Chapter 1 Introduction to Geology

Learning Objectives

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

- Explain what geology is, how it incorporates the other sciences, and how it is different from the other sciences.
- Discuss why we study Earth and what type of work geologists do.
- Define some of the properties of a mineral and explain the differences between minerals and rocks.
- Describe the nature of Earth's interior and some of the processes that take place deep beneath our feet.
- Explain how those processes are related to plate tectonics and describe a few of the features that are characteristic of plate boundaries.
- Use the notation for geological time, gain an appreciation for the vastness of geological time, and describe how very slow geological processes can have enormous impacts over time.

1.1 What is Geology?

In its broadest sense, geology is the study of Earth—its interior and its exterior surface, the minerals, rocks and other materials that are around us, the processes that have resulted in the formation of those materials, the water that flows over the surface and through the ground, the changes that have taken place over the vastness of geological time, and the changes that we can anticipate will take place in the near future. Geology is a science, meaning that we use deductive reasoning and scientific methods to understand geological problems. It is, arguably, the most integrated of all of the sciences because it involves the understanding and application of all of the other sciences: physics, chemistry, biology, mathematics, astronomy, and others. But unlike most of the other sciences, geology has an extra dimension, that of time—deep time—billions of years of it. Geologists study the evidence that they see around them, but in most cases, they are observing the results of processes that happened thousands, millions, and even billions of years in the past. Those were processes that took place at incredibly slow rates—millimetres per year to centimetres per year—but because of the amount of time available, they produced massive results.

Geology is displayed on a grand scale in mountainous regions, perhaps nowhere better than the Rocky Mountains in Canada (Figure 1.1.1). The peak on the right is Rearguard Mountain, which is a few kilometres northeast of Mount Robson, the tallest peak in the Canadian Rockies (3,954 metres). The large glacier in the middle of the photo is the Robson Glacier. The river flowing from Robson Glacier drains into Berg Lake in the bottom right. There are many geological features portrayed here. The sedimentary rock that these mountains are made of formed in ocean water over 500 million years ago. A few hundred million years later, these beds were pushed east for tens to hundreds of kilometres by tectonic plate convergence and also pushed up to thousands of metres above sea level. Over the past two million years this area—like most of the rest of Canada—has been repeatedly glaciated, and the erosional effects of those glaciations are obvious.

The Robson Glacier is now only a small remnant of its size during the Little Ice Age of the 15th to 18th centuries, and even a lot smaller that it was just over a century ago in 1908. The distinctive line on the slope on the left side of both photos shows the elevation of the edge of the glacier a few hundred years ago. Like almost all other glaciers in the world, it receded after the 18th century because of natural climate change, is now receding even more rapidly because of human-caused climate change.

Figure 1.1.1 *Rearguard Mountain and Robson Glacier in Mount Robson Provincial Park, BC. Left: Robson Glacier in 2012. Right: Robson Glacier circa 1908.*

Geology is also about understanding the evolution of life on Earth; about discovering resources such as water, metals and energy; about recognizing and minimizing the environmental implications of our use of those resources; and about learning how to mitigate the hazards related to earthquakes, volcanic eruptions, and slope failures. All of these aspects of geology, and many more, are covered in this textbook.

What are scientific methods?

There is no single method of inquiry that is specifically the “scientific method”; furthermore, scientific inquiry is not necessarily different from serious research in other disciplines. The most important thing that those involved in any type of inquiry must do is to be skeptical. As the physicist Richard Feynman once said: the first principle of science is that “you must not fool yourself—and you are the easiest person to fool.” A key feature of serious inquiry is the creation of a hypothesis (a tentative explanation) that could explain the observations that have been made, and then the formulation and testing (by experimentation) of one or more predictions that follow from that hypothesis.

Figure 1.1.2

For example, we might observe that most of the cobbles in a stream bed are well rounded (see photo above), and then derive the hypothesis that the rocks are rounded by transportation along the stream bed. A prediction that follows from this hypothesis is that cobbles present in a stream will become increasingly rounded as they are transported downstream. An experiment to test this prediction would be to place some angular cobbles in a stream, label them so that we can be sure to find them again later, and then return at various time intervals (over a period of years) to carefully measure their locations and roundness.

A critical feature of a good hypothesis and any resulting predictions is that they must be testable. For example, an alternative hypothesis to the one above is that an extraterrestrial organization creates rounded cobbles and places them in streams when nobody is looking. This may indeed be the case, but there is no practical way to test this hypothesis. Most importantly, there is no way to prove that it is false, because if we aren't able to catch the aliens at work, we still won't know if they did it!

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- Figure 1.1.2: © Steven Earle. CC BY.

1.2 Why Study Earth?

The simple answer to this question is that Earth is our home—our only home for the foreseeable future—and in order to ensure that it continues to be a great place to live, we need to understand how it works. Another answer is that some of us can't help but study it because it's fascinating. But there is more to it than that:

- We rely on Earth for valuable resources such as soil, water, metals, industrial minerals, and energy, and we need to know how to find these resources and exploit them sustainably.
- We can study rocks and the fossils they contain to understand the evolution of our environment and the life within it.
- We can learn to minimize our risks from earthquakes, volcanoes, slope failures, and damaging storms.
- We can learn how and why Earth's climate has changed naturally in the past, and use that knowledge to understand both natural and human-caused climate change.
- We can recognize how our activities have altered the environment in many ways and the climate in increasingly serious ways, and how to avoid more severe changes in the future.
- We can use our knowledge of Earth to understand other planets in our solar system, as well as those around distant stars.

An example of the importance of geological studies for minimizing risks to the public is illustrated in Figure 1.2.1. This is a slope failure that took place in January 2005 in the Riverside Drive area of North Vancouver. The steep bank beneath the house shown gave way, and a slurry of mud and sand flowed down, destroying another house below and killing one person. This event took place following a heavy rainfall, which is a common occurrence in southwestern B.C. in the winter.

Figure 1.2.1 The aftermath of a deadly debris flow in the Riverside Drive area of North Vancouver in January 2005.

The irony of the 2005 slope failure is that the District of North Vancouver had been warned in a geological report written in 1980 that this area was prone to slope failure and that steps should be taken to minimize the risk to residents. Very little was done in the intervening 25 years, and the consequences of that were deadly.

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1.3 What Do Geologists Do?

Geologists are involved in a range of widely varying occupations with one thing in common: the privilege and responsibility of studying this fascinating planet. In Canada, many geologists work in the resource industries, including mineral exploration and mining and energy exploration and extraction. Other major areas where geologists work include hazard assessment and mitigation (e.g., assessment of risks from slope failures, earthquakes, and volcanic eruptions); water supply planning, development, and management; waste management; and assessment of geological issues in the forest industry, and on construction projects such as highways, tunnels, and bridges. Most geologists are employed in the private sector, but many work for government-funded geological organizations, such as the Geological Survey of Canada or one of the provincial geological surveys. And of course, many geologists are involved in education at the secondary and the post-secondary levels.

Some people are attracted to geology because they like to be outdoors, and it is true that many geological opportunities involve fieldwork in places that are as amazing to see as they are interesting to study. But a lot of geological work is also done in offices or laboratories. Geological work tends to be varied and challenging, and for these reasons and many others, geologists are among those who are the most satisfied with their employment.

Figure 1.3.1 Geologists examining ash-layer deposits at Kilauea Volcano, Hawaii.

In Canada, most working geologists are required to be registered with an association of professional geoscientists. This typically involves meeting specific post-secondary educational standards and gaining several years of relevant professional experience under the supervision of a registered geoscientist. More information can be found at Engineers and Geoscientists British Columbia.

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- Figure 1.3.1: © Steven Earle. CC BY.

1.4 Minerals and Rocks

The rest of this chapter is devoted to a brief overview of a few of the important aspects of physical geology, starting with minerals and rocks. This is followed by a review of Earth's internal structure and the processes of plate tectonics, and an explanation of geological time.

The Earth is made up of varying proportions of the 90 naturally occurring elements—hydrogen, carbon, oxygen, magnesium, silicon, iron, and so on. In most geological materials, these combine in various ways to make minerals. Minerals will be covered in some detail in Chapter 2, but here we will briefly touch on what minerals are, and how they are related to rocks.

A mineral is a naturally occurring combination of specific elements that are arranged in a particular repeating three-dimensional structure or **lattice**.[1] The mineral **halite** is shown as an example in Figure 1.4.1.

In this case, atoms of sodium (Na: purple) alternate with atoms of chlorine (Cl: green) in all three dimensions, and the angles between the bonds are all 90°. Even in a tiny crystal, like the ones in your salt shaker, the lattices extend in all three directions for thousands of repetitions. Halite always has this composition and this structure.

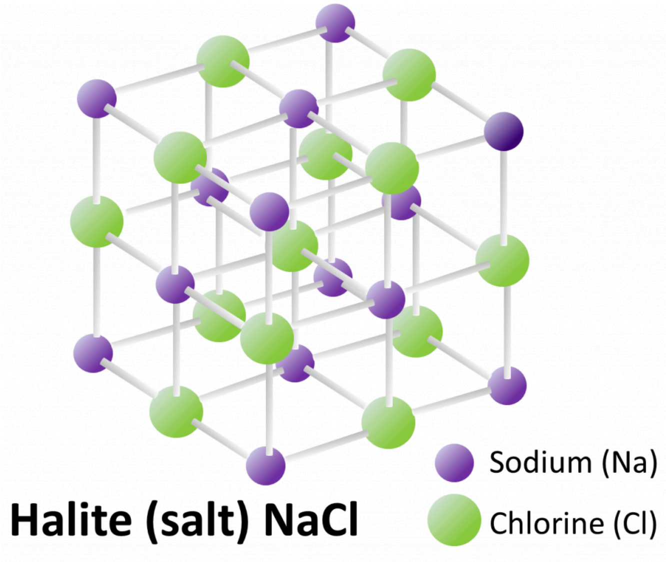

Figure 1.4.1 The lattice structure and composition of the mineral halite (common table salt).

Note: Element symbols (e.g., Na and Cl) are used extensively in this book. In Appendix 1, you will find a list of the symbols and names of the elements common in minerals and a copy of the periodic table. Please use those resources if you are not familiar with the element symbols.

There are thousands of minerals, although only a few dozen are mentioned in this book. In nature, minerals are found in rocks, and the vast majority of rocks are composed of at least a few different minerals. A close-up view of **granite**, a common rock, is shown in Figure 1.4.2. Although a hand-sized piece of granite may have thousands of individual mineral crystals in it, there are typically only a few different minerals, as shown here.

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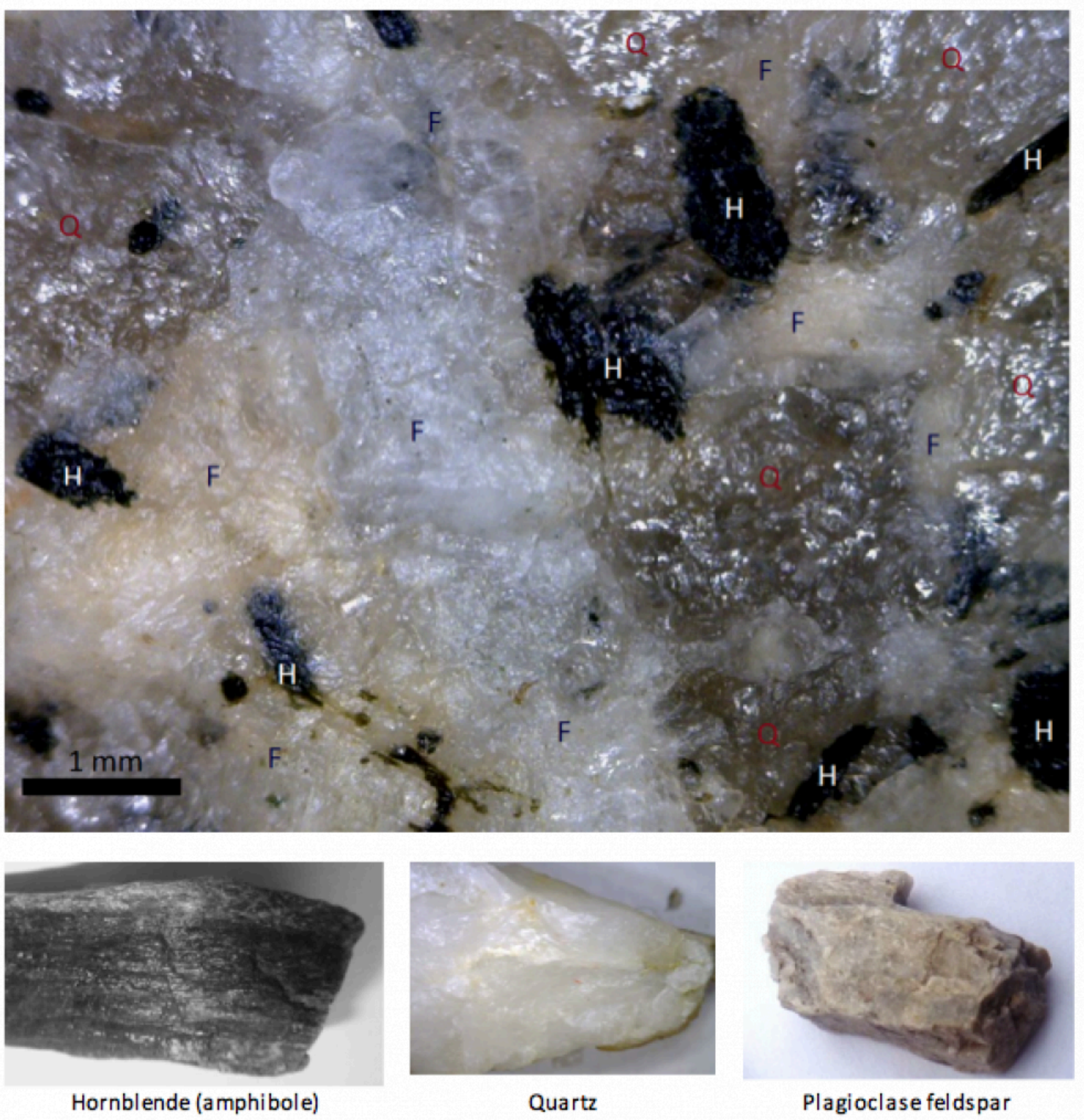
[1] Terms in bold are defined in the glossary at the end of the book.



Hornblende (amphibole) Quartz Plagioclase feldspar

Figure 1.4.2 A close-up view of the rock granite and some of the minerals that it typically contains (H = hornblende (amphibole), Q = quartz and F = feldspar). The crystals range from about 0.1 to 3 millimetres (mm) in diameter. Most are irregular in outline, but some are rectangular.

Rocks can form in a variety of ways. Igneous rocks form from **magma** (molten rock) that has either cooled slowly underground (e.g., to produce granite) or cooled quickly at the surface after a volcanic eruption (e.g., **basalt**). Sedimentary rocks, such as **sandstone**, form when the weathered products of other rocks accumulate at the surface and are then buried by other sediments. Metamorphic rocks form when either igneous or sedimentary rocks are heated and squeezed to the point where some of their minerals are unstable and new minerals form to create a different type of rock. An example is **schist**.

A critical point to remember is the difference between a mineral and a rock. A mineral is a pure substance with a specific composition and structure, while a rock is typically a mixture of several different minerals (although a few types of rock may include only one type of mineral). Examples of minerals are feldspar, quartz, mica, halite, calcite, and amphibole. Examples of rocks are granite, basalt, sandstone, limestone, and schist.

Key Takeaway: Know the difference between minerals and rocks!

If you are currently taking a geology course, you'll likely be asked more than once to name a mineral or a rock that has specific characteristics or composition, or was formed in a specific environment. Please make sure that if you're asked for a **rock name** that you don't respond with a **mineral name**, and *vice versa*. Confusing minerals and rocks is one of the most common mistakes that geology students make.

Exercise 1.1 Find a piece of granite

The rock granite is very common in most parts of North America, and unless everything is currently covered with snow where you live, you should have no trouble finding a sample of it near you. The best places to look are pebbly ocean or lake beaches, a gravel bar of a creek or river, a gravel driveway, or somewhere where gravel has been used in landscaping. In Figure 1.4.3, taken on a beach, the granitic pebbles are the ones that are predominantly light-coloured with dark specks. The one in the very centre is a good example.

Figure 1.4.3

Select a sample of granite and, referring to Figure 1.4.2, see if you can identify some of the minerals in it. It may help to break it in half with a hammer to see a fresh surface, but be careful to protect your eyes if you do so. You should be able to see glassy-looking quartz, dull white plagioclase feldspar (and maybe pink potassium feldspar), and black hornblende or, in some cases, flaky black biotite mica (or both).

In addition to identifying the minerals in your granite, you might also try to describe the texture in terms of the range sizes of the mineral crystals (in millimetres) and the shapes of the crystals (some may be rectangular in outline, most will be irregular). Think about where your granite might have come from and how it got to where you found it.

See Appendix 3 for Exercise 1.1 answers.

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- Figure 1.4.1, 1.4.2, 1.4.3: © Steven Earle. CC BY.

1.5 Fundamentals of Plate Tectonics

Plate tectonics is the model or theory that has been used for the past 60 years to understand and explain how the Earth works—more specifically the origins of continents and oceans, of folded rocks and mountain ranges, of earthquakes and volcanoes, and of continental drift. Plate tectonics is explained in some detail in Chapter 10, but is introduced here because it includes concepts that are important to many of the topics covered in the next few chapters.

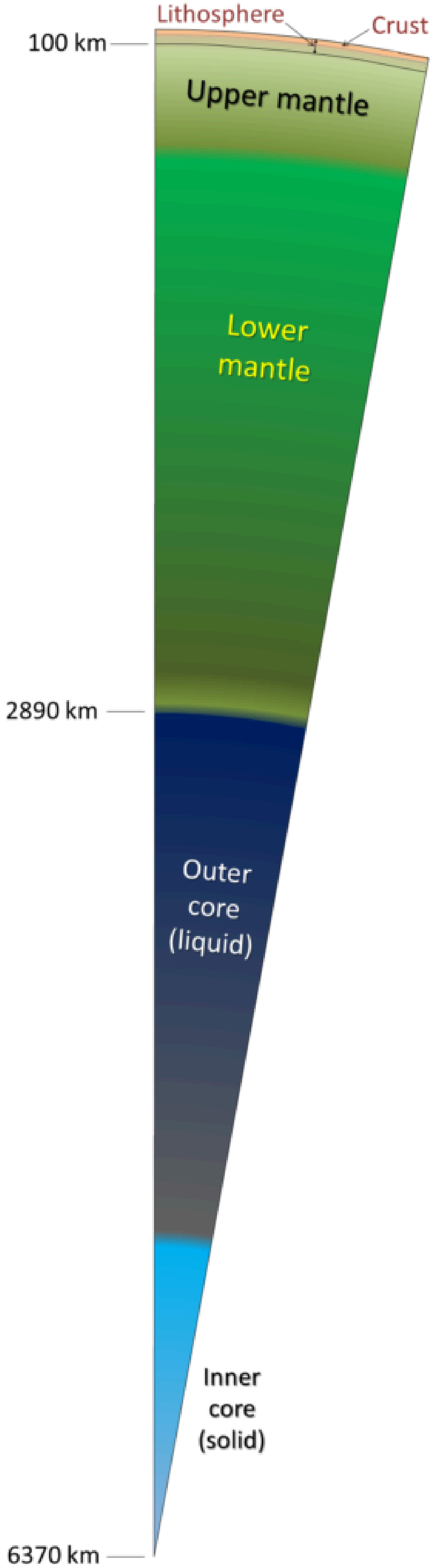

Figure 1.5.1 The components of the interior of the Earth (click on the image to see a

full-size version).

Key to understanding plate tectonics is an understanding of Earth's internal structure, which is illustrated in Figure 1.5.1. Earth's **core** consists mostly of iron. The outer core is hot enough for the iron to be liquid. The inner core—although even hotter—is under so much pressure that it is solid. The **mantle** is made up of iron and magnesium **silicate** minerals. The bulk of the mantle surrounding the outer core is solid rock, but is plastic enough to be able to flow slowly. The outermost part of the mantle is rigid. The **crust**—composed mostly of granite on the continents and mostly of basalt beneath the oceans—is also rigid. The crust and outermost rigid mantle together make up the **lithosphere**. The lithosphere is divided into about 20 **tectonic plates** that move in different directions on Earth's surface.

An important property of Earth (and other planets) is that the temperature increases with depth, from close to 0°C at the surface to about 7000°C at the centre of the core. In the crust, the rate of temperature increase is about 30°C every kilometre. This is known as the **geothermal gradient**.

Heat is continuously flowing outward from Earth's interior, and the transfer of heat from the core to the mantle causes convection in the mantle (Figure 1.5.2). This convection is the primary driving force for the movement of tectonic plates. At places where convection currents in the mantle are moving upward, new lithosphere forms (at ocean ridges), and the plates move apart (diverge). Where two plates are converging (and the convective flow is downward), one plate will be **subducted** (pushed down) into the mantle beneath the other. Many of Earth's major earthquakes and volcanoes are associated with convergent boundaries.

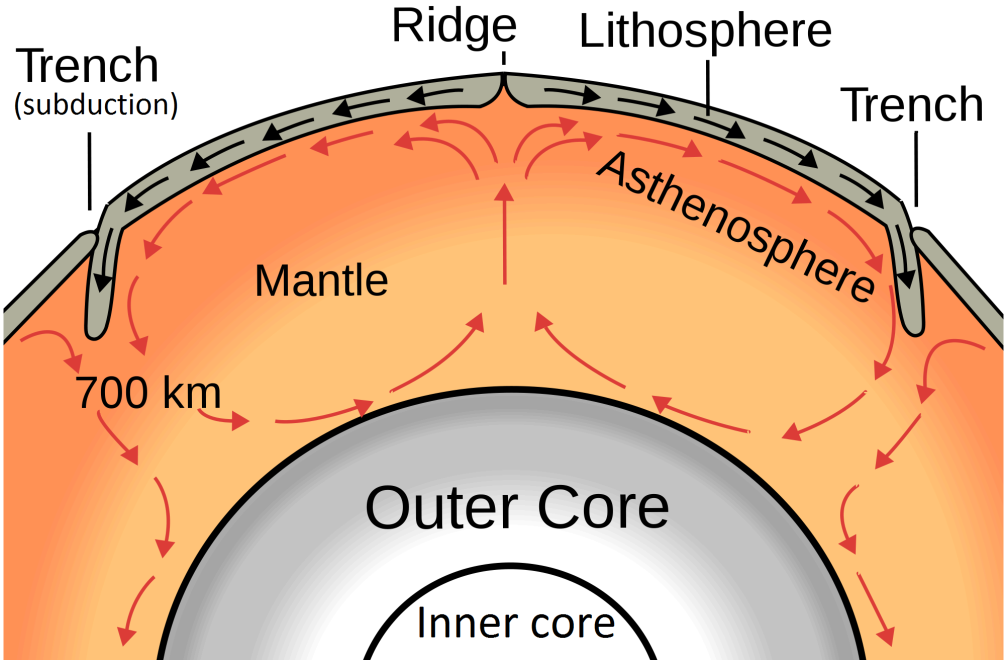

Figure 1.5.2 Depiction of the convection in the mantle and it's relationship to plate motion

Earth's major tectonic plates and the directions and rates at which they are diverging at sea-floor ridges, are shown in Figure 1.5.3.

Exercise 1.2 Plate

Using either a map of the tectonic plates from the Internet or Figure 1.5.3 determine which tectonic plate you are on right now, approximately how fast it is moving, and in what direction. How far has that plate moved relative to Earth's core since you were born?

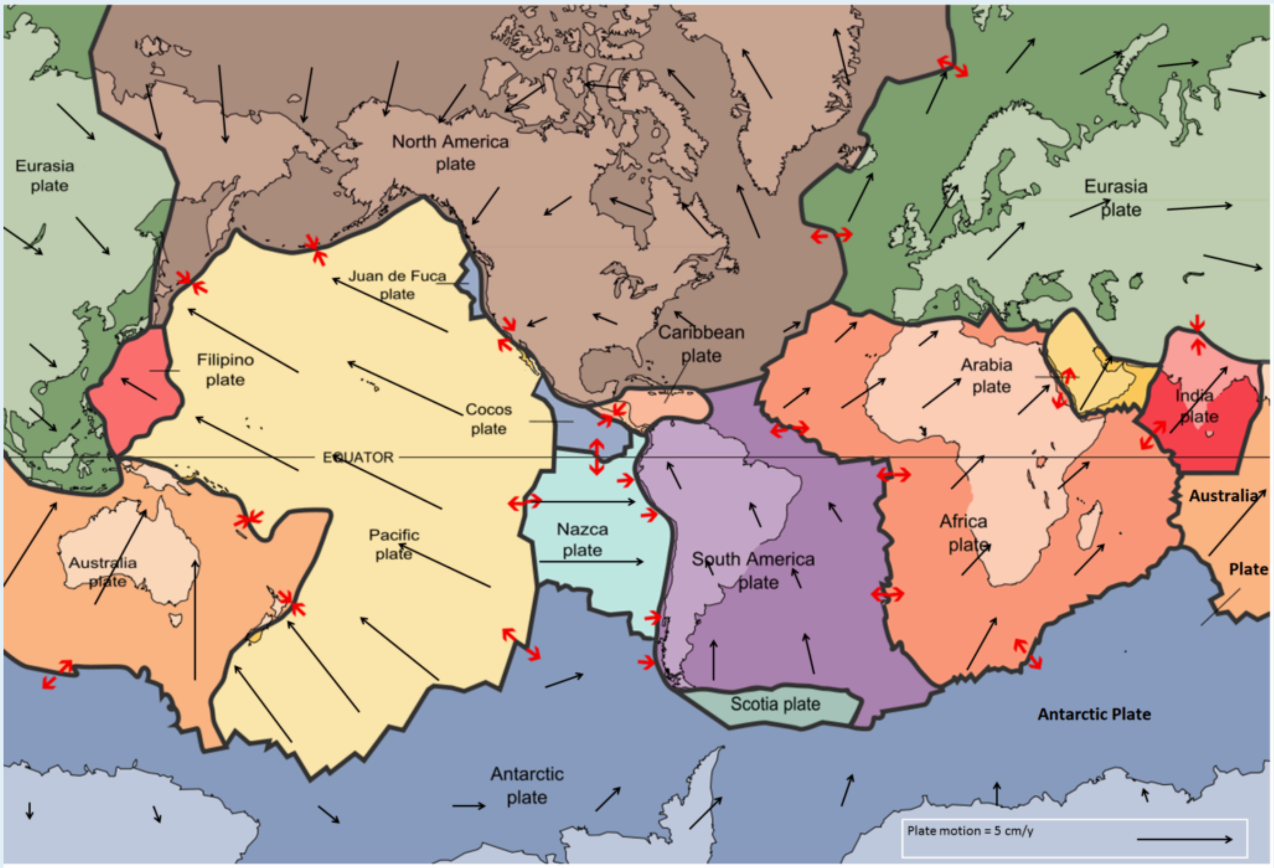

Figure 1.5.3 A map showing 15 of the Earth's tectonic plates and the approximate rates and directions of plate motions.

See Appendix 3 for Exercise 1.2 answers.

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- Figure 1.5.1: © Steven Earle. CC BY.
- Figure 1.5.2: Oceanic Spreading by Surachit. Public domain.
- Figure 1.5.3: Tectonic Plates by USGS. Public domain. Adapted by Steven Earle.

1.6 Geological Time

In 1788, after many years of geological study, James Hutton, one of the great pioneers of geology, wrote the following about the age of Earth: *The result, therefore, of our present enquiry is, that we find no vestige of a beginning — no prospect of an end.*[1] Of course he wasn't exactly correct, there was a beginning and there will be an end to Earth, but what he was trying to express is that geological time is so vast that we humans, who typically live for less than a century, have no means of appreciating how much geological time there is. Hutton didn't even try to assign an age to Earth, but we now know that it is approximately 4,570 million years old. Using the scientific notation for geological time, that is 4,570 **Ma** (for *mega annum* or "millions of years") or 4.57 **Ga** (for *giga annum* or billions of years). More recent dates can be expressed in **ka** (*kilo annum*); for example, the last cycle of glaciation ended at approximately 11.7 ka or 11,700 years ago. This notation will be used for geological dates throughout this book.

Exercise 1.3 Using geological time notation

To help you understand the scientific notation for geological time—which is used extensively in this book—write the following out in numbers (for example, 3.23 Ma = 3,230,000 years).

1. 2.75 ka
2. 0.93 Ga
3. 14.2 Ma

We use this notation to describe geological events in the same way that we might say "they arrived at 2 pm." For example, we can say "this rock formed at 45 Ma." But this notation is not used to express elapsed time. We don't say: "I studied for 4 pm for that test." And we don't say: "The dinosaurs lived for 160 Ma." Instead, we could say: "The dinosaurs lived from 225 Ma to 65 Ma, which is 160 million years."

See Appendix 3 for Exercise 1.3 answers.

Unfortunately, knowing how to express geological time doesn't really help us understand or appreciate its extent. A version of the geological time scale is included as Figure 1.6.1. Unlike time scales you'll see in other places, or even later in this book, this time scale is linear throughout its length, meaning that 50 Ma during the **Cenozoic** is the same thickness as 50 Ma during the **Hadean**—in each case about the height of the "M" in Ma. The Pleistocene glacial epoch began at about 2.6 Ma, which is equivalent to half the thickness of the thin grey line at the top of the yellow bar marked "Cenozoic." Most other time scales have earlier parts of Earth's history compressed so that more detail can be shown for the more recent parts. That makes it difficult to appreciate the extent of geological time.

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[1] Hutton, J, 1788. Theory of the Earth; or an investigation of the laws observable in the composition, dissolution, and restoration of land upon the Globe. Transactions of the Royal Society of Edinburgh.

To create some context, the **Phanerozoic** Eon (the last 542 million years) is named for the time during which visible (*phaneros*) life (*zoi*) is present in the geological record. In fact, large organisms—those that leave fossils visible to the naked eye—have existed for a little longer than that, first appearing around 600 Ma, or a span of just over 13% of geological time. Animals have been on land for 360 million years, or 8% of geological time. Mammals have dominated since the demise of the dinosaurs around 65 Ma, or 1.5% of geological time, and the genus *Homo* has existed since approximately 2.8 Ma, or 0.06% (1/1,600th) of geological time.

Geologists (and geology students) need to understand geological time. That doesn't mean memorizing the geological time scale; instead, it means getting your mind around the concept that although most geological processes are extremely slow, very large and important things can happen if such processes continue for enough time.

For example, the Atlantic Ocean between Nova Scotia and northwestern Africa has been getting wider at a rate of about 2.5 centimetres (cm) per year. Imagine yourself taking a journey at that rate—it would be impossibly and ridiculously slow. And yet, since it started to form at around 200 Ma (just 4% of geological time), the Atlantic Ocean has grown to a width of over 5,000 kilometres (km)!

A useful mechanism for understanding geological time is to scale it all down into one year. The origin of the solar system and Earth at 4.57 Ga would be represented by January 1, and the present year would be represented by the last tiny fraction of a second on New Year's Eve. At this scale, each day of the year represents 12.5 million years; each hour represents about 500,000 years; each minute represents 8,694 years; and each second represents 145 years. Some significant events in Earth's history, as expressed on this time scale, are summarized on Table 1.1.

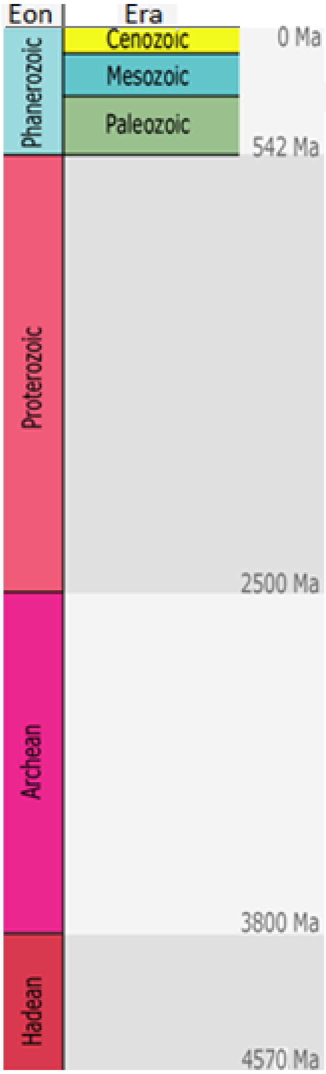

Figure 1.6.1 The geological time scale. [Image Description]

Table 1.1 A summary of some important geological dates expressed as if all of geological time was condensed into one year.

[Skip Table]

Event	Approximate Date	Calendar Equivalent
Formation of oceans and continents	4.5 to 4.4 Ga	January
Evolution of the first primitive life forms	3.8 Ga	early March
Formation of British Columbia’s oldest rocks	2.0 Ga	July
Evolution of the first multi-celled animals	0.6 Ga or 600 Ma	November 15
Animals first crawled onto land	360 Ma	December 1
Vancouver Island reached North America and the Rocky Mountains were formed	90 Ma	December 25
Extinction of the non-avian dinosaurs	65 Ma	December 26
Beginning of the Pleistocene ice age	2 Ma or 2000 ka	8 p.m., December 31
Retreat of the most recent glacial ice from southern Canada	14 ka	11:58 p.m., December 31
Arrival of the first people in British Columbia	10 ka	11:59 p.m., December 31
Arrival of the first Europeans on the west coast of what is now Canada	250 years ago	2 seconds before midnight, December 31

Exercise 1.4 Take a trip through geological time

We’re going on a road trip! Pack some snacks and grab some of your favourite music. We’ll start in Tofino on Vancouver Island and head for the Royal Tyrrell Museum just outside of Drumheller, Alberta, 1,500 km away. Along the way, we’ll talk about some important geological sites that we pass by, and we’ll use the distance as a way of visualizing the extent of geological time. Of course it’s just a “virtual” road trip, but it will be fun anyway. To join in, go to: Virtual Road Trip.

Once you’ve had a chance to do the road trip, answer these questions:

1. We need oxygen to survive, and yet the first presence of free oxygen (O_2 gas) in the atmosphere and the oceans was a “catastrophe” for some organisms. When did this happen and why was it a catastrophe?
2. Approximately how much time elapsed between the colonization of land by plants and animals?
3. Explain why the evolution of land plants was such a critical step in the evolution of life on Earth.

See Appendix 3 for Exercise 1.4 answers.

Image descriptions

Figure 1.6.1 image description: The Hadean eon (3800 Ma to 4570 Ma), Archean eon (2500 Ma to 3800 Ma), and Proterozoic eon (542 Ma to 2500 Ma) make up 88% of geological time. The Phanerozoic eon makes up the last 12% of geological time. The Phanerozoic eon (0 Ma to 542 Ma) contains the Paleozoic, Mesozoic, and Cenozoic eras. [Return to Figure 1.6.1]

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- Figure 1.6.1: © Steven Earle. CC BY.

Summary

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

Section	**Summary**
1.1 What is Geology?	Geology is the study of Earth. It is an integrated science that involves the application of many of the other sciences, but geologists also have to consider geological time because most of the geological features that we see today formed thousands, millions, or even billions of years ago.
1.2 Why Study Earth?	Geologists study Earth out of curiosity and for other more practical reasons, including understanding the evolution of life on Earth, searching for resources, understanding risks from geological events such as earthquakes, volcanoes, and slope failures, and documenting past environmental and climate changes so that we can understand how human activities are affecting Earth.
1.3 What Do Geologists Do?	Geologists work in the resource industries and in efforts to protect our natural resources and the environment in general. They are involved in ensuring that risks from geological events (e.g., earthquakes) are minimized and that the public understands what the risks are. Geologists are also engaged in fundamental research about Earth and in teaching.
1.4 Minerals and Rocks	Minerals are naturally occurring, specific combinations of elements that have particular three-dimensional structures. Rocks are made up of mixtures of minerals and can form though igneous, sedimentary, or metamorphic processes.
1.5 Fundamentals of Plate Tectonics	The Earth's mantle is convecting because it is being heated from below by the hot core. Those convection currents contribute to the movement of tectonic plates (which are composed of the crust and the uppermost rigid mantle). Plates are formed at divergent boundaries and consumed (subducted) at convergent boundaries. Many important geological processes take place at plate boundaries.
1.6 Geological Time	Earth is approximately 4,570,000,000 years old; that is, 4.57 billion years or 4.57 Ga or 4,570 Ma. It's such a huge amount of time that even extremely slow geological processes can have an enormous impact.

Questions for Review

Answers to Review Questions at the end of each chapter are provided in Appendix 2.

1. In what way is geology different from the other sciences, such as chemistry and physics?
2. How would some familiarity with biology be helpful to a geologist?
3. List three ways in which geologists can contribute to society.
4. Describe the lattice structure and elemental composition of the mineral halite.

5. In what way is a mineral different from a rock?
6. What is the main component of Earth’s core?
7. What process leads to convection in the mantle?
8. How does mantle convection contribute to plate tectonics?
9. What are some of the processes that take place at a divergent plate boundary?
10. Dinosaurs first appear in the geological record in rocks at 225 Ma and then disappear at 65 Ma. For what proportion (%) of geological time did dinosaurs exist?
11. If a typical rate for the accumulation of sediments is 1 mm/year, what thickness (metres) of sedimentary rock could accumulate over a period of 30 million years?