Materials of Earth's Crust

Dana Desonie, Ph.D.

AUTHOR
Dana Desonie, Ph.D.

To access a customizable version of this book, as well as other interactive content, visit www.ck12.org

CK-12 Foundation is a non-profit organization with a mission to reduce the cost of textbook materials for the K-12 market both in the U.S. and worldwide. Using an open-content, web-based collaborative model termed the **FlexBook®**, CK-12 intends to pioneer the generation and distribution of high-quality educational content that will serve both as core text as well as provide an adaptive environment for learning, powered through the **FlexBook Platform®**.

Printed: September 26, 2014

flexbook
next generation textbooks

CHAPTER 1 Materials of Earth's Crust

CHAPTER OUTLINE

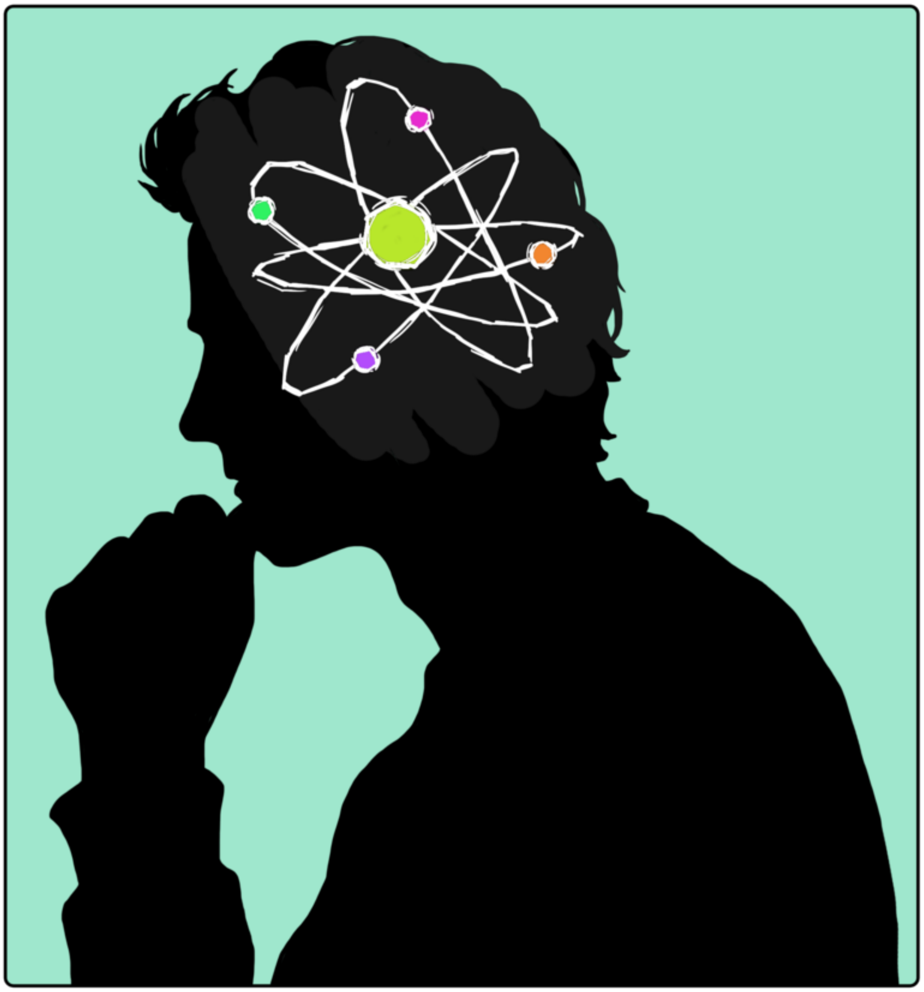
Introduction

What is Earth's crust made of?

The best way to learn about Earth's crust would be to travel around the world, viewing minerals, rocks and structures in a variety of places to see what they are and how they can be coaxed into telling Earth's story. A simpler thing to do to learn a lot about Earth materials is to visit a museum. In a museum you can see lots of samples with good explanations of what they are and, more importantly, what they tell scientists about our planet. So the next time you're in a major city, find a way to spend a few hours in a natural history museum! In this chapter we'll learn about a variety of Earth materials.

1.1 Atoms to Molecules

- Describe atoms and isotopes.



What is your brain made of?

Everything you can see, touch, smell, feel, and taste is made of atoms. Atoms are the basic building-block of all matter (including you and me, and everyone else you'll ever meet), so if we want to know about what Earth is made of, then we have to know a few things about these incredibly small objects.

Atoms

Everyday experience should convince you that matter is found in myriad forms, yet all the matter you have ever seen is made of atoms, or atoms stuck together in configurations of dizzying complexity. A chemical **element** is a substance that cannot be made into a simpler form by ordinary chemical means. The smallest unit of a chemical element is an **atom**, and all atoms of a particular element are identical.

Parts of an Atom

There are two parts to an atom (**Figure** 1.1):

- At the center of an atom is a **nucleus** made up of two types of particles called protons and neutrons.
  - **Protons** have a positive electrical charge. The number of protons in the nucleus determines what element the atom is.
  - **Neutrons** are about the size of protons but have no charge.
- **Electrons**, much smaller than protons or neutrons, have a negative electrical charge, move at nearly the speed of light, and orbit the nucleus at exact distances, depending on their energy.

An introduction to the atom is seen in this video: http://www.khanacademy.org/video/introduction-to-the-atom .

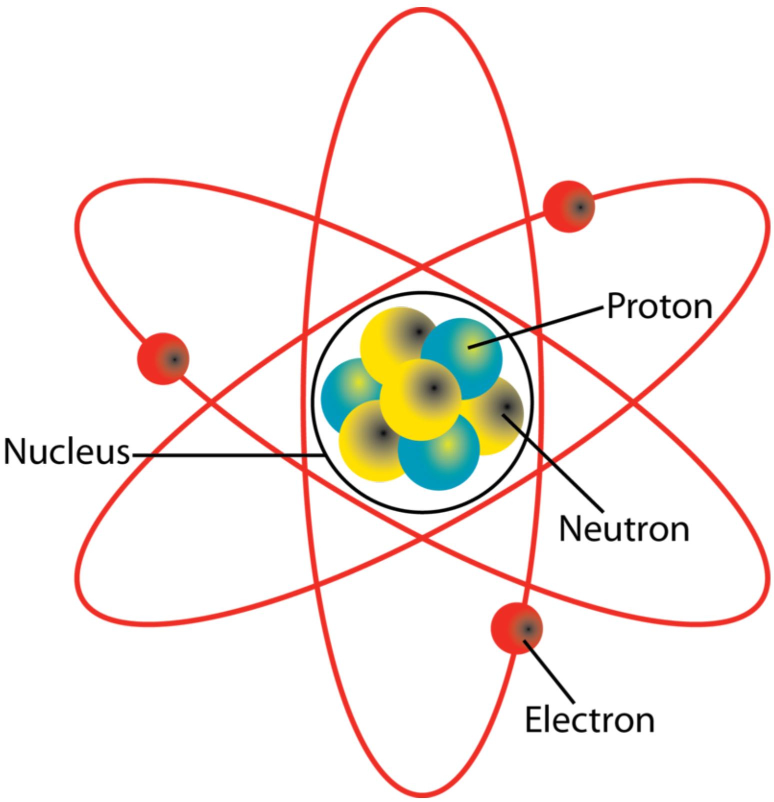


FIGURE 1.1
Major parts of an atom. What chemical element is this? (Hint: 3 protons, 3 electrons)

Atomic Mass

Because electrons are minuscule compared with protons and neutrons, the number of protons plus neutrons gives the atom its **atomic mass**. All atoms of a given element always have the same number of protons, but may differ in the number of neutrons found in the nucleus.

Isotopes

Atoms of an element with differing numbers of neutrons are called **isotopes**. For example, carbon always has 6 protons but may have 6, 7, or 8 neutrons. This means there are three isotopes of carbon: carbon-12, carbon-13, and carbon-14, however, carbon-12 is by far the most abundant.

Ions

Atoms are stable when they have a full outermost electron energy level. To fill its outermost shell, an atom will give, take, or share electrons. When an atom either gains or loses electrons, this creates an **ion**. Ions have either a positive or a negative electrical charge. What is the charge of an ion if the atom loses an electron? An atom with the same number of protons and electrons has no overall charge, so if an atom loses the negatively charged electron, it has a positive charge. What is the charge of an ion if the atom gains an electron? If the atom gains an electron, it has a negative charge.

Molecules

In the previous section we said that many atoms are more stable when they have a net charge: they are more stable as ions. When a cation gets close to an anion, they link up because of their different net charges —positive charges attract negative charges and vice versa. When two or more atoms link up, they create a **molecule**. A molecule of water is made of two atoms of hydrogen (H) and one atom of oxygen (O). The **molecular mass** is the sum of the masses of all the atoms in the molecule. A collection of molecules is called a compound.

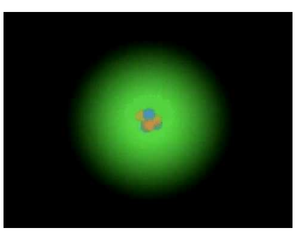
Summary

- An atom has negatively-charged electrons in orbit around its nucleus, which is composed of positively-charged protons and neutrons, which have no charge.
- Isotopes of an element must have a given number of protons but may have variety of numbers of neutrons.
- An atom that gains or loses electrons is an ion.

Explore More

Use the resource below to answer the questions that follow.

- **Basic Atomic Structure** at http://www.youtube.com/watch?v=lP57gEWcisY (1:57)



MEDIA
Click image to the left for use the URL below.
URL: http://gamma.ck12.org/flx/render/embeddedobject/100587

1. What is found at the center of an atom?
2. What makes up the nucleus?
3. What is the charge on the nucleus?
4. What is equal in neutral atoms?
5. List the parts of an atom and identify the charge of each.

Explore More Answers

1. the nucleus
2. protons and neutrons

3. Protons have a positive charge and neutrons have no charge so the overall charge of the nucleus is positive.
4. The number of protons and the number of electrons; their charges are equal in a neutral atom.
5. Protons - positive; neutrons - neutral; electrons - negative

Review

1. If an atom has 8 protons, 8 neutrons, and 8 electrons and then loses an electron, what is it? What is its charge?
2. What charge(s) does an ion have, positive, negative, or neutral?
3. What is a molecule made of and what is its molecular mass?

Review Answers

1. It would be an ion that is positively charged.
2. Ions can be positively or negatively charged but not neutral. A neutrally charged unit is an atom.
3. A molecule is the smallest unit of a chemical compound. Its mass is the total of all of the masses of all of its atoms.

1.2 Chemical Bonding

- Explain how different types of chemical bonds form.

How do compounds stick together?

When you think of bonding, you may not think of ions. Like most of us, you probably think of bonding between people. Like people, molecules bond —and some bonds are stronger than others. It's hard to break up a mother and baby, or a molecule made up of one oxygen and two hydrogens!

Chemical Bonding

Ions come together to create a molecule so that electrical charges are balanced; the positive charges balance the negative charges and the molecule has no electrical charge. To balance electrical charge, an atom may share its electron with another atom, give it away, or receive an electron from another atom.

The joining of ions to make molecules is called **chemical bonding**. There are three main types of chemical bonds that are important in our discussion of minerals and rocks:

- **Ionic bond**: Electrons are transferred between atoms. An ion will give one or more electrons to another ion. Table salt, sodium chloride (NaCl), is a common example of an ionic compound. Note that sodium is on the left side of the periodic table and that chlorine is on the right side of the periodic table. In the **Figure** 1.3, an atom of lithium donates an electron to an atom of fluorine to form an ionic compound. The transfer of the electron gives the lithium ion a net charge of +1, and the fluorine ion a net charge of -1. These ions bond because they experience an attractive force due to the difference in sign of their charges.

- **Covalent bond** : In a covalent bond, an atom shares one or more electrons with another atom.

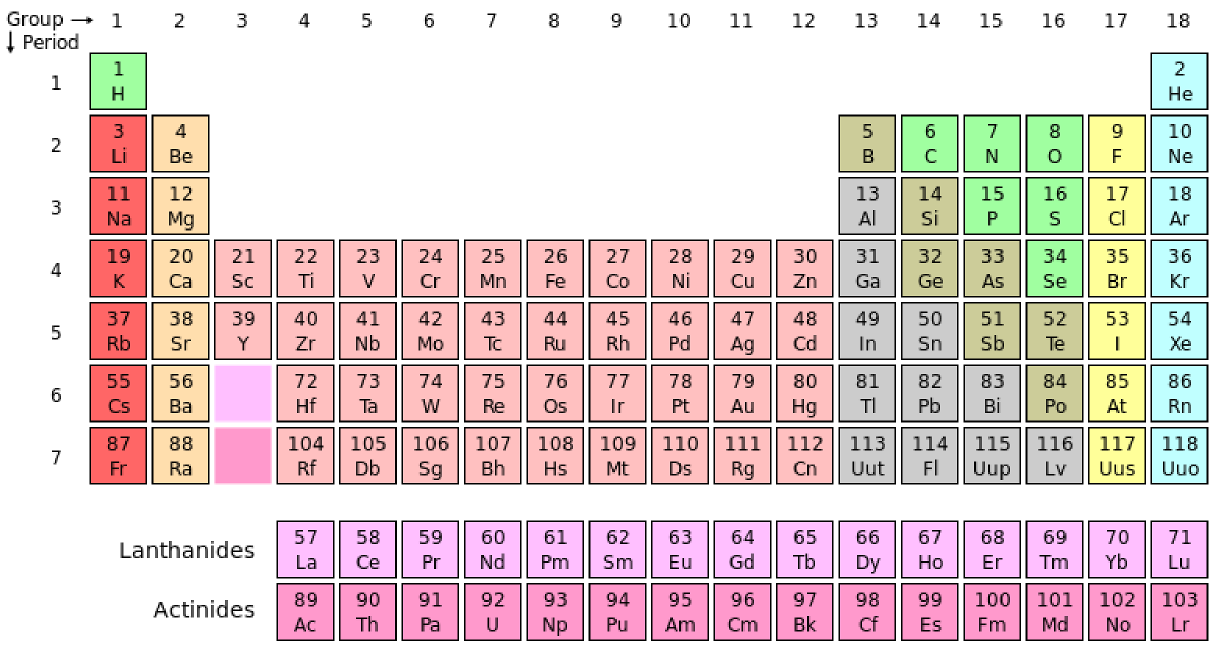


FIGURE 1.2

Periodic Table of the Elements.

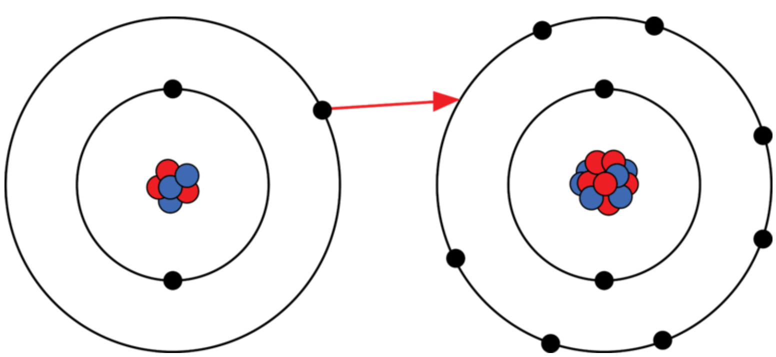


FIGURE 1.3

Lithium (left) and fluorine (right) form an ionic compound called lithium fluoride.

In the picture of methane (CH_4) below (**Figure** 1.4), the carbon ion (with a net charge of +4) shares a single electron from each of the the four hydrogens. Covalent bonding is prevalent in organic compounds. In fact, your body is held together by electrons shared by carbons and hydrogens! Covalent bonds are also very strong, meaning it takes a lot of energy to break them apart.

- **Hydrogen bond**: These weak, intermolecular bonds are formed when the positive side of one polar molecule is attracted to the negative side of another polar molecule.

Water is a classic example of a **polar molecule** because it has a slightly positive side, and a slightly negative side. In fact, this property is why water is so good at dissolving things. The positive side of the molecule is attracted to

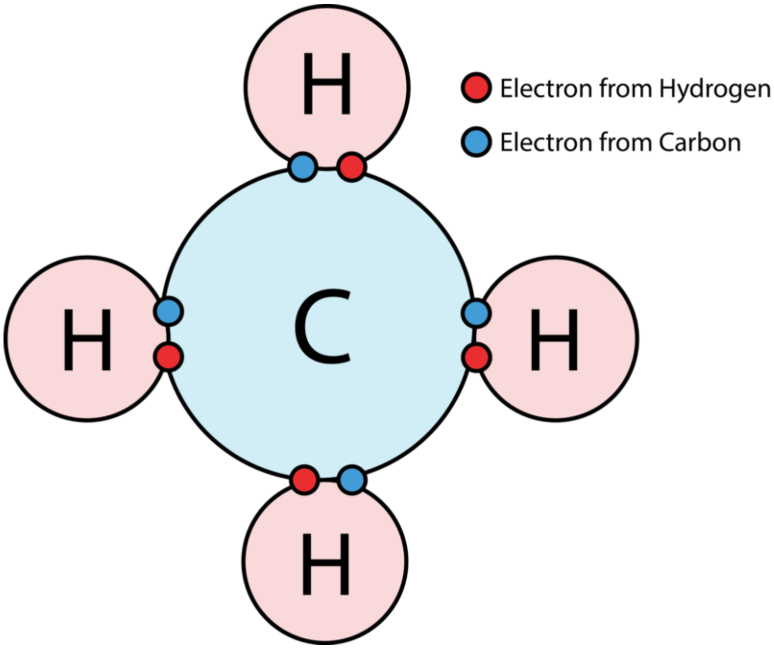


FIGURE 1.4
Methane is formed when four hydrogens and one carbon covalently bond.

negative ions and the negative side is attracted to positive ions.

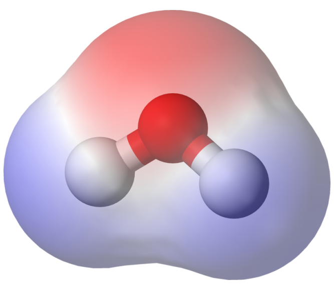


FIGURE 1.5
Water is a polar molecule. Because the oxygen atom has the electrons most of the time, the hydrogen side (blue) of the molecule has a slightly positive charge while the oxygen side (red) has a slightly negative charge.

A video about chemical bonding: http://www.khanacademy.org/video/ionic–covalent–and-metallic-bonds .

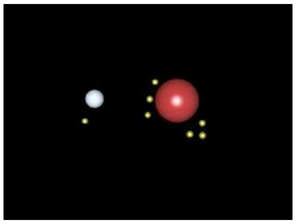
Water is a covalently bonded, polar molecule. Watch this animation to see how it forms: http://www.youtube.com/watch?v=qmgE0w6E6ZI .

Summary

- In an ionic bond, an atom gives away one or more electrons to another atom.
- In a covalent bond, two atoms share one or more electrons.
- A hydrogen bond is a relatively weak bond between two oppositely charged sides of two or more molecules. Water is a polar molecule.

Explore More

Use this resource to answer the questions that follow.



MEDIA

Click image to the left for use the URL below.

URL: http://gamma.ck12.org/flx/render/embeddedobject/624

1. What is ionic bonding?
2. How many valence electrons does sodium have? How many valence electrons does chlorine have?
3. How does chlorine bond with sodium?
4. What is the charge on a sodium ion? What about the chlorine ion?
5. When does covalent bonding occur? How does it work?
6. How many valence electrons does oxygen have?
7. Why do oxygen and hydrogen bond so well?

Explore More Answers

1. An ionic bond occurs between two atoms when one has enough attraction to remove an electron from the other.
2. One; seven
3. The chlorine atom removes an electron from sodium, which loses its only valence electron and becomes a positively charged sodium ion. The energy makes it stable with 8 electrons in the outer shell.
4. Negative; positive.
5. It occurs when one atoms is not strong enough to take an electron away from the other atom. They two atoms share an electron.
6. Six.
7. Oxygen shares electrons.

Review

1. How is a covalent bond different from an ionic bond?
2. Why is a hydrogen bond a relatively weak bond?
3. Diagram the polarity of a water molecule.

Review Answers

1. In an ionic bond, one atom gives and electron to another atom. In a covalent bond, the atoms share the electron.
2. No electrons are given or shared. The positive side of an atom is attracted to the negative side of another atom.
3. See image above.

1.3 Minerals

- Describe the characteristics that define minerals.

Are you a mineral?

There used to be a TV commercial that said "you are what you eat." If that's true - and to some extent it is - then you are a mineral. Nearly all of our food is salted, and what is salt but the mineral halite? You also wear minerals, play with and on minerals, and admire the beauty of minerals. However, a mineral by definition cannot be organic, so despite what you heard on TV, you aren't what you eat!

What is a Mineral?

Minerals are everywhere! Scientists have identified more than 4,000 minerals in Earth's crust, although the bulk of the planet is composed of just a few.

A **mineral** possesses the following qualities:

- It must be solid.
- It must be crystalline, meaning it has a repeating arrangement of atoms.
- It must be naturally occurring.
- It must be inorganic.
- It must have a specific chemical composition.

Minerals can be identified by their physical properties, such as hardness, color, luster (shininess), and odor. The most common laboratory technique used to identify a mineral is X-ray diffraction (XRD), a technique that involves shining an X-ray light on a sample, and observing how the light exiting the sample is bent. XRD is not useful in the field, however.

The definition of a mineral is more restricted than you might think at first. For example, glass is made of sand, which is rich in the mineral quartz. But glass is not a mineral, because it is not crystalline. Instead, glass has a random assemblage of molecules. What about steel? Steel is made by mixing different metal minerals like iron, cobalt, chromium, vanadium, and molybdenum, but steel is not a mineral because it is made by humans and therefore is not naturally occurring. However, almost any rock you pick up is composed of minerals. Below we explore the qualities of minerals in more detail.

Crystalline Solid

Minerals are "crystalline" solids. A **crystal** is a solid in which the atoms are arranged in a regular, repeating pattern. Notice that in **Figure** 1.6 the green and purple spheres, representing sodium and chlorine, form a repeating pattern. In this case, they alternate in all directions.

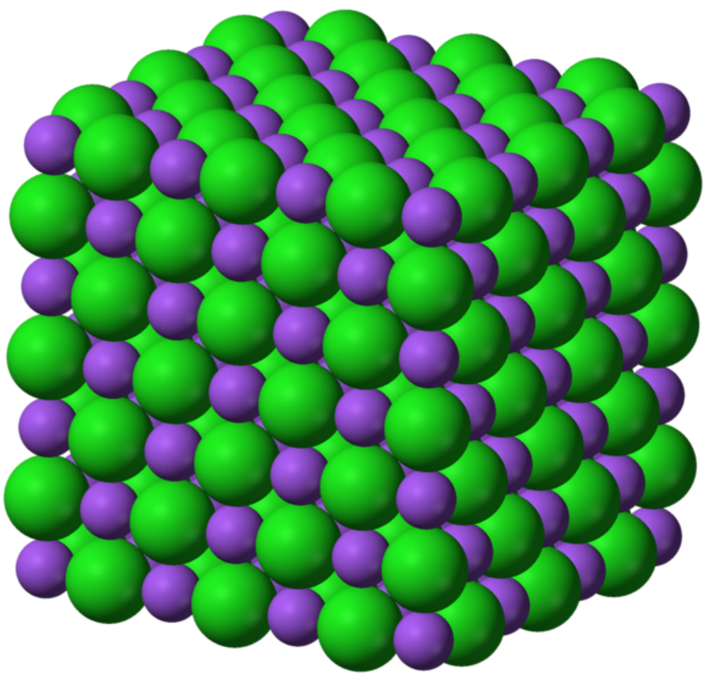


FIGURE 1.6
Sodium ions (purple balls) bond with chloride ions (green balls) to make table salt (halite). All of the grains of salt that are in a salt shaker have this crystalline structure.

Inorganic

Organic substances are the carbon-based compounds made by living creatures and include proteins, carbohydrates, and oils. Inorganic substances have a structure that is not characteristic of living bodies. Coal is made of plant and animal remains. Is it a mineral? Coal is a classified as a sedimentary rock, but is not a mineral.

Naturally Occurring

Minerals are made by natural processes, those that occur in or on Earth. A diamond created deep in Earth's crust is a mineral, but a diamond made in a laboratory by humans is not. Be careful about buying a laboratory-made "diamond" for jewelry. It may look pretty, but it's not a diamond and is not technically a mineral.

Chemical Composition

Nearly all (98.5%) of Earth's crust is made up of only eight elements –oxygen, silicon, aluminum, iron, calcium, sodium, potassium, and magnesium –and these are the elements that make up most minerals.

All minerals have a specific chemical composition. The mineral silver is made up of only silver atoms and diamond is made only of carbon atoms, but most minerals are made up of **chemical compounds**. Each mineral has its own chemical formula. Table salt (also known as halite), pictured in **Figure** 1.6, is NaCl (sodium chloride). Quartz is always made of two oxygen atoms (red) bonded to a silicon atom (grey), represented by the chemical formula SiO_2 (**Figure** 1.7).

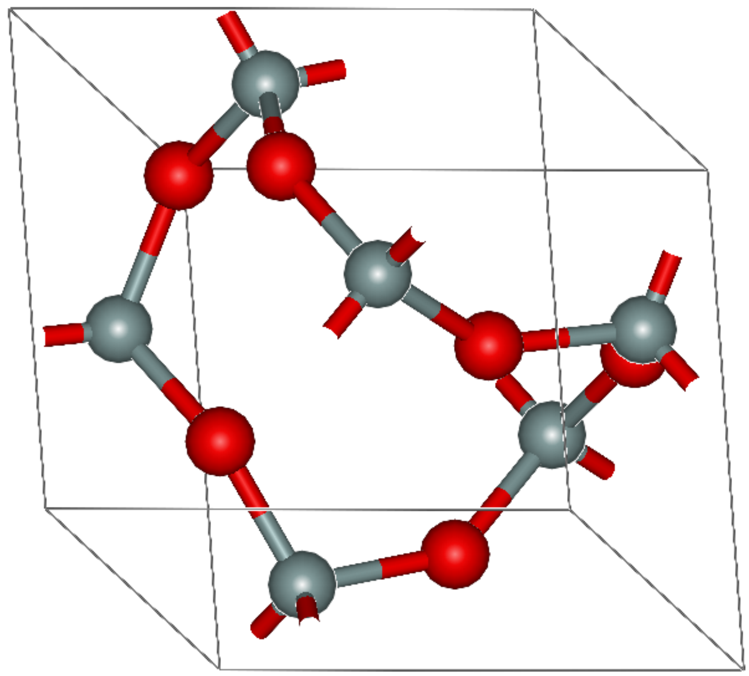


FIGURE 1.7
Quartz is made of two oxygen atoms (red) bonded to a silicon atom (grey).

In nature, things are rarely as simple as in the lab, and so it should not come as a surprise that some minerals have a range of chemical compositions. One important example in Earth science is olivine, which always has silicon and oxygen as well as some iron and magnesium, $(Mg, Fe)_2SiO_4$.

Physical Properties

Some minerals can be identified with little more than the naked eye. We do this by examining the physical properties of the mineral in question, which include:

- Color: the color of the mineral.
- Streak: the color of the mineral's powder (this is often different from the color of the whole mineral).
- Luster: shininess.
- Density: mass per volume, typically reported in "specific gravity," which is the density relative to water.
- Cleavage: the mineral's tendency to break along planes of weakness.
- Fracture: the pattern in which a mineral breaks.
- Hardness: which minerals it can scratch and which minerals can scratch it.

How physical properties are used to identify minerals is described in the concept "Mineral Identification."

Summary

- A mineral is an inorganic, crystalline solid.
- A mineral is formed through natural processes and has a definite chemical composition.
- Minerals can be identified by their characteristic physical properties, such as crystalline structure, hardness, density, breakage, and color.

Explore More

Use this resource to answer the questions that follow.

https://www.youtube.com/watch?v=8a7p1NFn64s

1. If you look carefully at a piece of granite, what can you see in it?
2. What are diamonds used for?
3. What is the mineral fluorite used for?
4. What five criteria must be met for a substance to be a mineral?
5. What are the majority of minerals on Earth's surface? What are they made up of and in what form?
6. Is ice a mineral? Why or why not?
7. What do all of the physical properties of a mineral come from?
8. Why does the element carbon create such different minerals as diamond and graphite?

Explore More Answers

1. You can see mineral crystals including quartz, biotite mica, and plagioclase feldspar.
2. jewelry, construction applications, tips of saw blades and other industrial uses
3. It is fluoride in toothpaste!
4. It must be solid, be naturally occurring on Earth, be inorganic, have a fixed chemical formula, and must have an orderly crystal structure.
5. Silicates are the most common; they are made of a silica tetrahedron of 4 oxygen atoms and 1 silicon atom.
6. Ice is a mineral because it meets the 5 criteria, but most places on Earth water is a liquid.
7. They are the result of the internal arrangement of atoms.
8. In diamond, the carbon atoms are all interlocking to create a really hard bond. In graphite the carbon atoms are arranged in sheets so it's a softer weaker mineral.

Review

1. Is coal a mineral? Why or why not?
2. Is a diamond made in a laboratory a mineral? Why or why not?
3. How does the internal structure of a mineral reflect in its physical appearance?

Review Answers

1. Coal is not a mineral because it is organic.
2. Anything made in a laboratory is not a mineral because a mineral must be something that occurs in nature.
3. A mineral with a distinct internal structure will break into the shape of its structure. For example, halite breaks into cubes.

1.4 Mineral Groups

- Describe the characteristics of mineral groups.

How could a mineral crystal grow as big as two giraffes?

The crystals in Giant Crystal Cave in Mexico measure up to 36 feet long. How could minerals grow that big? Beyond requiring many years, the environment was completely suited for crystal growth, with lots of space, a perfect 136^oF temperature and lots of mineral-rich water.

Mineral Groups

Minerals are divided into groups based on chemical composition. Most minerals fit into one of eight mineral groups.

Silicate Minerals

The roughly 1,000 silicate minerals make up over 90% of Earth's crust. **Silicates** are by far the largest mineral group. Feldspar and quartz are the two most common silicate minerals. Both are extremely common rock-forming minerals.

The basic building block for all silicate minerals is the silica tetrahedron, which is illustrated in **Figure** 1.8. To create the wide variety of silicate minerals, this pyramid-shaped structure is often bound to other elements, such as calcium, iron, and magnesium.

Silica tetrahedrons combine together in six different ways to create different types of silicates (**Figure** 1.9). Tetrahedrons can stand alone, form connected circles called rings, link into single and double chains, form large flat sheets of pyramids, or join in three dimensions.

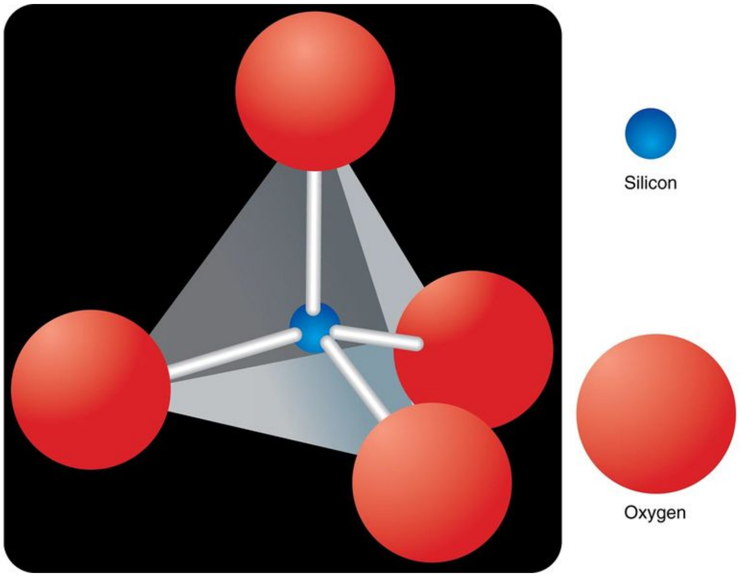


FIGURE 1.8
One silicon atom bonds to four oxygen atoms to form a silica tetrahedron.

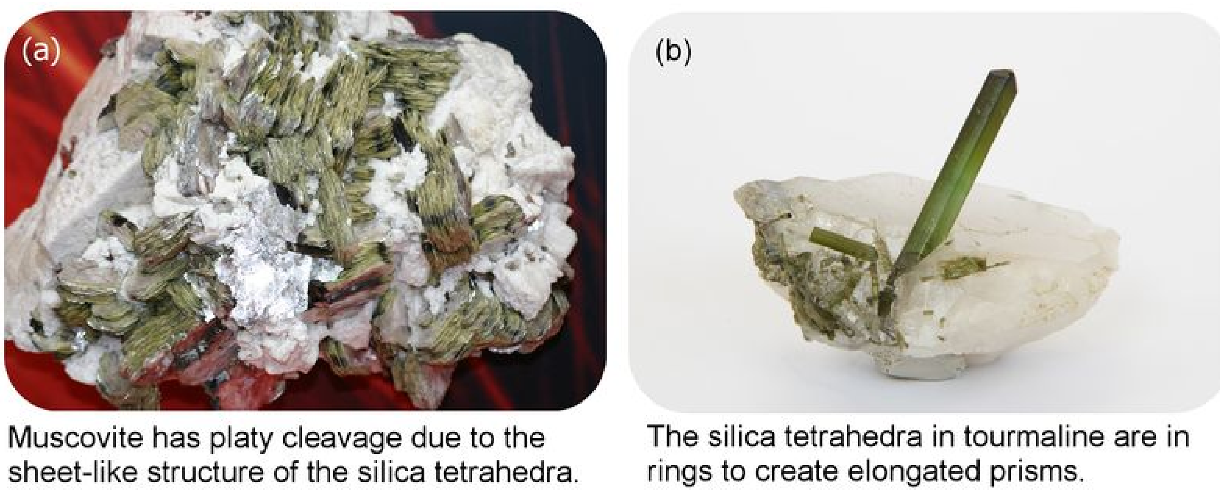


FIGURE 1.9
The different ways that silica tetrahedrons can join together cause these two minerals to look very different.

Native Elements

Native elements contain atoms of only one type of element. Only a small number of minerals are found in this category. Some of the minerals in this group are rare and valuable. Gold (**Figure** 1.10), silver, sulfur, and diamond are examples of native elements.

FIGURE 1.10
A gold nugget.

Carbonates

The basic carbonate structure is one carbon atom bonded to three oxygen atoms. Carbonates consists of some cation (like C, Fe, Cu, Mg, Ba, Sr, Pb) bonded to a carbonate molecule. Calcite ($CaCO_3$) is the most common carbonate mineral (**Figure** 1.11).

FIGURE 1.11
Calcite.

Halides

Halide minerals are salts that form when salt water evaporates. Halite is a halide mineral, but table salt (see **Figure** 1.13) is not the only halide. The chemical elements known as the halogens (fluorine, chlorine, bromine, or iodine) bond with various metallic atoms to make halide minerals. All halides are ionic minerals, which means that they are typically soluble in water.

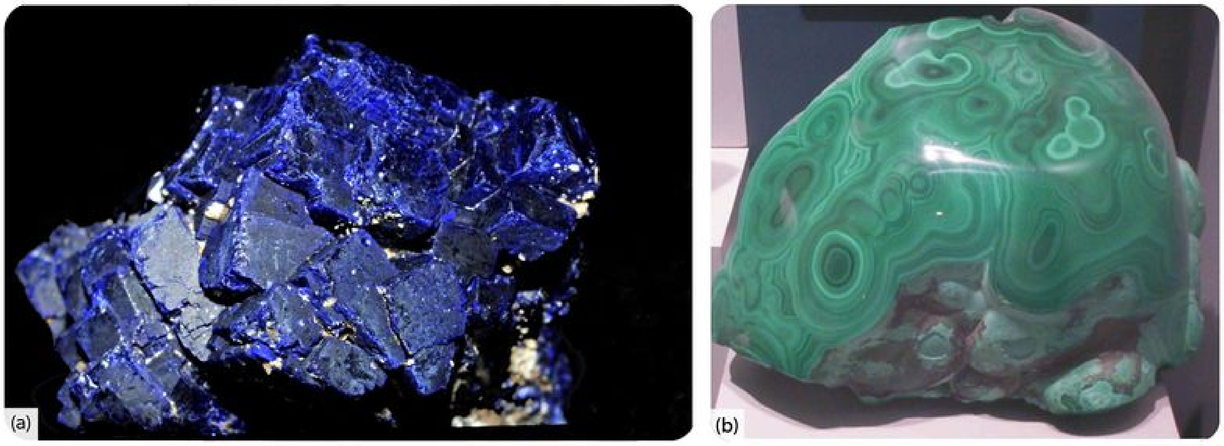


FIGURE 1.12
Two carbonate minerals: (a) deep blue azurite and (b) opaque green malachite. Azurite and malachite are carbonates that contain copper instead of calcium.

FIGURE 1.13
Beautiful halite crystal.

Oxides

Oxides contain one or two metal elements combined with oxygen. Many important metal ores are oxides. Hematite (Fe_2O_3), with two iron atoms to three oxygen atoms, and magnetite (Fe_3O_4) (**Figure** 1.14), with three iron atoms to four oxygen atoms, are both iron oxides.

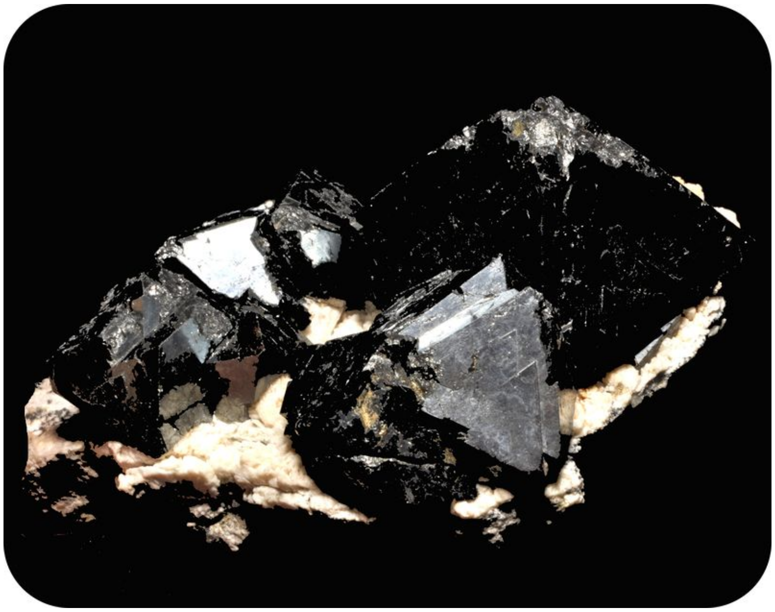


FIGURE 1.14
Magnetite is one of the most distinctive oxides since it is magnetic.

Phosphates

Phosphate minerals are similar in atomic structure to the silicate minerals. In the phosphates, phosphorus bonds to oxygen to form a tetrahedron. As a mineral group they aren't particularly common or important rock-forming minerals, but they are important for you and I. Apatite (**Figure** 1.15) is a phosphate ($Ca_5(PO_4)_3(F,OH)$) and is one of the major components of human bone!

FIGURE 1.15
Apatite.

Sulfates

Sulfate minerals contain sulfur atoms bonded to four oxygen atoms, just like silicates and phosphates. Like halides, they form where salt water evaporates. The most common sulfate mineral is probably gypsum ($CaSO_4(OH)_2$) (**Figure** 1.16). Some gigantic 11-meter gypsum crystals have been found (See opening image). That is about as long as a school bus!

FIGURE 1.16
Gypsum.

Sulfides

Sulfides are formed when metallic elements combine with sulfur in the absence of oxygen. Pyrite (**Figure** 1.17) (FeS_2) is a common sulfide mineral colloquially known as "fool's gold" because it has a golden metallic looking mineral. There are three easy ways to discriminate real gold from fools gold: real gold is extremely dense, real gold does not grow into perfect cubes, as pyrite commonly does, and pyrite smells like rotten eggs (because of the sulfur).

Summary

- Silicates, made of building blocks of silica tetrahedrons, are the most abundant minerals on Earth.
- Silica tetrahedrons combine together in six different ways to create rings, single and double chains, large flat sheets, or 3-dimensional structures.
- Other mineral groups have other anions like carbonates, oxides, or phosphates.
- Minerals that are native elements are made of only one element.

FIGURE 1.17
This mineral has shiny, gold, cubic crystals with striations, so it is pyrite.

Explore More

Use this resource to answer the questions that follow.

Introduction to Minerals, start at 6:40 https://www.youtube.com/watch?v=ahRTRV8l70c

1. What mineral group is 96% of Earth's crust made of? What are the two most common examples of this mineral group?
2. What are the halides and what are the common ions that create them, the anions (negatively charged) and cations (positively charged)?
3. What do all carbonates contain? If the cation is copper, what is the mineral?
4. What do all sulfates contain? Which sulfate is sheet rock made of?
5. What do all sulfides contain? What other element does pyrite contain?
6. What do all oxides contain? If an aluminum oxide is blue what is it?
7. What is the characteristic of native elements? Name Au, Cu, S, C

Explore More Answers

1. SiO2, quartz and feldspar
2. Halides are the salts that have the anions, chlorine and fluorine, combined with the cations ,sodium, potassium and calcium.
3. CO3; malachite
4. SO4; gypsum
5. S;iron
6. O bonded to an element other than silicon; sapphire
7. They are single elements not bonded with other elements. Gold, copper, sulfur, carbon (graphite or diamond).

Review

1. What is the most common group of minerals on Earth? What do they all contain?
2. How are the silicates categorized?

3. Your friend brings you a fist-sized perfect cube of a golden mineral, which he tells you is gold. What should you and your friend consider before determining that he is right?

Review Answers

1. Silicates are the most common. They all contain a silica tetrahedron made of one silicon and four oxygens.
2. They are categorized by how the silica tetrahedrons join together.
3. That it could be a mineral that looks like gold. Like pyrite.

1.5 Mineral Identification

- Explain how minerals are identified by their physical characteristics.

Can you identify this mineral?

Check out the mineral above. How would you figure out what kind of mineral it is? By color? Shape? Whether it's shiny or dull? Are there lines (striations) running across the minerals? This mineral has shiny, gold, cubic crystals with striations, and smells like sulfur. What is it? In this concept, we will discuss how to identify a mineral as one would "in the field," that is, without using fancy lab equipment.

How Are Minerals Identified?

There are a multitude of laboratory and field techniques for identifying minerals. While a mineralogist might use a high-powered microscope to identify some minerals, or even techniques like x-ray diffraction, most are recognizable using physical properties.

The most common field techniques put the observer in the shoes of a detective, whose goal it is to determine, by process of elimination, what the mineral in question is. The process of elimination usually includes observing things like color, hardness, smell, solubility in acid, streak, striations and/or cleavage.

Check out the mineral in the opening image. What is the mineral's color? What is its shape? Are the individual crystals shiny or dull? Are there lines (striations) running across the minerals? In this concept, the properties used to identify minerals are described in more detail.

Color, Streak, and Luster

Color

Color may be the first feature you notice about a mineral, but color is not often important for mineral identification. For example, quartz can be colorless, purple (amethyst), or a variety of other colors depending on chemical impurities **Figure** 1.18.

FIGURE 1.18
Purple quartz, known as amethyst, and clear quartz are the same mineral despite the different colors.

Streak

Streak is the color of a mineral's powder, which often is not the same color as the mineral itself. Many minerals, such as the quartz in the **Figure** 1.18, do not have streak.

Hematite is an example of a mineral that displays a certain color in hand sample (typically black to steel gray, sometimes reddish), and a different streak color (red/brown).

Luster

Luster describes the reflection of light off a mineral's surface. Mineralogists have special terms to describe luster. One simple 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. Different types of non-metallic luster are described in **Table** 1.1.

TABLE 1.1: **Six types of non-metallic luster.**

Luster	Appearance
Adamantine	Sparkly
Earthy	Dull, clay-like
Pearly	Pearl-like
Resinous	Like resins, such as tree sap
Silky	Soft-looking with long fibers
Vitreous	Glassy

FIGURE 1.19
The streak of hematite across an unglazed porcelain plate is red-brown.

Specific Gravity

Density describes how much matter is in a certain amount of space: density = mass/volume.

Mass is a measure of the amount of matter in an object. The amount of space an object takes up is described by its volume. The density of an object depends on its mass and its volume. For example, the water in a drinking glass has the same density as the water in the same volume of a swimming pool.

Gold has a density of about 19 g/cm^3; pyrite has a density of about 5 g/cm^3 - that's another way to tell pyrite from gold. Quartz is even less dense than pyrite and has a density of 2.7 g/cm^3.

The specific gravity of a substance compares its density to that of water. Substances that are more dense have higher specific gravity.

Hardness

Hardness is a measure of whether a mineral will scratch or be scratched. Mohs Hardness Scale, shown in **Table** 1.2, is a reference for mineral hardness.

TABLE 1.2: **Mohs Hardness Scale: 1 (softest) to 10 (hardest).**

Hardness	Mineral
1	Talc
2	Gypsum
3	Calcite
4	Fluorite
5	Apatite
6	Feldspar
7	Quartz
8	Topaz

TABLE 1.2: (continued)

Hardness	Mineral
9	Corundum
10	Diamond

With a Mohs scale, anyone can test an unknown mineral for its hardness. Imagine you have an unknown mineral. You find that it can scratch fluorite or even apatite, but feldspar scratches it. You know then that the mineral's hardness is between 5 and 6. Note that no other mineral can scratch diamond.

Cleavage and Fracture

Breaking a mineral breaks its chemical bonds. Since some bonds are weaker than other bonds, each type of mineral is likely to break where the bonds between the atoms are weaker. For that reason, minerals break apart in characteristic ways.

Cleavage is the tendency of a mineral to break along certain planes to make smooth surfaces. Halite (**Figure** 1.20) breaks between layers of sodium and chlorine to form cubes with smooth surfaces.

FIGURE 1.20
Halite has cubic cleavage.

Mica has cleavage in one direction and forms sheets (**Figure** 1.21).

Minerals can cleave into polygons. Magnetite forms octahedrons (**Figure** 1.22).

One reason gemstones are beautiful is that the cleavage planes make an attractive crystal shape with smooth faces.

Fracture is a break in a mineral that is not along a cleavage plane. Fracture is not always the same in the same mineral because fracture is not determined by the structure of the mineral.

Minerals may have characteristic fractures (**Figure** 1.23). Metals usually fracture into jagged edges. If a mineral splinters like wood, it may be fibrous. Some minerals, such as quartz, form smooth curved surfaces when they fracture.

FIGURE 1.21
Sheets of mica.

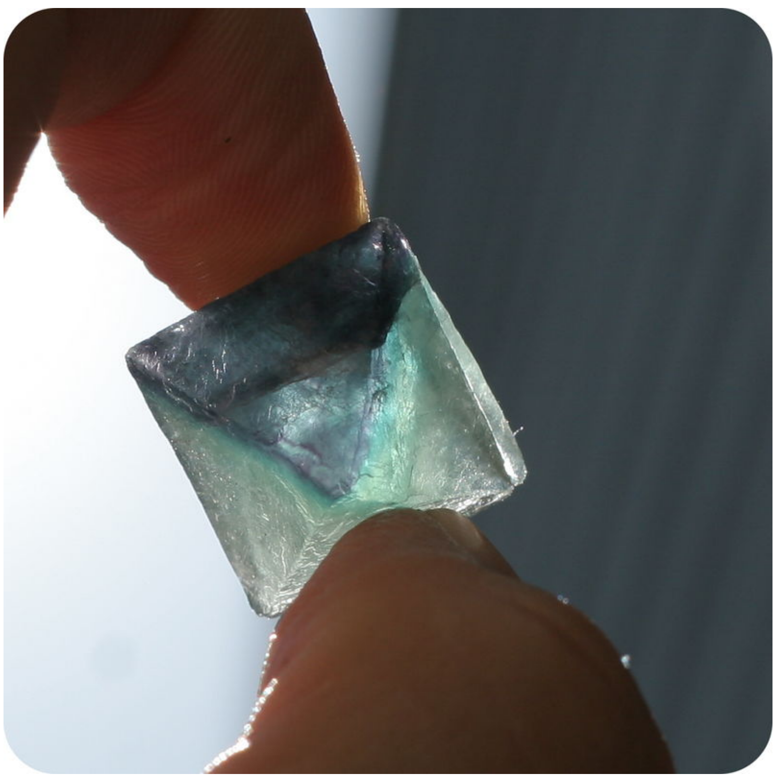


FIGURE 1.22
Fluorite has octahedral cleavage.

Other Identifying Characteristics

Some minerals have other unique properties, some of which are listed in **Table** 1.3. Can you name a unique property that would allow you to instantly identify a mineral that's been described quite a bit in this concept? (Hint: It is most likely found on your dinner table.)

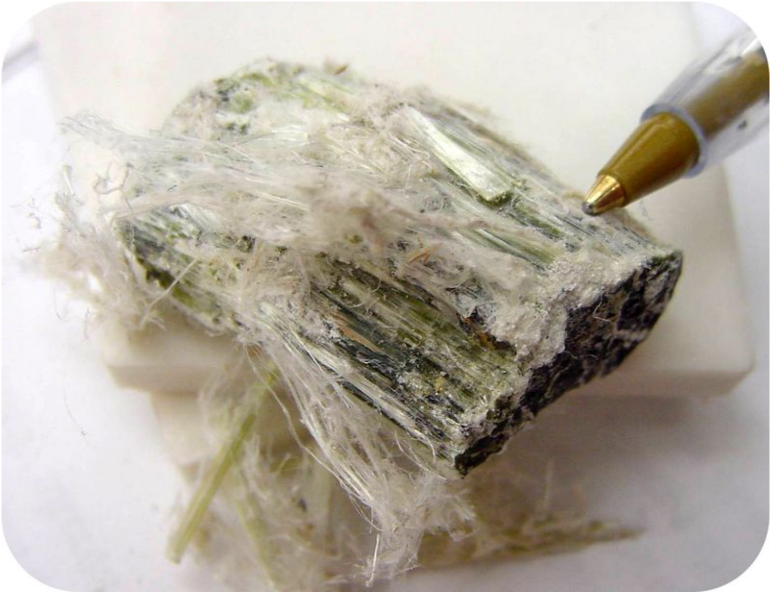


FIGURE 1.23
Chrysotile has splintery fracture.

TABLE 1.3: **Some minerals have unusual properties that can be used for identification.**

Property	Description	Example of Mineral
Fluorescence	Mineral glows under ultraviolet light	Fluorite
Magnetism	Mineral is attracted to a magnet	Magnetite
Radioactivity	Mineral gives off radiation that can be measured with Geiger counter	Uraninite
Reactivity	Bubbles form when mineral is exposed to a weak acid	Calcite
Smell	Some minerals have a distinctive smell	Sulfur (smells like rotten eggs)
Taste	Some minerals taste salty	Halite

A simple lesson on how to identify minerals is seen in this video: http://www.youtube.com/watch?v=JeFVwqBuYl4 .

Summary

- Some minerals have a unique property that makes them fairly easy to identify, such as high specific gravity or salty taste.
- Color is not a reliable indicator of mineral type for most minerals, but streak is for certain minerals.
- Cleavage can be a unique and beautiful indicator of mineral type.

Explore More

Use this resource to answer the questions that follow.

https://www.youtube.com/watch?v=yfOYEwryk1w Start at 1:42

1. What are two reasons that color isn't a good way to identify minerals?
2. What is luster? List are some types of luster with one to a few words to describe each.
3. What is streak? Why is streak color a better indicator of a mineral's color?
4. What is hardness? What are the least and most hard minerals on the Moh's scale?
5. How do you use reference minerals to tell the hardness of an unknown mineral?

7. No because it would be hard to make it into a multi-faceted gem.

Review

1. How does the color of a mineral differ from it's streak and luster?
2. Does diamond exhibit cleavage or fracture? Why is this important?
3. What's the first thing you should do when trying to identify a mineral? What do you do if you still can't identify it?

Review Answers

1. A mineral's color is the color of its outer appearance but it's streak is its internal color. Luster is the way a mineral reflects light and doesn't depend on color.
2. Diamond exhibits cleavage, which is important because it can be cut into beautiful shapes along cleavage planes.
3. First check for any really distinguishing characteristics, like smell or magnetism. Hardness is a good characteristic as is streak for some minerals. Go through all the tests and try to narrow it down. If you still can't identify it, ask for help or read more about the minerals you've narrowed it down to.

1.6 Mineral Formation

- Explain how different types of minerals form.

Is carbon a girl's best friend?

Yes! (At least if you think that diamond is a girl's best friend, anyway.) When people think of carbon they think of black dust left over from a fire, but the diamond is just carbon that was squeezed very hard at extremely high pressure. Formed at lower pressure, the carbon mineral is graphite, the mineral that is pencil "lead." Graphite would make a very different sort of ring.

Mineral Formation

Minerals form in a variety of ways:

- crystallization from magma
- precipitation from ions in solution

- biological activity
- a change to a more stable state as in metamorphism
- precipitation from vapor

Formation from Magma

Imagine a rock that becomes so hot it melts. Many minerals start out in liquids that are hot enough to melt rocks. **Magma** is melted rock inside Earth, a molten mixture of substances that can be hotter than 1,000°C. Magma cools slowly inside Earth, which gives mineral crystals time to grow large enough to be seen clearly (**Figure** 1.24).

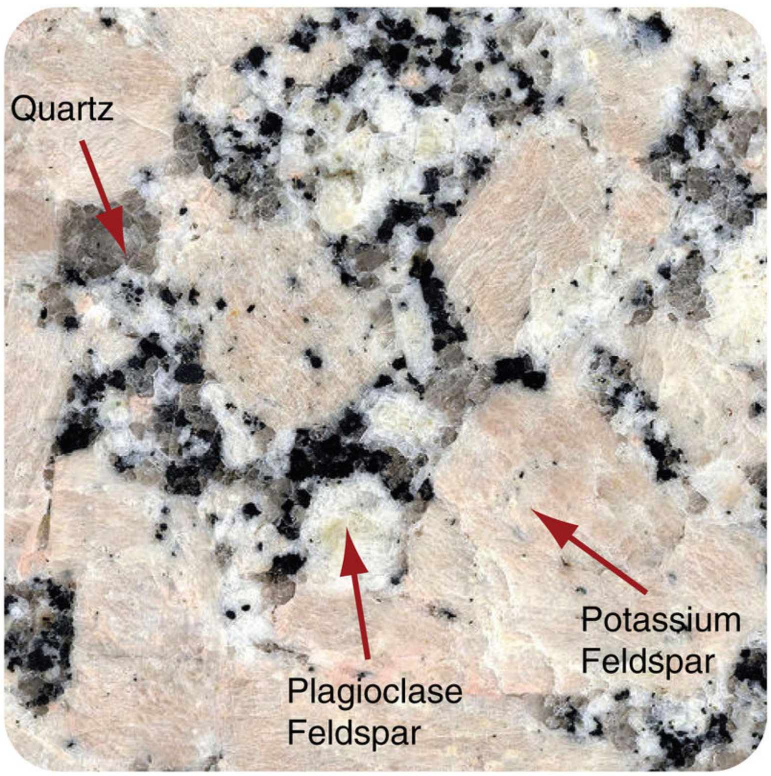


FIGURE 1.24
Granite is rock that forms from slowly cooled magma, containing the minerals quartz (clear), plagioclase feldspar (shiny white), potassium feldspar (pink), and biotite (black).

When magma erupts onto Earth's surface, it is called **lava**. Lava cools much more rapidly than magma. Crystals do not have time to form and are very small. The chemical composition between minerals that form rapidly or slowly is often the same, only their size differs.

Existing rocks may be heated enough so that the molecules are released from their structure and can move around. The molecules may match up with different molecules to form new minerals as the rock cools. This occurs during metamorphism, which will be discussed in the "Metamorphic Rocks" concept.

Formation from Solutions

Water on Earth, such as the water in the oceans, contains chemical elements mixed into a solution. Various processes can cause these elements to combine to form solid mineral deposits.

Minerals from Salt Water

When water evaporates, it leaves behind a solid precipitate of minerals, as shown in **Figure** 1.25.

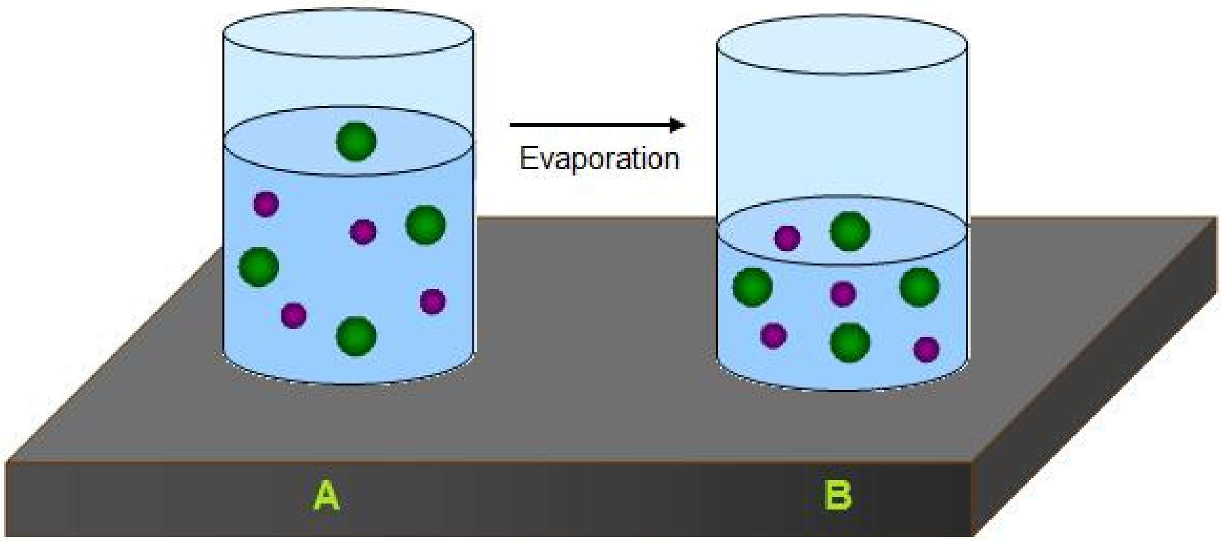


FIGURE 1.25
When the water in glass A evaporates, the dissolved mineral particles are left behind.

Water can only hold a certain amount of dissolved minerals and salts. When the amount is too great to stay dissolved in the water, the particles come together to form mineral solids, which sink. Halite easily precipitates out of water, as does calcite. Some lakes, such as Mono Lake in California (**Figure** 1.26) or The Great Salt Lake in Utah, contain many mineral precipitates.

Minerals from Hot Underground Water

Magma heats nearby underground water, which reacts with the rocks around it to pick up dissolved particles. As the water flows through open spaces in the rock and cools, it deposits solid minerals. The mineral deposits that form when a mineral fills cracks in rocks are called **veins** (**Figure** 1.27).

When minerals are deposited in open spaces, large crystals form (**Figure** 1.28).

Minerals Under Pressure

In the last several years, many incredible discoveries have been made exploring how minerals behave under high pressure, like rocks experience inside the Earth. If a mineral is placed in a special machine and then squeezed, eventually it may convert into a different mineral. Ice is a classic example of a material that undergoes solid-solid "phase transitions" as pressure and/or temperature is changed. A "phase diagram" is a graph which plots the stability of phases of a compound as a function of pressure and temperature.

A phase diagram for water (ice) is included in the **Figure** 1.29. The phase diagram is split up into 3 main areas for the solid crystalline phase (ice), the liquid phase (water), and the gas phase (water vapor). Notice that increasing

FIGURE 1.26
Tufa towers form when calcium-rich spring water at the bottom of Mono Lake bubbles up into the alkaline lake. The tufa towers appear when lake level drops.

FIGURE 1.27
Quartz veins formed in this rock.

pressure lowers the freezing point and raises the boiling point of water. What does that do to the stability conditions of the liquid phase?

Summary

- Minerals form as magma cools.
- Minerals form when they precipitate from hot fluids that have cooled down.
- Minerals form when the concentration of ions gets too great in a fluid.

Explore More

Use this resource to answer the questions that follow.

FIGURE 1.28
Amethyst formed when large crystals grew in open spaces inside the rock. These special rocks are called geodes.

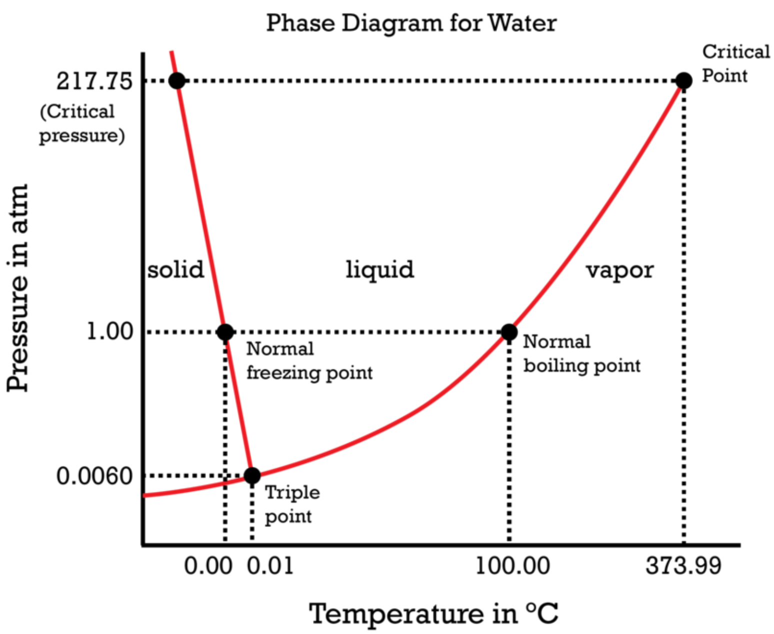


FIGURE 1.29
A sample phase diagram for water.

http://nature.berkeley.edu/classes/eps2//wisc/Lect3.html

1. How do minerals form from water?
2. What crystals come from water that are silica-based minerals?
3. What crystals come from water that are copper-based minerals?
4. How do hydrothermal minerals form?
5. What is a pegmatite?
6. What can magma rich in boron crystallize into?
7. What other gems can be found in cooled magma?

Explore More Answers

1. Water dissolves minerals and the ions stay in solution. If conditions change, minerals will precipitate out.
2. Amethyst, agate and opal.
3. Malachite, azurite and turquoise.
4. Hot water carries ions that precipitate from the hot solution, often as a vein of minerals in preexisting cracks.
5. A pegmatite is a magma body that has mostly cooled but the slat fraction is rich in water. The crystals grow quickly and are often very large.
6. tourmaline
7. zircon, topaz, ruby and others

Review

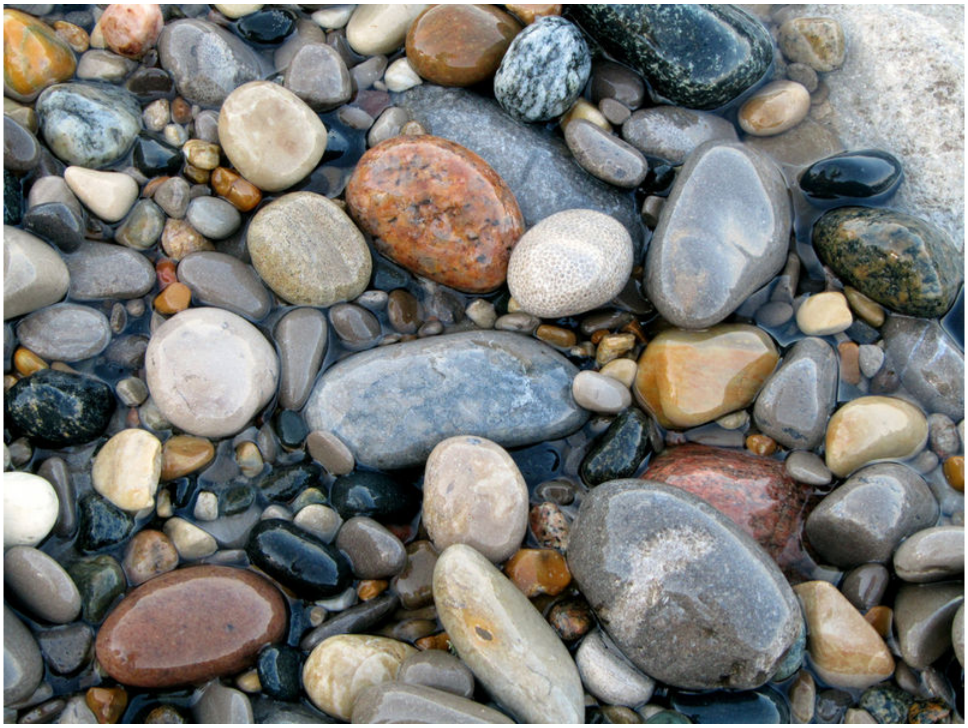
1. How do minerals form in veins?
2. How do minerals form from cool water?
3. When do large crystals form from magma? When do small crystals form from magma?

Review Answers

1. Fluids travel through cracks and then minerals precipitate.
2. Minerals are left as water evaporates.
3. Large crystals form where there is space, especially when the magma cools slowly. Small crystals form when the magma cools quickly or they are confined by space.

1.7 Rocks

- Define rock.



How many different rock types are in this photo?

A beach or river bed is a good place to see a lot of different rock types since the rocks there represent the entire drainage system. How could you tell how many different rock types were in the photo? What characteristics would you look for?

What Are Rocks?

A **rock** is a naturally formed, non-living Earth material. Rocks are made of collections of mineral grains that are held together in a firm, solid mass (**Figure** 1.30).

How is a rock different from a mineral? Rocks are made of minerals. The mineral grains in a rock may be so tiny that you can only see them with a microscope, or they may be as big as your fingernail or even your finger (**Figure** 1.31).

Rocks are identified primarily by the minerals they contain and by their texture. Each type of rock has a distinctive set of minerals. A rock may be made of grains of all one mineral type, such as quartzite. Much more commonly, rocks are made of a mixture of different minerals. Texture is a description of the size, shape, and arrangement of mineral grains. Are the two samples in **Figure** 1.32 the same rock type? Do they have the same minerals? The same texture?

FIGURE 1.30
The different colors and textures seen in this rock are caused by the presence of different minerals.

FIGURE 1.31
A pegmatite from South Dakota with crystals of lepidolite, tourmaline, and quartz (1 cm scale on the upper left).

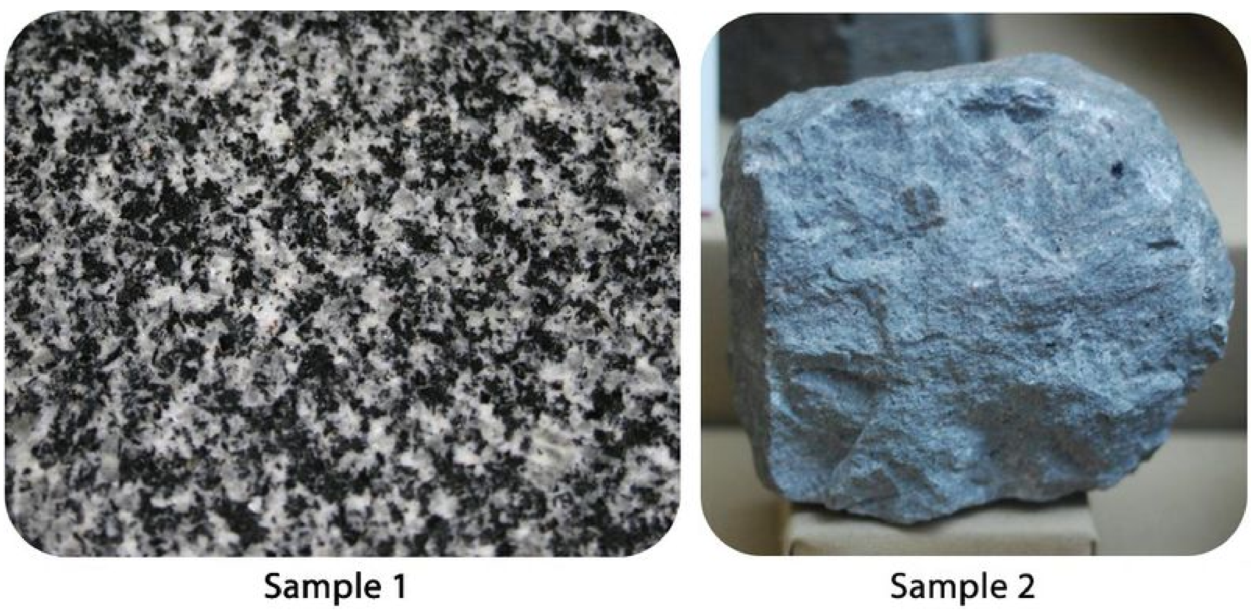


FIGURE 1.32
Rock samples.

TABLE 1.4: Properties of Sample 1 and Sample 2

Sample	Minerals	Texture	Formation	Rock type
Sample 1	plagioclase, quartz, hornblende, pyroxene	Crystals, visible to naked eye	Magma cooled slowly	Diorite
Sample 2	plagioclase, hornblende, pyroxene	Crystals are tiny or microscopic	Magma erupted and cooled quickly	Andesite

As seen in **Table** 1.4, these two rocks have the same chemical composition and contain mostly the same minerals, but they do not have the same texture. Sample 1 has visible mineral grains, but Sample 2 has very tiny or invisible grains. The two different textures indicate different histories. Sample 1 is a diorite, a rock that cooled slowly from magma (molten rock) underground. Sample 2 is an andesite, a rock that cooled rapidly from a very similar magma that erupted onto Earth's surface.

A few rocks are not made of minerals because the material they are made of does not fit the definition of a mineral. Coal, for example, is made of organic material, which is not a mineral. Can you think of other rocks that are not made of minerals?

Summary

- Nearly all rocks are made of minerals. A few are made of materials that do not fit the definition of minerals.
- Rocks are typically identified by the minerals they contain and their textures.
- The texture of a rock describes the size, shape, and arrangement of mineral grains and is a reflection of how the rock formed.

Making Connections

MEDIA

Click image to the left for use the URL below.

URL: http://gamma.ck12.org/flx/render/embeddedobject/5695

Explore More

Use this resource to answer the questions that follow.

https://www.youtube.com/watch?v=TSK2VIhLJn8

1. Where do all rocks begin their lives?
2. Which of the three rock types do they start as?
3. How many minerals are there?
4. What processes wear them down?
5. What is one of the places that sedimentary rocks form?

Explore More Answers

1. Deep underground.
2. Igneous rocks.
3. More than 4000.
4. weathering and erosion.
5. In the sea.

Review

1. Name a rock type that is not made of minerals and state how a rock could not be made of minerals.
2. Can a rock be made of only one type of mineral, or do rocks need to be made of at least two minerals?
3. Why is texture so important in classifying rock types?

Review Answers

1. Coal is not made of minerals because it is organic and organic material can't be minerals. It can be a rock though.
2. Rocks can be made of one mineral, like quartzite, or many minerals.
3. Texture gives an indication of how the rock formed.

1.8 Rocks and Processes of the Rock Cycle

- Explain the processes of the rock cycle.

Is this what geologists mean by the rock cycle?

Okay, very punny. The rock cycle shows how any type of rock can become any other type of rock. Some rocks may stay the same type for a long time, for example, if they're at the base of the crust, but other rocks may relatively rapidly change from one type to another.

The Rock Cycle

The **rock cycle**, illustrated in **Figure** 1.33, depicts how the three major rock types –igneous, sedimentary, and metamorphic - convert from one to another. Arrows connecting the rock types represent the processes that accomplish these changes.

Rocks change as a result of natural processes that are taking place all the time. Most changes happen very slowly. Rocks deep within the Earth are right now becoming other types of rocks. Rocks at the surface are lying in place before they are next exposed to a process that will change them. Even at the surface, we may not notice the changes. The rock cycle has no beginning or end.

The Three Rock Types

Rocks are classified into three major groups according to how they form. These three types are described in more detail in other concepts in this chapter, but here is a summary.

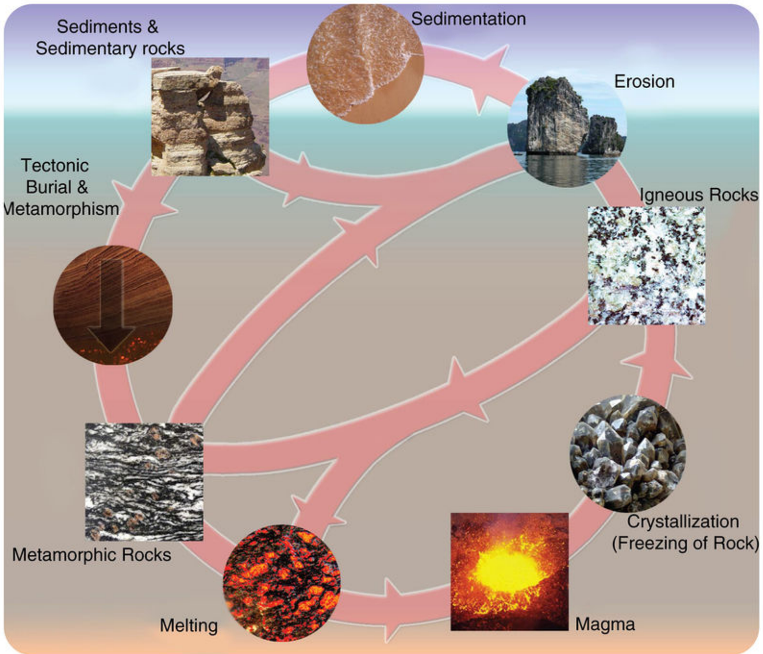


FIGURE 1.33
The Rock Cycle.

- **Igneous rocks** form from the cooling and hardening of molten magma in many different environments. The chemical composition of the magma and the rate at which it cools determine what rock forms. Igneous rocks can cool slowly beneath the surface or rapidly at the surface. These rocks are identified by their composition and texture. More than 700 different types of igneous rocks are known.
- **Sedimentary rocks** form by the compaction and cementing together of **sediments**, broken pieces of rock-like gravel, sand, silt, or clay. Those sediments can be formed from the weathering and erosion of preexisting rocks. Sedimentary rocks also include chemical **precipitates**, the solid materials left behind after a liquid evaporates.
- **Metamorphic rocks** form when the minerals in an existing rock are changed by heat or pressure below the surface.

A simple explanation of the three rock types and how to identify them can be seen in this video: http://www.youtube.com/watch?v=tQUe9C40NEE .

This video discusses how to identify igneous rocks: http://www.youtube.com/watch?v=Q0XtLjE3siE .

This video discusses how to identify a metamorphic rocks: http://www.youtube.com/watch?v=qs9x_bTCiew .

The Processes of the Rock Cycle

Several processes can turn one type of rock into another type of rock. The key processes of the rock cycle are crystallization, erosion and sedimentation, and metamorphism.

Crystallization

Magma cools either underground or on the surface and hardens into an igneous rock. As the magma cools, different crystals form at different temperatures, undergoing **crystallization**. For example, the mineral olivine crystallizes out of magma at much higher temperatures than quartz. The rate of cooling determines how much time the crystals will have to form. Slow cooling produces larger crystals.

Erosion and Sedimentation

Weathering wears rocks at the Earth's surface down into smaller pieces. The small fragments are called sediments. Running water, ice, and gravity all transport these sediments from one place to another by **erosion**. During **sedimentation**, the sediments are laid down or deposited. In order to form a sedimentary rock, the accumulated sediment must become compacted and cemented together.

Metamorphism

When a rock is exposed to extreme heat and pressure within the Earth but does not melt, the rock becomes metamorphosed. **Metamorphism** may change the mineral composition and the texture of the rock. For that reason, a metamorphic rock may have a new mineral composition and/or texture.

Summary

- The three main rock types are igneous, metamorphic and sedimentary.
- The three processes that change one rock to another are crystallization, metamorphism, and erosion and sedimentation.
- Any rock can transform into any other rock by passing through one or more of these processes. This creates the rock cycle.

Making Connections

MEDIA

Click image to the left for use the URL below.

URL: http://gamma.ck12.org/flx/render/embeddedobject/5705

Explore More

Use these resources to answer the questions that follow.

https://www.youtube.com/watch?v=pm6cCg_Do6k

1. What are the three major types of rocks?
2. What does the rock cycle mean?
3. What do wind and water do to rocks at the surface?
4. How do sedimentary rocks formed?
5. What must happen to a rock for it to become a metamorphic rock?
6. When a rock becomes metamorphic does it look the same as it did originally?
7. What must happen for an igneous rock to form?
8. What are the two places that a magma can cool?
9. Is there only one path through the rock cycle?

Review the rock cycle - click a rock to begin.

http://www.phschool.com/atschool/phsciexp/active_art/rock_cycle/index.html

Test your rock identification skills with this activity:

Name that Rock - http://library.thinkquest.org/J002289/rocks.html

Explore More Answers

1. Sedimentary, igneous and metamorphic
2. Each type of rock can change into any other type of rock.
3. Wind and water break down rocks into tiny pieces.
4. Tiny rock pieces collect and are buried and eventually fused together to form a new rock.
5. Heat and pressure must be applied.
6. No, heat and pressure cause the rock to change.
7. The original rock must be heated deep in the Earth so that it melts and becomes a magma.
8. A magma can cool in the Earth or at the surface.
9. No there are many paths.

Review

1. What processes must a metamorphic rock go through to become an igneous rock?
2. What processes must a sedimentary rock go through to become a metamorphic rock?
3. What types of rocks can become sedimentary rocks and how does that happen?

Review Answers

1. To become an igneous rock, any rock, including a metamorphic rock, must be exposed to so much heat that it melts completely to become a magma.
2. To become a metamorphic rock, any rock must be exposed to heat and pressure so that it changes.
3. Any type of rock can become a sedimentary rock. It must be broken into smaller pieces and then those pieces must be conolidated into a rock.

1.9 Igneous Rocks

- Describe the factors that determine the composition of igneous rocks.

What makes this landscape so remarkable?

This photo is of the Sierra Nevada Mountains in California. The rocks look so uniform because they are all igneous intrusive rocks that cooled from a felsic magma to create the granite that you see. Later, the rock was uplifted and modified by glaciers during the Pleistocene ice ages.

Magma Composition

Different factors play into the composition of a magma and the rock it produces.

Composition of the Original Rock

The rock beneath the Earth's surface is sometimes heated to high enough temperatures that it melts to create magma. Different magmas have different composition and contain whatever elements were in the rock or rocks that melted. Magmas also contain gases. The main elements are the same as the elements found in the crust. **Table** 1.5 lists the abundance of elements found in the Earth's crust and in magma. The remaining 1.5% is made up of many other elements that are present in tiny quantities.

TABLE 1.5: Elements in Earth's Crust and Magma

Element	Symbol	Percent

TABLE 1.5: (continued)

Element	**Symbol**	**Percent**
Oxygen	O	46.6%
Silicon	Si	27.7%
Aluminum	Al	8.1%
Iron	Fe	5.0%
Calcium	Ca	3.6%
Sodium	Na	2.8%
Potassium	K	2.6%
Magnesium	Mg	2.1%
Total		**98.5%**

How Rocks Melt

Whether rock melts to create magma depends on:

- Temperature: Temperature increases with depth, so melting is more likely to occur at greater depths.
- Pressure: Pressure increases with depth, but increased pressure raises the melting temperature, so melting is less likely to occur at higher pressures.
- Water: The addition of water changes the melting point of rock. As the amount of water increases, the melting point decreases.
- Rock composition: Minerals melt at different temperatures, so the temperature must be high enough to melt at least some minerals in the rock. The first mineral to melt from a rock will be quartz (if present) and the last will be olivine (if present).

The different geologic settings that produce varying conditions under which rocks melt will be discussed in the chapter Plate Tectonics.

What Melts and What Crystallizes

As a rock heats up, the minerals that melt at the lowest temperatures melt first. **Partial melting** occurs when the temperature on a rock is high enough to melt only some of the minerals in the rock. The minerals that will melt will be those that melt at lower temperatures. **Fractional crystallization** is the opposite of partial melting. This process describes the crystallization of different minerals as magma cools.

Bowen's Reaction Series indicates the temperatures at which minerals melt or crystallize (**Figure** 1.34). An understanding of the way atoms join together to form minerals leads to an understanding of how different igneous rocks form. Bowen's Reaction Series also explains why some minerals are always found together and some are never found together.

To see a diagram illustrating Bowen's Reaction Series, visit this website: http://csmres.jmu.edu/geollab/Fichter/RockMin/RockMin.html .

This excellent video that explains Bowen's Reaction Series in detail: http://www.youtube.com/watch?v=en6ihAM9fe8 .

If the liquid separates from the solids at any time in partial melting or fractional crystallization, the chemical composition of the liquid and solid will be different. When that liquid crystallizes, the resulting igneous rock will have a different composition from the parent rock.

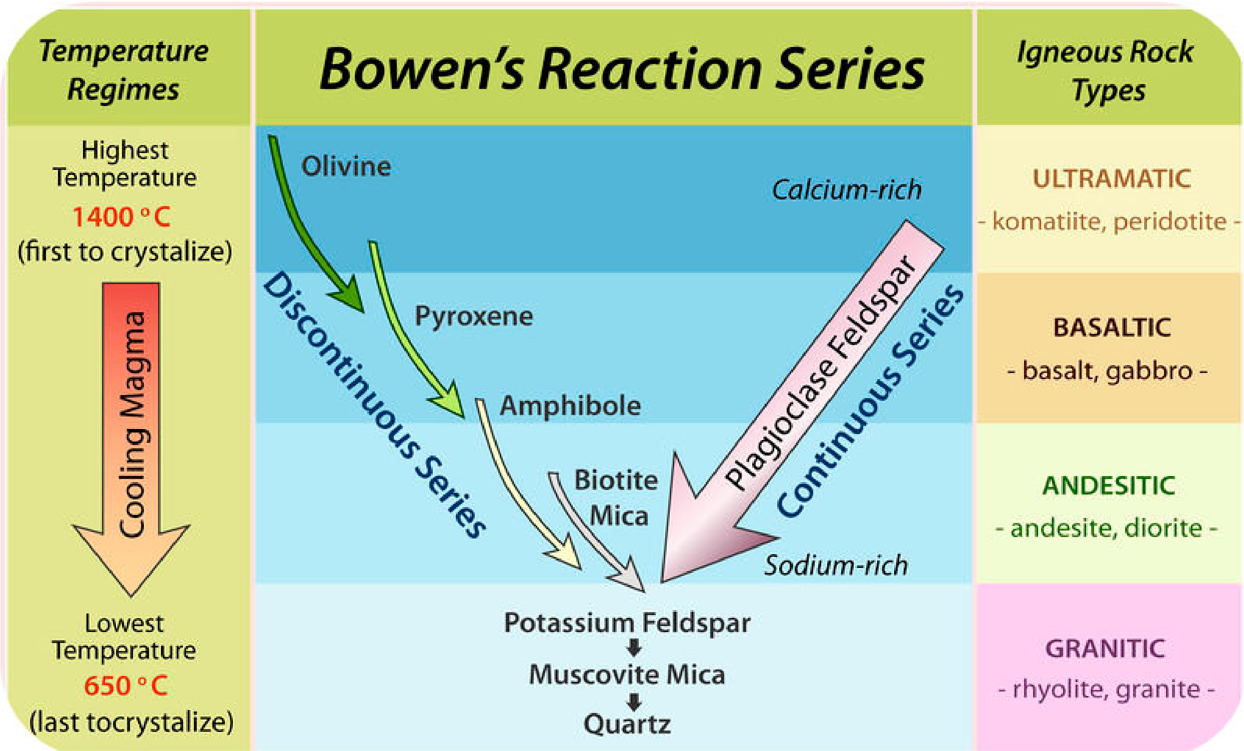


FIGURE 1.34
Bowen's Reaction Series.

Summary

- Melting of an existing rock to create magma depends on that rock's composition and on the temperature, pressure, and water content found in that environment.
- Bowen's Reaction Series indicates the temperatures at which minerals crystallize from a magma or melt from a rock.
- Since minerals melt at different temperatures, a rock in which some minerals have melted has undergone partial melting; the opposite process, in which some minerals crystallize out of a magma, is fractional crystallization.

Explore More

Use this resource to answer the questions that follow.

Geology: Igneous Rocks

http://www.videojug.com/film/geology-igneous-rocks

MEDIA

Click image to the left for use the URL below.

URL: http://gamma.ck12.org/flx/render/embeddedobject/116797

1. What do all igneous rocks form from?
2. How does crystallization occur?
3. Explain how extrusive igneous rock is formed. What is the sign that a rock is an extrusive rock?
4. Explain how intrusive igneous rock is formed. What is the sign that a rock is an intrusive rock?
5. What is pyroclastic rock?
6. How are pyroclastic rocks formed?

Explore More Answers

1. magma
2. As the magma cools mineral crystals cool out of it.
3. Magma is extruded onto Earth's surface and they cool quickly.
4. Magma cools beneath the surface. It's insulated by surrounding rock and it cools slowly. The crystals are larger and form nice faces.
5. A rock that is formed from little bits by an explosive eruption.
6. An explosion from a volcano that shoots ash up into the air and then it cools to form a rock.

Review

1. Why are olivine and quartz never found together in an igneous rock?
2. How do changes in temperature, pressure, and fluids cause melting?
3. Briefly describe what Bowen's Reaction Series depicts.

Review Answers

1. Olivine quartz are stable at different temperatures. If olivine forms then the magma is too hot for quartz to form. If quartz forms then the magma is too cool for olivine to form.
2. An increase in temperature will cause the parent rock to melt. A decrease in pressure will lower the melting temperature of the parent rock so that it melts. Adding water lowers the melting temperature of the parent rock so that it will melt at a lower temperature.
3. Bowen's Reaction Series shows the temperatures at which different minerals will crystallize from a magma or melt from a rock. The left side shows that different minerals are stable at different temperatures, but the right side shows a single mineral that has a range of stability at different temperatures so the composition changes with temperature.

1.10 Intrusive and Extrusive Igneous Rocks

- Compare and contrast intrusive and extrusive igneous rock.

How can igneous rock be so black and shiny?

This rock is lava that rapidly cooled on Kilauea volcano in Hawaii Volcanoes National Park on the Big Island of Hawaii. The lava cooled so fast that crystals had little time to form. How does this rock compare with the granite further down this lesson?

Intrusive and Extrusive Igneous Rocks

The rate at which magma cools determines whether an igneous rock is intrusive or extrusive. The cooling rate is reflected in the rock's texture.

Intrusive Igneous Rocks

Igneous rocks are called **intrusive** when they cool and solidify beneath the surface. Intrusive rocks form plutons and so are also called plutonic. A **pluton** is an igneous intrusive rock body that has cooled in the crust. When magma cools within the Earth, the cooling proceeds slowly. Slow cooling allows time for large crystals to form, so intrusive igneous rocks have visible crystals. Granite is the most common intrusive igneous rock (see **Figure** 1.35 for an example).

Igneous rocks make up most of the rocks on Earth. Most igneous rocks are buried below the surface and covered with sedimentary rock, or are buried beneath the ocean water. In some places, geological processes have brought igneous rocks to the surface. **Figure** 1.36 shows a landscape in California's Sierra Nevada Mountains made of granite that has been raised to create mountains.

FIGURE 1.35
Granite is made of four minerals, all visible to the naked eye: feldspar (white), quartz (translucent), hornblende (black), and biotite (black, platy).

FIGURE 1.36
California's Sierra Nevada Mountains are intrusive igneous rock exposed at Earth's surface.

Extrusive Igneous Rocks

Igneous rocks are called **extrusive** when they cool and solidify above the surface. These rocks usually form from a volcano, so they are also called **volcanic rocks** (**Figure** 1.37).

Extrusive igneous rocks cool much more rapidly than intrusive rocks. There is little time for crystals to form, so extrusive igneous rocks have tiny crystals (**Figure** 1.38).

Some volcanic rocks have a different texture. The rock has large crystals set within a matrix of tiny crystals. In this case, the magma cooled enough to form some crystals before erupting. Once erupted, the rest of the lava cooled rapidly. This is called **porphyritic** texture.

Cooling rate and gas content create other textures (see **Figure** 1.39 for examples of different textures). Lavas that

FIGURE 1.37
Extrusive igneous rocks form after lava cools above the surface.

FIGURE 1.38
Cooled lava forms basalt with no visible crystals. Why are there no visible crystals?

cool extremely rapidly may have a glassy texture. Those with many holes from gas bubbles have a **vesicular** texture.

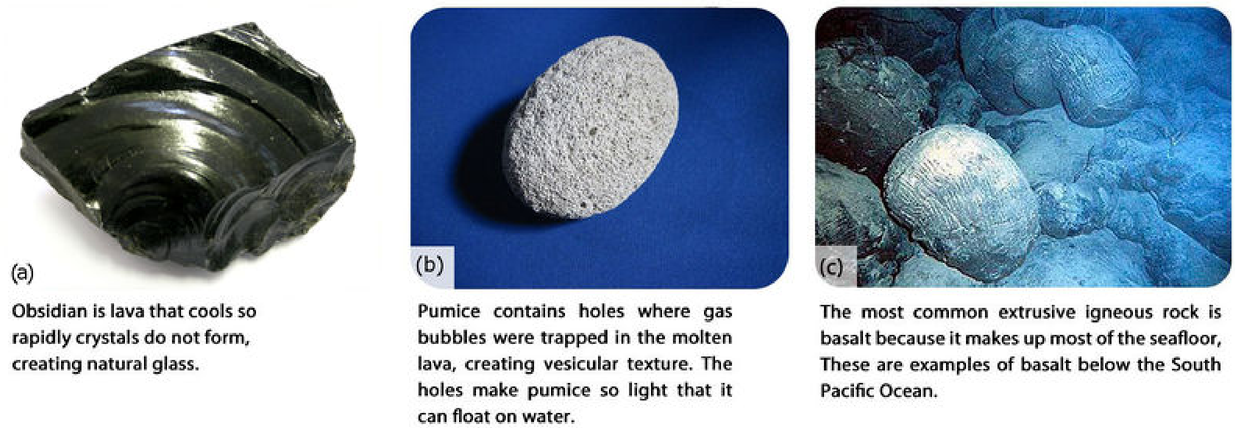


FIGURE 1.39
Different cooling rate and gas content resulted in these different textures.

Summary

- Intrusive igneous rocks cool from magma slowly because they are buried beneath the surface, so they have large crystals.
- Extrusive igneous rocks cool from lava rapidly because they form at the surface, so they have small crystals.
- Texture reflects how an igneous rock formed.

Explore More

Use this resource to answer the questions that follow.

https://www.youtube.com/watch?v=J03B2uyObL8

1. What are the two places igneous rocks can form?
2. What are the features of intrusive igneous rocks and how do these rocks form?
3. What are the features of extrusive igneous rocks and how do these rocks form?
4. What is the difference between granite and gabbro? What is the difference between rhyolite and basalt?
5. How does obsidian form? What is it's other name?

Explore More Answers

1. Igneous rocks can form inside of Earth or on the surface.
2. They form inside the Earth with the surrounding rock acting as insulation. The magma cools slowly so that the crystals are large, giving the rock a coarse grain size.
3. When magma is exposed to the atmosphere it cools more quickly so that it has smaller crystals and a fine-grain size.

4. Granite is light and gabbro is dark. Rhyolite is light and basalt is dark.
5. Lava is shot out of a volcano and cools almost instantly. Volcanic glass.

Review

1. How does a rock develop a vesicular texture?
2. What are the other names for igneous intrusive rock and igneous extrusive rocks and how do they get those names?
3. What sequence of events causes a rock to develop porphyritic texture?

Review Answers

1. A magma with gas bubbles in it cools quickly and small holes from where the gas was are left in the solidified rock.
2. Plutonic rocks are igneous intrusive rocks; they cool slowly and form rock bodies the large category of which is called plutons. Igneous extrusive rocks are also called volcanic because they form from volcanic processes.
3. Rock with a porphyritic texture forms when a magma begins to cool slowly so large crystals form, but then it erupts quickly so the rest cools into tiny or no crystals.

1.11 Igneous Rock Classification

- Explain how igneous rocks are classified by composition and by cooling rate.

Is this an intrusive or an extrusive igneous rock?

From this view the amazing structure of rocks that make up Devil's Tower doesn't really indicate whether the structure formed slowly or quickly. A close up view would show small crystals in a mafic rock, indicating a rapid cooling from a basalt lava. Cooling was slow enough that the hexagonal "posts" could form.

Igneous Rock Classification

Igneous rocks are first classified by their composition, from felsic to ultramafic. The characteristics and example minerals in each type are included in **Table** 1.6.

TABLE 1.6: Properties of Igneous Rock Compositions

Composition	Color	Density	Minerals
Felsic	Light	Low	Quartz, orthoclase feldspar
Intermediate	Intermediate	Intermediate	Plagioclase feldspar, biotite, amphibole
Mafic	Dark	High	Olivine, pyroxene
Ultramafic	Very dark	Very high	Olivine

Second to composition in igneous rock classification is texture. Texture indicates how the magma that formed the rock cooled.

TABLE 1.7: Silica Composition and Texture of Major Igneous Rocks

Type	Amount of Silica	Extrusive	Intrusive
Ultramafic	<45%	Komatiite	Peridotite
Mafic	45-52%	Basalt	Gabbro
Intermediate	52-63%	Andesite	Diorite
Intermediate-Felsic	63-69%	Dacite	Granodiorite
Felsic	>69% SiO_2	Rhyolite	Granite

Some of the rocks in **Table** 1.7 were pictured earlier in this concept. Look back at them and, using what you know about the size of crystals in extrusive and intrusive rocks and the composition of felsic and mafic rocks, identify the rocks in the photos in **Figure** 1.40:

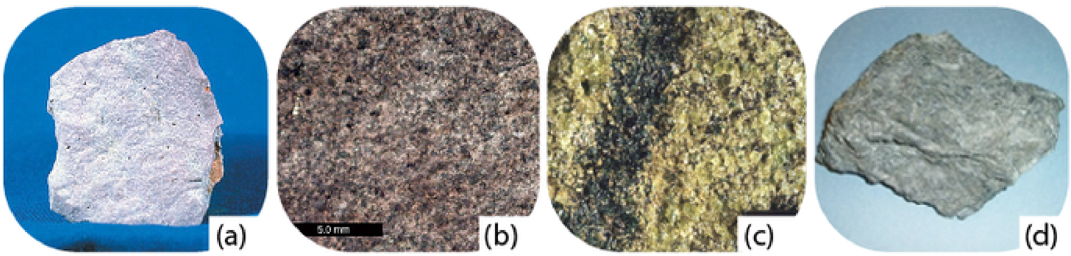


FIGURE 1.40

These are photos of A) rhyolite, B) gabbro, C) peridotite, and D) komatiite.

Summary

- Composition is the first criteria on which to classify igneous rocks, with categories from felsic to ultramafic; color is a first order indicator of composition.
- Texture is the second criteria for classifying igneous rocks because texture indicates how a rock cooled.
- Igneous rocks are categorized in pairs with the same composition but different textures: gabbro-basalt, diorite-andesite, and granite-rhyolite.

Explore More

Use this resource to answer the questions that follow.

Felsic and Mafic Igneous Rocks

https://www.youtube.com/watch?v=4W8oSfsHW6s

1. What is one way that igneous rocks are classified?
2. What are the two categories of igneous rocks based on composition?
3. How is felsic igneous rock?
4. What is mafic igneous rock?
5. What is the same about granite and rhyolite? What is different?
6. What is the same about gabbro and basalt? What is different?

Explore More Answers

1. By chemical composition, the elements and minerals they are made of.
2. Felsic and mafic.
3. Felsic rock is ligher colored; rich in aluminum, potassium, silicon and sodium
4. Mafic rock is darker colored; rich in calcium, iron and magnesium
5. Both are felsic in composition, but granite has visible crystal grains, but rhyolite doesn't.
6. Both are mafic in composition, but gabbro has visible crystal grains, but basalt doesn't.

Review

1. Describe the formation of the igneous rock pair gabbro-basalt. What makes the rocks the same and what makes them different?
2. How does the composition of a rock affect its color?
3. What are ultramafic rocks and where are they likely to be found?

Review Answers

1. Both of these rocks cool from mafic magma. Gabbro is an intrusive rock so it cooled more slowly and has larger crystals. Basalt is an extrusive rock so it cooled more quickly and has smaller crystals.
2. Mafic rocks are darker in color than felsic rocks.
3. Ultramafic rocks are extremely mafic. They are very dark in color and contain a lot of olivine. They are thought to be the composition of the mantle.

1.12 Sedimentary Rocks

- Describe factors that determine the composition of sedimentary rocks.

What is this material and what created the ripples?

If you've walked on a sandy beach or on a sand dune, you may have seen ripples like this formed from wind or waves. Sand is small broken pieces of rock that can be moved around. They can also be lithified to become a rock known as sandstone.

Sediments

Sandstone is one of the common types of sedimentary rocks that form from sediments. There are many other types. 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.

Rocks at the surface undergo mechanical and chemical weathering. These physical and chemical processes break rock into smaller pieces. Mechanical weathering simply breaks the rocks apart. Chemical weathering dissolves the less stable minerals. These original elements of the minerals end up in solution and new minerals may form. Sediments are removed and transported by water, wind, ice, or gravity in a process called erosion (**Figure** 1.41). Much more information about weathering and erosion can be found in the chapter Surface Processes and Landforms.

FIGURE 1.41
Water erodes the land surface in Alaska's Valley of Ten Thousand Smokes.

Streams carry huge amounts of sediment (**Figure** 1.42). The more energy the water has, the larger the particle it can carry. A rushing river on a steep slope might be able to carry boulders. As this stream slows down, it no longer has the energy to carry large sediments and will drop them. A slower moving stream will only carry smaller particles.

FIGURE 1.42
A river dumps sediments along its bed and on its banks.

Sediments are deposited on beaches and deserts, at the bottom of oceans, and in lakes, ponds, rivers, marshes, and swamps. Landslides drop large piles of sediment. Glaciers leave large piles of sediments, too. Wind can only transport sand and smaller particles. The type of sediment that is deposited will determine the type of sedimentary rock that can form. Different colors of sedimentary rock are determined by the environment where they are deposited. Red rocks form where oxygen is present. Darker sediments form when the environment is oxygen poor.

Summary

- Rocks undergo chemical or mechanical weathering to form smaller pieces.

- Sediments range in size from tiny bits of silt or clay to enormous boulders.
- Sediments are transported by wind, water, ice, or gravity into different environments.

Explore More

Use these resources to answer the questions that follow.

1. What are sedimentary rocks made of?
2. What is the cement?
3. What happens first?
4. What happens to the sediments to become rock?

Explore More Answers

1. Pieces of other rocks being cemented together.
2. Natural cement, like mud or clay.
3. An existing rock breaks down into sediments.
4. They get compacted and cemented together.

Review

1. What does sediment size indicate about the history of that depositional environment?
2. How are chemical precipitates different from rocks that form from sediment particles?
3. Why are organic materials considered sediments but not minerals?

Review Answers

1. It takes more energy to carry a larger sediment so if there are large cobbles, it means that at one time the water was moving very fast. If there are small particles, it means that the water was moving very slowly or not at all.
2. Chemical precipitates are continuous; they do not have mineral fragments in them like clastic rocks.
3. Minerals are inorganic, by definition. A rock can be organic.

1.13 Lithification of Sedimentary Rocks

- Explain how sediments become rock by the processes of lithification.

What steps led to this rock formation?

What do you see? The rock is a sandstone, so first there were rocks that weathered and eroded. The cross-bedding indicates that the sand was deposited in a dune. The sand was then buried deeply enough that it turned into rock. This concept will explore how something like sand could become a rock.

Sedimentary Rock Formation

Accumulated sediments harden into rock by **lithification**, as illustrated in the **Figure** 1.43. Two important steps are needed for sediments to lithify.

1. Sediments are squeezed together by the weight of overlying sediments on top of them. This is called **compaction**. Cemented, non-organic sediments become **clastic** rocks. If organic material is included, they are **bioclastic** rocks.
2. Fluids fill in the spaces between the loose particles of sediment and crystallize to create a rock by **cementation.**

The sediment size in clastic sedimentary rocks varies greatly (see **Table** in Sedimentary Rocks Classification).

Summary

- Sedimentary rocks are made of fragments of older rocks or pieces of organisms.

FIGURE 1.43
This cliff is made of sandstone. Sands were deposited and then lithified.

- Compaction and cementation lead to lithification of sedimentary rocks.
- Compaction is the squeezing of sediments by the weight of the rocks and sediments above them. Cementation is when cement from fluids bind sediments together.

Explore More

Use this resource to answer the questions that follow.

https://www.youtube.com/watch?v=EJZ4gUnJKuk

1. Describe the first step of lithificsation.
2. What happens when the water is pushed out?
3. What is the material located between the mineral grains called?

Explore More Answers

1. Compaction is when sediments go on top of other sediments and squeeze the air out.
2. Water is pushed out and leaves behind minerals. It's like a glue or cement.
3. The cement is called the matrix.

Review

1. How does compaction lead to lithification?
2. How does cementation lead to lithification?
3. What is the difference between clastic and bioclastic sedimentary rocks?

Review Answers

1. The weight of the overlying sediments squeezes the grains together and pushes the air and water out. This compressed material is more rock-like.
2. The mineral precipitates that are left between the grains act like a glue that holds the grains together.

3. Clastic is made of inorganic grains and bioclastic is made of organic grains, such as shell fragments, possibly in addition to inorganic grains.

1.14 Sedimentary Rock Classification

- Describe how sedimentary rocks are classified.

How do you know that this is a sedimentary rock?

If you look closely at the rock you will see that it is made of sand-sized particles that have been lithified to create sandstone. The rock is eroding into very unique shapes, but these shapes are more likely to form from a rock made of small cemented together grains than from an igneous or metamorphic rock.

Types of Sedimentary Rocks

TABLE 1.8: **Sedimentary rock sizes and features**

Rock	Sediment Size	Other Features
Conglomerate	Large	Rounded
Breccia	Large	Angular
Sandstone	Sand-sized	
Siltstone	Silt-sized, smaller than sand	
Shale	Clay-sized, smallest	

When sediments settle out of calmer water, they form horizontal layers. One layer is deposited first, and another layer is deposited on top of it. So each layer is younger than the layer beneath it. When the sediments harden, the layers are preserved. Sedimentary rocks formed by the crystallization of chemical precipitates are called **chemical sedimentary rocks**. As discussed in the concepts on minerals, dissolved ions in fluids precipitate out of the fluid and settle out, just like the halite in **Figure** 1.44.

FIGURE 1.44
The evaporite, halite, on a cobble from the Dead Sea, Israel.

Biochemical sedimentary rocks form in the ocean or a salt lake. Living creatures remove ions, such as calcium, magnesium, and potassium, from the water to make shells or soft tissue. When the organism dies, it sinks to the ocean floor to become a biochemical sediment, which may then become compacted and cemented into solid rock (**Figure** 1.45).

FIGURE 1.45
Fossils in a biochemical rock, limestone, in the Carmel Formation in Utah.

Table 1.9 shows some common types of sedimentary rocks.

TABLE 1.9: Common Sedimentary Rocks

Picture	Rock Name	Type of Sedimentary Rock
	Conglomerate	Clastic (fragments of non-organic sediments)
	Breccia	Clastic
	Sandstone	Clastic
	Siltstone	Clastic
	Shale	Clastic
	Rock Salt	Chemical precipitate

TABLE 1.9: (continued)

Picture	Rock Name	Type of Sedimentary Rock
	Rock Gypsum	Chemical precipitate
	Dolostone	Chemical precipitate
	Limestone	Bioclastic (sediments from organic materials, or plant or animal remains)
	Coal	Organic

Summary

- Sediments settle out of water in horizontal layers.
- Sedimentary rocks are classified based on how they form and on the size of the sediments, if they are clastic.
- Clastic sedimentary rocks are formed from rock fragments, or clasts; chemical sedimentary rocks precipitate from fluids; and biochemical sedimentary rocks form as precipitation from living organisms.

Explore More

Use this resource to answer the questions that follow.

https://www.youtube.com/watch?v=ZiI7_c5Sm0I

1. What are the three types of sedimentary rocks.
2. What is the first type he talks about and what are they made of?
3. Name and describe the first type of clastic sedimentary rocks that he talks about.
4. Name and describe the second type of clastic sedimentary rocks that he talks about.
5. Name and describe the third type of clastic sedimentary rocks that he talks about.
6. What is the 2nd type of sedimentary rock that he talks about? How does he make one of these types of rocks?
7. What are two other chemical sedimentary rocks?

8. What is the third type of sedimentary rock? What is their feature?
9. How does lignite form? How about bituminous and anthracite coal?
10. What is limestone that is formed by marine skeletons or coral called? Although it is chemical, it is also what?

Explore More Answers

1. Clastic, chemical, organic.
2. Clastic are made from fragments of rocks being stuck together
3. Shale is a fine-grained clastic sedimentary rock. All the sediments are very small and were cemented together.
4. Conglomerate is a coarse-grained clastic sedimentary rock. Large chunks of sediments are cemented together.
5. Sandstone is a medium-grained clastic sedimentary rock. The grains are sort of visible, but don't stick out a lot.
6. Chemical sedimentary rocks. He dissolves salt in water; over time the water evaporates. The salt crystallizes into a halite crystal.
7. Limestone, gypsum.
8. Organic is made of things that used to be living.
9. It is plants that are buried and squeezed and converted to carbon. They are lignite that is exposed to higher temperature and pressure so they have higher carbon contents.
10. Fossiliferous; organic.

Review

1. How does an organism become a sedimentary rock?
2. How do chemical sedimentary rocks differ from clastic sedimentary rocks?
3. What are the different sedimentary rock types based on grain size, from small to large?

Review Answers

1. The organism dies and falls to the bottom. It's skeleton or shell becomes part of the biochemical sediment, which is later lithified to become a biochemical sedimentary rock.
2. Chemical sedimentary rocks are made from ions that precipitate out of fluids, while clastic sedimentary rocks are made of small pieces of preexisting rocks.
3. Shale, siltstone, sandstone, conglomerate/breccia

1.15 Metamorphic Rocks

- Explain how metamorphic rocks form.

Can you decipher the history of this rock?

The rock in this photo is a banded gneiss. The bands are of different composition, more felsic and more mafic, that separated as a result of heat and pressure. The waviness of the bands also shows how the rock was hot enough to alter but not to melt all the way.

Metamorphism

Any type of rock –igneous, sedimentary, or metamorphic —can become a metamorphic rock. All that is needed is enough heat and/or pressure to alter the existing rock's physical or chemical makeup without melting the rock entirely. Rocks change during metamorphism because the minerals need to be stable under the new temperature and pressure conditions. The need for stability may cause the structure of minerals to rearrange and form new minerals. Ions may move between minerals to create minerals of different chemical composition. Hornfels, with its alternating bands of dark and light crystals, is a good example of how minerals rearrange themselves during metamorphism. Hornfels is shown in the table for the "Metamorphic Rock Classification" concept.

Texture

Extreme pressure may also lead to **foliation**, the flat layers that form in rocks as the rocks are squeezed by pressure (**Figure** 1.46). Foliation normally forms when pressure is exerted in only one direction. Metamorphic rocks may also be non-foliated. Quartzite and marble, shown in the concept "Metamorphic Rock Classification," are non-foliated.

FIGURE 1.46
A foliated metamorphic rock.

Types of Metamorphism

The two main types of metamorphism are both related to heat within Earth:

1. **Regional metamorphism**: Changes in enormous quantities of rock over a wide area caused by the extreme pressure from overlying rock or from compression caused by geologic processes. Deep burial exposes the rock to high temperatures.
2. **Contact metamorphism**: Changes in a rock that is in contact with magma. The changes occur because of the magma's extreme heat.

Summary

- Any type of rock - igneous, sedimentary or metamorphic - can become a metamorphic rock.
- Foliated rocks form when rocks being metamorphosed are exposed to pressure in one direction.
- Regional metamorphism occurs over a large area but contact metamorphism occurs when a rock is altered by a nearby magma.

Explore More

Use this resource to answer the questions that follow.

http://education-portal.com/academy/lesson/contract-metamorphism-vs-regional-metamorphism-definition-differences.html#lesson

1. What are metamorphic rocks?
2. What types of rocks could be transformed into metamorphic rocks?
3. What is contact metamorphism?
4. What does magma do to surrounding rocks?

Explore More Answers

1. Metamorphic rocks are previously-formed rocks that were transformed by exposure to heat and/or pressure into new rocks.
2. Any of the three rock types.

3. Rock minerals and texture are changed by heat due to contact with magma.
4. They change and become metamorphosed.

Review

1. Why do changes in temperature or pressure cause rocks to change?
2. What are the similarities and differences in conditions that cause regional versus contact metamorphism?
3. What causes foliation in a metamorphic rock? Under what circumstances would you expect this to happen?

Review Answers

1. Different minerals are stable in different pressure and temperature conditions so when these conditions change the minerals change to match the conditions.
2. Both involve increases in heat and pressure, but regional metamorphism is more pressure based and contact is more heat based. Regional takes place over a large area and contact takes place very near to an igneous intrusion.
3. Differential pressure causes foliation. This will happen when there is pushing in one direction; e.g. at a convergent plate boundary.

1.16 Metamorphic Rock Classification

- Describe how metamorphic rocks are classified.

Why is this called Marble Canyon?

Marble Canyon in the Grand Canyon is made of sedimentary rock. But Marble Canyon in Death Valley is made of marble, metamorphosed limestone. Notice how shiny the marble is where it was smoothed by sand in rushing water. The rock has the altered appearance of metamorphic rock.

Metamorphic Rocks

Table 1.10 shows some common metamorphic rocks and their original parent rock.

TABLE 1.10: Common Metamorphic Rocks

Picture	Rock Name	Type of Metamorphic Rock	Comments
	Slate	Foliated	Metamorphism of shale
	Phyllite	Foliated	Metamorphism of slate, but under greater heat and pressure than slate
	Schist	Foliated	Often derived from metamorphism of claystone or shale; metamorphosed under more heat and pressure than phyllite
	Gneiss	Foliated	Metamorphism of various different rocks, under extreme conditions of heat and pressure
	Hornfels	Non-foliated	Contact metamorphism of various different rock types
	Quartzite	Non-foliated	Metamorphism of quartz sandstone

TABLE 1.10: (continued)

Picture	Rock Name	Type of Metamorphic Rock	Comments
	Marble	Non-foliated	Metamorphism of limestone
	Metaconglomerate	Non-foliated	Metamorphism of conglomerate

Summary

- Foliated metamorphic rocks are platy; non-foliated metamorphic rocks are massive.
- The more extreme the amount of metamorphism, the more difficult it is to tell what the original rock was.
- Marble is metamorphosed limestone.

Explore More

Use this resource to answer the questions that follow. https://www.youtube.com/watch?v=EhxNHc2t-gM

1. Under what conditions do metamorphic rocks form?
2. What about the rock changes during metamorphism?
3. What is a foliated metamorphic rock?
4. What is a non-foliated metamorphic rock?
5. How does shale become a metamoprhic rock and what does it become first? What does it become when exposed to even higher metamorphic conditions second and third and forth?
6. What happens when you add heat and pressure to limestone? Is it foliated?

Explore More Answers

1. They form when a rock is placed under enough heat and pressure to change it but not to melt it.
2. The rock's structure, texture and composition can change.
3. Mineral grains are aligned into planes or bands.
4. There are no planes or bands.
5. If you add heat and pressure to shale it becomes slate. Then phyllite, next schist, then gneiss.
6. It becomes marble, which is not foliated.

Review

1. How do geologists tell what the parent rock of a metamorphic rock was, particularly a rock that was highly metamorphosed?
2. How do slate, phyllite, and schist differ from each other? How are they the same?
3. How does quartzite differ from a metamorphosed sandstone that is made of more than one mineral?

Review Answers

1. It's not always easy to tell, especially if the rock is highly metamorphosed. It's important to look for the original minerals and textures to try to determine the parent rock.
2. All of these are metamorphosed shale, just different amounts of metamorphism. They are all foliated but resemble the parent shale less as the amount of metamorphism increases.
3. Metamorphosed sandstone can contain any minerals but a quartzite must be nearly all quartz sandstone as the parent.

Summary

All matter is made of tiny particles. Protons, neutrons, and electrons form atoms that bond together to create molecules. Atoms are the smallest units that have the properties of the element they are and molecules are the smallest units of a compound. For example, water is made of hydrogen and oxygen, but a molecule of water is very different from an atom of hydrogen or an atom of oxygen. The atoms combine to form molecules by different types of chemical bonding. Molecules bond into structures as well. The structures created by molecules form the different types of minerals, most importantly silicates, which are the substances that make up most of Earth's crust. Other important minerals are carbonates and native elements, which are some of the most important materials used by society. Minerals come together to create the three major rock types, igneous, sedimentary, and metamorphic. These rocks are the material part of the rock cycle. Different processes can convert any type of rock into any other type of rock. These processes include weathering and erosion, melting and cooling, and burial and pressure, among others. Each rock contains a story of how it formed and what it formed from. Geologists piece together these stories to understand the geologic past of any region of our planet and of the planet as a whole.

1.17 References

1. Jodi So. Diagram of an atom. CC BY-NC 3.0
2. User:Cepheus/Wikimedia Commons. The periodic table. Public Domain
3. Laura Guerin. Lithium and fluorine react to form lithium fluoride. CC BY-NC 3.0
4. Laura Guerin. Diagram of methane. CC BY-NC 3.0
5. Ben Mills (User:Benjah-bmm27/Wikimedia Commons). Diagram of water, showing it is a polar molecule. Public Domain
6. Ben Mills (User:Benjah-bmm27/Wikimedia Commons). Halite crystals form from sodium and chloride ions. Public Domain
7. User:Materialscientist/Wikipedia. Quartz is made of two oxygen atoms bonded to a silicon atom. Public Domain
8. CK-12 Foundation. One silicon atom bonds to four oxygen atoms to form a silica tetrahedron. CC BY-NC 3.0
9. (a) Kevin Walsh; (b) Image copyright Manamana, 2014. Muscovite and tourmaline are both silicates, but their tetrahedrons join together in different ways. (a) CC BY 2.0; (b) Used under license from Shutterstock.com
10. Chris Ralph (User:Reno Chris/Wikipedia). A gold nugget. Public Domain
11. User:Alkivar/Wikipedia. A calcite crystal. Public Domain
12. (a) Parent Géry; (b) User:Alkivar/Wikipedia. Azurite and malachite are both carbonate minerals. Public Domain
13. Chris Ralph (User:Reno Chris/Wikipedia). A halite crystal. Public Domain
14. User:Parent Géry/Wikimedia Commons. A crystal of magnetite, which is magnetic. Public Domain
15. User:OG59/Wikimedia Commons. Apatite is a phosphate mineral. Public Domain
16. Courtesy of United States Geological Survey and the Mineral Information Institute. Gypsum is a sulfate mineral. Public Domain
17. Flickr:pnjunction2007. Pyrite, fool's gold, is a sulfide mineral. CC BY 2.0
18. Left: Stephanie Clifford; Right: Mauro Cateb. . CC BY 2.0
19. CK-12 Foundation. . CC BY-NC 3.0
20. Image copyright Nadezda Boltaca, 2014. . Used under license from Shutterstock.com
21. User: /Wikimedia Commons. . Public Domain
22. Bruce. . CC BY 2.0
23. Courtesy of Andrew Silver, USGS. . Public Domain
24. Kevin Walsh, modified by CK-12 Foundation. Granite is formed from magma, and contains quartz, feldspar, and biotite. CC BY 2.0
25. Rebecca Calhoun. Crystals form when water evaporates. CC BY-NC 3.0
26. Flickr:Zengame. Tufa towers in Mono Lake. CC BY 2.0
27. Image copyright Phon Promwisate, 2014. Picture of a quartz vein in rock. Used under license from Shutterstock.com
28. User:Pseudopanax/Wikipedia. An amethyst geode inside a rock. Public Domain
29. Christopher Auyeung. A phase diagram for water. CC BY-NC 3.0
30. User:Woudloper/Wikimedia Commons. Different minerals cause the different colors and textures in this rock. Public Domain
31. James Stuby (User:Jstuby/Wikipedia). This pegmatite contains lepidolite, tourmaline, and quartz. Public Domain
32. (a) User:Roll-Stone/De.Wikipedia; (b) Beatrice Murch. Two different rock samples to be analyzed. (a) Public Domain; (b) CC BY 2.0
33. User:Woudloper/Woodwalker; modified by CK-12 Foundation. The rock cycle. Public Domain
34. Hana Zavadska. Bowen's Reaction Series indicates how different igneous rocks form. CC BY-NC 3.0

35. James Bowe. Granite, an intrusive igneous rock, is made of feldspar, quartz, hornblende, and biotite. CC BY 2.0
36. Left: Miguel Vieira; Right: Tim Wilson. The Sierra Nevada Mountains are made of intrusive igneous rock. CC BY 2.0
37. Courtesy of J.D. Griggs/US Geological Survey. Lava cools to form extrusive igneous rock. Public Domain
38. Courtesy of the US Geological Survey. Basalt rock has no visible crystals. Public Domain
39. (a) Kevin Walsh (Flickr: kevinzim); (b) User:deltalimatrieste/Wikimedia Commons; (c) Courtesy of the National Oceanic and Atmospheric Administration. Obsidian, pumice, and basalt are extrusive igneous rocks that cool at different rates. (a) CC BY 2.0; (b) Public Domain; (c) Public Domain
40. A) Courtesy of the US Geological Survey and the Mineral Information Institute; B) Mark A. Wilson (User:Wilson44691/Wi Commons); C) User:Omphacite/Wikimedia Commons; D) User:GeoRanger/Wikipedia. Pictures of rhyolite, gabbro, peridotite, and komtiite. Public Domain
41. Courtesy of the National Oceanic and Atmospheric Administration. Water erosion in Alaska's Valley of Ten Thousand Smokes. Public Domain
42. User:ZackClark/Wikimedia Commons. A river dumps sediments along its bed and on its banks. Public Domain
43. Timo Kamph. A cliff made of sandstone. CC BY 2.0
44. Mark A. Wilson (User:Wilson44691/Wikimedia Commons). Halite forming on a rock in the Dead Sea. Public Domain
45. Mark A. Wilson (User:Wilson44691/Wikimedia Commons). Fossils in limestone in the Carmel Formation. Public Domain
46. Steven Coutts. A foliated metamorphic rock. CC BY 2.0