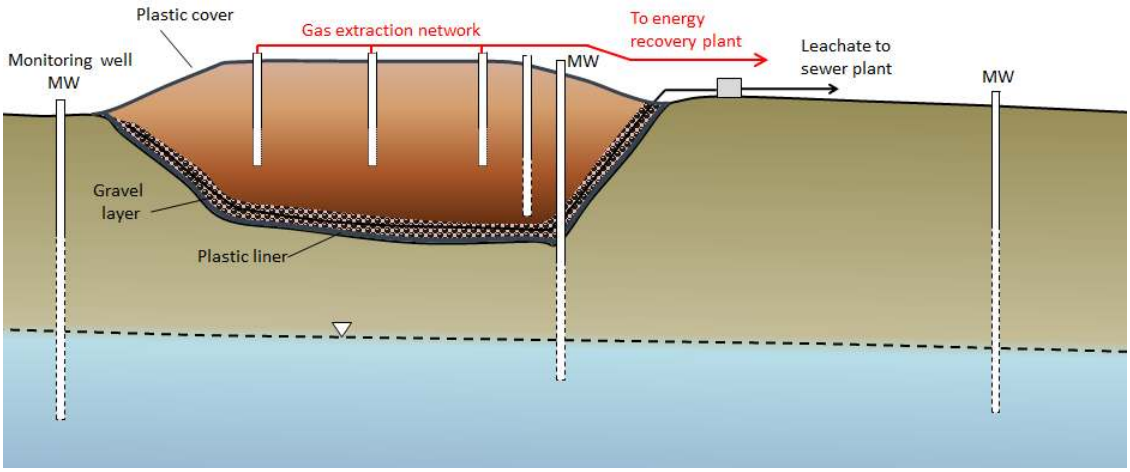


Figure 11.2.4 A cross-section of a typical modern landfill.

The monitoring wells are used to assess the level of the water table around the landfill and to collect groundwater samples so that any leakage can be detected. Because some leakage is almost inevitable, the ideal placement for landfills is in areas where the depth to the water table is significant (tens of meters if possible) and where the aquifer material is relatively impermeable. Landfills should also be situated far from streams, lakes, or wetlands so that contamination of aquatic habitats can be avoided.

Today there are hundreds of abandoned dumps scattered across the country; most have been left to contaminate groundwater that we might wish to use sometime in the future. In many cases, it's unlikely that we'll be able to do so.

Mines, Quarries, and Rock Excavations

Mines and other operations that involve the excavation of large amounts of rock (e.g., highway construction) have the potential to create serious environmental damage. The exposure of rock that has previously not been exposed to air and water can lead to the oxidation of sulfide-bearing minerals, such a pyrite (FeS2), within the rock. The combination of pyrite, water, oxygen, and a special type of bacteria (*Acidithiobacillus ferrooxidans*) that thrives in acidic conditions leads to the generation of acidity, in some cases to pH less than 2. Water that acidic is hazardous by itself, but the low pH also has the property of increasing the solubility of certain heavy metals. The water that is generated by this process is known as acid rock drainage (ARD). ARD can occur naturally where sulfide-bearing rocks are near the surface.



Figure 11.2.5 Acidic runoff at the abandoned Mt. Washington Mine near Courtenay, B.C. The issue of ARD is a major environmental concern at both operating mines and abandoned mines.

In streams around the Mt. Washington Mine on Vancouver Island (Figure 11.2.5), copper levels are high enough to be toxic to fish. Groundwater adjacent to the contaminated streams in the area is very likely contaminated as well.

Leaking Fuel Tanks



Figure 11.2.6 A closed and fenced gas station site in Nanaimo, B.C. The white pipes in the background are wells for monitoring groundwater contamination on the site.

Underground storage tanks (USTs) are used to store fuel at gas stations, industrial sites, airports, and anywhere that large volumes of fuel are used. They do not last forever, and eventually they start to leak their contents into the ground. This is a particular problem at older gas stations — although it may also become a future problem at newer gas stations. As mentioned in the previous section, you may have noticed gas stations that have been closed and then surrounded by chain-link fence (Figure 11.2.6). In virtually all such cases the closure has been triggered by the discovery of leaking USTs and the requirement to cease operations and remediate the site.

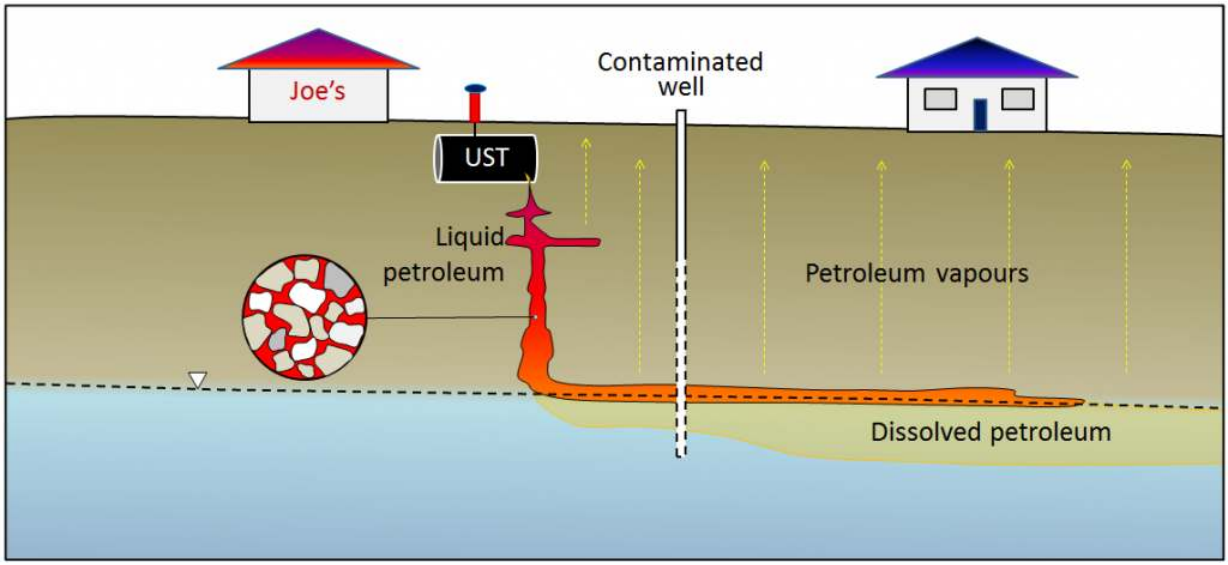


Figure 11.2.7 A depiction of the fate of different components of a petroleum spill from an underground storage tank.

Petroleum fuels are complex mixtures of hydrocarbon compounds and the properties of their components—such as density, viscosity, solubility in water, and volatility—tend to vary widely. As a result, a petroleum spill is like several spills for the price of one. The petroleum liquid slowly settles through the unsaturated zone and then tends to float on the surface of the groundwater (Figure 11.2.7). The more readily soluble components of the spill dissolve in the groundwater and are dispersed along with the normal groundwater flow, and the more volatile components of the spill rise toward the surface, potentially contaminating buildings.

Septic Systems

In areas that are not served by sewage networks leading to a central sewage treatment plant, most homeowners rely on septic systems for disposal of sewage. There are two primary components to a simple septic system, the septic tank and the drainage field (Figure 11.2.8). A typical septic tank is constructed of either concrete or plastic and has a volume of 5,000 liters to 10,000 liters (5 m^3 to 10 m^3). This forms the first treatment and is designed to be anaerobic (without oxygen). That promotes the activity of certain bacteria that help break down the waste. As the waste is degraded, some portions tend to sink to form sludge at the base of the tank, and others float to the surface, forming a scum layer. A septic tank may be divided into two parts to keep the sludge at the bottom and the scum on the top from draining out. The water then moves to the drainage field, which provides the right conditions for a different set of bacteria that operate in aerobic conditions. The drainage field includes an array of plastic pipes that are perforated to allow the effluent to drain out over a large area and seep slowly into the ground. In order to install a drainage field, it is first necessary to test the soil below, as it must be sufficiently permeable to allow the effluent to percolate away, but not so permeable that it flows too quickly, and the soil is not able to filter out the pathogenic bacteria.

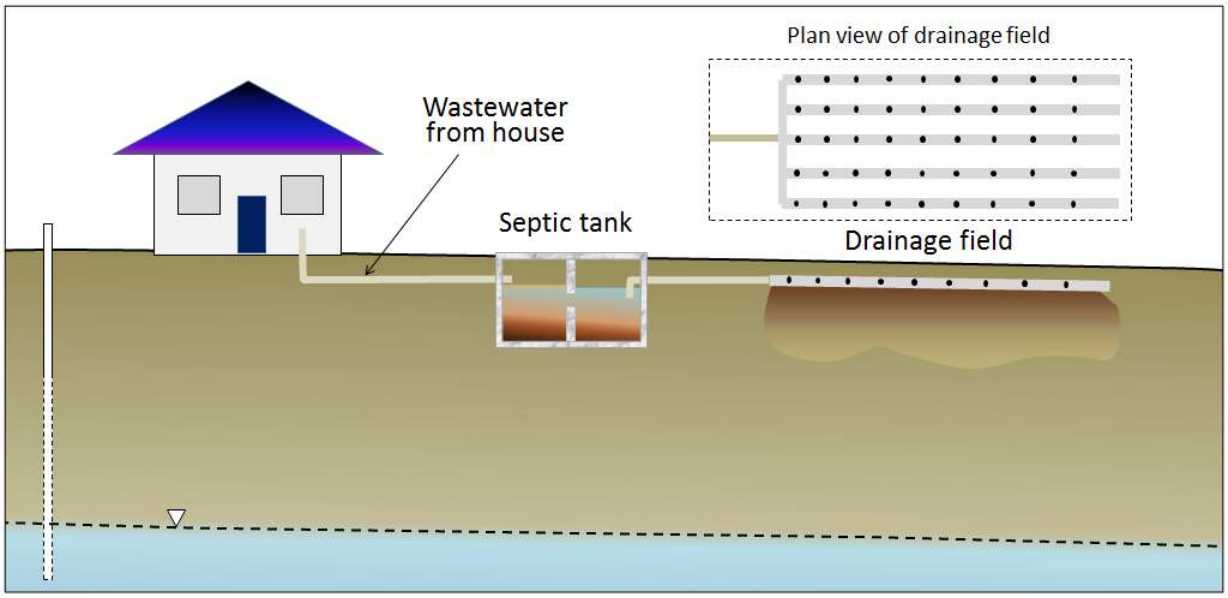


Figure 11.2.8 A typical septic system.

If they are properly installed and used, and if the sludge is periodically removed from the tank, a septic system should be effective in treating the sewage for decades. The anaerobic and aerobic bacteria should be able to break down the incoming waste and there should be little risk to the surface environment or groundwater. But many things can go wrong with a septic system, including the following:

- If inappropriate chemicals are added to the waste stream, they may interfere with the natural breakdown of the sewage.
- If the tank is not periodically pumped out, solids can get into the drainage field and compromise the drainage, resulting in the flow of effluent toward the surface.
- If the soil is either not sufficiently permeable or too permeable, the effluent will not drain away (and will start to pool at the surface) or it will drain too quickly.
- If the drainage field is constructed in an area where the water table is close to surface, some of the effluent is likely to flow into the groundwater without being treated.

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- **Figures** 11.2.4**,** 11.2.5**,** 11.2.6**,** 11.2.7**,** 11.2.8**:** © Steven Earle. CC BY.

1. "Adsorb" (with a "d") is not the same as "absorb" (with a "b"). Water can be absorbed by a sponge. Ions dissolved in water can be adsorbed onto—or desorbed from—the surfaces of clay minerals. ↵

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11.3: Air Pollution

Air Pollution Defined

Air pollution is the release of gases that cause harm to all of Earth's other spheres (lithosphere/geosphere, biosphere, hydrosphere), which include humans, into the air. Air pollution causes millions of people to die every year. According to the World Health Organization (WHO), 99% of humans breathe air that exceeds the guideline limits for pollutants. People living in second- and third-world countries suffer the most. The Clean Air Act was established in the United States in 1970. It authorizes the U.S. Environmental Protection Agency (EPA) to safeguard public health by regulating the emissions of these harmful air pollutants. Progress has been made, but there is more to go.

Causes and Types of Air Pollution

Most air pollution comes from energy use and production. This includes driving a gasoline powered car, heating a home with natural gas, running a plant on fracked or otherwise sourced gas, etc. In all these examples a fossil fuel is burned, and gases are released into the atmosphere. More information on specific types of pollution is below.

Greenhouse Gases and Ozone

Greenhouse gases are gases that trap the Earth's heat in the atmosphere, leading to warmer temperatures, which in turn lead to things like rising sea levels and more extreme weather. Common greenhouse gases are water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), and ozone (O_3). In 2021, carbon dioxide accounted for about 80% of the US's total greenhouse gas emissions, and methane made up more than 11%. Carbon dioxide comes from the burning of fossil fuels. Methane comes from natural (cows produce methane as they digest food) and industrial (decomposition of waste) sources, and include large amounts released during oil and gas drilling. While carbon dioxide emissions are very high, methane is more potent, so it is very dangerous.

Ozone is ozone no matter where it is in the atmosphere. Good ozone is good only because it is in the stratosphere where we cannot breathe it and it absorbs ultraviolet (UV) rays. Bad ozone is near the Earth's surface where we can breathe it. It also absorbs solar ultraviolet light, but but the dangers outweigh the benefits. For UV protection, we are interested in the total number of ozone molecules between us and the Sun. 90% of ozone molecules are in the stratosphere and 10% are in the troposphere - some down near Earth's surface where we can breathe them. There are important issues affecting human and ecological health for both good ozone and bad ozone. For good ozone, the most important issues are the reduction of ozone globally, the Antarctic Ozone Hole, and Arctic ozone loss that is caused by chlorofluorocarbons. Chlorofluorcarbons were widely used in various applications like refrigerants, aerosol propellants, and foam blowing agents, but are now largely phased out due to their significant contribution to ozone depletion in the Earth's atmosphere. Reduced ozone means more solar UV gets to the ground causing more skin cancer. For bad ozone, the most important issues include the production of too much ozone in cities and nearby regions that is caused by too many pollutants from traffic, industrial processes, power generation, and other human activities. Increased ozone means more people have respiratory and heart problems. It is important to note that in October 2016 (2022 for the US), more than 140 countries signed the Kigali Agreement to reduce the use of chlorofluorocarbons and develop greener alternatives over time.

Smog and Soot

Smog is the bad ozone written about above. **Soot** is made from tiny particles of chemicals, soil, smoke, dust, or allergens carried in the air. They are the two most prevalent types of air pollution. The sources of smog and soot are similar as they occur with emissions from cars and trucks, factories, power plants, incinerators, and engines generated by combusting fossil fuels.

Smog irritates eyes and throats and damages the lungs. Children, elderly, and people who work or exercise outdoors are at higher risk. It's even worse for people who have asthma or allergies; these extra pollutants can intensify their symptoms and trigger asthma attacks. The tiniest airborne particles in soot are especially dangerous because they can penetrate the lungs and bloodstream and worsen bronchitis, lead to heart attacks, and even hasten death.

Because some sources of these pollutants have been preferentially located in or next to low-income neighborhoods, the negative effects of this pollution are experienced at a higher rate by the people who live in these communities. This has become an important environmental justice issue.

Hazardous Pollutants

Several pollutants, even in tiny amounts, pose sometimes fatal health risks. Common pollutants include mercury, lead, dioxins, and benzene which are emitted as fossil fuels combust or are found in gasoline. Large amounts of lead can damage children's brains and kidneys, and small amounts can affect children's ability to learn. This is why pediatricians regularly test children for lead exposure. Mercury damages the central nervous system. Dioxins are usually found in food but can also be found in the air and is a carcinogen that affects the liver, immune system, nervous system, endocrine system, and reproductive functions. Benzene is also a carcinogen and causes eye, skin, and lung irritation, as well as blood disorders.

Another category of pollutants, polycyclic aromatic hydrocarbons (PAHs), are by-products of smoke generated by wildfires and exhaust by traffic. PAHs have been correlated to eye and lung irritation, blood and liver issues, and cancer.

Air Pollution in the United States

According to the American Lung Association (ALA), more than 33% of the people in the U.S. live in counties with unhealthy air. The Clean Air Act, enacted in 1970, has been critical in reducing air pollution by reducing harmful emissions from transportation, power plants, and manufacturing. Fossil fuel interests, often supported by industry-friendly lawmakers, have continuously sought to weaken its protections but maintaining the integrity of this law is crucial to improving and safeguarding air quality.

The latest findings reveal that climate change-driven wildfires and extreme heat are exacerbating the challenges to public health. Recent studies by the ALA focus on ozone levels, year-round particle pollution, and short-term particle pollution, revealing that people of color are 61% more likely than white people to live in counties with a failing grade in at least one of these categories, and three times more likely to live in areas where all three pollution types fail to meet health standards.

In the rankings for these pollution categories, central California cities (Bakersfield, Visalia, Fresno) occupy the top three spots for the worst air quality, despite the state's progress in reducing emissions over the past five decades. On the other end of the spectrum, cities like Burlington, Vermont; Honolulu; and Wilmington, North Carolina, consistently rank among the best for air quality in the country.

The most effective strategy to reduce air pollution is promoting the transition to cleaner fuels and industrial practices. By shifting to renewable energy sources like wind and solar, increasing fuel efficiency in vehicles, and replacing gasoline-powered cars with electric vehicles (assuming the electricity is not generated by fossil fuels), we can address pollution at its source while also mitigating the global warming that exacerbates its harmful health effects.

As for the economic costs of controlling air pollution, a report commissioned by the Natural Resources Defense Council (NRDC) shows that the benefits of cleaner air far outweigh the costs. Each year, the Clean Air Act's regulations result in benefits that are up to 32 times greater than the cost of enforcement. These benefits include preventing up to 370,000 premature deaths, reducing hospital admissions for respiratory and cardiac diseases by 189,000, and generating up to $3.8 trillion in net economic gains for the U.S. economy annually.

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CHAPTER OVERVIEW

12: Climate Change



This chapter first addresses Earth's climate over the past several hundred million years. This shows the natural fluctuation that does occur. Then it addresses how human activity has accelerated natural processes like warming and the subsequent changes to the atmosphere and sealevel.

12.1: Climate Change in Earth’s History

12.2: Increasing Temperatures

12.3: Melting Glacial Ice and Permafrost

12.4: Taking Climate Action

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12.1: Climate Change in Earth's History

We are currently in the middle of a **glacial** (cold) period that started about 34 million years ago but became more intense about one million years ago. During that time glaciers have expanded and contracted on a time scale of around 100,000 years. This is not the only period of glaciation in Earth's history. In general, the Earth has been warm enough to be ice-free for much more of the time than it has been cold enough to be glaciated. Since this is not a Historical Geology class, we will not cover all glaciations, but instead will highlight a few to show variation in timing and causes.

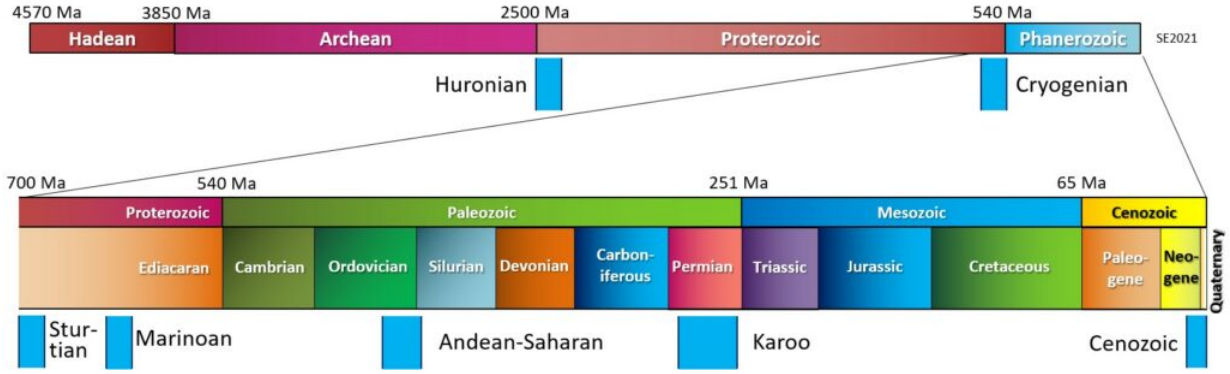


Figure 12.1.1: The Record of Major Glaciations During Earth's History

The oldest known glacial period is the Huronian and was likely initiated because of the evolution of photosynthetic organisms. This resulted in an increase of free oxygen in the atmosphere and a consequent drop in the levels of the greenhouse gas methane—which triggered cooling. Based on evidence of glacial deposits from the area around Lake Huron in Ontario (and elsewhere), the Huronian glaciation lasted from approximately 2450 to 2400 Ma. Because rocks of that age are rare, we don't know much about its intensity or global extent.

Evidence for the Andean-Saharan glaciation is found in rocks of the Andean region of South America and in the Sahara region of Africa during the Ordovician and Silurian (Figure 12.1.2). The glaciation may have lasted for up to 10 million years (from about 435 to 445 Ma) at a time when the supercontinent Gondwana (which was originally part of Pangea) was mostly close to the South Pole. Eyles (2008)[2] has suggested that the cooling that triggered this glacial episode might have resulted from the formation of a major mountain range in the northern part of what is now Africa, which would have led to enhanced erosion and weathering, and therefore to consumption of atmospheric carbon dioxide.

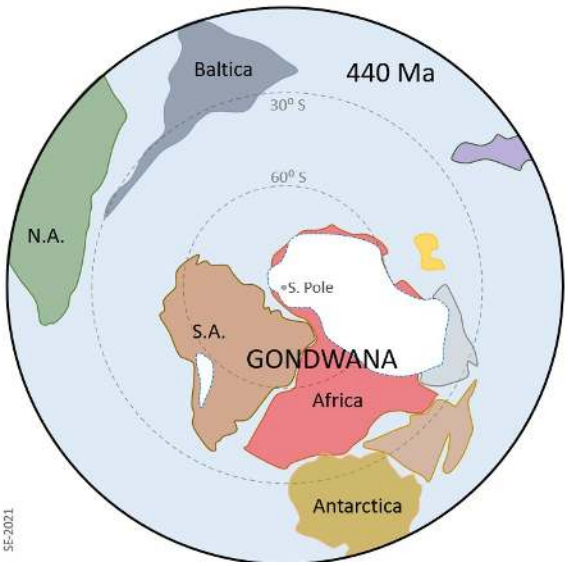


Figure 12.1.2: The Possible Extent of the Ordovician-Silurian Glaciation (white) on Gondwana at Around 440 Ma

The Earth was warm and essentially unglaciated throughout the Mesozoic (Figure 12.1.2). Although there may have been some alpine glaciation at this time, there is no longer any record of it; the dinosaurs, which dominated terrestrial habitats during the

Mesozoic, did not have to endure icy conditions. Sea levels were very high during this time, as Earth's water was stored in the ocean instead of as ice.

At around 15 Ma subduction-related volcanism between central and South America created the connection between North and South America, preventing water from flowing between the Pacific and Atlantic Oceans. This further restricted the transfer of heat from the tropics to the poles leading to a rejuvenation of the Antarctic glaciation. The expansion of that ice sheet increased the Earth's reflectivity enough to promote a positive feedback loop of further cooling: more reflective glacial ice, more cooling, more ice, etc. Ice sheets started to grow in Greenland by around 3.5 Ma, and in North America and northern Europe by around 1 Ma (Figure 12.1.3). The most intense part of the current ("Pleistocene") glaciation—and the coldest climate—was during the Pleistocene, but if we count Antarctic glaciation, it really extends from the Oligocene to the Holocene (Figure 12.1.2), and will likely continue into the future.

The Pleistocene has been characterized by significant temperature variations (through a range of approximately 8˚ C) on time scales of 40,000 to 100,000 years, and to corresponding expansion and contraction of ice sheets in the northern hemisphere. These variations are attributed to subtle changes in the orbital parameters of the Earth (Milankovitch Cycles). The angle of the Earth's axis, the shape of Earth's orbit, and the wobble of the Earth's axis all contribute to establish certain cyclical warming and cooling patterns. Over the past million years the glaciation cycles have been approximately 100,000 years, with glacials (cool periods) lasting about 100,000 years and **interglacials** (warm periods) lasting about 10,000 years.

Figure 12.1.3 shows global mean temperature in the past 500,000 years. The last five glacial periods are marked with snowflakes. The most recent one, which peaked at around 20 ka, is known as the Wisconsin Glaciation. The current interglacial (Holocene) is marked with an H.

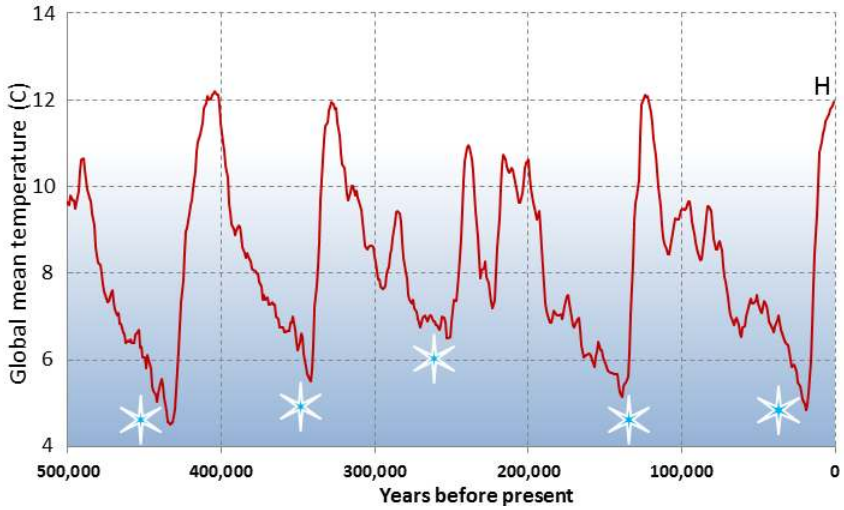


Figure 12.1.3: Temperature Fluctuations Over the Past 500,000 Years

At the height of the last glaciation (Wisconsin Glaciation) massive ice sheets covered virtually all of Canada and much of the northern United States (Figure 12.1.4). The massive Laurentide Ice Sheet covered most of eastern Canada, as far west as the Rockies, and the smaller Cordilleran Ice Sheet covered most of the western region. At various other glacial peaks during the Pleistocene and Pliocene the ice extent was like this, and in some cases even more extensive. The combined Laurentide and Cordilleran Ice Sheets were comparable in volume to the current Antarctic Ice Sheet.



Figure 12.1.4: The Extent of the Cordilleran and Laurentide Ice Sheets Near to the Peak of the Wisconsin Glaciation, around 18.5 ka

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1. Hoffman, P. F., Abbot, D. S., Ashkenazy, Y., … Warren, S. G. (2017). Snowball Earth climate dynamics and Cryogenian geology-geobiology. *Science Advances*, *3*(11), e1600983. https://doi.org/10.1126/sciadv.1600983 ↵
2. Eyles, N. (2008). Glacio-epochs and the supercontinent cycle after ~3.0 Ga: tectonic boundary conditions for glaciation. *Palaeogeography, Palaeoclimatology, Palaeoecology, 258*(1–2), 89–129. https://doi.org/10.1016/j.palaeo.2007.09.021 ↵
3. Berry, C. (2019). Palaeobotany: The rise of the Earth's early forests. *Current Biology*, *29*(16), R792-R794. https://doi.org/10.1016/j.cub.2019.07.016 ↵

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12.2: Increasing Temperatures

Global temperatures are rising (Figure 12.2.1), and there is no doubt that humans are part of that rise, mostly because of our use of fossil fuels. Over a 60-year period (from 1960 to 2020) the global mean annual temperature in both land and sea areas rose from 14° C to 15° C. Although the temperature rise was erratic in the early part of the 20th century, it has been quite consistent since 1960, increasing at a rate of 0.16° C per decade over the 60-year period, and by about 0.25° C per decade since 2000. If that continues, we are on track to exceed the Paris agreement's aspirational goal of limiting warming to 1.5° C above pre-industrial levels by 2050.

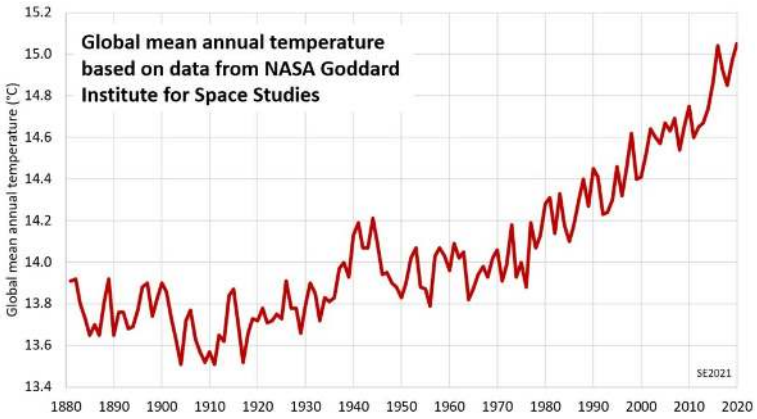


Figure 12.2.1: Variations in the Global Mean Annual Temperature, 1880 to 2020

As shown on Figure 12.2.2, most of the warming over the past 40 years has been in the northern hemisphere, and especially the far north. That is partly because of the much greater landmass of the northern hemisphere (since land areas warm faster than ocean areas). The far north is particularly affected by warming because of the significant loss of sea ice in the Arctic Ocean. Late summer Arctic Ocean sea ice extent is now typically about 60% of what it was in 1980, and the large areas of open water absorb a great deal more solar energy than the snow-covered ice that used to be there, adding to the warming. Another positive feedback from warming in the Arctic is the melting of permafrost, releasing stored methane and carbon dioxide.

In addition to the far north, central and eastern Europe and the Arabian Peninsula have seen very strong warming, and there has also been strong warming in the rest of Europe, northern China, much of Africa, Brazil, the southeastern USA and eastern Australia.

The significant warming of our climate has resulted in increased evaporation, and that is one reason why forests are so dry in many regions, leading to the increased incidence of wildfires. The other reason is localized and periodic reduced rainfall.

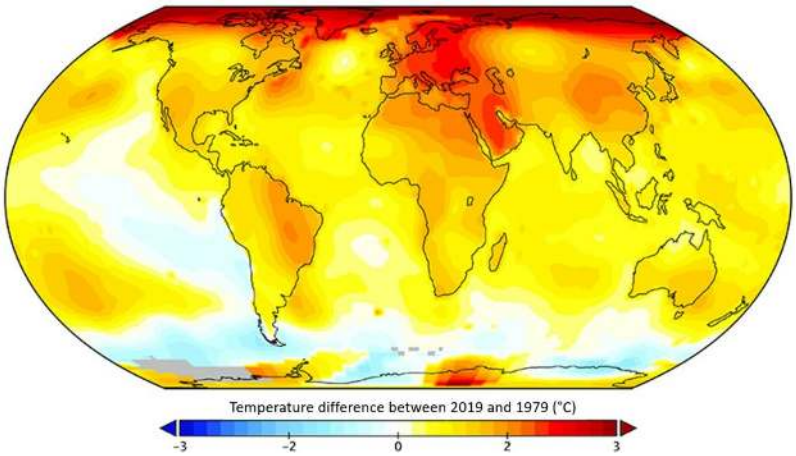


Figure 12.2.2: Spatial Pattern of Differences in Mean Annual Temperatures. 1979 to 2019

While the heat has made many places drier, some regions have become wetter because warmer air can hold more moisture than cold air. For example, much of the interior of British Columbia has seen higher levels of precipitation in recent decades. A typical

British Columbia interior precipitation record is shown on Figure 12.2.3. The average precipitation in Kaslo in the period 1915 to 1925 was 51 mm/month and the monthly amount never exceeded 70 mm. In the period from 1997 to 2007 the average was 72 mm/month (a 40% increase), and it only dropped below 60 mm for five months during that decade. This significant increase in precipitation has not been without consequences. In July 2012 part of a slope near to Kaslo failed, leading to a debris flow that killed four people in the community of Johnsons Landing.

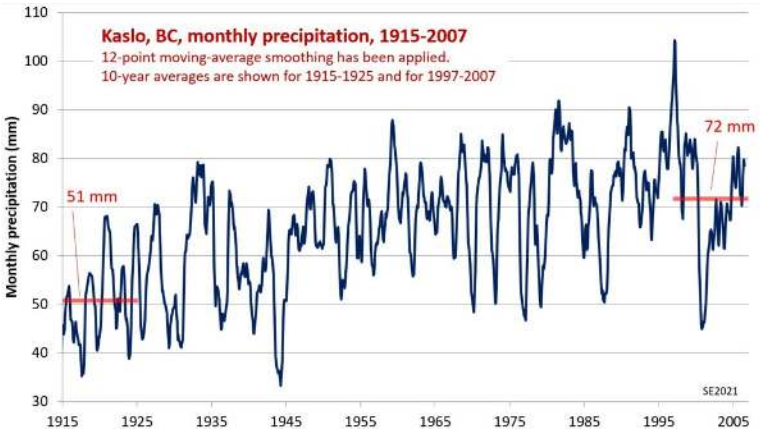


Figure 12.2.3: Monthly Precipitation at Kaslo, British Columbia,1915 to 2007

The excess heat that exists within the atmosphere is slowly being transferred to the oceans and this is illustrated on Figure 12.2.4. Since the early years of the 20th century there has been a 1° C increase in the temperature of the surface waters of the ocean. Because warm water takes up more space than cold water, this has contributed to sea level rise and to an increased incidence of tropical cyclones. Warm water can hold less carbon dioxide than cold water, so some of the ocean's CO_2 is being transferred to the atmosphere. Warm water can also hold less oxygen than cold water, and that is slowly contributing to lower oxygen levels in the oceans and in lakes.

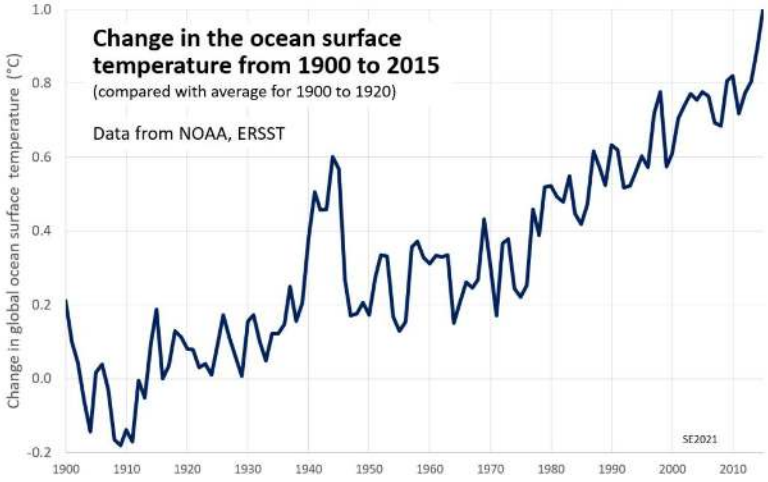


Figure 12.2.4: Global Average Ocean Surface Temperatures, 1900 to 2015, Compared With the Average for 1900 to 1920

An important implication of warming ocean water is the breakdown of reef ecosystems. Damage to corals within tropical reefs occurs when the water temperature exceeds their range of tolerance and the symbiotic relationship between the coral structures and the algae living within their tissues breaks down. The result is bleached—and therefore, likely dead—coral. Coral reefs are a vital component of ocean ecosystems, and their breakdown also has implications for marine sedimentation and the stability of the sea floor.

The famous Great Barrier Reef in Australia was suffering from successive disturbances. Marine heatwaves in 2016 and 2017 resulted in coral bleaching. Cyclones caused further damage resulting in widespread death of many corals. In the early 2020s the Reef rebounded. Generally cooler La Niña conditions mean corals made significant recovery, regrowing from very low levels to record high levels in 2022 across two-thirds of the reef. What happens in the future is yet to be seen. Higher global temperatures will cause further destruction of the reef, though it has shown it can recover significantly in short periods of time.

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12.3: Melting Glacial Ice and Permafrost

Melting Glaciers

Anthropogenic climate change has led to a rapid acceleration in the rate of melting of glacial ice. All around the world glaciers are receding. Valley glaciers are getting shorter, narrower and thinner; in recent decades some of the smaller ones have disappeared completely. The large glaciers covering most of Greenland and Antarctica are getting thinner.

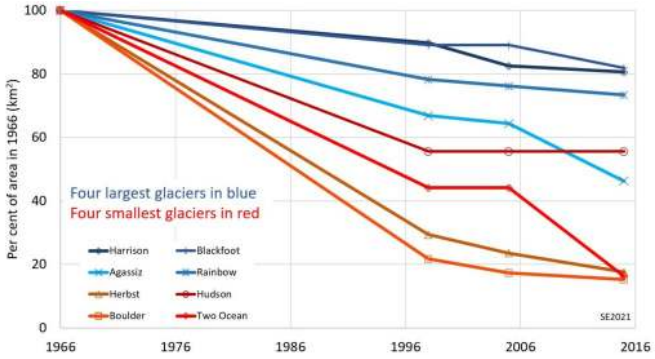


Figure 12.3.1: The Change in Area of the Four Largest and Four Smallest Glaciers in Glacier National Park, Montana, 1966 to 2015

Figure 12.3.1 shows the rate of area loss of eight of the glaciers in Glacier National Park on the US-Canada border. Over the past 50 years the four largest of the park's glaciers now have lost 20 to 50% of their area. The smaller glaciers have lost an even greater proportion: 45 to 85%. The 37 named glaciers in the park have lost a total area of 7.2 km^2, from 20.8 km^2 in 1966, to 13.6 km^2 in 2015. And that is only the loss in area; all these glaciers are now much thinner than they were 50 years ago, so their ice volumes have decreased much more than that.

A more recent global study of alpine glaciers and ice-sheet outflow glaciers has shown that their loss of mass is increasing by about 20% per year and that thinning rates have doubled over the past two decades. As shown on Figure 12.3.2, some of the greatest losses are in Alaska, Yukon and British Columbia, while Asian glacier loss rates are amongst the lowest.

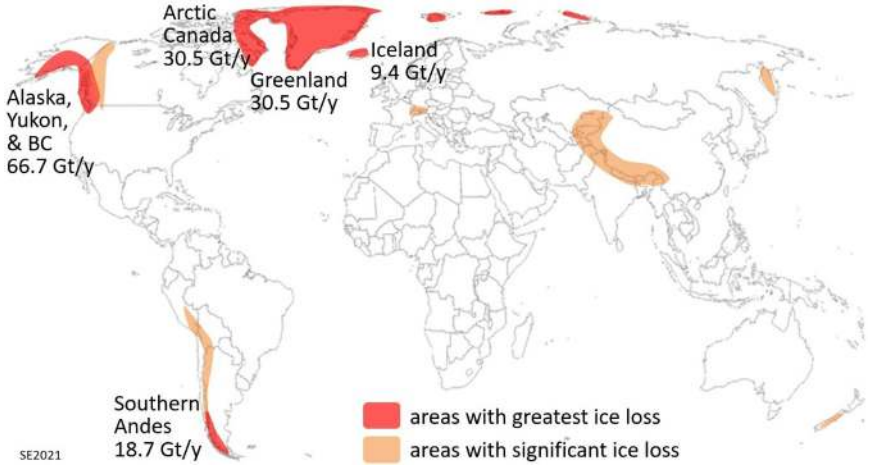


Figure 12.3.2: Annual Rates of Ice Loss From Alpine Glaciers, and from Greenland Outflow Glaciers (Antarctica, where there has also been significant ice loss, is not shown on this map.)

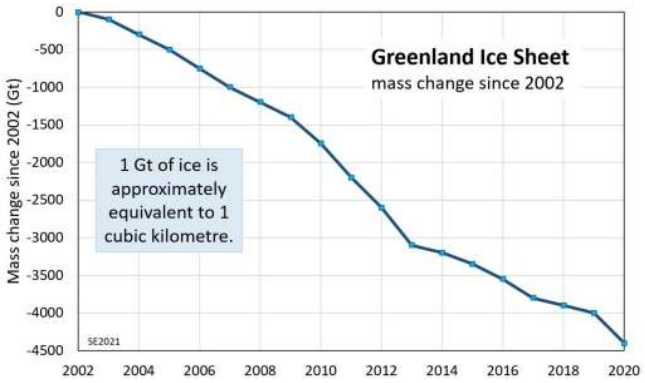


Figure 12.3.3: Loss of Mass from the Greenland Ice Sheet, 2002 to 2020

Of course, large ice sheets are also melting rapidly. The amount of ice lost from the Greenland Ice Sheet in this century is shown on Figure 12.3.3. The rate has been consistent over that time, and the total volume of ice lost is almost 4,500 km^3, or about nine times the volume of Lake Erie (~480 km^3). Although that is just a tiny fraction of the volume of Greenland's ice (about 0.02%), it is still a huge amount of lost ice.



Figure 12.3.4: Berg Glacier Flowing into Berg Lake, on the Flanks of Mt. Robson, British Columbia

But as we've seen, the loss of glaciers has other more practical implications. Billions of people depend on glacial meltwater for drinking and for agriculture, especially in the dry summers. Berg Glacier, for example, contributes to the flow of the Fraser River, which is a water source for many communities in British Columbia, and for the important "Fraser Valley" agricultural region east of Vancouver. As glaciers (and snowpacks) lose volume, the summertime flow of rivers like the Fraser will decrease and there will be less of that water available for human needs.

Glaciers do play a leading role in creating the steep slopes that later become prone to major slope failures, but while they are still around, they play a supporting role in delaying those slope failures. Glacial ice buttresses both the bedrock of a steep U-shaped valley and the glacial and other sediments that overly it. When a glacier recedes and thins, that buttressing will be lost, the exposed rock and sediments will expand in response to the reduced pressure, water will be able to seep into fractures and along bedding planes and freeze-thaw cycles will start working. All of these changes will result in an increased risk of rock falls, rock slides, rock avalanches and debris flows.

Paradoxically, a receding glacier is likely to be sliding forward faster than it was when the climate was cold. That's partly because under warming conditions there is more water flow along the base and also because, in the case of glaciers that end at the ocean or

in a lake, there is more calving and melting at the front and the ice is thinner.[1] As the rate of sliding increases, the production of sediments also increases, and so the stronger flows of water from the front of glacier will be carrying significantly more sediment than would have been the case under colder conditions. That has implications for stream dynamics and for aquatic habitats, including fish habitat.

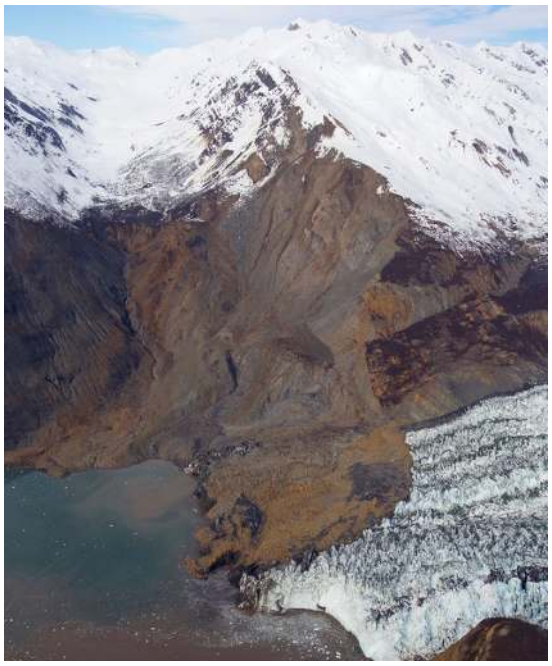


Figure 12.3.5: The Tyndall Glacier (right) and Taan Fjord (left) and the remnants of the 2015 Rock Avalanche. What is left of the Daisy Glacier occupies the hanging valley at the upper left.

The Tyndall Glacier in Alaska provides an example of both slope failure and changing sedimentation patterns related to glacial retreat. The front of the glacier retreated over 17 km from 1961 to 1991, and then stalled because of a narrow bedrock restriction. In October 2015, a 76 million cubic meter block of rock on the side of the mountain near to the terminus of the glacier failed, becoming a rock avalanche that covered part of the front of the glacier (Figure 12.3.5) and extended into the head of Taan Fjord, producing a 192 m high tsunami. According to Williams and Koppes (2019) the failure is attributed to the loss of buttressing by the Tyndall Glacier and its tributary Daisy Glacier.

The ongoing strong melting of glaciers in areas with extensive ice sheets—such as northern Canada or Greenland—has the potential to reduce the salinity of ocean water. This leads to a reduction in the density of ocean water which can result in changes in the ocean's circulation system. Although the ramifications of such changes could be global, the most immediate effect would be a slowing of the Gulf Stream, which would have significant implications for the climate of western Europe and Iceland.

The more obvious effect of melting glacial ice is sea-level rise. A 140-year record of sea-level change is shown on Figure 12.3.6.

During the early part of this period the rate of increase was just over 1 mm/y. By the latter part of the 20th century, it was over 2 mm/y and since 2000 it has been closer to 4 mm/y. Although the total rise in sea level has been relatively small so far (25 cm, or about the height of a bottle of wine) the rate is going to continue to increase, and we will very likely see that much again in the next 30 to 40 years. The total will probably exceed one meter by the end of this century and some estimates show that it could exceed 2.5 meters.[2] Most (about two-thirds) of this rise is related to addition of water from melting glaciers, but some of it is caused by an increase in the temperature of ocean water, which has made it expand.

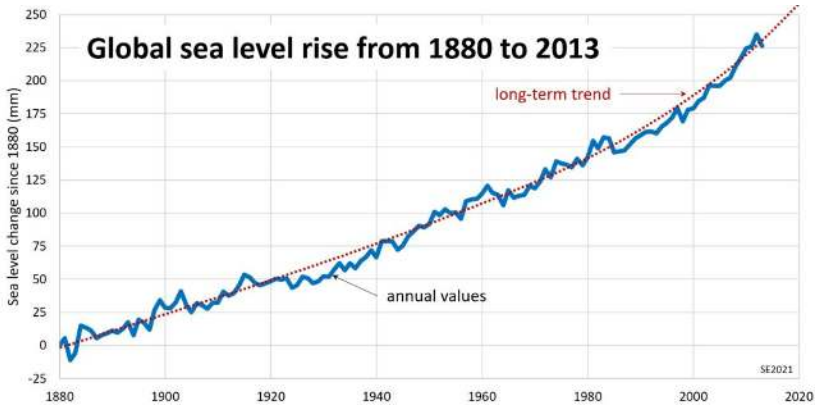


Figure 12.3.6: Average Global Sea Level Rise, 1880 to 2013

A meter of sea level rise will have life-changing implications for hundreds of millions of people around the world. A recent study shows that by 2100 over 300 million people will be at risk of at least annual flooding events, if not complete inundation, most of them in China, followed by India, Bangladesh and Vietnam, and then by most other countries in Southeast Asia as well as USA, Egypt, Japan, Netherlands, Great Britain and Brazil.[3] The risks associated with a rising sea level are exacerbated by an increase in the number of extreme weather events, especially tropical storms.

Melting Permafrost

The Batagaika Crater is a giant gaping hole in the Yakutia region of Siberia. It is 60 m deep with an area equivalent to 111 soccer fields (780,000 m^2) and it is growing by the equivalent of about 3 soccer fields a year. It started forming in the 1960s when the trees in the surrounding region were cut. That allowed the **permafrost** to start thawing, and now there is nothing that can stop it.[4] [5] The permafrost that is collapsing is rich in carbon, and that carbon is being released into the atmosphere in the form of carbon dioxide and methane.

Permanently frozen soil exists in non-glaciated areas at high latitudes or at high elevations where the mean annual temperature is consistently below 0^o C (Figure 12.3.7). It is called permafrost if it persists for at least two years, although most permafrost has existed at least since the last deglaciation (about 12,000 years). Permafrost conditions extend across about 25% of the land in the northern hemisphere. The greatest areas are in Arctic regions of Russia, Canada, and Alaska, but there is also extensive permafrost on the Tibetan Plateau and adjacent Himalayan Mountains, and less extensive areas on other mountain ranges in the northern hemisphere and the Andes in South America (not shown).

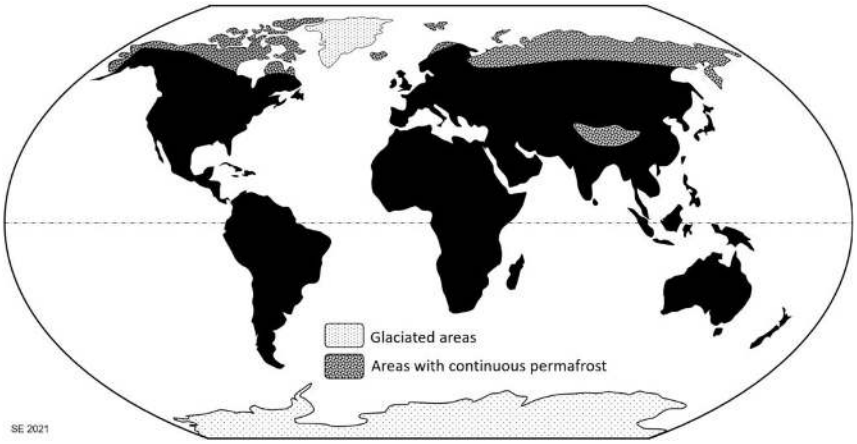


Figure 12.3.7: Regions with Continuous Permafrost. Discontinuous (patchy) permafrost also exists over a wider area than that shown, and within mountainous areas that are difficult to depict accurately at the scale of this map.

Batagaika Crater is perhaps the most striking example of permafrost collapse and disintegration, but there are thousands of other similar sites around the Arctic where melting of ice is leading to significant slope failure and, in some cases, loss of land.

It has been estimated that the frozen materials that make up permafrost hold twice as much carbon as is currently in the atmosphere,[6] and when these materials thaw and collapse most of that carbon gets released as methane and carbon dioxide. While

this process will take centuries, the rate of breakdown is accelerating, and the feedbacks, which include higher greenhouse gas levels and a decrease in the albedo of degrading sites (more solar energy is absorbed by the dark surfaces of the degraded permafrost, and so more melting takes place) are strongly positive.

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- **Figure** 12.3.7**:** Steven Earle, CC BY 4.0

1. Williams H. & Koppes M. (2019). A comparison of glacial and paraglacial denudation responses to rapid glacial retreat. *Annals of Glaciology 60*(80), 151–164. https://doi.org/10.1017/aog.2020.1 ↵
2. Sweet, W. et al. (2017). *Global and Regional Sea Level Rise Scenarios for the United States*. NOAA Tech. Rep. NOS CO-OPS 083. National Oceanic and Atmospheric Administration, National Ocean Service. ↵
3. Kulp, S. & Strauss, B. (2019). New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding. *Nature Communications*, 10(1), 4844. https://doi.org/10.1038/s41467-019-12808-z ↵
4. Murton, J. et al. (2017). Preliminary paleoenvironmental analysis of permafrost deposits at Batagaika megaslump, Yana Uplands, northeast Siberia. *Quaternary Research*, *87*(2), 314-330. doi:10.1017/qua.2016.15 ↵
5. Vadakkedath, V., Zawadzki, J. & Przeździecki, K. (2020). Multisensory satellite observations of the expansion of the Batagaika crater and succession of vegetation in its interior from 1991 to 2018. *Environmental Earth Sciences*, *79*(150), https://doi.org/10.1007/s12665-020-8895-7 ↵
6. Turetsky, M. et al. (2019). Permafrost collapse is accelerating carbon release. *Nature*, *569*(7754), 32–34. https://doi.org/10.1038/d41586-019-01313-4 ↵

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12.4: Taking Climate Action

Despite the gloomy scenarios described in the preceding sections, all is not lost when it comes to slowing climate change; there are many ways that all of us can contribute to turning things around, and, as we've seen in other chapters in this book, there are new technologies that are going to help us live with a lower climate footprint. The key thing is that we have start making changes now.

We can look for leadership from governments. Many state, provincial, and municipal governments are well ahead of our federal governments.

We can expect business leaders to make changes—and some are—but, by definition, businesses must focus on the bottom line, so they will need some signals and incentives to do the right things.

We can look in the mirror, and think about what personal changes we can make, because it is the individual actions of billions of us that have got us in the mess that we are in, and that is what is ultimately going to get us out.

Here are some things that you can do—some of them very simple—as your contribution to slamming the brakes on climate change.

The Political Realm

1. Vote! If you're reading this you are probably old enough to vote, and in a democracy, you have a responsibility to do so, because every voice should be heard. In the US less than 44% of those under 24 voted in the 2024 federal election. Older people vote at a much higher rate. It is evident that about half of those under 25 were willing to leave the important decisions about their future to their parents and grandparents.
2. Vote for a candidate that understands climate change and its implications, that has articulated a platform that is going to make a climate difference and has demonstrated a commitment to work on policies that will reduce our climate impact. These might include enhancing facilities for cycling and walking, improving public transit, promoting the adoption of electric vehicles, and encouraging the shift to renewable energy.
3. Write, e-mail, call, text, tweet or communicate however you want, and let political candidates and sitting politicians know that climate change is important to you.
4. Make your views known, in class, amongst your friends, at home, on social media or on the streets.

The Economic Realm

1. Stop supporting businesses that don't get it, such as those that make cheap throw-away products, or energy-inefficient products, or those that keep urging you to buy new stuff to replace the stuff you already have that is still perfectly OK.
2. Make a point of buying goods and services that have the lowest carbon footprints, such as smaller appliances, energy-efficient appliances, or—where there is an option—electricity that doesn't involve fossil fuels.
3. Write, e-mail, call, text, tweet to let businesses know that climate-sensitive policies and products matter to you and will influence your purchasing decisions.

The Personal Realm

1. Single-occupant fossil-fuel vehicles are the biggest source of greenhouse gases in most areas, so we all have to make every effort not to drive. Instead, choose transit, a bicycle (or an electric bicycle), or walk if possible. If there is no option other than to drive, create a car-pool.
2. Choose to live in places where transit, biking or walking are viable options.
3. If you must drive, drive an electric car, or small and efficient gas-powered car, and don't make car trips that you don't absolutely have to. It should be noted there are environmental costs to driving electric cars as well related to excess tire wear and in the production of batteries. Additionally, often the electricity used to charge them is generated using fossil fuels.
4. Reduce your consumption of meat (especially beef) and dairy products. Production of beef results in far higher greenhouse gas emissions than any other food, by a wide margin. Beef and sheep are ruminants; methane is produced in their rumens and then burped up. Pork and chicken are better meat choices.
5. Eat local foods in preference to foods brought from far away, and choose foods grown on small farms (and in gardens) over those from large monoculture and chemical-intensive operations.
6. Eat everything on your plate and make every effort to avoid throwing good food away.

7. To reduce greenhouse gas emissions, avoid sending anything organic to the landfill. That includes any food and food waste, any lawn or garden trimmings, and all paper products.
8. Turn the thermostat down and put on a sweater and turn the air-conditioner down and look for other ways or places to stay cool.
9. Don’t buy stuff you don’t need.
10. Don’t fly to places that you don’t need to go to.
11. Donate some of your time, or some money, to a local organization that is working to fight climate change.

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13: Key Terms

CHAPTER 2

asthenosphere - the semi-fluid layer of the mantle beneath the lithosphere that allows tectonic plates to move

biochemical sedimentary rock - rock formed as shells made of precipitated mineral material collect and cement together

chemical sedimentary rock - rock formed as minerals precipitate from solution

clastic sedimentary rock - rock formed from the accumulation, compression and cementation of sediments

cleavage - the way a mineral naturally breaks along specific planes of weakness in its crystal structure, forming smooth, flat surfaces

convergent boundary - boundary between two tectonic plates at which the two plates move toward one another

core - the central part of Earth, consisting of a solid inner layer and a liquid outer layer, made mostly of iron and nickel

crust - the thin, outermost layer of Earth, made up of solid rock

decompression melting - the process by which rocks melt due to a decrease in pressure, typically occurring at mid-ocean ridges or hot spots

divergent boundary - boundary between two tectonic plates at which the two plates move away from one another

earthquakes - the shaking of the Earth's surface caused by the release of energy along fault lines or from volcanic activity

extrusive rock - an igneous rock that forms from lava cooling quickly at or near the Earth's surface

felsic - a type of igneous rock rich in silica and light-colored minerals

foliated - characteristic of a metamorphic rock by which it has a fabric of aligned minerals or aligned bands of minerals

hardness - a measure of how resistant a mineral is to being scratched

igneous rock - rock formed as molten material cools

intermediate - a type of igneous rock with a composition between felsic and mafic, often lighter than mafic rocks but darker than felsic rocks

intrusive rock - an igneous rock that forms from magma cooling slowly beneath the Earth's surface

lava - molten rock on the surface

lithosphere - the rigid outer layer of Earth, made up of the crust and the uppermost part of the mantle, broken into tectonic plates

mafic - a type of igneous rock that is rich in magnesium and iron and darker in color

magma - molten rock below the surface

mantle - the thick, middle layer of Earth's interior, located below the crust and above the core, made of a mix of solid and semi-solid rock

mass wasting - the failure and down-slope movement of rock or unconsolidated materials in response to gravity

metamorphic rock - rock that has been changed from its original form by heat, pressure, or chemical processes

mineral - a naturally occurring, inorganic solid with a specific chemical composition and crystal structure

organic sedimentary rock - rock formed through the accumulation of organic material

plate - a rigid piece of Earth's lithosphere that moves on top of the asthenosphere.

plate boundary - the area where two tectonic plates meet

rock cycle - the continuous process by which rocks are formed, altered, destroyed, and reformed through geological processes like melting, cooling, erosion, and exposure to pressure

rocks - aggregates of the crystals of one or more minerals

sedimentary rock - rock formed from the accumulation and compression of sediments, through the accumulation of precipitated minerals, or through the accumulation of organic material

silica tetrahedron - a basic building block of silicate minerals, consisting of one silicon atom bonded to four oxygen atoms in a pyramid shape

silicate minerals - minerals that contain silicon and oxygen as their main elements, forming the majority of Earth's crust

specific gravity - the ratio of a mineral's density compared to the density of water

transform boundary - boundary between two tectonic plates at which the two plates slide past one another

volcanic rock - a type of igneous rock formed from lava that cools and solidifies quickly on or near Earth's surface

CHAPTER 3

chemical weathering - the chemical change of earth material into materials with a different composition resulting from exposure to the atmosphere

clay - any unconsolidated material with a grain diameter less than 0.004 mm, or the group of minerals called clay minerals, which are sheet silicates

exfoliation - the process by which layers or sheets of rock peel off due to changes in temperature or pressure

frost wedging - the process by which the water seeps into cracks in a rock, expands on freezing, and thus enlarges the cracks

hydrolysis - a chemical weathering process where minerals in rock react with water, causing them to break down and form new minerals, usually clay

mechanical weathering - the physical breakdown of rock into smaller pieces

oxidation - a chemical weathering process where minerals, especially those containing iron, react with oxygen in the air or water, causing them to lose electrons and become weaker

parent material - the material from which a soil forms

relief - the slope of a surface

soil - loose material formed in place by weathering the underlying materials

soil horizon - a distinct layer of soil that differs in color, texture, and composition from the layers above or below it

weathering - the process by which rock breaks down

CHAPTER 4

cinder cone - a small, steep-sided volcano made of ash, cinders, and other volcanic debris that erupts explosively and is usually made of mafic materials

composite volcano - a large, steep-sided volcano formed by alternating eruptions of lava flows and explosive ash, creating layers of solidified lava and debris

lahar - volcanic mudflow or debris flow

shield volcano - a broad, gently sloping volcano formed by the eruption of low-viscosity, mafic lava that flows easily, creating wide, shield-like shapes

tephra - volcanic rock fragments of any size such as the very small volcanic ash

volatiles — components that behave as gases during volcanic eruptions

CHAPTER 5

body waves - seismic waves that travel through the Earth's interior, including P-waves (primary waves) and S-waves (secondary waves), during an earthquake

earthquake intensity - a measure of what people felt and how much damage was done during an earthquake

earthquake magnitude - a measure of the amount of energy released during an earthquake

elastic deformation - he temporary change in shape or size of rocks due to stress, which can return to its original form once the stress is removed

epicenter - the point on the land surface directly above the hypocenter of the earthquake

hypocenter - the actual location of an individual earthquake's starting point at depth in the ground

intraplate - being located away from a plate boundary in the more center part of the plate

liquefaction - process by which otherwise solid body of sediment gets transformed into a liquid mass that can flow, often as a result of an earthquake

stress - force applied to a body

strain - change in shape caused by stress

surface waves - seismic waves that travel along the Earth's surface, causing most of the shaking felt during an earthquake; they include Love waves and Rayleigh waves

tsunami - very large wave, usually in the ocean, generated as the seafloor moves as a result of an earthquake event

CHAPTER 6

creep - very slow movement of soil or other unconsolidated material on a slope

debris flow - the down slope movement of a mix of different size materials that occurs when a mass of sediment becomes completely saturated with water, to the extent that the mass loses strength and flows

mud flow - the down slope movement of mud-sized materials that occurs when a mass of sediment becomes completely saturated with water, to the extent that the mass loses strength and flows

rock avalanche - the sliding motion of rock along a sloping surface at very fast rates

rock fall - abrupt movement of rock which become detached from steep slopes or cliffs

rock slide - the sliding motion of rock along a sloping surface

slump - a type of slide that takes place within thick unconsolidated deposits where there is movement along a curved surface such that there is downward motion near to the top and outward motion towards the bottom

CHAPTER 7

ammonification - the process by which decomposers break down organic matter (like dead plants and animals) and release nitrogen in the form of ammonia

carbon cycle - the process by which carbon is exchanged between the atmosphere, oceans, soil, plants, and animals, helping regulate Earth's climate

climate - the average weather for a region over time

denitrification - the process by which bacteria convert nitrates back into nitrogen gas, returning it to the atmosphere

exosphere - the outermost layer of Earth's atmosphere, where particles are very spread out and can escape into space

mesosphere - the middle layer of Earth's atmosphere, where meteors burn up upon entering

nitrification - the process by which certain bacteria convert ammonia into nitrites and then into nitrates, which plants can use as a nutrient

nitrogen cycle - the process by which nitrogen moves between the atmosphere, soil, plants, and animals, involving various bacteria and other organisms

nitrogen fixation - the process by which certain bacteria convert nitrogen gas from the atmosphere into forms (like ammonia) that plants can use for growth

photosynthesis - the process by which plants use sunlight, carbon dioxide, and water to produce food (glucose) and oxygen

stratosphere - the layer above the troposphere, where the ozone layer is located and where weather is more stable

thermosphere - a layer of the atmosphere above the mesosphere, where temperatures increase with altitude and where the auroras occur

troposphere - the lowest layer of Earth's atmosphere, where weather happens and clouds form

weather - the summation of current atmospheric conditions at any given moment

CHAPTER 8

aquifer - a layer of rock or sediment that stores and transmits groundwater, often used as a source of potable water

aquitard - a layer of rock or sediment that slows or prevents the flow of groundwater, acting as a barrier between aquifers

cone of depression - a funnel-shaped depression in the water table that forms around a well when groundwater is being pumped out faster than it can be replenished

confined aquifer - an aquifer that is trapped between two layers of impermeable rock or sediment, preventing easy flow of water

drainage basin - the area of land where all water drains into a single river or stream, including its tributaries

drainage divide - high spot that separates two drainage basins

drought - a period of reduced rainfall and/or snowfall that results in water-related problems

floodplain - the flat area of land next to a stream that is prone to flooding during heavy rain or when the river overflows

flood recurrence interval - the probability that a flood of a certain size will happen at some time in the future

groundwater - the water stored in the open spaces within unconsolidated sediment and the underlying bedrock

overland flow - the movement of water across the land's surface, usually after heavy rainfall, before it reaches streams

permeability - the interconnectedness of the pores in a rock or sediment which determines how well fluid can flow through the body

porosity - the amount of open pore space in a rock or sediment

saturated zone - the layer of rock or sediment where all the pore spaces are filled with water, located below the water table

stream - a body of flowing surface water of any size

subsidence - the lowering of the Earth's surface due to the removal of groundwater

transpiration - evaporation by solar energy from plants

tributary - a smaller stream that feeds into the larger one

turbidity - a measure of the amount of solid matter suspended in water

unconfined aquifer - an aquifer that is not sealed by an impermeable layer and is open to the surface, allowing water to easily flow in and out

unsaturated zone - the layer of rock or sediment above the water table, where pore spaces contain both air and water

water table - the upper limit of the saturated zone

CHAPTER 9

fossil fuels - natural fuels like coal, oil, and natural gas formed from the remains of ancient plants and animals, used to produce energy

geothermal energy - energy derived from the heat stored inside the Earth, often used for heating or generating electricity

hydroelectric power - energy produced by the movement of water, typically from dams or flowing rivers, to generate electricity

non-renewable sources - energy sources that once they are extracted from Earth materials and consumed, they are gone

nuclear energy - the energy that is stored in the nuclei of atoms

nuclear fission - a process in which the nucleus of an atom splits into smaller parts, releasing a large amount of energy

nuclear fusion - a process where two atomic nuclei combine to form a heavier nucleus, releasing energy; this is the process that powers the Sun

solar energy - energy harnessed from the Sun, typically using solar panels or solar collectors

tides - the regular rise and fall of sea levels caused by the gravitational pull of the Moon and Sun on Earth's oceans

wind energy - energy generated by the movement of air, typically captured using wind turbines

CHAPTER 10

dump - a place where waste is discarded

landfill - an engineered structure with barriers to contain the waste, mechanisms to capture and treat liquid and gaseous waste byproducts, and procedures in place to monitor the surrounding water and air

monitoring wells - wells constructed around a landfill to sample the groundwater and determine if any contaminants are escaping

CHAPTER 11

greenhouse gases - gases that trap the Earth's heat in the atmosphere, leading to warmer temperatures

nonpoint sources - pollution that comes from multiple, scattered sources, such as runoff from roads or farmland, rather than a single identifiable location

point sources - pollution that comes from a single, specific location, such as a factory or wastewater treatment plant

underground storage tanks

smog - a type of air pollution made up of smoke, fog, and chemical pollutants, often caused by vehicle emissions and industrial activity

soot - Fine black particles produced by burning fossil fuels or wood, which pollute the air

CHAPTER 12

glacial - a period of cooler climate often referred to as an ice age when glaciers are advancing/growing

interglacial - a period of warmer climate between glacials, when glaciers are retreating/melting

permafrost - ground that remains frozen year-round

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Glossary

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mafic | a type of igneous rock that is rich in magnesium and iron and darker in color

magma | molten rock below the surface

mantle | the thick, middle layer of Earth's interior, located below the crust and above the core, made of a mix of solid and semi-solid rock

mass wasting | the failure and down-slope movement of rock or unconsolidated materials in response to gravity

mechanical weathering | the physical breakdown of rock into smaller pieces

mesosphere | the middle layer of Earth's atmosphere, where meteors burn up upon entering

metamorphic rock | rock that has been changed from its original form by heat, pressure, or chemical processes

mineral | a naturally occurring, inorganic solid with a specific chemical composition and crystal structure

monitoring wells | wells constructed around a landfill to sample the groundwater and determine if any contaminants are escaping

mud flow | the down slope movement of mud-sized materials that occurs when a mass of sediment becomes completely saturated with water, to the extent that the mass loses strength and flows

nitrification | the process by which certain bacteria convert ammonia into nitrites and then into nitrates, which plants can use as a nutrient

nitrogen cycle | the process by which nitrogen moves between the atmosphere, soil, plants, and animals, involving various bacteria and other organisms

nitrogen fixation | the process by which certain bacteria convert nitrogen gas from the atmosphere into forms (like ammonia) that plants can use for growth

non-renewable sources | energy sources that once they are extracted from Earth materials and consumed, they are gone

nonpoint sources | pollution that comes from multiple, scattered sources, such as runoff from roads or farmland, rather than a single identifiable location

nuclear energy | the energy that is stored in the nuclei of atoms

nuclear fission | a process in which the nucleus of an atom splits into smaller parts, releasing a large amount of energy

nuclear fusion | a process where two atomic nuclei combine to form a heavier nucleus, releasing energy; this is the process that powers the Sun

organic sedimentary rock | rock formed through the accumulation of organic material

overland flow | the movement of water across the land's surface, usually after heavy rainfall, before it reaches streams

oxidation | a chemical weathering process where minerals, especially those containing iron, react with oxygen in the air or water, causing them to lose electrons and become weaker

parent material | the material from which a soil forms

permafrost | ground that remains frozen year-round

permeability | the interconnectedness of the pores in a rock or sediment which determines how well fluid can flow through the body

photosynthesis | the process by which plants use sunlight, carbon dioxide, and water to produce food (glucose) and oxygen

plate | a rigid piece of Earth's lithosphere that moves on top of the asthenosphere.

plate boundary | the area where two tectonic plates meet

point sources | pollution that comes from a single, specific location, such as a factory or wastewater treatment plant

porosity | the amount of open pore space in a rock or sediment

relief | the slope of a surface

rock avalanche | the sliding motion of rock along a sloping surface at very fast rates

rock cycle | the continuous process by which rocks are formed, altered, destroyed, and reformed through geological processes like melting, cooling, erosion, and exposure to pressure

rock fall | abrupt movement of rock which become detached from steep slopes or cliffs

rock slide | the sliding motion of rock along a sloping surface

rocks | aggregates of the crystals of one or more minerals

saturated zone | the layer of rock or sediment where all the pore spaces are filled with water, located below the water table

sedimentary rock | rock formed from the accumulation and compression of sediments, through the accumulation of precipitated minerals, or through the accumulation of organic material

shield volcano | a broad, gently sloping volcano formed by the eruption of low-viscosity, mafic lava that flows easily, creating wide, shield-like shapes

silica tetrahedron | a basic building block of silicate minerals, consisting of one silicon atom bonded to four oxygen atoms in a pyramid shape

silicate minerals | minerals that contain silicon and oxygen as their main elements, forming the majority of Earth's crust

slump | a type of slide that takes place within thick unconsolidated deposits where there is movement along a curved surface such that there is downward motion near to the top and outward motion towards the bottom

smog | a type of air pollution made up of smoke, fog, and chemical pollutants, often caused by vehicle emissions and industrial activity

soil | loose material formed in place by weathering the underlying materials

soil horizon | a distinct layer of soil that differs in color, texture, and composition from the layers above or below it

solar energy | energy harnessed from the Sun, typically using solar panels or solar collectors

soot | Fine black particles produced by burning fossil fuels or wood, which pollute the air

specific gravity | the ratio of a mineral's density compared to the density of water

strain | change in shape caused by stress

stratosphere | the layer above the troposphere, where the ozone layer is located and where weather is more stable

stream | a body of flowing surface water of any size

stress | force applied to a body

subsidence | the lowering of the Earth's surface due to the removal of groundwater

surface waves | seismic waves that travel along the Earth's surface, causing most of the shaking felt during an earthquake; they include Love waves and Rayleigh waves

tephra | volcanic rock fragments of any size such as the very small volcanic ash

thermosphere | a layer of the atmosphere above the mesosphere, where temperatures increase with altitude and where the auroras occur

tides | the regular rise and fall of sea levels caused by the gravitational pull of the Moon and Sun on Earth’s oceans

transform boundary | boundary between two tectonic plates at which the two plates slide past one another

transpiration | evaporation by solar energy from plants

tributary | a smaller stream that feeds into the larger one

troposphere | the lowest layer of Earth's atmosphere, where weather happens and clouds form

tsunami | very large wave, usually in the ocean, generated as the seafloor moves as a result of an earthquake event

turbidity | a measure of the amount of solid matter suspended in water

unconfined aquifer | an aquifer that is not sealed by an impermeable layer and is open to the surface, allowing water to easily flow in and out

unsaturated zone | the layer of rock or sediment above the water table, where pore spaces contain both air and water

volcanic rock | a type of igneous rock formed from lava that cools and solidifies quickly on or near Earth's surface

water table | the upper limit of the saturated zone

weather | the summation of current atmospheric conditions at any given moment

weathering | the process by which rock breaks down

wind energy | energy generated by the movement of air, typically captured using wind turbines

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Overview

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