MINERALS AND ROCKS

From the inside and out, Earth contains solid matter of all shapes, sizes, and colors. Our planet comprises thousands of different solids that have changed in abundance and composition throughout its long 4.54 billion year history. These solids are called minerals and rocks and they have literally built the Earth. Every solid foundation, every grain of sand, or gigantic mountain is built of individual rocks and minerals.

Rocks and minerals are not the same, but they are related. A rock is defined as a substance that contains at least one mineral or mineraloid. Thus, rocks are made out of minerals. In geology, a mineral is an inorganic, crystalline solid with a predictable chemical composition. Examples of rock names are: granite, basalt, limestone, sandstone. Examples of mineral names are quartz, mica, pyrite, olivine, etc.

Minerals make up rocks, with some exceptions. A rock can be a mineral. That happens when the rock is completely made out of a single mineral, for example, salt rock, which is composed of the mineral halite (NaCl). Another example is gypsum rock. The mineral gypsum ($CaSO_4$) is very abundant and can form entire layers or rocks. Some rocks contain solidified organic matter (coal) or amorphous glass (obsidian). These solids do not fit the definition of mineral. They are examples of mineraloids (like-minerals). All rocks on Earth's surface can be divided into three categories based on how they form: Igneous, Sedimentary, and Metamorphic. Igneous rocks crystallize from molten material, Sedimentary rocks cement from weathered sediment or precipitate from chemical ions, and Metamorphic rocks are warped products of preexisting rocks under heat and pressure.

Identifying rocks and minerals gives geoscientists a lot of key advantages, such as

Predicting which regions or formations could be susceptible to hazards such as sinkholes or landslides.
Finding economic resources such as precious metals, fossil fuels, and building materials.
Determining locations of freshwater resources.
Identifying hazardous materials.
Mastering the art of rock and mineral identification can save lives and build livelihoods. This chapter has a lot of tricks and techniques to get us started!

Learning Objectives
At the end of this chapter, you will be able to…

Describe the characteristics of minerals and their identifying physical properties.
Identify major rock-forming minerals and their impact on society.
Explain the rock cycle and the processes that form different rocks.
Characterize the identifying properties of igneous, sedimentary, and metamorphic rocks.
Identify important rocks in the igneous, sedimentary, and metamorphic groups and their use in society.

3.1 What Is A Mineral?
CHARLENE ESTRADA

Minerals
You have probably heard the term “mineral” commonly used before to describe ingredients in food, beverages, or beauty products. In geosciences, a mineral is something different. Geologists define a mineral as an inorganic crystalline solid substance with a definite chemical composition that forms through natural processes.

Image of a mineral crystal
Figure 3.1.1 Clear quartz crystals.
This sounds like a pretty narrow definition, but this precise wording helps scientists decide when materials are – or are not – minerals. Let’s inspect each of the requirements that a material must meet in order to be considered a mineral!

Minerals are crystalline solids
For a substance to be considered a mineral, it first must be solid. For example, we do not consider liquid water a mineral; but frozen water, or ice, is a mineral. Why do we make this distinction? Aren’t ice and water made of the same thing, H2O?

A key identifier in mineralogy is the crystal structure of a mineral. Let’s do a quick review of some chemistry! All matter or “stuff” in our universe can take on just one of four forms: solid, liquid, gas, or plasma. When matter settles into one of these forms, the atoms that compose it will act differently. There is a lot of space between atoms in a gaseous state. The atoms or molecules occupy all the space available. In the liquid state, the atoms are closer together, they move at a slower pace and have less range of motion. However, liquids will take the shape of the container and flow. In a solid state, the densely packed atoms are nearly “frozen” in place. Thus, solids have a defined volume and shape. They also have a predictable structure, as we discuss below. Remember, in geology, a mineral must be a solid.

Illustration of States of Matter, solid, liquid and gas.
Figure 3.1.2. The three most commonly encountered types of matter: solid, liquid, and gas.
A crystal is a solid in which the atoms are arranged into a repeating pattern that can be predicted, that is a crystal structure. This definition means that if you had two samples of ice, one from Antarctica, and one from your freezer, they should have the exact same atomic arrangement! Knowing this property allows scientists to identify unknown crystals with instruments called X-ray Diffractometers that can view their atomic structure.

Atomic-level crystal structure of NaCl
Figure 3.1.3. Crystal structure of the mineral halite (NaCl).
How It Works: X-ray Diffraction How can scientists map the location of atoms in a crystal structure? Believe it or not, this has been a widely available technique long before the development of powerful (and expensive) microscopes that can view objects down at the atomic level. In the early 1900s, scientists discovered that they can determine the distance of bonds

between atoms in a crystal by passing X-rays through it. This is done by aiming the X-rays at many different angles throughout the crystals and observing how the crystal structure interferes with – or "diffracts" – the beams.

Freeze-frame image of X-ray Diffractometer in action
Figure 3.1.4. Still image of an X-ray diffractometer in action.
In the world of mineralogy, predictability is key, which is why solid crystals like ice are called "minerals". There are still lots of solid materials out there that do not meet the definition of crystal. A good example is glass. Most glass is made of silica, which has the formula SiO_2. However, most glass is also an amorphous solid, meaning that it has no predictably ordered arrangement of the silicon and oxygen atoms.

Minerals have definite chemical composition
All minerals have a definite chemical composition. To understand chemical composition, we first need to understand elements and bonds. A chemical element is a pure substance, all the atoms are the same. The atoms that make up chemical elements are represented in the Periodic Table of Elements (Fig. 3.1.5). One atom can make up a chemical element and bond with another chemical element. When two atoms of different elements combine, or bond, they form a compound. A molecule is a version of a compound that could have the same or different elements.

Video 3.1.2. In this chemistry video, you can review the differences between element, mixture, and compound using iron and sulfur as an example (5:05).

The Periodic Table of Elements
Figure 3.1.5. The Periodic Table of Elements.
A "definite" chemical composition means that every time we encounter the substance, we will know what type of elements compose it. For example, if you were lucky enough to find a nugget of gold, you would know that it contains only gold (Au) atoms. The mineral diamond is made of only carbon (C) atoms, in a specific arrangement. Most minerals comprise compounds rather than single elements. We still assign each mineral a chemical formula so that we may know what is in it. Halite (rock salt) has the formula NaCl (sodium chloride). Quartz is made of silica, which is represented by the formula SiO_2. Sometimes the elements within a chemical formula give a mineral unique properties such as toxicity or radioactivity. For instance, the mineral uraninite is radioactive because it contains uranium in its chemical formula, UO_2.

A good way to tell that a substance is NOT a mineral is the absence of a chemical formula. This is often true for rocks; most rocks contain multiple minerals and thus their composition ranges. While we know what minerals need to be present in a rock to be called a basalt, sandstone, or schist, the specific formula for each rock will vary.

Minerals are inorganic substances
Organic substances are compounds made of carbon and hydrogen bonds that include proteins, carbohydrates, and oils. Inorganic substances have a structure that is not characteristic of living

tissues. Let’s consider coal as an example. Coal is a sedimentary rock that generally consists of the element carbon (C). Does that make coal a mineral?

No. Coal is not a mineral because it forms when plants and animals decay and their organic matter is compacted together over millions of years. Because coal consists of organic substances, it cannot be a mineral, even if it is also solid. But what about calcite? Some organisms such corals, coccolithophores, bivalves, and brachiopods will build their shells out of calcium carbonate ($CaCO_3$), which is the formula for the mineral calcite. In fact, the ancient trilobites precipitates eyes made out of this mineral. Does that mean that calcite, like coal, is not a mineral?

Not exactly! Think about how we define organic substances above–they are things that are built with carbon and hydrogen bonds to develop living tissues. The formula for calcite is $CaCO_3$. Furthermore, not all calcite crystals make up living materials – in fact, most calcite is NOT precipitated by life! A mineral CAN be produced by natural processes such as a biological precipitation; however, we cannot have minerals made of proteins or sugars.

Minerals are formed by natural processes

Minerals are only made by natural processes that occur in our universe. This criterion has been made more important because of the recent innovation of synthetic minerals. In the last several decades, scientists have made breakthroughs in mimicking the extraordinary pressures and temperatures required in nature to produce expensive gemstones such as diamonds. It is now possible to take any source of carbon, such as peanut butter or even a favorite pet’s ashes, and subject them to mantle conditions in a laboratory setting to create a brand new diamond.

Lab-grown diamonds, which are about 2 mm wide.

Figure 3.1.7 Examples of unpolished lab-grown diamonds of different colors.

As exciting as this process is, these synthetic gemstones are not “real” minerals. Minerals are only formed naturally by geologic processes or are naturally precipitated by organisms. Be sure that if you consider purchasing a laboratory-made gemstone you know that most geoscientists (and gemologists) do not think of them as real minerals!

Key Takeaways

A mineral is:

✔solid

✔with a crystal or atomic structure

✔definite chemical composition that you can write as a chemical formula

✔formed by natural processes, and

✔ inorganic.

3.2 How to Identify Minerals
CHARLENE ESTRADA

Identifying Minerals
Given the narrow criteria, you might think that minerals are pretty rare on Earth. However, our planet (and the greater universe) has thousands of unique ways to combine elements into crystalline solids. Scientists have discovered over 5,600 minerals on Earth so far! We also think there are at least another thousand or more that have yet to be discovered by mineral scientists, mineralogists. And we are just beginning to explore the mineral composition of Mars and other planets in our solar system.

If there are so many minerals on Earth, how does a scientist tell one apart from another? If you found the crystal cluster pictured in Fig. 3.2.1. in a cave, how would you know whether it was gypsum and not quartz?

Image of a colorless cluster of crystals
Figure 3.2.1.. A cluster of colorless crystals, each with well-defined faces. What might this mineral be?
Physical Properties of Minerals
We categorize minerals based on their chemical composition (see table 3.2.1). Some minerals within the same compositional group will have similar physical characteristics, such as color or shape. These properties are usually related to the type of elements within a mineral or the types of chemical bonds holding the atoms together.

Table 3.2.1 Main chemical groups of rock-forming minerals.

Group Name	Chemical Composition	Examples
Native Elements	Single Elements	Sulfur, Silver, Gold
Silicates	SiO2 Family	Quartz, Feldspars, Micas
Carbonates	CO3 Family	Calcite
Sulfates	SO4 Family	Gypsum
Oxides	Oxygen Anion	Hematite, Magnetite
Sulfides	Sulfur Anion (S–)	Pyrite, Galena
Halides	Chloride or Fluoride Anion	Halite, Fluorite

Mineralogists have identified some simple physical tests (described in the above video) to determine the identity of different minerals. These tests are ideal because, prior to their use, scientists had to rely on complex (and expensive!) instruments such as X-ray Diffractometers. With these physical identification tests, most minerals can be identified in the field by scientists and nonscientists alike. We will break the code for you. The physical properties of minerals include:

Color
Streak
Luster
Habit

Hardness
Breakage
Unique Properties
Video 3.2.1. Overview of how to identify and classify minerals (7:31 min).

Below, we will explore each of these tests in more detail. You will find that some tests will be more useful than others. Which tests will you find to be the most reliable when identifying an unknown mineral?

Color

Color is one of the first things we notice about minerals, and for good reason. Some minerals are bright with reds, greens, blues, and yellows. These colors are determined by the main elements in a mineral's chemical formula. For example, copper (Cu), will cause azurite to be blue and malachite to be green.

Green Malachite and Blue Azurite

Figure 3.2.2. Rock containing green malachite and blue azurite.

Sometimes, minerals have trace elements within their structure that cause them to take on unique colors. These trace elements are often metals such as chromium (Cr), manganese (Mn), or titanium (Ti), and because they are present in such limited amounts, they do not appear in the mineral's chemical formula.

There are certain minerals that are reliably a specific color. Malachite is green. Azurite is blue. Sulfur is yellow. Knowing these patterns makes it easier to identify certain minerals. However, there are a lot of minerals that take on a wide variety of colors. Quartz is a good example–depending on the trace elements hiding within its structure, it can be clear, white, pink, gray, black, yellow, or brown!

The many different colors of quartz

Figure 3.2.3. Quartz can be nearly any color as shown in these pebbles.

Streak

Both gray and red hematite leave a diagnostic reddish-brown streak.

Figure 3.2.4. Both samples of hematite (Fe2O3, gray on the left, red on the right) leave a diagnostic red-brown streak on a porcelain streak plate.

Streak is the color of a mineral's powder. Streak is a more reliable property than color because streak does not vary between two samples of a mineral, even when those samples are different colors (see above example). Minerals that are the same color may have a different colored streak. Many minerals, such as quartz, do not have a streak.

To check the streak, scrape the mineral across an unglazed porcelain plate. Yellow-gold pyrite has a blackish streak, another indicator that pyrite is not gold, which always has a golden-yellow streak.

Brassy yellow pyrite leaves a dark gray streak and pink rhodochrosite leaves a white streak.
Figure 3.2.5. Some minerals leave a different streak color than their bulk mineral would indicate. Left: Pyrite, Right: Rhodochrosite.

Luster

Luster describes the reflection of light off a mineral's surface. Mineralogists have specific terms to describe luster. One straightforward way to classify luster is based on whether the mineral is metallic or non-metallic. Minerals that are opaque and shiny, such as pyrite, have a metallic luster.

Minerals such as quartz have a non-metallic luster, but there are still a variety of ways to describe how the light reflects off the mineral. Let's look below:

Table 3.2.2. Visual examples of common luster types.

LUSTER TYPE	EXAMPLE
Adamantine	Diamond with Adamantine Luster Figure 3.2.6. Polished diamond.
Vitreous	Quartz demonstrating vitreous luster Figure 3.2.7. Vitreous quartz.
Silky	Selenite Gypsum demonstrating silky luster Figure 3.2.8. Selenite with silky luster.
Greasy	Greasy luster demonstrated by Graphite Figure 3.2.9. Greasy graphite.
Waxy	Waxy luster shown by Mimetite Figure 3.2.10. Mimetite with waxy luster.
Dull/ Earthy	Earthy, Dull luster as shown by Kaolinite Figure 3.2.11. Kaolinite with dull luster.
Metallic	Metallic luster as shown by pyrite Figure 3.2.12. Pyrite with metallic luster.

Habit

A mineral's habit is the crystal shape or texture in a specimen. It can refer to the expression of a crystal shape or the shape of multiple crystals aggregated or bunched together. Besides color, it is often the first thing you might notice about a mineral. Crystal shapes are usually determined by the arrangement of the atoms within the crystal structure. For instance, minerals with a cubic atomic structure will have a tendency to grow into cube shapes. Table 3.2.3 displays some common mineral habits.

Table 3.2.3 Common mineral habits
HABIT TYPE DESCRIPTION EXAMPLE
Prismatic Column-like with visible crystal faces
Quartz with Prismatic Habit
Figure 3.2.13. Quartz with prismatic habit.
Acicular Thin, needle-like or in clusters
Acicular Crystal Habit shown by Rutile
Figure 3.2.14. Rutile displays acicular habit.
Micaceous Flat and flaky, peels apart into layers
Micaeous habit shown by muscovite
Figure 3.2.15. Micaceous habit in muscovite.
Botryoidal[/pb_glossary] Bubbling or globular, circular crystals
[caption id="attachment_1966" align="aligncenter" width="300"]Botryoidal habit demonstrated with hemimorphite Figure 3.2.16. Botryoidal habit in hemimorphite.[/caption]

[pb_glossary id="1631"]Equant Boxy or round with roughly equal dimensions
Equant habit shown with rounded zircon crystals
Figure 3.2.17. Round zircons showing equant habit.
Bladed Elongated but flattened crystals or clusters
Bladed crystal habit shown in Diopside
Figure 3.2.18. Bladed crystal habit in diopside.
Massive Grainy, with no distinct crystals
Massive/Granular habit shown by cobaltite
Figure 3.2.19. Cobaltite showing massive habit.
Breakage
What does a mineral look like when it is broken? Cleavage and/or fracture describes the appearance of a mineral when a crystal is broken from an external force such as physical weathering or when you strike it with a hammer.

Video 3.2.2. This video shows what happens when you break minerals with planes of weakness (cleavage) and a mineral with equally strong bonds (fracture) (3:25).

Cleavage is the tendency for crystals to break along planar surfaces that are parallel to atomic planes. It is common to observe:

Table 3.2.4 Common types of cleavage.
CLEAVAGE TYPE EXAMPLE
Basal: 1 direction of cleavage

Muscovite demonstrating basal cleavage.
Figure 3.2.20. Muscovite demonstrating basal cleavage.
2 directions of cleavage, perpendicular

Orthoclase feldspar demonstrating 2-directional cleavage at 90 angles from one another.
Figure 3.2.21. Orthoclase feldspar showing 2-directional cleavage at 90° angles from one another.
2 directions of cleavage, non-perpendicular
Albite feldspar demonstrating 2-directional cleavage planes at non-90 angles
Figure 3.2.22. Albite feldspar displaying 2-directional cleavage planes at non-90° angles.
Cubic: 3 directions of cleavage, perpendicular
Halite demonstrating cubic cleavage
Figure 3.2.23. Halite showing cubic cleavage.
Rhombohedral: 3 directions of cleavage, rhombohedral
Calcite demonstrating rhombohedral cleavage.
Figure 3.2.24. Calcite demonstrating rhombohedral cleavage.
Octahedral: 4 directions of cleavage (rare)
Fluorite demonstrating octahedral cleavage.
Figure 3.2.25. Fluorite showing octahedral cleavage.
Some minerals do not break along smooth planes at all! Such a tendency for a mineral to break unevenly is called fracture. Metals usually fracture into jagged edges. Some minerals, such as quartz, form smooth curved surfaces when they fracture. This special type of breakage is called conchoidal fracture, and it is also seen in rocks such as obsidian and chert.

Conchoidal fracture demonstrated by quartz.
Figure 3.2.26. Conchoidal fracture in quartz.
Hardness
Mineral hardness is the mineral's resistance to being scratched. The hardness of the mineral can be defined by a scale of relative hardness, called the Mohs Hardness Scale, it goes from 0 (softest) to 10 (hardest). You can test the hardness of a mineral using everyday objects like a penny, fingernail, nail, glass, or file to find out where on the hardness scale the mineral lies.

Mohs Hardness Scale of Minerals: From 1 (softest) to 10 (hardest), the order goes: talc, gypsum, fingernail (2.5), calcite, penny (3.5), fluorite, apatite, glass plate (5.5), feldspar, steel file (6.5), quartz, topaz, corundum, diamond.
Figure 3.2.27. Mohs hardness scale of minerals. Friedrich Mohs created and named the hardness scale.
If you can scratch the mineral with the object, then the object is harder than the mineral. If the mineral can scratch the object, then the mineral is harder than the object. You can also use other minerals to assign a hardness number to a mineral. In other words, we assign a hardness number to a mineral by making relative observations!

Unique Properties
Some minerals have unique properties that make them much more easily identifiable. Some glow brightly under UV light; others are magnetic. Some fizz when dilute acid is dripped onto their surfaces, and some are explosive in contact with water! There's a wide range of unusual and interesting things that these minerals can do!

Magnetism
Certain iron-bearing minerals can be strongly or weakly magnetic. The most well-known of these is the mineral for which this property is named: Magnetite.

Magnetite, or lodestone, attracting iron filings
Figure 3.2.28. Magnetite, or lodestone, attracting iron filings
Fluorescence
When specific minerals are exposed to high-energy ultraviolet light, the atoms within them are excited to a higher energy state. As those atoms relax back down to their default state, they'll emit light at a new wavelength, which can mean that we'll see beautiful and bright neon colors! This neat visual property is called fluorescence.

Minerals glowing bright, neon colors under UV light, or "fluorescing"
Figure 3.2.29. Minerals glowing bright, neon colors under UV light, or "fluorescing."
Effervescence
Effervescence is a mineral's reaction to acid. Geologists can often identify certain minerals by dripping small amounts of dilute hydrochloric acid (HCl) on them. This is called the "acid test". We often see the strongest reaction from the mineral calcite.

Video 3.2.3. Watch the fizzing reaction between a drop of HCl with the calcium carbonate in calcite (0:20).

[Video Description: Hydrochloric acid is dripped onto the white calcite mineral and it begins to loudly fizz, foam, and bubble. Some smoke also begins to rise from the mineral as a very tiny amount of it dissolves.]

The reaction in the above video occurs because the carbonate group in calcite ($CaCO_3$) easily dissolves into carbon dioxide (CO_2) gas, which you can see by the fizzing and bubbling at the surface. Sometimes, depending on the purity of the mineral, you might even see vapor or smoke rising from the fizzing mineral!

This test is extremely useful for geologists because only carbonate materials will strongly react to the acid. Geologists can also identify some sedimentary and metamorphic rocks that contain these very same minerals based on this test.

Optical Properties
Some minerals can be completely transparent, but even if we can view images through certain crystals, they can appear different or distorted! Calcite is well-known to "double" images if you look through clear, transparent samples of this crystal. This property is called "Double Refraction".

Doubling of images with transparent calcite, called double refraction
Figure 3.2.30. Doubling of images with transparent calcite, called double refraction.
Translucent ulexite can transmit an entire image when polished. This unique ability to transmit images has given ulexite the nickname "TV Stone".

Polished ulexite demonstrating image transmission
Figure 3.2.31. Polished ulexite showing image transmission.

3.3 A Visual Guide to Common Minerals

CHARLENE ESTRADA

Now that we know some of the identifying properties of minerals, we will go over some of the most common minerals we encounter on the Earth. Many of these are the main ingredients of rocks, and others have been extraordinarily useful in our society. What makes these minerals unique?

Video 3.3.1. The following brief lecture will show you the most common diagnostic properties of minerals (11:29).

Native Elements

The native elements are a group of minerals that are composed of only one element. Many of these play a vital role in the global economy and industry. Table 3.3.1 contains common examples of native element minerals.

Table 3.3.1 Common native elements.

MINERAL	COLOR(S)	STREAK	LUSTER	BREAKAGE	HARDNESS
Gold (Au) Precious Metal Gold nugget interactive model Figure 3.3.1. Gold nugget. Click on this image to go to a 3D interactive model by scrampunk (CC BY)					
Brassy yellow	Deep yellow	Metallic	Uneven Fracture	2.5 – 3.0	
Silver (Ag) Precious Metal bonsai branch_ silver, copper, crystal gem					

Figure 3.3.2. “bonsai branch_ silver, copper, crystal gem” by subarcticmike is licensed under CC BY 2.0

Metallic gray Light Gray Metallic None 2.5 -3.0
Copper (Cu)

Economic Mineral, Industrial Use in Technology and Ores

Large native copper amygdule (Mesoproterozoic, 1.05-1.06 Ga; Ahmeek Mine, Ahmeek, Upper Peninsula of Michigan, USA) 1

Figure 3.3.3. “Large native copper amygdule (Mesoproterozoic, 1.05-1.06 Ga; Ahmeek Mine, Ahmeek, Upper Peninsula of Michigan, USA) 1” by James St. John is licensed under CC BY 2.0

Bronze red-brown Red-Brown Metallic Uneven Fracture 2.5 – 3.0
Diamond (C)

Precious Mineral, Conflict Resource

Diamond Interactive Model
Figure 3.3.4. Polished Diamond. Click on this image to go to a 3D interactive model by joae12 (CC BY)
Clear, blue, brown, gray None Adamantine Fracture 10
Graphite (C)

Economic Mineral, pencil “lead”

Graphite

Figure 3.3.5. “Graphite” by James St. John is licensed under CC BY 2.0

Light to dark gray Dark gray GreasyFracture 1.0 – 2.0
Sulfur(S)

Economic Mineral used in explosives

Sulfur Interactive Model
Figure 3.3.6. Sulfur. Click on this image to go to a 3D interactive model by rocks and minerals (CC BY)
Bright yellow Colorless Dull to Vitreous Uneven to Conchoidal Fracture 1.5 – 2.5
Silicates

Minerals of the silicate group are composed of some combination of silicon (Si) and oxygen (O). Silicate minerals make up the majority of the planet, both on the surface and within the interior. There are many types of silicate minerals, but below are the most common varieties.

Table 3.3.2 Common minerals in the silicate group.

MINERAL COLOR(S) STREAK LUSTER BREAKAGE HARDNESS

Quartz (SiO_2)

Use in glassmaking, significant ingredient in sand

Quartz interactive model

Figure 3.3.7. Cluster of quartz crystals. Click on this image to go to a 3D interactive model by geolab. unilasalle (CC BY-NC-SA)

Variable White Vitreous Conchoidal Fracture 7.0

Potassium Feldspar ($KAlSi_3O_8$)

Orthoclase

Figure 3.3.8. “Orthoclase” by Photographer: John Bosworth is licensed under CC BY 4.0

Orange-pink (orthoclase) or blue-green (microcline) White Vitreous to Dull 2 cleavage directions at 90° 6.0

Plagioclase ($NaAlSi_3O_8$ to $CaAl_2Si_2O_8$)

Moonstone (iridescent peristerite-oligoclase feldspar) (Chupa Pegmatite Field, Mesoproterozoic, 1.75 to 2.10 Ga; at or near Chupa Bay, Karelia, Russia) 2

Figure 3.3.9. “Moonstone (iridescent peristerite-oligoclase feldspar) (Chupa Pegmatite Field, Mesoproterozoic, 1.75 to 2.10 Ga; at or near Chupa Bay, Karelia, Russia) 2” by James St. John is licensed under CC BY 2.0

Commonly white, sometimes blue White Vitreous 2 cleavage directions, non-90° 6.0 – 6.5

Muscovite (Mica) $KAl_2(AlSi_3O_{10})(F,OH)_2$

Flaky, pulls apart in sheets

Muscovite Interactive Model

Figure 3.3.10. Muscovite. Click on this image to go to a 3D interactive model by rocksandminerals (CC BY)

Clear, white, gray, tan White Vitreous Basal Cleavage 2.0 – 2.5 (but breaks very easily!)

Biotite (Mica) $K(Mg,Fe)_3(AlSi_3O_{10})(F,OH)_2$

Flaky, pulls apart in sheets

Biotite interactive model.

Figure 3.3.11. Biotite. Click on this image to go to a 3D interactive model by rocksandminerals (CC BY)
Black, dark gray, black-brown White Vitreous Basal Cleavage 2.5 – 3.0 (but breaks very easily!)
Kaolinite (Clay) $Al_2Si_2O_5(OH)_4$
Key ingredient in porcelain/china

Kaolinite (Cretaceous; Twiggs County, Georgia, USA)

Figure 3.3.12. “Kaolinite (Cretaceous; Twiggs County, Georgia, USA)” by James St. John is licensed under CC BY 2.0

Commonly white or tan White Dull/Earthy Basal Cleavage 2.0 – 2.5
Talc (Clay) $Mg_3Si_4O_{10}(OH)_2$
Use in cosmetics and paint

Talc schist 2

Figure 3.3.13. “Talc schist 2” by James St. John is licensed under CC BY 2.0

White, gray, clear, light green, brown White Waxy to greasy Basal Cleavage 1.0
Almandine (Garnet) $Fe^{2+}{}_3Al_2Si_3O_{12}$
Almandine Garnet interactive model.
Figure 3.3.14. Almandine garnets. Click on this image to go to a 3D interactive model by Lapworth Museum of Geology (CC BY-NC)
Dark red to purplish-red White Vitreous Conchoidal Fracture 7.0 -7.5
Hornblende (Amphibole) $(Ca,Na)_{2-3}(Mg,Fe,Al)_5(Al,Si)_8O_{22}(OH,F)_2$
File:Magnesio-hornblende (cropped).png

Figure 3.3.15. “File:Magnesio-hornblende (cropped).png” by Creator:Robert Lavinsky is licensed under CC BY-SA 3.0

Black to dark green Light gray to white Vitreous to Dull 2 Cleavage directions at 56° and 124°
Uneven Fracture

5.0 – 6.0
Enstatite (Pyroxene) $MgSiO_3$
File:Enstatite-pas-146a.jpg

Figure 3.3.16. Pyroxene, var. Enstatite

Gray, green, brown, yellow Gray Vitreous 2 Cleavage directions at 90°
Uneven Fracture

5.0 – 6.0
Olivine (Mg,Fe)SiO4
AKA Peridot

Olivine Interactive Model
Figure 3.3.17. Olivine. Click on this image to go to a 3D interactive model by UQ School of Earth and Environmental Science (CC BY)
Green, sometimes Yellow-green None Vitreous Conchoidal Fracture 6.5 – 7.0
Carbonates
Minerals in the carbonate group all have the elements carbon (C) and oxygen (O) arranged into what is called the carbonate anion, which is a carbon bonded with three oxygens: CO3–. Carbonate minerals play a key role in storing the world's carbon dioxide, a greenhouse gas, in solid form. They also make up the "hard parts" of some animals such as shells in marine life. Table 3.3.3 shows some of the carbonate minerals you will most commonly encounter:

Table 3.3.3 Common minerals of the carbonate group.
MINERAL COLOR(S) STREAK LUSTER BREAKAGE HARDNESS
Calcite CaCO3
Main ingredient in limestone, fizzes with dilute acid, double refraction, sometimes fluoresces

Calcite Interactive Model
Figure 3.3.18. Calcite. Click on this image to go to a 3D interactive model by Dr. Parvinder Sethi (CC BY)
Variable, but commonly colorless or white White Vitreous 3 Cleavage Directions; non-90°
Conchoidal Fracture

3.0
Dolomite CaMg(CO3)2
Material in fossilized shells

File:Dolomite Eugui MNHN Minéralogie.jpg

Figure 3.3.19. "File:Dolomite Eugui MNHN Minéralogie.jpg" by Marie-Lan Taÿ Pamart is licensed under CC BY-SA 4.0

White, colorless, gray, brown White Vitreous 3 Cleavage Directions; non-90°; Rhombohedral
Conchoidal Fracture

3.5 – 4.0
Malachite $Cu_2CO_3(OH)_2$
Always green

Malachite Interactive Model
Figure 3.3.20. Malachite. Click on this image to go to a 3D interactive model by Malopolska`s Virtual Museums CC0 Public Domain.
Green Green Vitreous to Dull Basal Cleavage
Uneven Fracture

3.5 – 4.0
Azurite $Cu_3(CO_3)_2(OH)_2$
Always blue

image

Figure 3.3.21. "File:Azurite from China.jpg" by E. Hunt is licensed under CC BY-SA 2.5

Blue Light Blue Vitreous to Dull 2 Directions
Conchoidal Fracture

3.5 – 4.0
Sulfates
Sulfate minerals are made of the elements sulfur (S) and oxygen (O) that are arranged into a sulfate ion: $SO_4^{–}$. Some of the most common sulfate minerals form within hot, dry environments when bodies of water, such as lakes, evaporate. These minerals build our homes and cities. Here are some of their properties below:

Table 3.3.4 Sulfate minerals
MINERAL COLOR(S) STREAK LUSTER BREAKAGE HARDNESS
Gypsum $CaSO_4·2H_2O$
Use in construction materials

Rock Gypsum Interactive Model
Figure 3.3.22. Click on this image to go to a 3D interactive model by EDUROCK – EDUCATIONAL VIRTUAL ROCK COLLECTION (CC BY)
Colorless, white, tan or yellowish White Vitreous, silky or waxy 3 Cleavage Directions, but one direction is perfect
Conchoidal Fracture

2.0

Anhydrite $CaSO_4$
Stable, dehydrated version of gypsum

Anhydrite.

Figure 3.3.23. “Anhydrite.” by Holly Leighanne. is licensed under CC BY 2.0

Variable: white, gray, pale blue, colorless White Vitreous to greasy 3 Cleavage Directions, almost cubic
Conchoidal Fracture

3.5

Oxides

Oxides are a mineral group that are defined by a combination of a metal cation bonded with oxygen (O). A lot of these minerals tend to be metallic and have found use in industry as sources of metal ores. However, this group also includes hydroxide minerals, which are minerals that contain oxygen bonded with hydrogen. Some of these minerals are used in our everyday lives!

Table 3.3.5 Common oxide minerals.

MINERAL	COLOR(S)	STREAK	LUSTER	BREAKAGE	HARDNESS
Magnetite $Fe^{2+}Fe^{3+}_2O_4$ Magnetic mineral Magnetite-118736.jpg Figure 3.3.24. “File:Magnetite-118736.jpg” by Rob Lavinsky, iRocks.com licensed under CC BY-SA 3.0	Black, Dark Gray	Black	Metallic	Uneven Fracture	5.5 – 6.5
Hematite Fe_2O_3 Heme means “blood”. Hematite Interactive Model. Figure 3.3.25. Hematite. Click on this image to go to a 3D interactive model by rockdoc CC BY.	Dark Gray to Red-Brown	Red-Brown to Bright Red	Metallic	Uneven Fracture	5.5 – 6.5
Corundum Al_2O_3 AKA “Ruby” (when red), “Sapphire” (when blue)					

This mineral is 6-sided an reddish-purple. It can also be blue.
Figure 3.3.26. Corundum, var. “Ruby”
Reddish pink to blue for gemstones, also brown to gray	Colorless	Adamantine to Vitreous	Fracture only	9.0
Ice H_2O
Only a mineral at freezing temperatures.

Ice-cubes.

Figure 3.3.27. “Ice-cubes.” by rawdonfox is licensed under CC BY 2.0

Colorless, White, Pale Blue	White	Vitreous	Conchoidal Fracture	1.5
Sulfides
Minerals within the sulfide group all contain a metallic cation that is bonded with sulfur (S) as an anion. Nearly all the world’s ore materials can be found within the sulfide group. Metallic sulfides form in association with volcanic activity.

Table 3.3.6 Common sulfide minerals.

MINERAL	COLOR(S)	STREAK	LUSTER	BREAKAGE	HARDNESS
Pyrite FeS_2 AKA “Fool’s Gold” Pyrite Interactive model Figure 3.3.28. Pyrite. Click on this image to go to a 3D interactive model by Earth Sciences, University of Newcastle CC BY-NC.	Brassy Yellow	Dark Gray to Brownish-Black	Metallic	Uneven Fracture	6.0 – 6.5
Galena PbS Heavy/ High density. Galena (Missouri, USA) Figure 3.3.29. “Galena (Missouri, USA)” by James St. John is licensed under CC BY 2.0	Silver Gray to Dark Gray	Dark Gray	Metallic	3 Cleavage Directions at 90°; Cubic Near-Conchoidal Fracture	2.5 – 3.0

Halides
Minerals in the halide group are composed of a cation element bonded with a halogen anion element. Some of these minerals are known as salts because, like several sulfates, they form when water evaporates in hot, arid environments. One of the most well-known halides is something that we use in our kitchen every day!

Table 3.3.7. Common halides.

MINERAL COLOR(S) STREAK LUSTER BREAKAGE HARDNESS

Halite $NaCl$

Rock Salt, salty taste

Rock Salt/Halite Interactive Model

Figure 3.3.30. Rock Salt/Halite. Click on this image to go to a 3D interactive model by Dexter Perkins (CC BY-NC)

Colorless, white White Vitreous 3 directions of perfect cleavage at 90°; Cubic

Conchoidal Fracture

2.0 – 2.5

Fluorite CaF_2

Often Fluorescent

Fluorite (Denton Mine, near Cave-in-Rock, Illinois, USA) 2

Figure 3.3.31. “Fluorite (Denton Mine, near Cave-in-Rock, Illinois, USA) 2” by James St. John is licensed under CC BY 2.0

Variable White Vitreous 6 directions; Octahedral

Conchoidal Fracture

4.0

3.4 The Rock Cycle

CHARLENE ESTRADA

The Rock Cycle: Recycle and Reuse

We previously learned that Earth is an efficient recycler of its solid materials through the processes of plate tectonics, in which the rigid oceanic lithosphere will eventually descend into the asthenosphere, melt, and form again at spreading centers. Another way in which the Earth can rework and recycle its crust is through the Rock Cycle.

Video 3.4.1. The rock cycle (3:22).

The Rock Cycle describes how the three main rock types that compose the Earth’s lithosphere are constantly transformed into one another through geologic processes. These three rock types, which we will learn about in more detail in the following chapters, are igneous, sedimentary, and metamorphic rocks. For now, let’s focus on the process that creates these different rock types.

Figure 3.4.1. “Rock Cycle” by Siyavula Education is licensed under Creative Commons Attribution 2.0 Generic.
Igneous rocks: melting, cooling, and crystalizing
image
Figure 3.4.2. “Sarychev Peak Eruption, Kuril Islands” by NASA’s Earth Observatory is licensed under Public Domain.
Extremely hot rock from the mantle that has melted is called molten rock or magma. When magma rises to the crust and erupts at the earth’s surface from volcanoes, it is called lava. Eventually, these molten materials cool and solidify, and they might grow minerals through crystallization. The solid products from magma, lava, or volcanic activity are called igneous rocks.

Igneous rocks are not only formed from mantle material. Sometimes a sedimentary rock can be buried deep within the crust and come in contact with magma, which causes the molten rock’s composition to change. The same can happen with metamorphic rocks or even preexisting igneous rocks. When ANY type of rock melts, it becomes molten, and it thus has the potential to become an igneous rock.

Sedimentary rocks: Weathering, deposition, and lithification

Sedimentary layers of sandstone deposited at Zion National Park, Utah
Figure 3.4.3. Sedimentary layers of cross-bedded sandstone at Zion National Park, Utah.
When any rock is exposed to the Earth’s surface, it will undergo weathering and erosion, which produces sediment. Weathering is the physical and chemical breakdown of rocks into smaller fragments by the atmosphere, hydrosphere, or biosphere. Erosion is the removal of those fragments from their original location. The sediment from the original rock will be transported by streams, glaciers, or wind, but it will ultimately accumulate on the earth’s surface due to gravity. This accumulation is called deposition.

The deposited sediments will eventually build in layers and will become buried on the Earth’s surface. As the sediments reach deeper, they eventually become a solid rock through a process called lithification, which requires both compaction and cementationof the loose solids. The weight of the overlying layers will compact the sediment closer together, and as groundwater leaks between the individual grains, it will glue or cement the sediment as solid rock.

In other circumstances, weathering strips rocks of their very elements at an atomic level; these elements later precipitate as new solids in oceans or lakes. Both lithification and precipitation will produce Sedimentary Rocks.

Metamorphic rocks: Burial, deformation, and exhumation

Figure 3.4.4. Folded metamorphic rock gneiss found in Soldier Canyon, Arizona
When any type of rock – igneous, sedimentary, or metamorphic – is buried within the earth's lithosphere, it will reach zones of higher temperatures and/or pressures at depth. The alteration of rock by heat and pressure is called metamorphism.

Rocks will change during metamorphism because the minerals that compose them are only stable under a specific range of temperatures and pressures. Therefore, greater heat and pressure will cause new minerals to grow, and in some rocks, the pressure will squeeze and stretch minerals in patterns of lines or waves called foliation. These transformed and deformed products of heat and pressure are called metamorphic rocks.

Metamorphic rocks do not form at the Earth's surface as the heat and/or pressures required for metamorphism are found kilometers deep within the lithosphere. But we see metamorphic rock formations at the surface of the Earth. Why is this? Sometimes the deeply buried layers of metamorphic rock are forced toward the light of day by mountain building processes or the sudden weathering and erosion of overlying rocks. This process is called exhumation, and it is why we can see a variety of rocks from different time periods in Earth's history!

Written in stone
The Rock Cycle is truly is a cycle. There is no single point in which it "begins" or "ends", and it has been operating for billions of years. There is a natural tendency to think that the rocks on Earth's surface progress as igneous -> sedimentary -> metamorphic -> igneous, but that is not the case. Any type of rock on Earth's surface has the potential to become any other type of rock through geologic processes!

For example, a sedimentary rock might be buried deep within the Earth's surface and melt in contact with a plume of magma. The magma and molten sedimentary rock mix and produce a new igneous rock. That igneous rock is then buried very deeply in the crust and becomes warped and deformed; it transforms into a metamorphic rock. Finally, after hundreds of millions of years, the metamorphic rock formation is exhumed and weathered away. The fragments of that metamorphic rock lithify to form a brand new sedimentary rock. What a cycle!

One last thing! The processes involved in the rock cycle, and the rocks themselves, tell a story of the events that happened in Earth's 4.54 billion year history. While even the best geologic cannot reconstruct every page of Earth's story from a single rock formation, they can get a glimpse of what might have happened in a region to form a certain type of rock.

An igneous rock can tell us a story of magma chambers or volcanic activity. Sedimentary rocks tell us where rivers, deserts, beaches, and oceans once resided, and metamorphic rocks help us reconstruct the times tectonic plates collided or spread apart from one another.

In his poem, Auguries of Innocence, Walt Whitman once wrote:

“To see a World in a Grain of Sand” [1]

What will you see in an entire rock?

3.5 Igneous Rocks

CHARLENE ESTRADA

Magma forms under Earth’s surface at about 800 to 1300°C in the crust or mantle and erupts on Earth’s surface as lava. When magma or lava cools, it solidifies by crystallization in which minerals grow within the magma or lava. The rock that results from this is an igneous rock from the Latin word ignis, meaning “fire.” [2] Igneous rocks are traditionally defined as the solid products from the cooling and hardening of molten magma in many different environments. We identify these rocks by their composition and texture.

Igneous Rock Composition

Composition refers to a rock’s chemical and mineralogical make-up. For an igneous rock, the composition is generally divided into four groups: ultramafic, mafic, intermediate, and felsic. These groups refer to differing amounts of silica (SiO_2), iron (Fe), and magnesium (Mg) found in the minerals that make up the rocks.

Classification of igneous rocks by composition. Darker rocks are ultramafic or mafic whereas lighter rocks are intermediate/felsic.

Figure 3.5.1. Classification of igneous rocks by composition. Darker rocks are ultramafic or mafic, whereas lighter rocks are intermediate/felsic. Y-axis refers to the abundance of Fe and Mg-containing minerals in each rock type.

Ultramafic refers to rocks composed of mostly olivine and some pyroxene. These rocks have even more magnesium and iron and even less silica than ‘ordinary’ mafic rocks. Ultramafic rocks are rare on the surface, but they make up the primary composition of the upper mantle. Ultramafic rocks are very poor in silica, in the 40% or less range (this means that the rock would be less than 40 weight percent silica).

Mafic refers to igneous rocks with an abundance of ferromagnesian minerals (those with the elements Mg and Fe in their chemical formulae) plus plagioclase feldspar. Such minerals are dark-colored and include pyroxene and olivine. Mafic rocks are low in silica (in the 45-50% range), but they make up most of the oceanic crust and lithosphere.

Intermediate describes the igneous rock composition between mafic and felsic. It contains roughly equal amounts of light and dark minerals, including light grains of plagioclase feldspar and dark grains of amphibole. It is intermediate in silica (in the 55-60% range).

Felsic refers to a predominance of light-colored minerals, including Feldspar and silica (quartz). These minerals have more silica as a proportion of their overall chemical formulae. Minor amounts of dark-colored minerals, such as biotite mica, may sometimes be present. Felsic igneous rocks are rich in silica (in the 65-75% range), and they tend to represent the composition of the continental crust or lithosphere.

Igneous Rock Texture

Phaneritic/Coarse-grained texture, where individual crystals and minerals are easily spotted by the naked eye within the rock.

Figure 3.5.2. Phaneritic/Coarse-grained texture, where individual crystals and minerals within the rock are easily spotted by the naked eye.

If magma cools slowly, deep within the crust, the resulting rock is called intrusive. The slow-cooling process beneath the surface allows crystals to grow large, giving the rock a coarse-grained or "phaneritic" texture. The individual crystals in a coarse-grained texture are visible to the unaided eye.

Aphanitic/Fine-grained texture, where individual crystals and minerals cannot be spotted by the naked eye within the rock.

Figure 3.5.3. Aphanitic/Fine-grained texture, where individual crystals and minerals cannot be spotted by the naked eye within the rock.

When lava erupts onto the surface or rises into shallow in a mountain and cools, the rock that will cool from it is called an extrusive igneous rock. Extrusive igneous rocks have a fine-grained or "aphanitic" texture, in which the grains are too small to see with the unaided eye. This fine-grained texture tells us that the quickly-cooling lava did not have time to grow large crystals.

Porphyritic texture illustrated by large, visible crystals found within a fine-grained matrix in igneous rock.

Figure 3.5.4 Porphyritic texture illustrated by large, visible crystals found within a fine-grained matrix in igneous rock.

Some igneous rocks have a mixture of large crystals within a fine-grained matrix. Such a texture is called porphyritic. A porphyritic texture tells us that the magma underwent multiple stages of cooling; it first cooled slowly when it was deep under the surface, and then it rose to a shallow depth where it cooled quickly.

Vesicular texture, in which the rock contains many pores where gases escaped during formation.

Figure 3.5.5. Vesicular texture, in which the rock contains many pores where gases escaped during formation.

All magmas contain dissolved gases called volatiles. When magma quickly rises to the surface as lava, these volatiles sometimes become trapped in the cooling molten rock and form a bubbling texture that appears sponge-like. Such a texture is called vesicular because the holes in the rock are called vesicles by scientists.

Glassy texture, which is very smooth without the presence of crystals or minerals

Figure 3.5.6. Glassy texture, which is very smooth without the presence of crystals or minerals

Lava will sometimes cool so quickly that not even microscopic crystals will form in it. As a result, volcanic glass will form with a shiny, smooth appearance that reflects light. This texture is called glassy. Just like the mineral quartz, a glassy rock will have conchoidal fracture with distinctive, rounded fracture edges. This is because, like quartz, most glassy rocks are made of the compound SiO2 in the form of the mineraloid amorphous silica.

Pyroclastic texture shown by angular rock fragments mixed with fine ash and volcanic glass in igneous rock.
Figure 3.5.7. Pyroclastic texture shown by angular rock fragments mixed with fine ash and volcanic glass in igneous rock.
The final volcanic texture is a result of explosive, violent eruptions. These eruptions produce not only lava, but clouds of ash, rock, gases, and glass. The solid material of the eruption, which is called tephra, eventually falls back onto the earth and consolidates into a solid mass. The rock that will form from this process has a pyroclastic texture. This texture consists of volcanic ash, glass shards, and small rock fragments.

Igneous Rock Field Guide
Video 3.5.1. Classifying igneous rocks by texture and composition explained (7:37).

Komatiite
Komatiite Interactive Model. Komatiite is a dark greenish rock with bladed black/brown minerals.
Figure 3.5.8. Komatiite, South Africa. Click on this image to go to a 3D interactive model by Sara Carena CC BY-NC.
"KO-MAT-EE-ITE"

Most commonly confused with: basalt

An ultramafic, fine-grained (extrusive) igneous rock. This rock will form from rapidly cooling lava, but it is very rare. Molten ultramafic rock was more prevalent on early Earth, and it can be found in the mantle. Komatiite is composed primarily of olivine and pyroxene minerals, which causes the rock to take on a dark, greenish color.

Chances are that if you are holding a fine-grained, dark igneous rock, it will be basalt since komatiites are not very common but look twice if it has a strong green tint. Olivine and pyroxene are more susceptible to weathering than minerals found in felsic rocks; therefore, this igneous rock may erode easier than a felsic counterpart.

Peridotite

Peridotite Interactive Model. Peridotite is a bright green, coarse-grained rock made mostly of olivine.

Figure 3.5.9. Peridotite. Click on this image to go to a 3D interactive model by Sara Carena CC BY-NC.

“PUR-ID-DO-TITE”

Most commonly confused with: olivine (mineral), gabbro

An ultramafic, coarse-grained (intrusive) igneous rock. Peridotite will form under Earth’s surface from slowly-cooling magma. It is less rare than Komatiite, but still not very common. Ultramafic magma composes the Earth’s upper and lower mantle; therefore, when a plume of magma rises to the lithosphere and cools as a “Xenolith“, peridotite will form.

Peridotite is composed of visible, and sometimes large, crystals of olivine and pyroxene. It is often dark and with distinctively green crystals. When distinguishing this rock from gabbro, consider the percentage of olivine in the rock; peridotite has at least more than 25%. As with komatiite, peridotite will also erode more easily than other igneous rocks because it contains minerals that are more susceptible to weathering.

Basalt

Basalt Interactive Model. Basalt is a very fine-grained, dark gray rock.

Figure 3.5.10. Basalt. Click on this image to go to a 3D interactive model by Sara Carena CC BY-NC.

“BAH-SALT”

Most commonly confused with: komatiite, shale (sedimentary), limestone (sedimentary)

A mafic, fine-grained (extrusive) igneous rock. About 90% of all volcanic rocks that form are on the Earth’s surface are basalt as this rock represents a common magma composition of the upper mantle mixed with the crust. When this magma erupts as lava and cools, basalt is the final product.

Basalts are characterized by low (~50%) silica content and minerals with iron (Fe) and magnesium (Mg). Such minerals typically include amphibole and pyroxene, and sometimes small amounts of olivine. Additionally, basalts include a significant amount of calcium-plagioclase feldspar in their matrix. Basalt often is dark gray, and unlike komatiite, does not have a green tint. When distinguishing this rock from shale and limestone, use a hand lens to identify the notable minerals in its matrix. Additionally, basalt is more resistant to scratching than shale and limestone; try scratching it with a penny!

The elevated iron content in basalt makes this rock easier to rust and erode under Earth’s atmosphere. As a mafic rock, it is more susceptible to weathering than felsic igneous rocks.

Gabbro
Gabbro Interactive Model. Gabbro is a coarse-grained, dark gray rock with visible black and green minerals that are rough to the touch.
Figure 3.5.11. Gabbro. Click on this image to go to a 3D interactive model by Sara Carena CC BY-NC.
“GAB-BRO”

Most commonly confused with: peridotite

A mafic, coarse-grained (intrusive) igneous rock. Gabbro makes up the majority of oceanic lithosphere, and it often forms at divergent boundaries when magma with a composition similar to the upper mantle rises and slowly cools beneath the surface. This rock has the same general composition as basalt, but its minerals are easily visible to the naked eye due to its slow cooling history.

Gabbro is dark gray or black, sometimes with noticeable flecks of white calcium plagioclase or green olivine. Gabbro can be distinguished from peridotite by its limited olivine content. If the number of olivine crystals in an unknown, coarse-grained rock is small or nonexistent, then you are looking at gabbro.

Like basalt, gabbro will erode at Earth’s surface at a faster rate than other felsic, intrusive rocks. The effects of weathering by the atmosphere may be more noticeable on gabbro because it contains larger crystals of iron-rich minerals.

Andesite

Andesite Interactive Model. Andesite is light gray and porphyritic, meaning that it is mostly fine-grained with larger dark minerals in its matrix.
Figure 3.5.12. Andesite. Click on this image to go to a 3D interactive model by Sara Carena CC BY-NC.
“AN-DEH-SITE”

Most commonly confused with: rhyolite

An intermediate, extrusive igneous rock. Andesite cools from lavas that are between mafic and felsic in composition. As such, andesite typically has a silica content of 55-60%. Andesite can often be found near volcanoes along the Pacific Ring of Fire or at stratovolcanoes, which are sometimes called Andesite volcanoes. Andesitic lavas are typical of subduction zones, such Andes Mountains subduction zone for which it received its name.

Andesite is commonly light gray. Unlike other extrusive igneous rocks that cool from lava, andesite is also porphyritic, which means that medium and small dark crystals can be seen in its fine-grained matrix by the naked eye. These crystals are usually amphibole and pyroxene minerals, whereas the light matrix is mostly composed of calcium plagioclase feldspar. The porphyritic texture of andesite clearly distinguishes it from rhyolite, which is sometimes a light beige-grey color.

Andesite is primarily composed of the silica-rich mineral Ca-plagioclase, which is resistant to weathering at the Earth's surface; however, its pyroxene and amphibole minerals are just as vulnerable to chemical erosion by the atmosphere as those in basalt. This rock is more resistant to weathering than mafic rocks, but felsic rocks will last longer.

Diorite
Diorite interactive model. Diorite is a coarse-grained rock with highly visible white and black minerals.
Figure 3.5.13. Diorite. Click on this image to go to a 3D interactive model by Sara Carena CC BY-NC.
"DYE-O-RITE"

Most commonly confused with: granite

An intermediate, coarse-grained (intrusive) igneous rock. Diorite cools slowly from molten rock that forms beneath the Earth's surface along subduction zones, such as the Andes Mountains and other convergent margins at the Ring of Fire.

Diorite has a "cookies and cream" or "Dalmation"-like appearance, which is caused by black amphibole and white plagioclase crystals that are easily identifiable by the naked eye. Although this rock is much lighter in color than gabbro, it should be easily distinguished from granite due to the abundance of dark crystals in its matrix.

Like andesite, the calcium-rich plagioclase mineral in diorite will be resistant to weathering; however, the dark amphibole minerals are more likely to be oxidized (rusted) by Earth's atmosphere over long periods of time.

Rhyolite
Rhyolite Interactive Model. Rhyolite is a fine-grained rock with light-tan to pink coloring.
Figure 3.5.14. Rhyolite. Click on this image to go to a 3D interactive model by Dr. Parvinder Sethi CC BY
"RYE-O-LITE"

Most commonly confused with: andesite, tuff

A felsic, fine-grained (extrusive) igneous rock. Rhyolite rapidly cools from a high-silica (65-75%) lava. Rhyolite is not as common as its coarse-grained counterpart, granite, because felsic lavas cannot move very far once they erupt.

Rhyolite is typically light tan to pinkish tan in color, and individual crystals are usual difficult to see with the naked eye. Therefore, this rock can be distinguished from andesite, which often has medium and small crystals within its matrix. There are also no pyroclastic debris within rhyolite, which can be confirmed by examining the rock under light; unlike tuff, rhyolite does not have visible flecks of volcanic glass in its matrix.

Rhyolite can be found at explosive volcanoes, such as at Yellowstone National Park. It is primarily made of quartz, which is very resistant against physical and chemical weathering. As a result, rhyolite formations are very stable on the Earth’s surface.

Granite

Granite Interactive Model. Granite is a coarse-grained rock with multi-colored minerals in its matrix, but is mostly light-colored. It is rough to the touch.

Figure 3.5.15. Granite. Click on this image to go to a 3D interactive model by Sara Carena CC BY-NC.

“GRAN-IT”

Most commonly confused with: diorite

A felsic, coarse-grained (intrusive) igneous rock. Granite is often used to approximate the composition of the continental crust in both composition and density. This estimation is typical because granite usually forms within the cores of mountains and thick lithosphere when magma with high silica content slowly cools and crystallizes.

Granite can be identified by its light to pinkish color, and the presence of abundant quartz. Granite commonly has large amounts of salmon-pink potassium feldspar and white, sodium-feldspar (plagioclase), which can even have visible cleavage planes on the crystals. Some varieties of granite have black flecks in the matrix, which are typically biotite mica. To distinguish granite from the intermediate coarse-grained rock, diorite, examine the minerals in its matrix carefully. Granite, unlike diorite, has few dark minerals, and a tendency to have more pink K-Feldspar.

Granite is among the most resistant igneous rocks to both mechanical and chemical weathering. It has been used in society in construction and manufacturing trades, and it has more popularly been used in interior decorating for the last several decades.

Obsidian

Obsidian Interactive Model. Obsidian is an extremely smooth, glassy rock with no visible minerals and conchoidal fracture at its broken edges.

Figure 3.5.16. Obsidian. Click on this image to go to a 3D interactive model by jonathan.davidson CC BY.

“OB-CID-DEE-AN”

Most commonly confused with: chert(sedimentary)

A felsic, glassy (extrusive) igneous rock. Obsidian is commonly found along cooled lava fields with rhyolite. Obsidian forms when lava cools so quickly it does not have time to even develop microscopic crystals. When cooled, obsidian is very smooth, brittle, and shiny. Although obsidian is felsic and has a high silica content, is often black, brown, or red.

Obsidian is usually identifiable by its glassy texture alone. Like the mineral quartz, it displays conchoidal fracture, which can appear as curved or rounded fracture edges. The sedimentary rock chert, which is mostly composed of silica, also has conchoidal fracture; however, this rock is often much duller in both luster and color.

Because obsidian is both brittle and hard, it has been traditionally used as tools and weapons by indigenous people for thousands of years. Many of these weapons hold an edge after centuries, which demonstrate this rock's resistance to weathering.

BACKYARD GEOLOGY: APACHE TEARS
A rounded pebble of dark obsidian, known as an Apache Tear.
Figure 3.5.17. An obsidian Apache Tear.

Volcanic deposits are common throughout the western United States and Mexico, and these rocks have played an important role Native American culture and history. Obsidian can be reshaped and carved to form surgical instruments or weapons such as knives. There are also naturally occurring varieties of rounded obsidian that are said to absorb grief and depression. Today these stones are called "Apache Tears". There are variations in the folklore behind this stone, each story is united by the tragic theme of loss.

The most popular legend behind the Apache Tears focuses upon a Pinal Apache Tribe that was vastly outnumbered by the U.S. military during the nation's westward expansion in the 1800s. The majority of the the warriors were killed in a surprise raid near Picacho Peak, AZ. The remaining Native Americans preferred suicide over imprisonment or execution.

The family of the warriors gathered not far from the peaks, where the remains of the brave warriors remained at the base. The women grieved deeply, day and night, for their lost men. The Great Father placed their tears in the obsidian. Should a person find one of these stones, they would not need to grieve since the women of the Pinal Apache Tribe have already given their tears inside the stone [3].

Scoria
Scoria interactive model
Figure 3.5.18. Scoria. Click on this image to go to a 3D interactive model by Sara Carena CC BY-NC.
"SCOR-EE-AH"

Most commonly confused with: pumice

A mafic, vesicular (extrusive) igneous rock. Scoria forms when lava containing volatile gases erupts. The gases trapped within the lava form large cavities, or vesicles, as it rapidly cools at the surface. Scoria cools from mafic lava, and contains microscopic crystals of silica-poor, ferromagnesian minerals such as amphibole, pyroxene, and calcium plagioclase.

Scoria is usually dark gray in color and is easily distinguished from other mafic rocks by its vesicular texture. Although pumice is also vesicular, scoria is much darker and denser. Despite having large cavities, scoria will never float above water.

Some varieties of scoria are rust-red in color, which reflects the tendency of the minerals within the mafic rock to oxidize under Earth's atmosphere. Furthermore, the abundant vesicles make a greater surface area available for weathering, which cause this rock to weather at a faster rate in comparison to other mafic rocks.

Pumice
Pumice Interactive Model
Figure 3.5.19. Pumice. Click on this image to go to a 3D interactive model by Sara Carena CC BY-NC.
"PUHM-IS"

Most commonly confused with: tuff, scoria

A felsic, vesicular (extrusive) igneous rock. Pumice forms when felsic lava, which can contain significantly higher amounts of volatile gases, very rapidly cools. As with scoria, the cooling rock traps many vesicles of gas, and it takes on a "frothy" appearance as it solidifies. Pumice often cools too quickly to form minerals, and it is sometimes referred to as a volcanic glass. We can find this rock along the slopes of explosive volcanoes with pyroclastic deposits.

Pumice is usually light tan, pink, or gray. It is very low density, and most varieties contain enough vesicles that when placed in a bowl or cup of water, the rock will float. This unique characteristic will often distinguish pumice from similar-looking rocks such as tuff or scoria.

Video 3.5.2. How to tell if a rock is a pumice? (0:32).

Pumice does not typically contain minerals, but it is silica-rich, and therefore more resistant to erosion than scoria. It has been more popularly used in society as a cleaning and beauty tool. Nonetheless, like scoria, this rock has more exposed surface area than granite and rhyolite, and it will be more susceptible to weathering over geologic time.

Tuff
Tuff interactive model
Figure 3.5.20. Rhyolite. Click on this image to go to a 3D interactive model by rocksandminerals CC BY.
"TOUGH"

Most commonly confused with: pumice, rhyolite

A felsic to intermediate, pyroclastic igneous rock. Tuff forms from the solid debris or tephra of an explosive volcanic eruption. When ash, volcanic glass, and rock fragments are ejected by the volcano or related pyroclastic flow eventually accumulate together, they form tuff. This type of rock usually indicates a violent eruption, and it is commonly found along the Ring of Fire and stratovolcanoes.

Tuff often does not have any single distinguishing mineralogical composition, although it often contains angular rock fragments and shiny flecks of glass within a fine-grained matrix of ash. Tuff is typically pale tan or gray in color. Its pyroclastic texture sometimes makes it less dense than other volcanic rocks; however, unlike pumice, it does not flow in water
3.6 Sedimentary Rocks
CHARLENE ESTRADA

When a geologist encounters a sedimentary outcrop, they can reconstruct ancient landscapes – rapidly flowing mountain streams, frightening avalanches, or vast deserts – from these rocks. As the name suggests, Sedimentary Rocks are composed of sediments that have been cemented and compacted together, or lithified, over long periods of time.

Deposition is the settling of clasts, compaction is the movement of clasts closer together, and cemention is the bonding of the clasts together.
Figure 3.6.1. The process of lithification to form sedimentary rocks: Deposition is the settling of clasts, compaction is the movement of clasts closer together, and cementation is the bonding of the clasts together.
Sediments may include:

Fragments of other rocks that often have been worn down into small pieces, such as sand, silt, or clay.
Organic materials, or the remains of once-living organisms.
Chemical precipitates, which are materials that get left behind after the water evaporates from a solution.
Both physical and chemical weathering processes that take place at the Earth's surface are responsible for accumulating this source of sediment from preexisting igneous rocks, metamorphic rocks, and even other sedimentary rocks. Physical weathering breaks the rocks

apart, while chemical weathering dissolves the less stable minerals. These original elements of the minerals end up in solution, and new minerals may form. Water, wind, ice, or gravity remove and transport sediments in a process called erosion.

Sandstone cliff formation near a beach in San Diego showing evidence of physical weathering.
Figure 3.6.2. Sandstone cliff formation near a beach in San Diego, showing evidence of physical weathering.

We can classify sedimentary rocks in two broad categories: clastic and chemical. Clastic sedimentary rocks are made from the fragments of eroded bedrock and sediment, which is usually derived from physical weathering. We classify clastic rocks by their grain size, shape, and sorting. Chemical Sedimentary rocks are precipitated from water that contains a very high concentration of dissolved elements, or ions. We usually classify these chemical rocks based on the precipitated minerals or whether biological processes play a role in the rock's formation.

Clastic Sedimentary Rocks

Clastic sedimentary rocks consist of preexisting rock fragments, or clasts, that come from weathered bedrock. The majority of this sediment has been physically weathered, but some of it may also be chemically weathered. We classify this type of sedimentary rock with three main identifiers: grain size, shape, and sorting.

Grain size

The size of the individual clasts making up a sedimentary rock is a strong indicator for the amount of energy a landscape had available for transporting the sediment. For example, extremely large fragments, such as boulders, might only be deposited by high energy processes, such as avalanches, whereas wind environments may be able to deposit smaller grains such as silt, mud and clay. Below is a diagram that gives an approximate size range for the different types of clasts that geologists encounter in clastic sedimentary rocks.

Grain Size Chart. Coarse grained clasts (pebbles to boulders) are between 2 mm to over 256 mm. Medium-grained sand is between 2mm down to 63 microns. Fine grained clasts (silt and clay) is between 63 micron to smaller than 2 microns.
Figure 3.6.3. Classification of grain sizes.

Grain shape

The general shape of the individual clasts within a sedimentary rock is also an excellent method to determine the type of geologic environment that may have deposited the sediment long ago. Clastic rocks with rounded grains were likely transported by water over long distances and with more energy, in which the individual sediments were abraded and physically rounded as they moved along the riverbed (Fig. 3.6.5). By contrast, angular grains indicate the sediments were transported over a relatively short distance by a landslide or mass wasting event, which did not involve water.

Transportation of sediment clasts by stream flow.

Figure 3.6.4. Transportation of clasts by stream flow. Water can move clasts over long distances and cause the abrasion of clasts that results in rounding. This abrasion happens by the movement of clasts on the stream bed.

Grain sorting

The third identifying property of clastic rocks is the sorting of the individual clasts. A well sorted clastic rock contains clasts that have the same general size in its matrix (Fig. 3.6.5). Such an arrangement means that the clasts were transported over longer distances and/or with greater energy. A poorly sorted clastic rock contains clasts that are a mixture of different sizes in its matrix. This type of clastic rock typically tells a story of sediment being transported over very short distances.

Sorting of clasts/grains from well-sorted to poorly sorted and the rounding of grains from angular to rounded.

Figure 3.6.5. Sorting of clasts/grains from well-sorted to poorly sorted and the rounding of grains from angular to rounded.

Chemical Sedimentary Rocks

Chemical sedimentary rocks are formed by processes that do not directly involve physical weathering. When preexisting bedrock is weathered by chemical reactions that take place in water, the atmosphere, or the biosphere, that rock is broken down into its constituent elements or ions that are dissolved and transported in water.

The dissolved ions in the planet’s water supply will eventually precipitate as solid, chemical sedimentary rocks. The type of chemical sedimentary rocks that form broadly varies based on the type of elements that precipitate the rock, as well as whether organic materials contribute to the process. Chemical sedimentary rocks may contain silica, evaporite ions (sulfate and chloride), and carbonate.

We can divide chemical sedimentary rocks into two general categories: inorganic and biochemical/organic. Inorganic chemical sedimentary rocks are precipitated from only dissolved ions in the water. However, if a chemical rock requires microscopic fossils, shells, or organic material to precipitate, it is called a Biochemical or Organic sedimentary rock. As you will discover with some examples in the field guide below, a sedimentary rock can sometimes be both inorganic and organic!

Sedimentary Rock Field Guide

Conglomerate

Conglomerate Interactive Image
Figure 3.6.6. Conglomerate. Click this image to go to an interactive model by Sara Carena CC-BY.
“CON-GLOM-ER-AT”

Most commonly confused with: breccia

A clastic sedimentary rock. Conglomerate is poorly sorted with well-rounded clasts that are larger than sand (cobble or pebble-sized) within a cementing fine-grained matrix. In a conglomerate, the rock fragments within are sub-rounded to rounded, implying that they traveled along a high energy water source such as a steep stream or river. To tell conglomerate apart from breccia, take a careful look at the individual clasts that compose it. If most of the clasts are rounded, then your rock sample is a conglomerate.

Conglomerate often contains large rock fragments within a very fine-grained matrix, and as a result, these larger clasts are typically the first to dislodge under physical weathering.

Breccia
Breccia interactive model
Figure 3.6.7. Breccia. Click this image to go to an interactive model of breccia by Sara Carena CC-BY.
“BRECH-AH”

Most commonly confused with: conglomerate

A clastic sedimentary rock. Breccia is a poorly sorted rock with angular clasts that are larger than sand. These clasts are cemented within a much finer-grained matrix. Breccia usually indicated that the clasts were transported over a short distance by a high energy event, such as a landslide or the movement of a glacier across the Earth’s surface. To tell breccia apart from conglomerate, look at the individual clasts within the rock. If the edges of the clasts are angular or sharp, then the rock sample is breccia.

Like conglomerate, breccia contains very large rock fragments within a fine-grained matrix, and these clasts have a tendency to dislodge first under physical weathering.

Sandstone
Sandstone Interactive Model
Figure 3.6.8. Sandstone. Click this image to go to an interactive model by Sara Carena CC-BY.
“SAND-STONE”

Most commonly confused with: quartzite (metamorphic)

A clastic sedimentary rock. Sandstone contains sand-sized clasts, is most easily identified by its “sandpaper” feel. Sandstone usually appears as a uniform accumulation of cemented sand, and it can vary in color as pink, gray, or beige. Sandstone is reliably deposited by desert environments as well as beaches.

Sandstone can sometimes be confused with the metamorphic rock quartzite and for good reason, sandstone is quartzite's parent rock before it is subjected to high temperatures and pressures! (See section 3.7). Sandstone is typically rougher to the touch and contains smaller individual grains of quartz, whereas quartzite has larger, recrystallized grains of quartz throughout its matrix.

Light tan varieties of sandstone with well-sorted grains of quartz are among the most resistant sedimentary rocks to physical and chemical weathering. Sandstone is often used as bricks and other construction materials for its durable properties.

Shale

Shale interactive model

Figure 3.6.9. Shale. Click this image to go to an interactive model by Dr. Parvinder Sethi CC-BY.

"SHAIL"

Most commonly confused with: slate, limestone, basalt

A clastic sedimentary rock. Shale is well-sorted with silt, mud, or clay-sized clasts that are tightly packed into a solid matrix. It is most easily identified by its tendency to split into thin planes, which is a property called fissility. Shale derives from very low energy environments, in which fine-grained sediment can slowly settle from still water and accumulate over time. Examples of these environments are lagoons, lakes, and continental shelves.

"Shale" is sometimes an umbrella term for fine-grained clastic rocks and the term "mudstone", which refers to rocks made of clasts smaller than sand, also applies to shale. For the purposes of this course, "shale" and "mudstone" are interchangeable. Shale is often composed of quartz, feldspar, and clay minerals, although its color can significantly vary depending on the presence of other minerals. Shale can be pigmented red, black, green, gray, brown, etc., by different minerals.

Shale can easily be confused with metamorphic counterpart, slate, which is also fine-grained and separates into thin planes. However, with slate, the breakage is much more pronounced and foliated lines can be observed. Light and dark gray varieties of shale are similar in appearance to limestone, but shale does not contain significant quantities of calcium carbonate, and it will not react to dilute hydrochloric acid.

Shale is very susceptible to physical weathering due to the ease with which it breaks into planes. However, when buried under the Earth's surface, shale's fine-grained matrix can prevent liquids from seeping past, and consequently, shale has held important roles in natural gas and oil exploration.

Rock salt
Rock Salt/Halite Interactive Model
Figure 3.6.10. Rock Salt/Halite. Click on this image to go to a 3D interactive model by Dexter Perkins (CC BY-NC)
Most commonly confused with: rock gypsum and calcite.

A chemical sedimentary rock. Almost every variety of rock salt precipitates inorganically from excess sodium (Na+) and chloride (Cl–) ions in water. Rock salt is one of the few rocks that is composed of a single mineral, halite (NaCl), and as such, it has a predictable chemical formula and structure. As with halite, rock salt is typically white or colorless with a cubic shape or clusters of cubic crystals that have a distinctive, salty taste.

The presence of rock salt usually indicates that a wet environment has or is undergoing significant drought. Designated as an evaporite, rock salt will commonly precipitate along the edges of an evaporating lake; as water evaporates into the atmosphere, the sodium and chloride ions remaining in the dwindling water become more concentrated until rock salt forms. Rock salt may also be common to dry plains that receive periodic rainfall or regions with briny water.

The formation of evaporite sedimentary rocks. As a closed off body of water, such as a lake, evaporates over time, minerals will precipitate in the following order: calcite, gypsum, halite.
Figure 3.6.11. The formation of evaporite sedimentary rocks. As a closed off body of water, such as a lake, evaporates over time, minerals will precipitate in the following order: calcite, gypsum, halite.
Rock salt is sometimes confused with another clear, single-mineral sedimentary rock called rock gypsum. The primary difference between these two rocks can be found in the shape of the crystals. Rock salt has cubic-shaped crystals, whereas rock gypsum can have rhomb-shaped crystals. And, you cannot scratch rock salt with a fingernail.

Rock Salt has been popularly used in the food industry, city-planning (de-icing frozen streets), and agriculture. This rock can completely dissolve in freshwater, and it has a Mohs hardness of 3. Therefore, it is very susceptible to both physical and chemical weathering, and often causes sinkholes if dissolved underground.

Rock gypsum
Rock Gypsum Interactive Model
Figure 3.6.12. Rock gypsum. Click on this image to go to a 3D interactive model by EDUROCK – Educational virtual rock collection (CC BY)
“ROCK JIP-SOME”

Most commonly confused with: rock salt, calcite

A chemical sedimentary rock. Almost every variety of rock gypsum precipitates inorganically from excess calcium (Ca2+) and sulfate (SO42-) ions in water. Rock gypsum is an evaporite rock that is composed of a single mineral, gypsum ($CaSO_4 \cdot 2H_2O$). Therefore, this rock has a predictable chemical formula and atomic structure. Rock gypsum is usually white or colorless with rhomb-shaped crystals or sometimes prismatic crystals. Rock gypsum is also very soft, and its surface can be scratched by a fingernail.

Similar to rock salt, the presence of rock gypsum in an environment or outcrop tells you that it was deposited at an arid region with either a briny or evaporating water source. These environments are often evaporating lakes or salt flats that accumulate a high concentration of calcium carbonate. It is not unusual to find both rock gypsum, rock salt, and calcite in a sequence in the same outcrop. An evaporating body of water will usually precipitate calcite first, followed by rock gypsum, and then rock salt.

Rock gypsum does not react to dilute hydrochloric acid, unlike the mineral calcite, and its crystals are usually prismatic or rhomb-shaped, unlike rock salt. Rock gypsum is softer than both calcite and halite, and therefore more susceptible to physical weathering. Rock gypsum has been traditionally used in the construction industry as a building material, such as drywall.

Chert
Chert interactive model
Figure 3.6.13. Chert. Click on this image to go to a 3D interactive model by rocksandminerals (CC BY).
“CHURT”

Most commonly confused with: obsidian, quartz

A chemical sedimentary rock. Chert can be both inorganically and biochemically precipitated in groundwater or the ocean, and it is usually composed of silica. Inorganic varieties of chert form exclusively from dissolved silica in high-temperature, high-pressure groundwater. When this geothermal water source rises to the surface, it can no longer keep the silica in a dissolved state, and it precipitates as solid chert.

Biochemical varieties are formed when silica-based skeletons such as radiolarians and diatoms accumulate on the seafloor after they die. That sediment cements together to form biogenic chert.

Microscopic silica-based organisms that make up the ocean. They have intricately built skeletons that are rounded and detailed like snowflakes.
Figure 3.6.14. Various diatoms (left) and radiolarian (right) phytoplankton.
We call chert “jasper”, “flint”, “onyx”, and “agate”, which reflect the wide variety of hues and colors that this rock can have. However, chert is most easily identified by the curved conchoidal fracture pattern it displays, which is also present in obsidian and quartz. But, chert is not as glassy or reflective as these rocks and minerals.

Because of its high silica content, chert is very durable and resistant to weathering. This property has made chert desirable in the construction trade as a road material and gravel. Like onyx, it has been traditionally used as a weapon in spearheads and arrowhead for thousands of years.

Limestone

Limestone outcrop interactive model

Figure 3.6.15. Outcrop of gray limestone that shows weathering. Click on this image to go to a 3D interactive model by Théobald GUFFON (CC BY-NC-SA)

Most commonly confused with: shale, basalt

A chemical sedimentary rock. Limestone can be both inorganically and biochemically precipitated in seawater, and it primarily composed of calcium carbonate. Inorganic limestone forms in the deep ocean when seawater reaches colder depths that cause the dissolved ions calcium (Ca2+) and carbonate (CO32-) to precipitate as solid rock. There are several varieties of limestone that incorporate both the ions and organic material from marine organisms when forming a solid matrix. These types of limestone, described in more detail below, are biochemical sedimentary rocks.

Limestone is often light to dark gray, or tan, and it can be scratched by a penny. Limestone is composed of calcium carbonate (calcite, (CaCO3) and dolomite (CaMg(CO3)2). This rock will strongly fizz when exposed to dilute hydrochloric acid (remember the properties of calcite in video 3.2.3). This reaction clearly distinguishes limestone from other dark gray rocks such as shale and basalt.

Limestone is very susceptible to chemical weathering by dissolution as rainwater and groundwater are both slightly acidic. Consequently, regions with underlying limestone often have caves and experience sinkholes. Despite its tendency to weather over long periods of time, limestone has been (and remains) a popular construction material for thousands of years, dating back to the Great Pyramid of Giza in Ancient Egypt.

Fossiliferous Limestone

Fossiliferous limestone interactive model.

Figure 3.6.16. Fossiliferous limestone. Click on this image to go to a 3D interactive model by rocksandminerals (CC BY)

“FOSSIL-LIFF-ER-RUS LIME-STONE”

Most commonly confused with: limestone

A biochemical sedimentary rock. Fossiliferous limestone specifies a type of limestone that includes visible fossils within the rock’s matrix, and therefore, it is biochemically precipitated. Fossiliferous limestone may contain the remains of shells, brachiopods, trilobites, plants or many other types of other animals.

Fossiliferous limestone can form in the deep ocean or near coral reefs, which are composed primarily of calcium carbonate. The surrounding matrix has the same properties as limestone (see above), and this rock will react when exposed to dilute hydrochloric acid. However, macrofossils within the rock distinguish fossiliferous limestone from inorganically precipitated limestone.

Coquina

Coquina Interactive Model
Figure 3.6.17. Coquina. Click on the image to go to an interactive model by the Digital Atlas of Ancient Life (CC BY-SA)
“CO-KEEN-AH”

Most commonly confused with: n/a

A biochemical sedimentary rock. Coquina is a biochemical variety of limestone that is composed of shells, fossils, and sand that have been poorly cemented together. Coquina is often tan in color with shells that are easily visible to the naked eye. Most of the material within coquina is composed of calcium carbonate, and it fizzes in contact with dilute hydrochloric acid.

Coquina can often be found along beaches or tidal pools in which there are abundant shelly creatures. The leftover shells, sand, and fossils are eventually clustered together by wave action and cemented together upon burial. Coquina is usually not well-cemented together, and it is easily weathered and reworked by physical and chemical weathering processes.

Chalk

Chalk interactive model
Figure 3.6.18. Chalk. Click the image to open an interactive model by PalomarESES CC BY-ND.
Most commonly confused with: n/a

A chemical sedimentary rock, sometimes also called marlstone or marl. Chalk is a biochemical variety of limestone that is composed of microscopic shells from an oceanic organism called a coccolithophore or coccolith. When these organisms die, their calcium carbonate-based shells accumulate along the bottom of the ocean as an ooze-like sediment, which eventually cements as chalk.

Chalk is distinctively white, powdery, and extremely soft to the point of crumbling when touched. It is easily weathered on the Earth’s surface and typically is collected by mining. Chalk has traditionally been used on school boards, but its use has since been widely discontinued in favor of gypsum.

Coal
Coal Interactive Model
Figure 3.6.19. Coal. Click on the image to go to an interactive model by the Byrd Polar & Climate Research Center (CC BY-ND)
Most commonly confused with: obsidian

An organic sedimentary rock. Coal is one of the few organic sedimentary rocks that is composed of dead plant matter. When enormous amounts of plant matter decay and accumulate from an environment, such as swamplands or dense forests, it eventually becomes buried within the Earth's surface. There, over millions of years and at high temperatures and pressures, this matter will transform into solid, black rock.

Coal is easily identified by its low density, dark black color, and soft, crumbling surface. Because it has been formed by organic matter, it is mostly made of carbon (C). Although obsidian is also black and shines like coal sometimes does, obsidian is much harder and more resistant to breaking.

Coal is combustible, and it has reshaped how societies are powered by electricity. Byproducts of burning this rock are commonly called fossil fuels, and they have contributed to significant climate problems that the world is currently facing.

3.7 Metamorphic Rocks

CHARLENE ESTRADA

Layers of rock in an outcrop are folded together like an accordion. These types of folds are possible due to metamorphism. This
Figure 3.7.1. Limestone and chert layers of rock that have been folded at high temperatures and pressures due to metamorphism.
The word "metamorphic" is Greek: meta means change; morphos means form. When rock units are buried very deeply within Earth's crust, they are subjected to high temperatures and pressures. These rocks are squeezed and warped like putty in a process called metamorphism; some of these rocks grow new minerals and textures and others lose minerals. The result of this high temperature and pressure transformation is a metamorphic rock.

Metamorphic rocks can involve high temperatures, but unlike igneous rocks, they do not melt into magma. They also involve the transformation of one rock type into another, but unlike sedimentary rocks, they do not reduce the original rock into fragments before reassembling. Metamorphism is a unique process that takes any type of preexisting rock (even old metamorphic units) and subjects it to heat and pressure over long periods of time until it has changed.

Metamorphism usually happens at least a couple kilometers beneath the Earth's surface. Tectonic boundaries, in particular, cause different types of metamorphism at mountain-building cores, subduction zones, and spreading centers. The metamorphic rocks that form at elevated temperatures and pressures are categorized by both metamorphic texture and the amount of change that the original rock appears to have undergone: metamorphic grade.

Metamorphic Texture

Metamorphic texture describes the shape and orientation of mineral grains within a metamorphic rock. As the original rock is subjected to higher temperatures and pressures, some of its minerals might stretch out in a single direction, recrystallize, or enlarge. Therefore, the new metamorphic rock will have a different texture than the parent rock.

Metamorphic texture is broadly categorized as either foliated or non-foliated.

Foliated texture

Foliation is a term that describes how minerals line up along a preferred direction. Some minerals, particularly micas, are usually thin and planar by default. Rocks with foliated texture look like they have their minerals stacked together as though they were pages in a book; hence the term “folia”, or leaflike.

This rock formation contains rock with wavy, stacked layers that are thin and easily break apart.
Figure 3.7.2. Foliated texture can look like very thin horizontal layers in rock that appear like they can peel apart like leaves, like in this mica-schist formation.
Why do foliated rocks form during metamorphism? At least two conditions need to be satisfied. First, the original rock must contain minerals that will easily deform or align with applied pressure into a flat plane. We know that mica minerals such as muscovite and biotite will do this as well as amphibole; however, stronger minerals like quartz and feldspar will often resist most pressure in the Earth’s crust.

This metamorphic rock shows striping or white and black banding of its minerals.
Figure 3.7.3. Mineral banding in the high-grade metamorphic rock gneiss. This segregation of minerals together is a type of foliation.
The second requirement needed for a foliated texture is directed pressure called differential stress. If pressure is applied unevenly, the weak minerals in the original rock will easily deform into long planes. This type of stress could be squeezing (compression), stretching (tensional), or sliding (shear) the rock unit.

Foliation that develops when minerals are squeezed and deform by lengthening in the direction perpendicular to the greatest stress (indicated by black arrows). Left- before squeezing. Right- after squeezing.
Figure 3.7.4. Foliation that develops when minerals are squeezed and deform by lengthening in the direction perpendicular to the greatest stress (indicated by black arrows). Left- before squeezing. Right- after squeezing.
Non-Foliated texture
Tan-colored rock with a granular, interlocking crystalline texture

Figure 3.7.5. Non-foliated texture does not have any distinct layering or banding. Instead, the rock appears granular or crystalline, as seen in the rock quartzite.

Non-foliated metamorphic rocks do not have any preferential alignments of mineral grains. These rocks are also called “Granoblastic“, which references the tendency of the individual grains to have somewhat equal shapes and dimensions. The majority of a non-foliated metamorphic rock contains mostly one mineral. Nonetheless, metamorphism has still taken place within these rocks; the mineral grains have recrystallized, interlocked, and grown larger. As a consequence, non-foliated rocks are much more durable and resistant to weathering than their parent rocks.

Metamorphic Grade

Video 3.7.1. What does a rock look like as it undergoes increasing grade in metamorphism? (1:22).

Metamorphic Grade refers to the extent to which metamorphism can transform the preexisting rock. This original rock is called the parent rock, and it can undergo low-grade metamorphism (little metamorphic change) to high-grade metamorphism (significant metamorphic change).

Low-grade metamorphism begins at temperatures and pressures that are not much higher than those that form sedimentary rocks. This type of metamorphism often results from rocks being buried at depths of at least 2 km. The conditions in such an environment are typically low temperature and pressure. The parent rock still transforms into a new metamorphic rock; however, it is often easy to identify visual similarities between the resulting metamorphic rock and original rock.

High-grade metamorphism requires both high temperatures and pressures. Burial depths for high-grade metamorphic rocks can be up to 35 km! Mountain-building centers and subduction zones are prime examples of regions where high-grade metamorphism might take place. When a parent rock undergoes metamorphism at these conditions, the resulting metamorphic rock bears very few similarities to the original specimen; it often has strong foliation or banding of minerals.

Metamorphic rocks are often not restricted to either low or high-grade. Geologists typically rank these rocks on a scale of how many (or few) similarities they bear to the parent rock. In a sequence or outcrop filled with metamorphic rocks, you might observe some units that appear similar to the parent rock and others that look nothing like it. In general, the following rocks have been ranked in order of increasing metamorphic grade:

Metamorphic Rock Field Guide

Slate

Slate interactive model
Figure 3.7.6. Slate. Click on this image to go to a 3D interactive model by rocksandminerals CC BY.
“SLAYTE”

Most commonly confused with: shale, phyllite

A foliated, low-grade metamorphic rock. Slate is fine-grained and composed of clays, and mica minerals that are usually too small to see with the naked eye. Slate displays strong foliation in thin sheets or layers that sometimes resemble sedimentary bedding or the linae of shale. It is usually dark gray, but it can also be red, green, brown, and even blue.

Although slate often forms from shale and bears a strong resemblance to this parent rock, its foliation pattern is typically more pronounced. Slate is also sometimes confused with a higher grade metamorphic rock, phyllite, which contains visible grains of mica minerals.

Slate will easily break into sheets along its foliation planes, but the silicate minerals that compose its fine-grained structure make it durable against physical weathering processes directed perpendicular to the foliation line. Slate is therefore used as a building material for roofs and tiles in construction.

Phyllite
Phyllite interactive model
Figure 3.7.7. Phyllite. Click on this image to go to a 3D interactive model by Dr. Parvinder Sethi CC BY.
“FY-LITE”

Most commonly confused with: slate, schist

A foliated, low to medium-grade metamorphic rock. Phyllite is fine-grained and composed mostly of quartz, feldspar, and visible flakes of mica minerals. These enlarged mica crystals give phyllite a shimmering or silky appearance under light. Phyllite, like slate, is foliated with thin sheets that sometime separate into uneven layers that give an individual rock a wavy appearance.

The color of phyllite is often gray, black, tan, or green, and it is sometimes confused for either slate or schist. Phyllite can generally be thought of a version of slate that has undergone more metamorphism; it can be distinguished from slate by its visible, glittering mica minerals. By contrast, phyllite can very broadly be thought of as the lower-grade version of schist. Schist has much larger, foliated plates of mica.

Schist
Video 3.7.2. Let’s observe a garnet schist. The sample is foliated. The shiny minerals are mica while the dark red grains are garnet (0:31).

“SHIST”

Most commonly confused with: phyllite

A foliated, medium-grade metamorphic rock. Schist contains large, leaflike grains of mica such as muscovite and biotite, that are strongly oriented into a single direction. Some varieties of schist have garnets, which only form at elevated temperatures and pressures, although most schists also contain quartz and feldspar. Due to the presence of large mica plates and their flattened orientation, schist is usually shiny or vitreous under light.

Schist is often gray or brown in color, and it is sometimes confused with phyllite, which contains smaller grains of mica. Schist can also be identified by its strong foliation pattern, which is called “schistosity”. This pattern is much more pronounced than lower grade metamorphic rocks such as slate and phyllite.

Gneiss
Gneiss Interactive Model
Figure 3.7.8. Gneiss. Click on this image to go to a 3D interactive model by Sara Carena CC BY-NC.
“NICE”

Most commonly confused with: granite, diorite

A foliated, high-grade metamorphic rock. Gneiss has a visible separation of light and dark bands, which is called lineation. Gneiss is coarse-grained and mostly contains silicate minerals that are resistant to high temperatures such as quartz, feldspar, biotite, and garnet. The banding pattern on gneiss is usually wavy or folded, which reflects how the parent rock deformed like putty at extremely high temperatures and pressures; indeed, sometimes the rock partially melts.

Gneiss is occasionally mislabeled as the igneous rock granite or diorite. Although gneiss may contain similar silicate minerals as these rocks, it is distinctively banded, whereas the igneous rocks are granular and have no preferred orientation. Because gneiss is not easily broken into sheets, it is a useful construction material in landscaping and architecture.

Marble
Marble Interactive Model
Figure 3.7.9. Marble. Click on this image to go to a 3D interactive model by EDUROCK – EDUCATIONAL VIRTUAL ROCK COLLECTION CC BY.
Most commonly confused with: quartzite

A non-foliated metamorphic rock. Marble forms under low grade or high-grade metamorphism, although at the latter it will grow larger, more interlocked crystals that reflect its higher temperature and pressure origins. The parent rock of marble is limestone, although marble typically appears to have more identifiable grains. Marble contains the mineral calcite and/or dolomite, and it may fizz with dilute hydrochloric acid.

Marble is light in color, and it can be white, pink, tan, or gray. Some varieties of marble look similar to another non-foliated metamorphic rock, quartzite. However, the minerals calcite and dolomite that primarily compose marble are much softer than those found in quartz, and marble is easier to scratch with an iron nail.

Although marble that contains calcite will react to acidic rainwater and groundwater over long periods of time, marble has traditionally been a sculpting material in art and architecture for thousands of years. Polished material remains a popular building and decorative material to this day.

Quartzite

Quartzite interactive model

Figure 3.7.10. Quartzite. Click on this image to go to a 3D interactive model by rocksandminerals CC BY.

Most commonly confused with: marble, sandstone

A non-foliated, high-grade metamorphic rock. Quartzite only forms from the sedimentary rock sandstone, and it almost exclusively contains quartz. The high temperatures and pressures in the metamorphic environment have caused the individual quartz grains to increase in size and interlock.

Quartzite is usually light tan or pink in color and coarse-grained. Like other rocks that predominately contain silica, it can display conchoidal fracture, although it is very resistant to mechanical breakage. Although this rock can look similar to marble, it will not fizz in contact with dilute hydrochloric acid, and it will not easily scratch.

Quartzite is also more durable than its parent rock, sandstone, which weakly cements sand grains together. For example, if sandstone is hit with a rock hammer, the individual grains will remain intact and the cement would crumble. If quartzite is hit with a rock hammer, it would probably spark from the friction and cause the hammer to bounce back, and, thus, is NOT recommended!

Quartzite will resist both chemical and physical weathering. As such, this rock has been used for thousands of years as a tool, construction, manufacturing, and architectural material.

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Fig. 3.5.5. James St. John. (2014, Aug 24). “Rhyodacite pumice (late August 1883 eruption of Krakatoa Volcano, Indonesia; collected at Takwa Beach, coastal Kenya, eastern Africa) 2.” [Online Image]. Flickr.
https://www.flickr.com/photos/jsjgeology/15023091491/in/album-72157651212529712/ CC BY 2.0.

Vesicular igneous rock texture.
Fig. 3.5.6. Glassy igneous rock texture

James St. John. (2015, Mar 9). “Black obsidian with streaks of mahogany obsidian.” [Online Image]. Flickr. https://www.flickr.com/photos/jsjgeology/16768859775/in/album-72157651212529712/ CC BY 2.0.
Fig. 3.5.7. James St. John. (2015, Mar 11). “Volcanic breccia with jelly opal (Cenozoic; Mexico).” [Online Image]. Flickr. https://www.flickr.com/photos/47445767@N05/16788260245 CC BY 2.0.

Pyroclastic igneous rock texture.
Video 3.5.1. Wendy Van Norden. (Jun 28, 2012) Igneous Rocks. [Online Video]. YouTube. https://www.youtube.com/watch?v=laVDypLGdbs

Lecture showcasing main processes producing igenous rocks.
Fig. 3.5.8. Sara Carena. (2020, Jun 6). “Komatiite, South Africa.” [Online Model]. SketchFab. https://sketchfab.com/3d-models/komatiite-south-africa-cd7cf872fd4745dca0ee908868ebc375 CC BY-NC.

Komatiite
Fig. 3.5.9. Sara Carena. (2020, May 8 “Peridotite xenoliths, USA.” [Online Model]. SketchFab. https://sketchfab.com/3d-models/peridotite-xenoliths-usa-1c49a6cb73a349f0a7da14fdd1a6e7ba CC BY-NC.

Peridotite
Fig. 3.5.10. Sara Carena. (2020, May 7). “Basalt, USA.” [Online Model]. SketchFab. https://sketchfab.com/3d-models/basalt-usa-f2b81c5a53c9427492875173e2fb5619 CC BY-NC.

Basalt
Fig. 3.5.11. Sara Carena. (2020, Jun 9). “Gabbro, Brazil.” [Online Model]. SketchFab. https://sketchfab.com/3d-models/gabbro-brazil-e004b43d7b3b4e8da8f3b79418a35134 CC BY-NC.

Gabbro
Fig. 3.5.12. Sara Carena. (2020, Jul 30). “Basaltic Andesite Spain.” [Online Model]. SketchFab. https://sketchfab.com/3d-models/basaltic-andesite-spain-4ac59e24353d41f8b631aa02c1b0ec1a CC BY-NC.

Andesite
Fig. 3.5.13. Sara Carena. (2020, Sep 18). “Diorite.” [Online Model]. SketchFab. https://sketchfab.com/3d-models/diorite-301bbc33e581435cbb71e09e33df5938 CC BY-NC.

Diorite
Fig. 3.5.14. Dr. Parvinder Sethi. (2020, Sep 13). “Rhyolite / RU Geology / by Grace Psenicska.” [Online Model]. SketchFab. https://sketchfab.com/3d-models/rhyolite-ru-geology-by-grace-psenicska-a0b3c6df003a4e71859da28686abeea9 CC BY.

Rhyolite
Fig. 3.5.15. Sara Carena. (2020, Nov 18). “Granite, Kenya.” [Online Model]. SketchFab. https://sketchfab.com/3d-models/granite-kenya-8d39a566d3df4d7d97a565e4785c2271 CC BY-NC.

Granite
Fig. 3.5.16. Jonathan.davidson. (2018, Mar 1). “Obsidian.” [Online Model]. SketchFab. https://sketchfab.com/3d-models/obsidian-66b9a744a4ce436cb08b285c1555f0ef CC BY.

Obsidian
Fig. 3.5.17. Simon Eugster. (2006, Apr 14). “ApachenträneGegenlicht.” [Online Image]. Wikimedia Commons. https://commons.wikimedia.org/wiki/File:Apachentr%C3%A4neGegenlicht.jpg CC BY SA.

Apache Tear
Fig. 3.5.18. Scoria

Sara Carena. (2021, Mar 19). “Scoriaceous basalt, Spain.” [Online Model]. SketchFab. https://sketchfab.com/3d-models/scoriaceous-basalt-spain-2aaf28c806c24830a0fb512cbeb10a88 CC BY-NC.
Fig. 3.5.19. Sara Carena. (2020, May 15). “Pumice.” [Online Model]. SketchFab. https://sketchfab.com/3d-models/pumice-5374302b2d204984accda59833e5a85b CC BY-NC.

Pumice
Video 3.5.2. Estrada, C. (2021). Igneous rock 8. [Online Video]. Retrieved May 19, 2022 from https://www.youtube.com/watch?v=O4BoGgMku2A&ab_channel=CharleneEstrada

Video Description: The pumice depicted in the video is beige and filled with small holes. It is very low density, and when placed in a bowl of water, it floats.
Fig. 3.5.20. rocksandminerals. (2020, Apr 23). “Rhyolite tuff #10 04-23-2020.” [Online Model]. SketchFab. https://sketchfab.com/3d-models/rhyolite-tuff-10-04-23-2020-dc53b855efa5433987778b0c38c47432 CC BY.

Tuff
3.6
Fig. 3.6.1. Karla Panchuk. (2016). “lithification-1024×409.” [Online Image]. Physical Geology, First University of Saskatchewan Edition. https://openpress.usask.ca/physicalgeology/chapter/9-1-clastic-sedimentary-rocks-2/ CC BY 4.0.

Process of sedimentary rock lithification.

Fig. 3.6.2. Charlene Estrada. (2021, Apr 21). “Weathered sandstone cliffs at sunset.” [Online Image]. Sedimentary Rocks. https://open.maricopa.edu/app/uploads/sites/119/2021/01/A8C88EF2-64AA-4764-B010-5E4B595611C8.jpeg CC BY 4.0.

Sandstone cliff formation.
Fig. 3.6.3. Karla Panchuk. (2016). “Grain-size-chart.” [Online Image]. Physical Geology, First University of Saskatchewan Edition. https://openpress.usask.ca/physicalgeology/chapter/8-4-weathering-and-erosion-produce-sediments/ CC BY 4.0.

Classification of clast grain sizes.
Fig. 3.6.4. Steven Earle. (n.d.). “sediment-clasts.” [Online Image]. Physical Geology – 2nd Edition. https://opentextbc.ca/physicalgeology2ed/chapter/6-1-clastic-sedimentary-rocks/ CC BY 4.0.

Transportation of sediments by stream flow
Fig. 3.6.5. Reagan, M.K., Pearce, J.A., Petronotis, K., and the Expedition 352 Scientists. (2015). “02_F05.” [Online Image]. Expedition 352 methods. http://publications.iodp.org/proceedings/352/102/figures/02_F05.png CC BY 3.0.

Sorting and rounding of clasts.
Fig. 3.6.6. Sara Carena. (2021, Jan 22). “Conglomerate.” [Online Model]. SketchFab. https://sketchfab.com/3d-models/conglomerate-9c2b5e3b70a0410394e2c61e31851164 CC BY.

Conglomerate.
Fig. 3.6.7. Sara Carena. (2020, May 5). “Tectonic breccia.” [Online Model]. SketchFab. https://sketchfab.com/3d-models/tectonic-breccia-caf9f8d8461445b6bc15ee17f1af94ba CC BY.

Breccia
Fig. 3.6.8. Sara Carena. (2020, May 15). “Sandstone, USA.” [Online Model]. SketchFab. https://sketchfab.com/3d-models/sandstone-usa-357ebf487b5a4c42850af5fcf95429c7 CC BY.

Sandstone
Fig. 3.6.9. Dr. Parvinder Sethi. (2020, Oct 8). “Shale / RU Geology / by Grace Psenicska.” [Online Model]. SketchFab. https://sketchfab.com/3d-models/shale-ru-geology-by-grace-psenicska-80e4de099de248b9abb5d7b5b96d89b3 CC BY.

Shale
Fig. 3.6.10. rockdoc. (2020, Aug 11). “Halite.” [Online Model]. SketchFab. https://sketchfab.com/3d-models/halite-323cf8eb403d459e9d0359d68ab1cf1d CC BY-NC.

Rock Salt/Halite

Fig. 3.6.11. Charlene Estrada. (2021, Apr 20). “Formation of evaporite rocks.” [Online Image]. Sedimentary Rocks. https://open.maricopa.edu/app/uploads/sites/119/2021/01/Screen-Shot-2021-04-20-at-10.04.02-PM.png CC BY 4.0.

Formation of evaporite sedimentary rocks.
Fig. 3.6.12. EDUROCK – EDUCATIONAL VIRTUAL ROCK COLLECTION. (2019, Sep 9). “Gypsum.” [Online Model]. SketchFab. https://sketchfab.com/3d-models/gypsum-de785119fe014b5e998a17e0fdcf6850 CC BY.

Rock gypsum
Fig. 3.6.13. rocksandminerals. (2020, Jun 4). “Chert #1637 06-04-20.” [Online Model]. SketchFab. https://sketchfab.com/3d-models/chert-1637-06-04-20-4d7a2916c0014af18564b4963e020358 CC BY.

Chert

Fig. 3.6.14. Mary Ann Tiffany and Andrea Dawes. (2017). “figure12.3.1.” [Online Image]. https://rwu.pressbooks.pub/app/uploads/sites/7/2017/01/figure12.3.1.png CC BY.

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Limestone
Fig. 3.6.16. rocksandminerals. (2020, Feb 16). “Fossiliferous Limestone 2/16/2020.” [Online Model]. SketchFab. https://sketchfab.com/3d-models/fossiliferous-limestone-2162020-106bbda8989e47ed95a676e5cbff4964 CC BY.

Fossiliferous limestone.
Fig. 3.6.17. Digital Atlas of Ancient Life. (2020, Jul 21). “Sedimentary Rock: Coquina.” [Online Model]. SketchFab. https://sketchfab.com/3d-models/sedimentary-rock-coquina-8e6d63f9a7ab42b0ac65b9178b6eff3e CC BY-SA.

Coquina
Fig. 3.6.18. PalomarESES. (2021, Feb 15). “Chalk.” [Online Model]. SketchFab. https://sketchfab.com/3d-models/chalk-225a3dec9c114026a1f0f19e2ae5690d CC BY-ND.

Chalk

Fig. 3.6.19. Byrd Polar & Climate Research Center. (2021, Jan 28). “UN-225 (Bituminous Coal [Kentucky]).” [Online Model]. SketchFab. https://sketchfab.com/3d-models/un-225-bituminous-coal-kentucky-bcc7c84830ef49eaab5b6323dd4418bc CC BY-ND.

Coal
3.7
Fig 3.7.1. Dieter Mueller. (2004, Oct 30). “Folding_of_alternate_layers_of_limestone_layers_with_chert_layers.” [Online Image]. Wikimedia Commons. https://commons.wikimedia.org/wiki/File:Folding_of_alternate_layers_of_limestone_layers_with_chert_layers.jpg CC BY-SA 4.0.

Heavily folded limestone and chert layers.
Fig. 3.7.2. Woudloper. (2007, Sep 2). “Zermatt_schists.” [Online Image]. Wikimedia Commons. https://commons.wikimedia.org/wiki/File:Zermatt_schists.JPG Public Domain.

Foliated layers of mica-schist.
Fig. 3.7.3. Oymtu. (2010, Feb18). “Gneisssic_texture.” [Online Image.] Wikimedia Commons. https://commons.wikimedia.org/wiki/File:Gneisssic_texture.JPG Public Domain.

Banded gneiss.
Fig. 3.7.4. Steven Earle. (n.d.). “image006.” [Online Image]. Physical Geology – 2nd Edition. https://openpress.usask.ca/physicalgeology/chapter/10-2-foliation-and-rock-cleavage/ CC BY 4.0.

Differential stress causes banding of mineral grains in metamorphic rocks.
Fig. 3.7.5. Randolph Black. (2018, Jan 10). “Quartzite_01_10x_(27840457419).” [Online Image]. Wikimedia Commons. https://commons.wikimedia.org/wiki/File:Quartzite_01_10x_(27840457419).jpg Public Domain.

Non-foliated metamorphic rock texture.
Video 3.7.1. Estrada, C. (Apr 22, 2021) In a Nutshell: Metamorphic Grade. [Online Video]. YouTube. https://www.youtube.com/watch?v=kxFnG2v4rkQ

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Slate
Fig 3.7.7. Dr. Parvinder Sethi. (2020, Sep 19). “Phyllite / RU Geology / by Grace Psenicska.” [Online Model]. Sketchfab. https://sketchfab.com/3d-models/orthogneiss-ab4861c508bb4b0a8e39eefeb191661c CC BY.

Phyllite
Video 3.7.2. Estrada, C. (Apr 22, 2021). Garnet Schist Hand Sample. [Online Video]. YouTube. https://www.youtube.com/watch?v=FPbOd14O0Bs

Fig. 3.7.8. Sara Carena. (2021, Jan 23). “Orthogneiss.” [Online Model]. Sketchfab. https://sketchfab.com/3d-models/orthogneiss-ab4861c508bb4b0a8e39eefeb191661c CC BY-NC.

Gneiss
Fig. 3.7.9. EDUROCK – EDUCATIONAL VIRTUAL ROCK COLLECTION. (2019, Nov 11). “Marble.” [Online Model]. Sketchfab. https://sketchfab.com/3d-models/marble-3e6a621e4b084e44b78e71e9eabfad99 CC BY.

Marble
Fig. 3.7.10. rocksandminerals. (2020, May 26). “quartzite #76 05-26-2020.” [Online Model]. Sketchfab. https://sketchfab.com/3d-models/quartzite-76-05-26-2020-d67bc8e8f2724e0c808bbf14724a050a CC BY-NC.

Quartzite