Komar University of Science and Technology

Physical Geology and Lab

Laboratory Manual

Lecturer**:**

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Preface

The first lecture in this manual deals with how to identify and describe the minerals through their properties like hardness, chemical reaction with acid, streak and so on. In line with the first lesson, the second lecture explains about the type of rocks and their classification. The third lab lesson in this manual deals with how to read and use topographic and geologic maps. This lesson follows a sequence that progresses through the basics of plate tectonics, seismology, and geologic time and concludes with such overarching topics as Earth's major geologic features (e.g., the deformation of Earth's surface like folds and faults) and economic geology resources.

Learning Outcomes

The following learning outcomes in this lab manual have been specified for the students who have selected the *Physical Geology and Lab* course. After successfully completing the lab exercises, the students should be able to:

1. Effectively apply the concepts, principles, and theories of geology to make accurate observations and to identify and distinguish among mineral and rock samples and Earth's structures/landscapes.
2. Read a topographic and geologic map and correlate them with the Earth's features.
3. Gather and analyze data for making a topographic and geologic map, formulate and test geological hypotheses, solve problems, and come to supportable conclusions given various scenarios and research topics.

Features

Each lesson includes specific learning objectives that the students should use to prepare for the lab. The lab manual includes the procedures that illuminate the central principles of physical geology and lab course. The procedures can help the students to review, analyze, and apply their knowledge of the materials covered in the lab course. Reading this lab manual, completing the activities and exercises, watching the video clips in the online component, and doing the field trip at the end of lab course will provide the pupils with useful information that they would receive in the classroom if you were taking this lab course on campus.

The laboratory kit contains most of the mineral and rock samples, which are necessary to conduct the lab exercises involved in each lesson. Each lesson in the lab manual contains the following elements:

- **Overview**

  This section introduces the topics covered in the lab exercises, explains why they are important, and makes connections to previous lesson concepts that the pupils will need to remember.

- **Learning Objectives**

  The test questions are designed after completing and learning each lesson to achieve the significant objectives and consequently help to the students focus their study.

- **Materials**

  This section provides a list of materials that are needed to complete the lab exercises. Some items are provided in the accompanying lab kit, and others may need to be purchased or borrowed if they are not readily available in the laboratory.

- **Illustrations**

  These drawings and photographs have been included to amplify your understanding of specific concepts or to illustrate particular steps and procedures within the course of various lab experiments.

- **Online Activities**

  This section involves using the Internet to access the course website, where the pupils will participate in a variety of simulations like: watching geologic-video clips, viewing images (e.g., minerals, rocks, deformed features, etc.), and finally completing the due tests based on these activities.

This lab manual has been designed to be used as a tool to help reinforce topics and concepts on which the pupils will later be tested. To complete this lab course successfully, they will need to complete exercises that:

- Provide them with information that the pupils can apply to their everyday experiences.

- Provide visual reinforcement to help the pupils understand and appreciate the complexity of the various physical geologic processes that occur above and beneath the surface of the earth as you know it.
- Provide the pupils with the opportunity to practice what they have learned.
- Help make the study of physical geology more organized, systematic, and enjoyable.

Part 1: Introduction

Regardless of your educational background or interests, you probably have already done some thinking like a geologist. This lab will help you think and act even more like a geologist.

What does it mean to start thinking like a geologist?

You start thinking like a geologist when you focus on questions about planet Earth and try to answer them. You were thinking like a geologist if you ever observed an interesting landform, rock, or fossil, and wondered about how it formed. You were also thinking like a geologist if you ever wondered where your drinking water comes from, the possibility of earthquakes or floods where you live, where to find gold, how to vote on environmental issues, or what environmental risks may be associated with buying or building a home. Wondering or inquiring about such things leads one to fundamental questions about Earth and how it operates. **Science** is a way of answering these questions by *gathering data* (information, evidence) based on investigations and careful observations, *thinking critically* (applying, analyzing, interpreting, and evaluating the data), *engaging in discourse* (verbal or written exchange, organization, and evaluation of information and ideas), and *communicating inferences* (conclusions justified with data and an explanation of one's critical thinking process). **Geology** is the science of Earth. Its name comes from two Greek words, *geo* = Earth and *logos* = discourse. So geologists are also Earth scientists or geoscientists.

Why think like a geologist?

The products of geologic science are all around you—in the places where you live, the products you enjoy, the energy you use, and the government's environmental codes and safety policies that you must follow. For example, your home contains bricks, concrete, plaster wall boards (sheet-rock), glass, metals, and asphalt roof shingles made with raw materials that were located by geologists. The safe location of your home was likely determined with the help of geologists. The wooden materials and foods in your home were processed with tools and machines containing metals that were extracted from ore minerals found by geologists. The electricity you use comes from generating plants that are fueled with coal, gas, oil, or uranium that was found by geologists. The safe location of the generating plants was evaluated by geologists, and the electricity is transported via copper wires made from copper ore minerals located by geologists. Even your trash and sewage are processed and recycled or disposed of in accordance with government policies developed with geologists and related to surface and groundwater. So geologists are Earth detectives who try to locate and manage resources, identify and mitigate hazards, predict change, and help communities plan for the future. These things lay the foundation upon which all industrial societies are based. Yet the growing societies of the world are now testing the ability of geoscientists to provide enough materials, energy, and wisdom to sustain people's wants and needs. Now, more than ever, geologists are addressing fundamental questions about natural resources, the environment, and public policies in ways that strive to ensure the ability of Earth to sustain the human population.

How to start thinking and acting like a geologist?

As you complete exercises in this laboratory manual, think and act like a geologist or Earth detective.

- ✓ **Focus on questions** about things like Earth materials and history, natural resources, processes and rates of environmental change, where and how people live in relation to the environment, and how geology contributes to sustaining the human population.
- ✓ **Conduct investigations and use your senses and tools to make observations** (determine and characterize the qualities and quantities of materials, energies, and changes).
- ✓ As you make observations, **record data** (factual information or evidence used

as a basis for reasoning).

- ✓ **Engage in critical thinking**—apply, analyze, interpret, and evaluate the evidence to form tentative ideas or conclusions.
- ✓ **Engage in discourse** or collaborative inquiry with others (exchange, organization, evaluation, and debate of data and ideas).
- ✓ **Communicate inferences**—write down or otherwise share your conclusions and justify them with your data and critical thinking process.

These components of doing geology are often not a linear "scientific method" to be followed in steps. You may find yourself doing them all simultaneously or in odd order. For example, when you observe an object or event, you may form an initial interpretation of it or a hypothesis (tentative conclusion) about it. However, a good geologist (scientist) would also question these tentative conclusions and investigate further to see if they are valid or not. Your tentative ideas and conclusions may change as you make new observations, locate new information, or apply a different method of thinking.

How to record your work?

When making observations, you should observe and record **qualitative data** by describing how things look, feel, smell, sound, taste, or behave. You should also collect and record **quantitative data** by counting, measuring or otherwise expressing in numbers what you observe. Carefully and precisely record your data in a way that others could use it.

Your instructor will not accept simple yes or no answers to questions. He or she will expect your answers to be complete inferences justified with data and an explanation of your critical thinking (in your own words). Show your work whenever you use mathematics to solve a problem so your method of thinking is obvious.

Part 1.1: Direct and Remote Investigation of Geology

The most reliable information about Earth is obtained by direct observation, investigation, and measurement in the field (out of doors, in natural context) and laboratory. Most geologists study *outcrops*—field sites where rocks *crop out* (stick out of the ground). The outcrops are made of rocks, and rocks are made of minerals. Samples obtained in the field (from outcrops at field sites) are often removed to the laboratory for further analysis using basic science. Careful observation (use of your senses, tactile abilities, and tools to gather information) and critical thought lead to questions and hypotheses (tentative ideas to test). Investigations are then designed and carried out to test the hypotheses and gather data (information, evidence). Results of the investigations are analyzed to answer questions and justify logical conclusions. Refer to the example of field and laboratory analysis in Figure 1. Observation 1 (in the field) reveals that Earth's rocky geosphere crops out at the surface of the land. Observation 2 reveals that outcrops are made of rocks. Observation 3 reveals that rocks are made of mineral crystals such as the mineral *chalcopyrite*. This line of reasoning leads to the next **logical question:** *What is chalcopyrite composed of?*

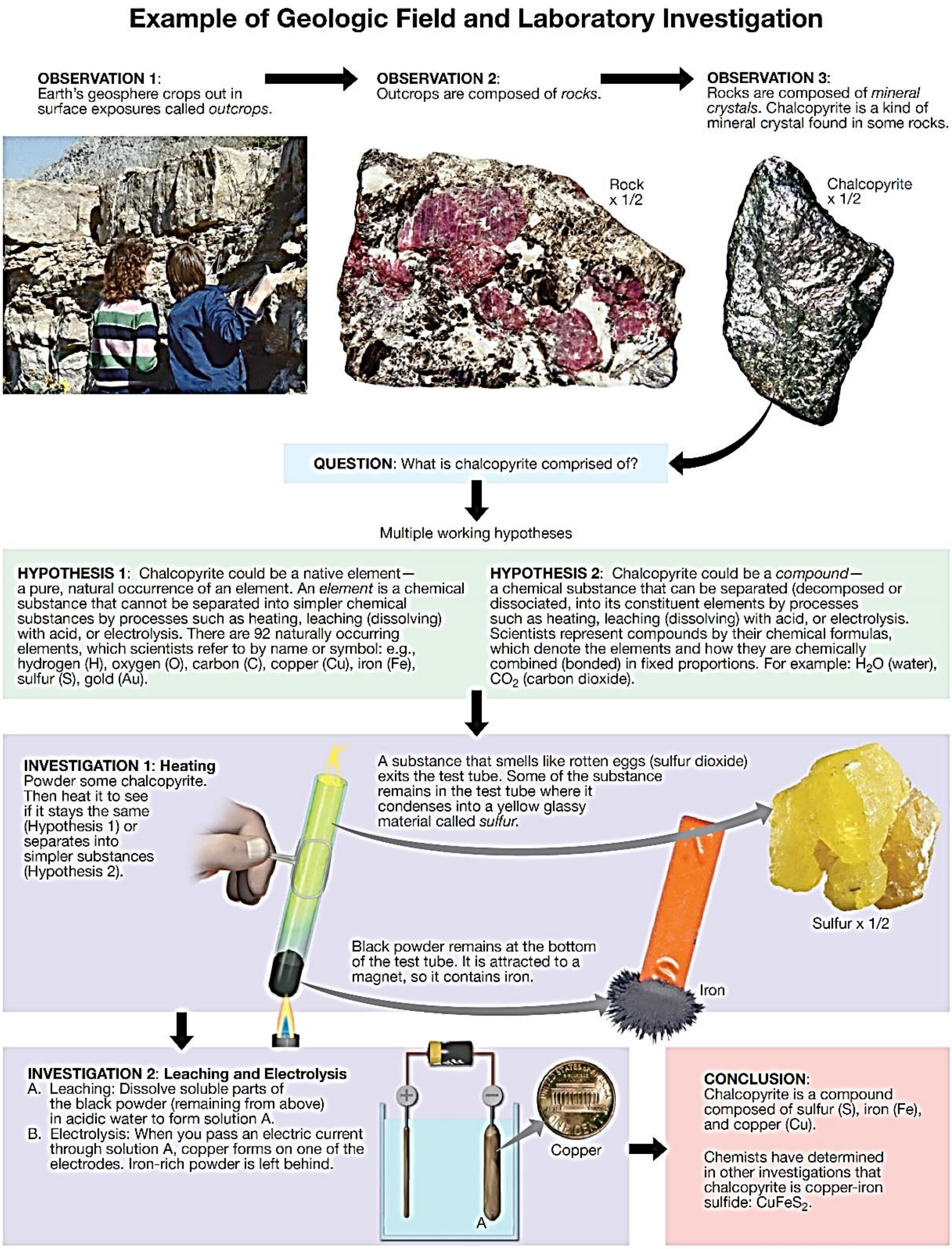


Figure 1

Geosphere

The **geosphere** is Earth's rocky body (Figure 2). The inner core has a radius of 1196 km and is composed mostly of iron (Fe) in a solid state. The outer core is 2250 km thick and is composed mostly of iron (Fe) and nickel (Ni) in a liquid state. The mantle is 2900 km thick and is composed mostly of oxygen (O), silicon (Si), magnesium (Mg), and iron (Fe) in a solid state. The crust has an average thickness of about 25 km and is composed mostly of oxygen (O), silicon (Si), aluminum (Al), and iron (Fe) in a solid state. Some people consider the cryosphere as a sub-sphere of the geosphere. The **cryosphere** is composed of snow crystals and ice that form from freezing parts of the hydrosphere or atmosphere. Ice is a rock made of mineral crystals (like snowflakes), so the cryosphere is actually a sub-sphere of the geosphere. Most of it exists in the polar ice sheets (continental glaciers), permafrost (permanently frozen moisture in the ground), and sea ice (ice on the oceans).

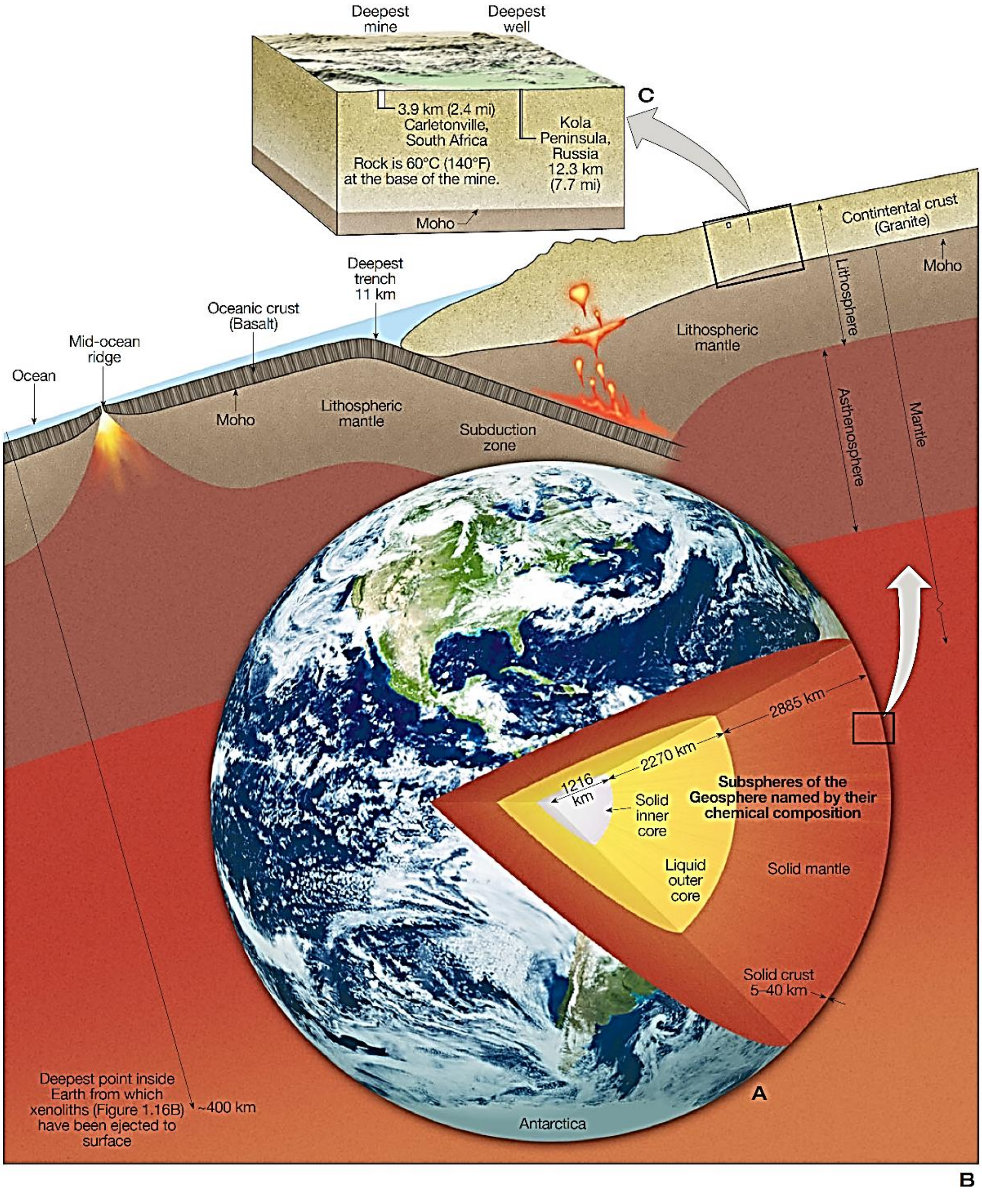


Figure 2

Hydrosphere

The **hydrosphere** is all of the liquid water on Earth's surface and in the ground (groundwater). Most of the hydrosphere is salt water in the world ocean, which has an average depth (thickness) of 3.7 km. However, the hydrosphere also includes liquid water in lakes, streams, and the ground (called *groundwater*).

Atmosphere

The **atmosphere** is the gaseous envelope that surrounds Earth. It consists of about 78% nitrogen (Ni), 21% oxygen (O), 0.9% argon (Ar) and trace amounts of other gases like carbon dioxide, water vapor, and methane. About 80% of these gases (including nearly all of the water vapor) occur in the lowest layer of the atmosphere (troposphere), which has an average thickness of about 16 km (10 miles). From there, the atmosphere thins and eventually ends (no air) at about 1000 km above sea level.

Biosphere

The **biosphere** is the living part of Earth, the part that is organic and self-replicating. It includes all bacteria, plants, and animals, so you are a member of the biosphere.

Magnetosphere

Earth's **magnetosphere** is its magnetic force field; not a material. It is generated from the core of the planet, and it is important because it shields Earth from the solar wind (a radiation of energy and particles from the Sun) that would otherwise make our planet lifeless.

Energy, Matter, and Force

A *force* is a push or a pull. For example, the force of gravity (the mutual attraction between two objects) pulls us towards the center of Earth. Magnetic force has polarity. Unlike poles attract (pull the magnets together), and like poles repel (push the magnets apart). As a force pushes or pulls, it causes objects to build up potential energy, start moving, change direction of movement, or stop moving. Unlike matter, which you can see and feel, you cannot see a force. But you can feel the push or pull of a force, and you can see how it affects the motion or change in shape (deformation) of objects. When a force acts on matter, the matter has potential energy (energy stored in an object because of its position in a force field) or kinetic energy (the capacity to work as a function of its motion). So when we say that energy is the capacity to do work, it means that energy is the potential to exert a force. The force is what does the moving. The force also transfers energy and transforms energy.

When you push a heavy object, some of your chemical energy is converted to mechanical energy, which powers the force. During the force, the mechanical energy is transformed into potential energy until the object moves (whereupon it is transformed into kinetic energy). When you stop pushing, there is no more force (the force is destroyed), but the energy was transformed and conserved (not created or destroyed). This is a basic *law* (fundamental principle) of nature. Of course, matter cannot be created or destroyed either, so the two concepts are combined into one law. The Law of Conservation of Matter and Energy is that matter and energy can be transferred and transformed but cannot be created or destroyed.

Part 1.2: Processes and Cycles of Change

Earth is characterized by the transfer (flow) of matter (materials) and energy during processes of change at every spatial and temporal scale of observation. Most of these processes involve organic (biological; parts of living or once living organisms) and inorganic (non-biological) materials in solid, liquid, and gaseous states, or *phases.* Note that many of the processes have opposites depending on the flow of energy to or from a material: melting and freezing, evaporation and condensation, sublimation and deposition, dissolution and chemical precipitation, photosynthesis (food energy storage) and respiration (food energy release or "burning").

Part 1.3: Measuring Earth Materials

Every material has a *mass* that can be weighed and a *volume* of space that it occupies. An object's mass can be measured by determining its weight under the pull of Earth's gravity (using a balance). An object's volume can be calculated by determining the multiple of its linear dimensions (measured using a ruler) or directly measured by determining the volume of water that it displaces (using a graduated cylinder). In this laboratory, you will use metric balances, rulers, and graduated cylinders to analyze and evaluate the dimensions and density of Earth materials. Refer to page xiii at the front of this manual for illustrations of this basic laboratory equipment.

Part 2: Minerals and Rocks

Many people think of minerals as the beautiful natural crystals mined from the rocky body of Earth and displayed in museums or mounted in jewelry. But table salt, graphite in pencil leads, and gold nuggets are also minerals.

What are minerals?

According to geologists, **minerals** are inorganic, naturally occurring solids that have a definite chemical composition, distinctive physical properties, and crystalline structure. In other words, each mineral:

- ✓ occurs in the solid, rocky body of Earth, where it formed by processes that are inorganic (not involving life),
- ✓ has a definite chemical composition of one or more chemical elements that can be represented as a chemical formula (like NaCl for halite),
- ✓ has physical properties (like hardness, how it breaks, and color) that can be used to identify it,
- ✓ has crystalline structure—an internal patterned arrangement or geometric framework of atoms that can be revealed by external crystal faces, the way a mineral breaks, and in atomic- resolution images

How are minerals classified?

Geologists have identified and named thousands of different kinds of minerals, but they are often classified into smaller groups according to their importance, use, or chemistry. For example, a group of only about twenty are known as **rock-forming minerals,** because they are the minerals that make up most of Earth's crust. Another group is called the **industrial minerals**, because they are the main non-fuel raw materials used to sustain industrialized societies like ours. Some industrial minerals are used in their raw form, such as quartz (quartz sand), muscovite (used in computer chips), and gemstones. Most are refined to obtain specific elements such as iron, copper, and sulfur. All minerals are also classified into the following chemical classes:

Silicate minerals are composed of pure silicon dioxide (SiO_2, called quartz) or silicon-oxygen ions $(SiO_4)^{4-}$ combined with other elements. Examples are olivine: (Fe, Mg)$_2$SiO$_4$.

Oxide minerals contain oxygen (O^{2-}) combined with a metal (except for those containing silicon, which are silicate minerals). Examples are hematite: Fe_2O_3, magnetite: Fe_2O_3, and corundum: Al_2O_3.

Hydroxide minerals contain hydroxyl ions $(OH)^{-}$combined with other elements (except for those containing silicon, which are silicate minerals). Examples are limonite: $FeO(OH)$.

Sulfide minerals contain sulfur ions (S^{2-}) combined with metal(s) and no oxygen. Examples are pyrite: FeS_2, galena: PbS, and sphalerite: ZnS.

Sulfate minerals contain sulfate ions $(SO_4)^{2-}$ combined with other elements. An examples includes gypsum.

Carbonate minerals contain carbonate ions $(CO_3)^{2-}$ combined with other elements. Examples include calcite: $CaCO_3$ and dolomite: $CaMg(CO_3)_2$.

Halide minerals contain a halogen ion (F^-, Cl^-, Br^-, or I^-) combined with a metal. Examples are halite: $NaCl$ and fluorite: CaF_2.

Phosphate minerals contain phosphate ions $(PO_4)^{3-}$ combined with other elements. An example is apatite: $Ca_5F(PO_4)_3(OH, F, Cl)$.

Native elements are elements in pure form, not combined with different elements. Examples include graphite: C, copper: Cu, sulfur: S, gold: Au, and silver: Ag.

How are minerals related to rocks?

Most **rocks** are aggregates of one or more mineral crystals. For example, mineral crystals comprise all of the rocks in Figure 3. Notice that you can easily detect the mineral crystals in Figure 3 by their flat **faces**, which are an external feature of the internal geometric framework of their atoms. However, the crystals in many rocks have grown together in such a crowded way that few faces are visible. Some rocks are also **cryptocrystalline**, made of crystals that are only visible under a microscope. Earth is sometimes called the “third rock” (rocky planet) from the Sun, because it is mostly made of rocks. But rocks are generally made of one or more minerals, which are the natural materials from which every inorganic item in our industrialized society has been manufactured. Therefore, minerals are the physical foundation of both our rocky planet and our human societies.

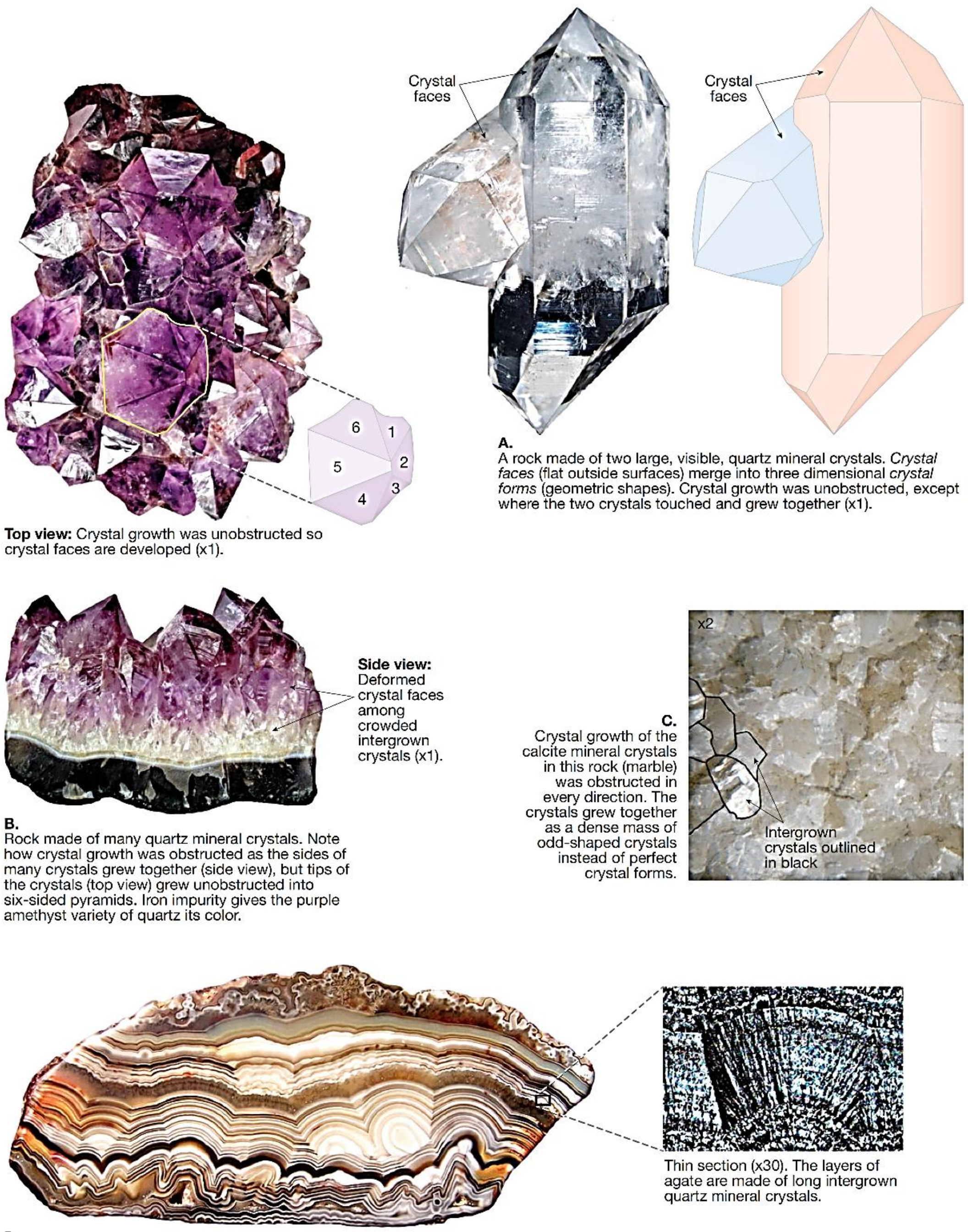


Figure 3

What are a mineral's chemical and physical properties?

The **chemical properties** of a mineral are its characteristics that can only be observed and measured when or after it undergoes a chemical change due to reaction with another material. This includes things like if or how it tarnishes (reacts with air or water) and whether or not it reacts with acid. For example, calcite and other carbonate (CO_3- containing) minerals react with acid, and native copper tarnishes to a dull brown or green color when it reacts with air or water.

The **physical properties** of a mineral are its characteristics that can be observed (and sometimes measured) without changing its composition. This includes things like how it looks (color, luster, and clarity) before it tarnishes or weathers by reacting with air or water, how well it resists scratching (hardness), how it breaks or deforms under stress (cleavage, fracture, tenacity), and the shapes of its crystals. For example, quartz crystals are hard to scratch, glassy, and transparent, while talc is easily scratched, opaque, and feels greasy.

In this activity, you will use the properties of color and clarity (before and after tarnishing), crystal form, luster (before and after tarnishing), streak, hardness, cleavage, and fracture to describe mineral samples. Additional properties— such as tenacity, reaction with acid, magnetic attraction, specific gravity, striations, and ex-solution lamellae—can also be helpful in analyzing particular minerals.

***Color and Clarity*.** A mineral's **color** is usually its most noticeable property and may be a clue to its identity. Minerals normally have a typical color, like gold. A rock made up of one color of mineral crystals is usually made up of one kind of mineral, and a rock made of more than one color of mineral crystals is usually made up of more than one kind of mineral. However, there are exceptions, like the agate in Figure 3. It has many colors, but they are simply *varieties* (var.)—different colors— of the mineral quartz. This means that a mineral cannot be identified solely on the basis of its color. The mineral's other properties must also be observed, recorded, and used collectively to identify it. Most minerals also tend to exhibit one color on freshly broken surfaces and a different color on tarnished or weathered surfaces. Be sure to note this difference, if present, to aid your identification.

Mineral crystals may vary in their **clarity**: degree of transparency or their ability to transmit light. They may be *transparent* (clear and see-through, like window glass), *translucent* (foggy, like looking through a steamed- up shower door), or *opaque* (impervious to light, like concrete and metals). It is good practice to record not only a mineral's color, but also its clarity. For example, the crystals in Figure 3 are purple in color and have transparent to translucent clarity.

***Crystal Forms and Mineral Habits*.** The geometric shape of a crystal is its **crystal form**. Each form is bounded by flat **crystal faces** that intersect at specific angles and in symmetrical relationships (Figure 3). The crystal faces are the outward reflection of the way that atoms or groups of atoms bonded together in a three-dimensional pattern as the crystal grew under specific environmental conditions. There are many named crystal forms (Figure 4). Combinations of two or more crystals can also form named patterns, shapes, or twins (botryoidal, dendritic, radial, and fibrous: Figure 4). A mass of mineral crystals lacking a distinctive pattern of crystal growth is called *massive*.

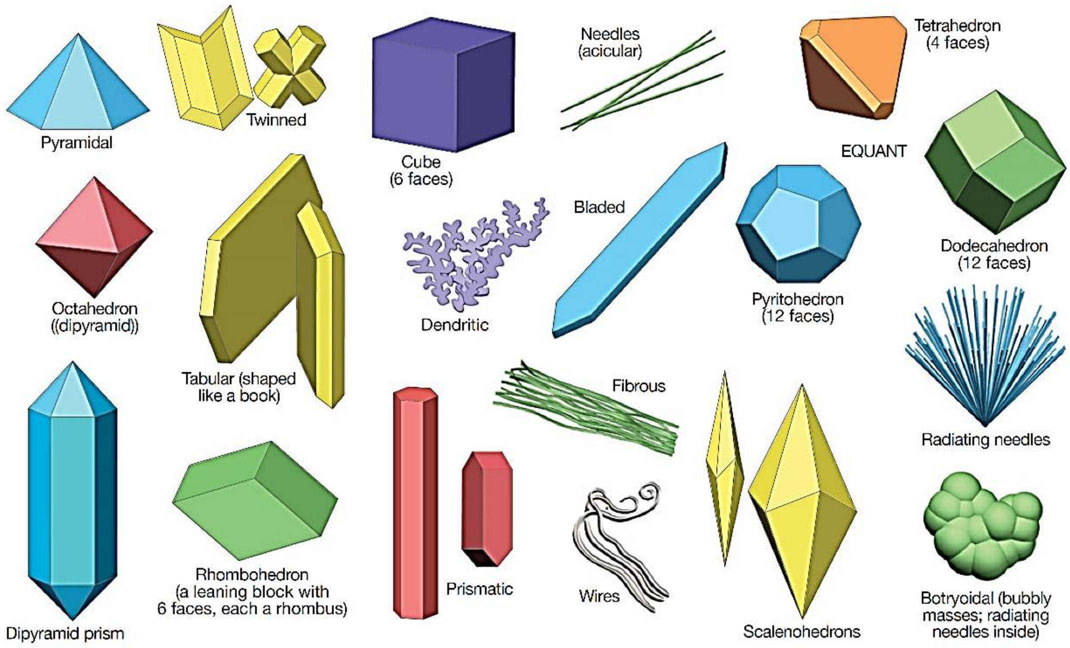


Figure 4

***Development of Crystal Faces*.**

The terms euhedral, subhedral, and anhedral describe the extent to which a crystal's faces and form are developed. *Euhedral crystals* have well developed crystal faces and clearly defined and recognizable crystal forms (Figure 3). They develop only if a mineral crystal is unrestricted as it grows. This is rare. It is more common for mineral crystals to crowd together as they grow, resulting in a massive network of inter-grown crystals with deformed crystal faces and odd shapes or imperfect crystal forms (Figure 4). *Subhedral* crystals are imperfect but have enough crystal faces that their forms are recognizable. *Euhedral* crystals have no crystal faces, so they have no recognizable crystal form (Figure 4). Most of the laboratory samples of minerals that you will analyze do not exhibit their crystal forms because they are small broken pieces of larger crystals. But whenever the form or system of crystals in a mineral sample can be detected, then it should be noted and used as evidence for mineral identification.

***Crystal Systems*.** Each specific crystal form can be classified into one of six *crystal systems* (Figure 5) according to the number, lengths, and angular relation- ships of imaginary geometric axes along which its crystal faces grew. The crystal systems comprise 32 classes of crystal forms, but only the common crystal forms are illustrated in Figure 5.

***Mineral Habit*.** A mineral's **habit** is the characteristic crystal form(s) or combinations (clusters, coatings, twinned pairs) that it habitually makes under a given set of environmental conditions. Pyrite forms under a variety of environmental conditions so it has more than one habit. Its habit is cubes, pyritohedrons, octahedrons, or massive (Figure 4).

***Luster*.** A mineral's **luster** is a description of how light reflects light from its surfaces. Luster is of two main types— metallic and nonmetallic—that vary in intensity from bright (very reflective, shiny, polished) to dull (not very reflective, not very shiny, not polished). For example, if you make a list of objects in your home that are made of metal (e.g., coins, knives, keys, jewelry, door hinges, aluminum foil), then you are already familiar with metallic luster. Yet the metallic objects can vary from bright (very reflective—like polished jewelry, the polished side of aluminum foil, or new coins) to dull (non-reflective—like unpolished jewelry or the unpolished side of aluminum foil).

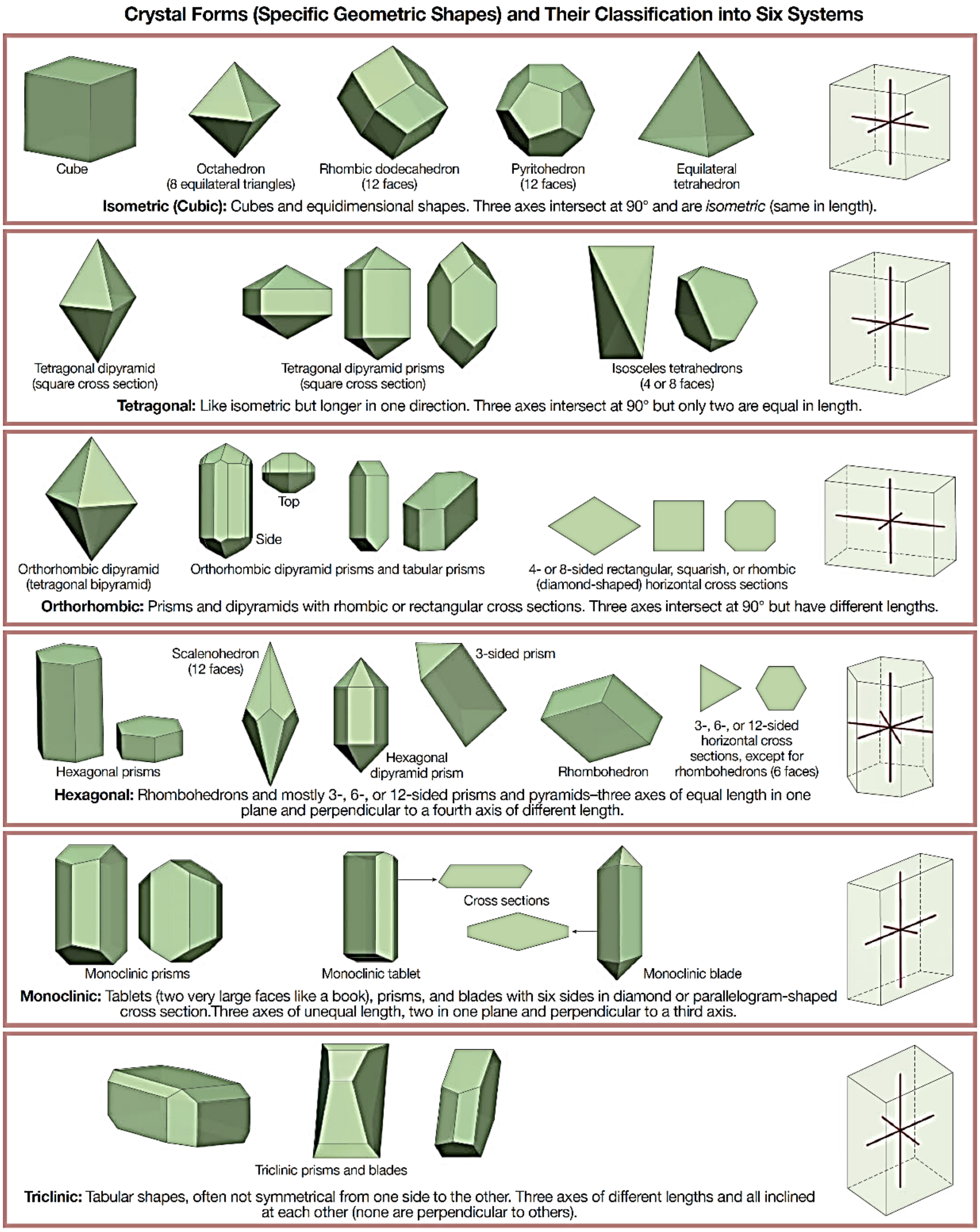


Figure 5

***Streak*. Streak** is the color of a mineral or other substance after it has been ground to a fine powder (so fine that you cannot see the grains of powder). The easiest way to do this is simply by scratching the mineral back and forth across a hard surface such as concrete, or a square of unglazed porcelain (called a *streak plate*). The color of the mineral's fine powder is its streak. Note that the brassy mineral in Figure 6 has a dark gray streak, but the reddish silver mineral has a red-brown streak. A mineral's streak is usually similar even among all of that mineral's varieties.

If you encounter a mineral that is harder than the streak plate, it will scratch the streak plate and make a white streak of powder from the streak plate. The streak of such hard minerals can be determined by crushing a tiny piece of them with a hammer (if available). Otherwise, record the streak as unknown.

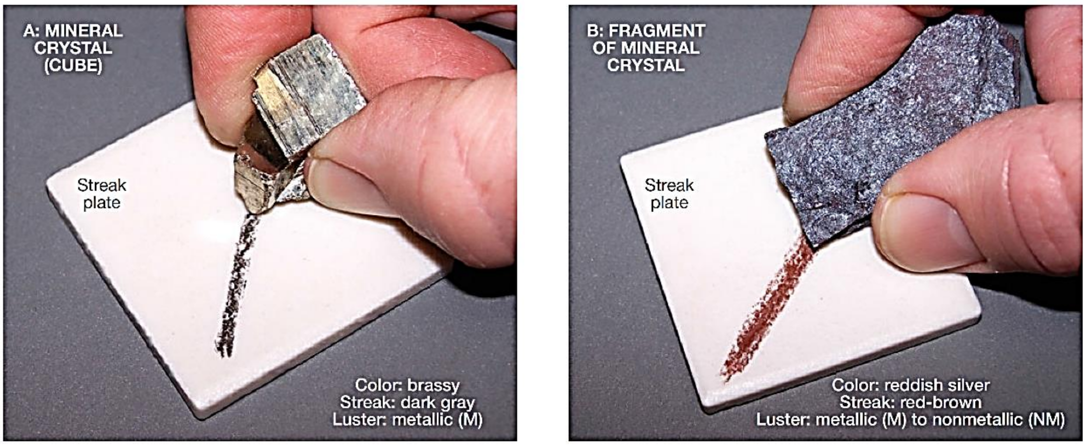


Figure 6

***<u>Hardness (H)</u>*.** A mineral's **hardness** is a measure of its resistance to scratching. A harder substance will scratch a softer one (Figure 7). German mineralogist Friedrich Mohs (1773–1839) developed a quantitative scale of relative mineral hardness on which the softest mineral (talc) has an arbitrary hardness of 1 and the hardest mineral (diamond) has an arbitrary hardness of 10. Higher- numbered minerals will scratch lower-numbered minerals (e.g., diamond will scratch talc, but talc cannot scratch diamond). **Mohs scale of Hardness** (Figure 8) is widely used by geologists and engineers. When identifying a mineral, you should mainly be able to distinguish minerals that are relatively hard (6.0 or higher on Mohs scale) from minerals that are relatively soft (less than or equal to 5.5 on Mohs scale). You can use common objects such as a glass plate (Figure 8), pocket knife, or steel masonry nail to make this distinction as follows.

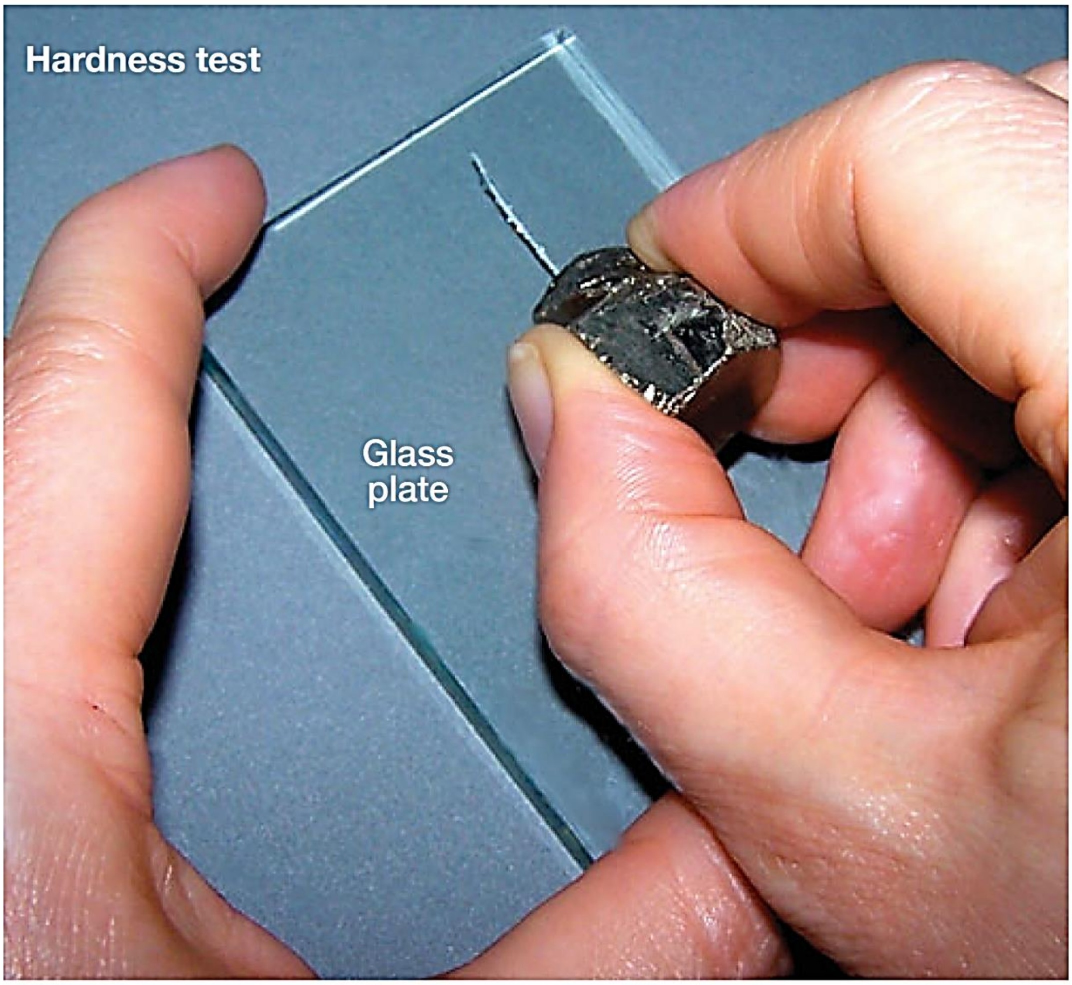


Figure 7

- ✓ **Hard minerals:** Will scratch glass; cannot be scratched with a knife blade or masonry nail.
- ✓ **Soft minerals:** Will not scratch glass; can be scratched with a knife blade or masonry nail.

You can determine a mineral's hardness number on Mohs scale by comparing the mineral to common objects shown in Figure 8 or pieces of the minerals in Mohs scale. Commercial *hardness kits* contain a set of all of the minerals in Figure 8 or a set of metal scribes of known hardness.

When using such kits to make hardness comparisons, remember that the harder mineral/object is the one that scratches, and the softer mineral/object is the one that is scratched.

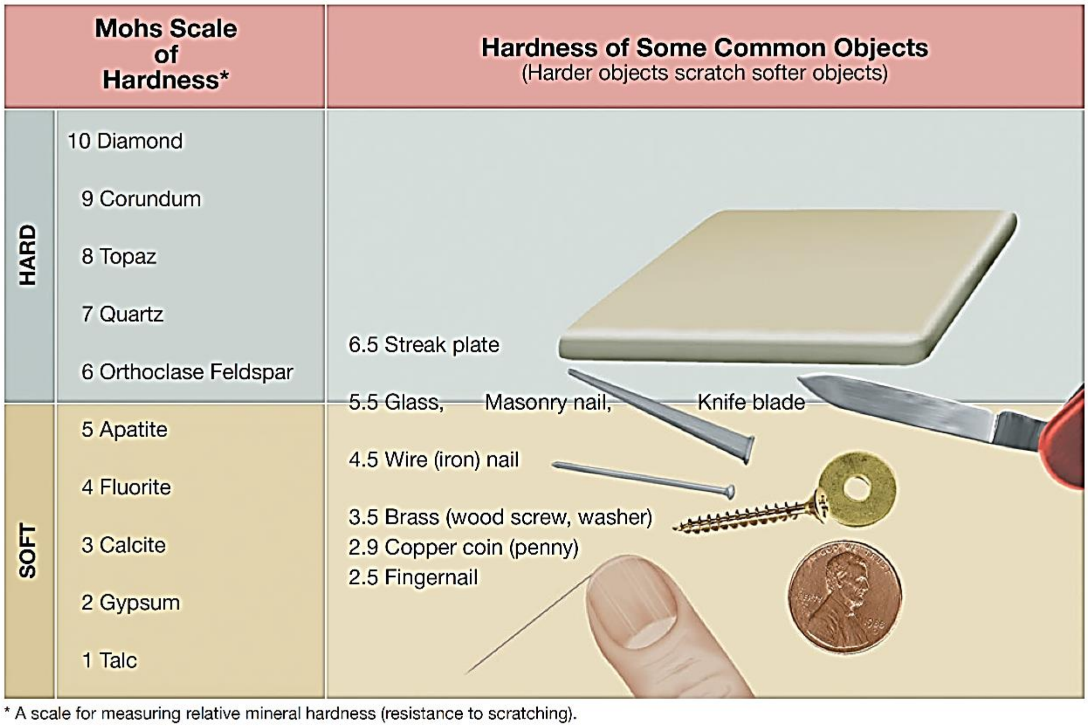


Figure 8

***<u>Cleavage and Fracture</u>*.** **Cleavage** is the tendency of some minerals to break (*cleave*) along flat, parallel surfaces (**cleavage planes**) like the flat surfaces on broken pieces of galena (Figure 3). Cleavage planes are surfaces of weak chemical bonding (attraction) between repeating, parallel layers of atoms in a crystal. Each different set of parallel cleavage planes is referred to as a *cleavage direction*. Cleavage can be described as excellent, good, or poor (Figure 9). An *excellent cleavage* direction reflects light in one direction from a set of obvious, large, flat, parallel surfaces. A *good cleavage* direction reflects light in one direction from a set of many small, obvious, flat, parallel surfaces. A *poor cleavage* direction reflects light from a set of small, flat, parallel surfaces that are difficult to detect. Some of the light is reflected in one direction from the small cleavage surfaces, but most of the light is scattered randomly by fracture surfaces separating the cleavage surfaces.

Fracture refers to any break in a mineral that does not occur along a cleavage plane. Therefore, fracture surfaces are normally not flat and they never occur in parallel sets. Fracture can be described as *uneven* (rough and irregular, like the milky quartz in, *splintery* (like splintered wood), or *hackly* (having jagged edges, like broken metal). Pure quartz and mineraloids like opal tend to fracture like glass—along ribbed, smoothly curved surfaces called *conchoidal fractures*.

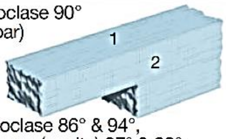
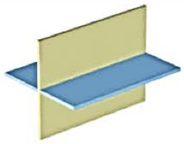
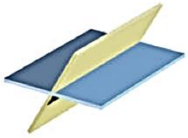
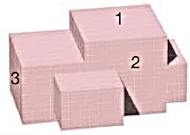
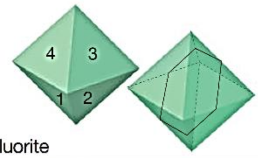
Number of Cleavages and Their Directions	Name and Description of How the Mineral Breaks	Shape of Broken Pieces (cleavage directions are numbered)	Illustration of Cleavage Directions
No cleavage (fractures only)	No parallel broken surfaces; may have conchoidal fracture (like glass)	 Quartz	None (no cleavage)
1 cleavage	**Basal (book) cleavage** "Books" that split apart along flat sheets	 Muscovite, biotite, chlorite (micas)	
2 cleavages intersect at or near 90°	**Prismatic cleavage** Elongated forms that fracture along short *rectangular* cross sections	Orthoclase 90° (K-spar)  Plagioclase 86° & 94°, pyroxene (augite) 87° & 93°	
2 cleavages do not intersect at 90°	**Prismatic cleavage** Elongated forms that fracture along short *parallelogram* cross sections	 Amphibole (hornblende) 56° & 124°	
3 cleavages intersect at 90°	**Cubic cleavage** Shapes made of cubes and parts of cubes	 Halite, galena	
3 cleavages do not intersect at 90°	**Rhombohedral cleavage** Shapes made of rhombohedrons and parts of rhombohedrons	 Calcite and dolomite 75° & 105°	
4 main cleavages intersect at 71° and 109° to form octahedrons, which split along hexagon-shaped surfaces; may have secondary cleavages at 60° and 120°	**Octahedral cleavage** Shapes made of octahedrons and parts of octahedrons	 Fluorite	
6 cleavages intersect at 60° and 120°	**Dodecahedral cleavage** Shapes made of dodecahedrons and parts of dodecahedrons	 Sphalerite	

Figure 9

***Cleavage Direction*.** Cleavage planes are parallel surfaces of weak chemical bonding (attraction) between repeating parallel layers of atoms in a crystal, and more than one set of cleavage planes can be present in a crystal. Each different set has an orientation relative to the crystalline structure and is referred to as a **cleavage direction** (Figure 10). For example, muscovite has one excellent cleavage direction and splits apart like pages of a book (book cleavage). Galena breaks into small cubes and shapes made of cubes, so it has three cleavage directions developed at right angles to one another. This is called cubic cleavage.

A: Pyroxenes (like augite) have two prominent cleavage directions that intersect at nearly right angles (87° and 93°). They form prismatic crystals with a squarish cross section. The crystals break into blocky fragments.

B: Amphiboles (like hornblende) have two prominent cleavage directions that intersect at 56° and 124°. They form more blade-like crystals with a six-sided diamond-shaped cross section and break into blade-like fragments.

Figure 10

Other Properties**.** There are additional mineral proper- ties, too numerous to review here. However, the following other properties are typical of specific minerals or mineral groups:

Tenacity is the manner in which a substance resists breakage. Terms used to describe mineral tenacity include *brittle* (shatters like glass), *malleable* (like modeling clay or gold; can be hammered or bent permanently into new shapes), *elastic* or *flexible* (like a plastic comb; bends but returns to its original shape), and *sectile* (can be carved with a knife).

Reaction to acid differs among minerals. Cool, dilute hydrochloric acid (1–3% HCl) applied from a dropper bottle is a common "acid test." All of the so-called *carbonate* minerals (minerals with a chemical composition including carbonate, CO_3) will effervesce ("fizz") when a drop of such dilute HCl is applied to one of their freshly exposed surfaces (Figure 11). Calcite ($CaCO_3$) is the most commonly encountered carbonate mineral and effervesces in the acid test.

Specific Gravity (SG)**.** Density is a measure of an object's mass (weighed in grams, g) divided by its volume (in cubic centimeters, cm^3). **Specific gravity** is the ratio of the density of a substance divided by the density of water. Since water has a density of 1 g $>cm^3$ and the units cancel out, specific gravity is the same number as density but without any units. For example, the mineral quartz has a density of 2.65 g$>cm^3$ so its specific gravity is 2.65 (i.e., SG = 2.65). **Hefting** is an easy way to judge the specific gravity of one mineral relative to another. This is done by holding a piece of the first mineral in one hand and holding an equal-sized piece of the second mineral in your other hand. Feel the difference in weight between the two samples (i.e., heft the samples). The sample that feels heavier has a higher specific gravity than the other. Most metallic minerals have higher specific gravities than nonmetallic minerals.

Figure 11

Why are density and specific gravity important?

Have you ever considered buying silver coins as an investment? If so, then you should be wary of deceptive sales. For example, there have been reports of less valuable silver-plated copper coins marketed as pure silver coins. Copper has a specific gravity of 8.94, which is very close to silver's specific gravity of 9.32. So, even experienced buyers cannot tell a solid silver coin from a silver-plated copper coin just by hefting it to approximate its specific gravity. They must deter- mine the coin's exact specific gravity as one method of ensuring its authenticity. Mineral identification is also aided by knowledge of specific gravity. If you heft same-sized pieces of the minerals galena (lead sulfide, an ore of lead) and quartz, you can easily tell that one has a much higher specific gravity than the other. But the difference in specific gravities of different minerals is not always so obvious. In this activity you will learn how to measure the volume and mass of mineral samples, calculate their specific gravities, and use the results to identify them.

How to Determine Volume. Recall that **volume** is the amount of space that an object takes up. Most mineral samples have odd shapes, so their volumes cannot be calculated from linear measurements. Their volumes must be determined by measuring the volume of water they displace. This is done in the laboratory with a *graduated cylinder* (Figure 12), an instrument used to measure volumes of fluid (fluid volume). Most graduated cylinders are graduated in metric units called milliliters (mL or ml), which are thousandths of a liter. *You should also note that 1 mL (1 ml) of fluid volume is exactly the same as 1 cm^3 of linear volume*.

Procedures for determining the volume of a mineral sample are provided in Figure 12. Note that when you pour water into a glass graduated cylinder, the surface of the liquid is usually a curved *meniscus*, and the volume is read at the bottom of its concave surface. In most plastic graduated cylinders, however, there is no meniscus. The water level is flat and easy to read.

If you slide a mineral sample into a graduated cylinder full of water (so no water splashes out), then it takes up space previously occupied by water at the bottom of the graduated cylinder. This displaced water has nowhere to go except higher into the graduated cylinder. Therefore, the volume of the mineral sample is exactly the same as the volume of fluid (water) that it displaces.

How to Determine Mass. Earth materials do not just take up space (volume). They also have a mass of atoms that can be weighed. You will use a gram balance to measure the **mass** of materials (by determining their weight under the pull of Earth's gravity). The gram (g) is the basic unit of mass in the metric system, but instruments used to measure grams vary from triple-beam balances to spring scales to digital balances (page viii). Consult with your laboratory instructor or other students to be sure that you understand how to read the gram balance provided in your laboratory.

How to Calculate Density and Specific Gravity. Every material has a *mass* that can be weighed and a *volume* of space that it occupies. However, the relationship between a material's mass and volume tends to vary from one kind of material to another. For example, a bucket of rocks has much greater mass than an equal-sized bucket of air. Therefore a useful way to describe an object is to determine its mass per unit of volume, called **density**. *Per* refers to division, as in miles *per* hour (distance divided by time). So density is the measure of an object's mass divided by its volume (density = mass ÷ volume). Scientists and mathematicians use the Greek character rho (**r**) to represent density. Also, the gram (g) is the basic metric unit of mass, and the cubic centimeter is the basic unit of metric volume (cm^3), so density (**r**) is usually expressed in grams per cubic centimeter (g/cm^3).

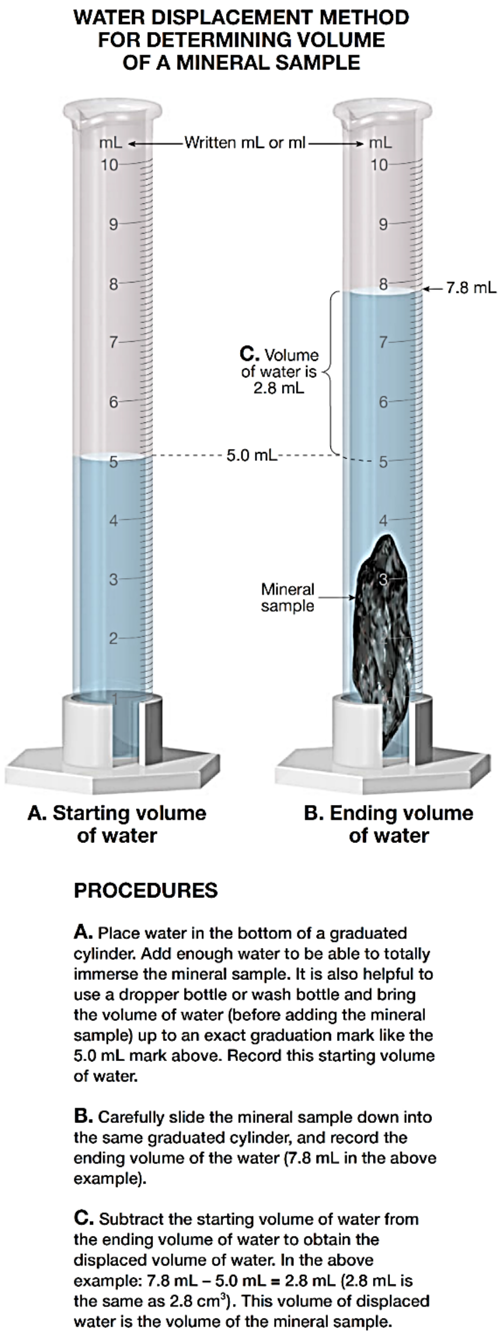


Figure 12

Part 3: Rocks and the Rock Cycle

Most rocks are solid aggregates of mineral grains (particles), either mineral crystals or clasts (broken pieces) of mineral crystals and rocks (e.g., pebbles, gravel, sand, and silt). There are, however, a few notable rocks that are not made of mineral grains. For example, *obsidian* is a rock made of volcanic glass, and *coal* is a rock made of plant fragments.

Three Main Groups of Rocks

Rock-forming materials come from Earth's mantle (as molten rock called *magma* while underground and *lava* when it erupts to the surface), space (meteorites), organisms (parts of plants and animals), or the fragmentation and chemical decay of mineral crystals and other rocks. Environmental changes and processes affect these materials and existing rocks in ways that produce three main rock groups (Figure 13):

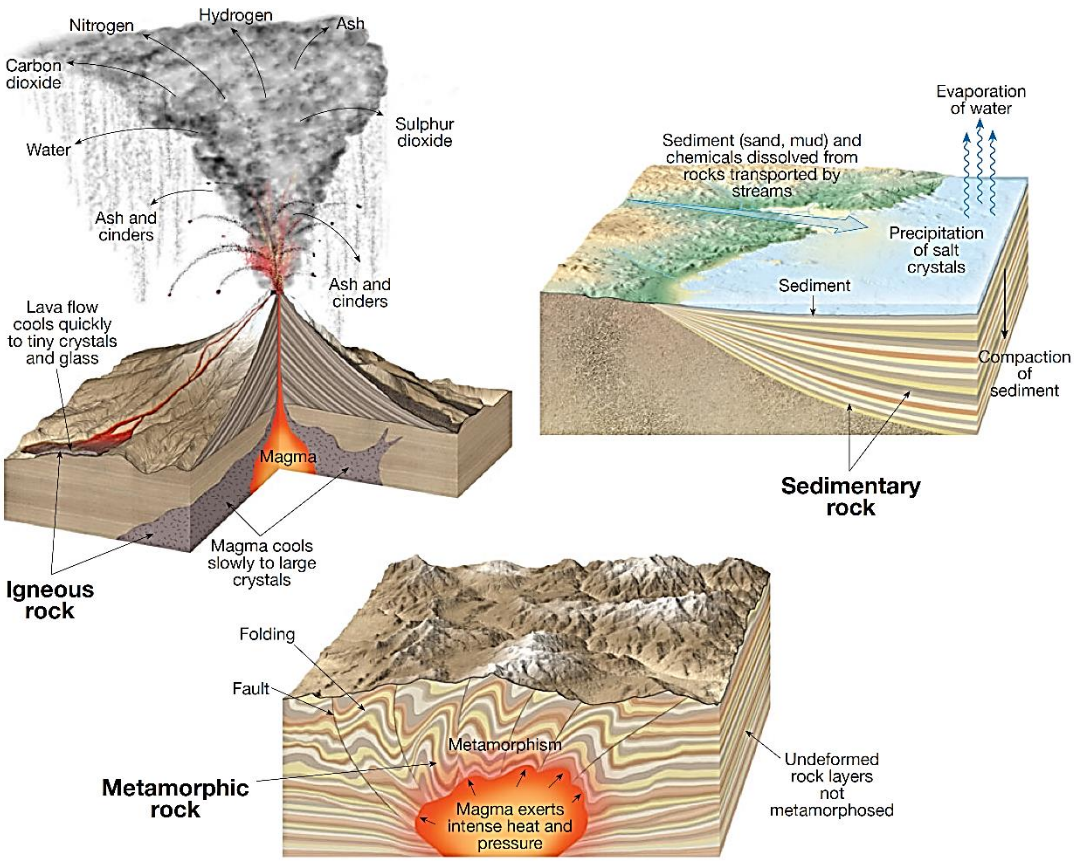


Figure 13

1) **Igneous rocks** form when magma or lava cool to a solid form—either glass or masses of tightly inter-grown mineral crystals. The crystals are large if they had a long time to grow in a slowly cooling magma, and they are small if they formed quickly in a rapidly cooling lava.
2) **Sedimentary rocks** form mostly when mineral crystals and clasts (broken pieces, fragments) of plants, animals, mineral crystals, or rocks are compressed or naturally cemented together. They also form when mineral crystals precipitate from water to form a rocky mass such as *rock salt* or cave stalactites.
3) **Metamorphic rocks** are rocks deformed or changed from one form to another (transformed) by intense heat, intense pressure, and/or the action of hot fluids. This causes the rock to recrystallize, fracture, change color, and/or flow. As the rock flows, the flat layers are folded and the mineral crystals are aligned like parallel needles or scales.

The Rock Cycle

All rocks are part of a system of rock-forming processes, materials, and products that is often portrayed in a conceptual model called the **rock cycle** (Figure 14). The rock cycle model explains how all rocks can be formed, deformed, transformed, melted, and reformed as a result of environmental factors and natural processes that affect them.

- **Igneous Processes.** An idealized path (broad purple arrows) of rock cycling and redistribution of matter is illustrated in Figure 14, starting with igneous processes.

  If magma (from the mantle or lower crust) cools, then it solidifies into igneous rocks that are masses of glass or aggregates of inter-grown mineral crystals.
- **Sedimentary Processes.** If these igneous rocks are uplifted, then sedimentary processes force other changes to occur. The igneous rocks are **weathered** (fragmented into grains, chemically decayed to residues, or even dissolved), **eroded** (worn away) and **transported** (moved to a new place), and later deposited to form **sediment** (an accumulation of chemical residues and fragmented rocks, mineral crystals, plants, or animals).

  Meteorites (dust and rocks from space) may be incorporated into the sediment. Sediment is **lithified** (hardened) into sedimentary rock as it compacts under its own weight or gets naturally cemented with crystals precipitated from water.

- **Metamorphic Processes.** If the sedimentary rock is subjected to metamorphic processes (intense heat, intense pressure, or the chemical action of hot fluids), then it will *deform* (fold, fracture, or otherwise change its shape) and *transform* (change color, density, composition, and/or general form) to metamorphic rock. And if the heat is great enough, then the metamorphic rock will melt (an igneous process) to form another body of magma that will begin the cycle again.

Multiple Pathways through the Rock Cycle. Of course, not all rocks undergo change along such an idealistic path. There are *at least* three changes that each rock could undergo. The arrows in Figure 14 to either of the other two groups *or* recycled within its own group. Igneous rock can be (1) weathered and eroded to form sediment that is lithified to form sedimentary rock; (2) transformed to metamorphic rock by intense heat, intense pressure, and/or hot fluids; or (3) re-melted, cooled, and solidified back into another igneous rock. Sedimentary rock can be (1) melted, cooled, and solidified into an igneous rock; (2) transformed to metamorphic rock by intense heat, intense pressure, and/or hot fluids; or (3) weathered and eroded back to sediment that is lithified back into another sedimentary rock. Metamorphic rock can be (1) weathered and eroded to form sediment that is lithified into sedimentary rock; (2) melted, cooled, and solidified into igneous rock; or (3) re-metamorphosed into a different type of metamorphic rock by intense heat, intense pressure, or hot fluids.

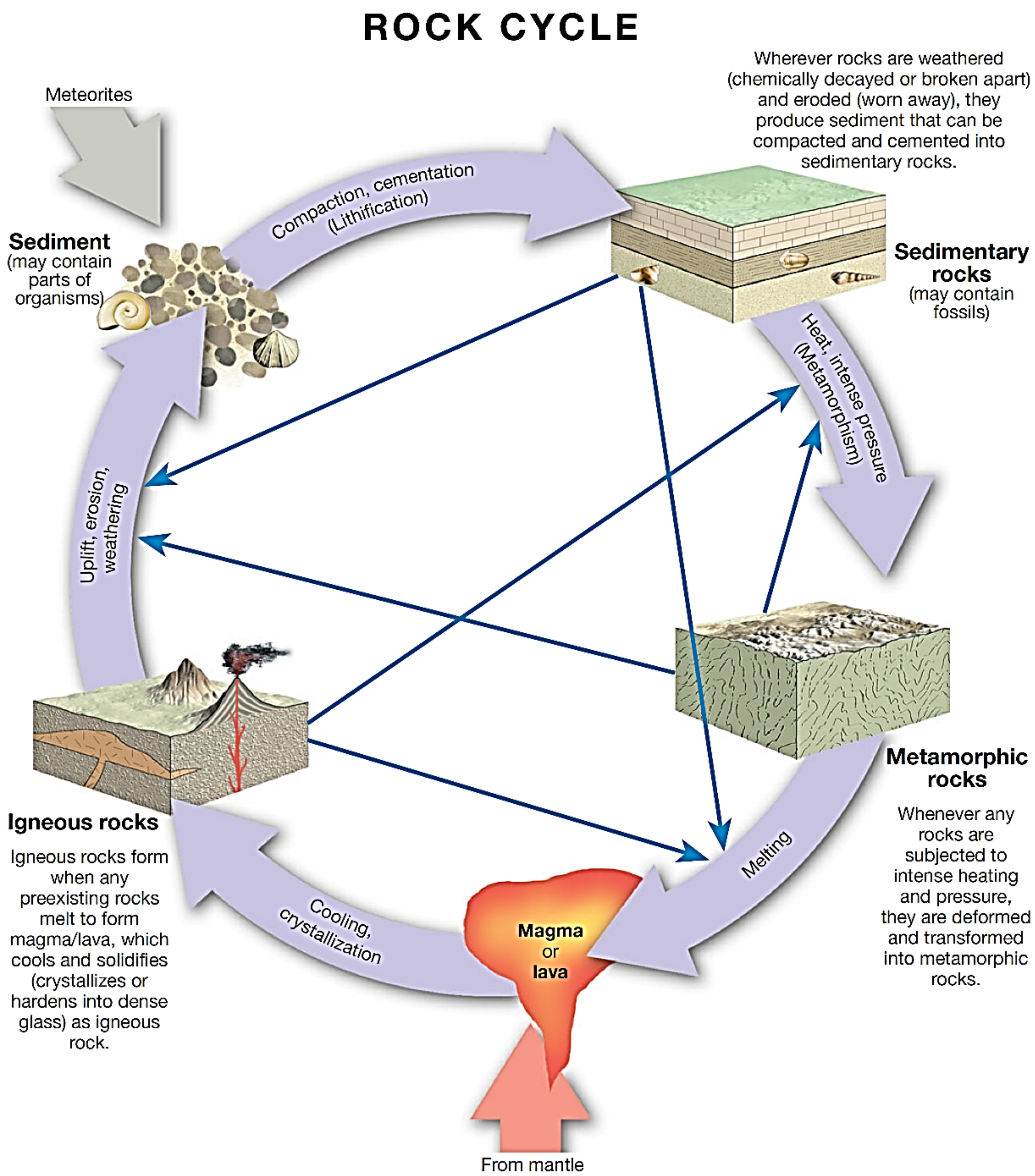


Figure 14

Part 2.1: Rock Composition

Composition of a rock refers to what it is made of. *Chemical composition* refers to the chemical elements that make up the rock. This determines how the rock will react with materials of different composition, such as whether or not it will react with and decay (tarnish, dissolve, chemically disintegrate) in air or water. It also determines rock color. For example, ferromagnesian-rich rocks (iron- and magnesium-rich rocks) generally have a dark color and ferromagnesian-poor rocks generally have a light color. But the chemical elements in a rock are normally bonded together in tangible materials like minerals that, in turn, make up most rocks. So the *physical composition* of rocks is a description of what visible materials they are made of, in whole or part. It is your job as a geologist, using your eyes and simple tools (like a hand magnifying lens), to describe and identify what physical materials are made of.

Volcanic Glass

Glass is an amorphous (containing no definite form; not crystalline) solid that forms by cooling molten (liquefied by heat) materials like melted rock (lava) or quartz sand (the main ingredient that is melted to make window glass). Volcanic glass (obsidian) looks and breaks just like window glass, except that it is usually dark colored. But how does it form? When a volcano erupts, and lava is erupted onto Earth's surface, it begins to cool. If the lava is fluid enough (has low viscosity), and stays liquefied long enough, then its elements and molecules will bond together and form mineral crystals. But if the lava is too viscous, and cools too quickly, then mineral crystals do not form and the solid material that remains is volcanic glass.

Grains in Rocks

Most rocks are made of **grains** —mineral crystals or other hard, visible particles. To view the grains in a rock hand sample, start with your own eyes and look closely. If you cannot see or identify the grains, then also try using a hand lens. Most geologists use a 10x hand lens, meaning that objects viewed through the lens appear ten times larger than in real life. Here is a list of the kinds of grains that comprise most rocks. You should look for the following:

- ✓ ***Mineral grains*.** Mineral crystals are the most common kind of grains in rocks. There are thousands of kinds of minerals, but twenty or fewer make up the bulk of most rocks and are known as rock-forming minerals. Whenever possible, try to identify and record what kind(s) of mineral crystals are present in any rock that you analyze. Also try to determine if the mineral crystals are *in situ* or not. **In situ mineral grains** are present in the rock where they originally formed. Examples are the inter-grown mineral crystals in an igneous rock that formed from cooling of lava or magma and inter-grown halite crystals in rock salt that formed in an evaporating sea. The inter-grown mineral crystals lock together to form the rock. Also, *in situ* mineral crystals are usually arranged randomly, and they may be engulfed in glass or a mass of smaller inter-grown crystals. **Detrital mineral grains** are not *in situ* —they are not inter-grown, and do not lock together to form the rock. This is because they were removed from the place or rock where they originally formed and were transported by wind, water, ice, organisms, and/or gravity to a new place. There, they may become or have already become part of another rock. Most detrital mineral grains are clasts (see below), such as quartz pebbles.

- ✓ ***Clasts*****.** Physical weathering is the cracking, crushing, and wearing away of Earth materials. The cracking and crushing causes big rocks, animal shells, and plants to be fragmented into broken pieces called **clasts**. Plant fragments and shells or bones that have been separated or broken are often singled out as **bioclasts**. Broken mineral crystals are **detrital mineral grains** (described above), and broken pieces of rock are called **rock fragments**. Similarly, geologists have names for size classes of clasts (gravel, sand, silt, clay).
- ✓ ***Gravel, sand, silt, and clay*****.** These terms are often used to describe what a rock or other feature is made of. For example, there is sand in a sandbox, and sandstone is made of sand. But the terms are actually names for size classes of clasts (called Wentworth size classes after C.K. Wentworth, who devised the scale in 1922).

  Gravel is a mass of grains that are mostly larger than 2 mm (like aquarium gravel, pebbles, cobbles, and boulders). **Sand** is a mass of grains that are mostly 1/16 to 2 mm in diameter (like sand in a sandbox or making up a sandy beach). **Silt** is finer than sand so much that you can barely see and feel the grains. The grains are generally too small to identify with a hand lens or your unaided eye, so geologists refer to them collectively as silt. **Clay** is even finer than silt. If you ever played with pottery clay, then you know that it can dry on your hands as a light-colored slippery powder. You can tell it is there, but grains are too small to feel or see individually (even with a hand lens). Thus, geologists refer to these microscopic grains collectively as clay.

Part 2.2: Rock Texture

Another very important property of rocks is **texture** —a description of the grains and other parts of a rock and their size, shape, and arrangement. Carefully review the textures below.

- ✓ ***Glassy*** refers to rocks that have no visible grains, and break along wavy, curved glossy surfaces—just like a broken glass bottle. An example is *obsidian*, a dense dark-colored volcanic glass. Another example is anthracite coal (hard coal), which has a glassy texture but is not really glass. It is made of plant fragments and parts that are so small and compacted together, that rock just looks glassy. Coal is also opaque in hand sample and less dense than true glass.

- ✓ ***Fine-grained*** refers to rocks made mostly of grains that are barely visible and too small to identify even when magnified with a hand lend (grains generally < 1 mm in diameter).
- ✓ ***Coarse-grained*** refers to rocks made mostly of grains that are visible and large enough to identify with either a hand lens or your unaided eyes (grains generally > 1 mm in diameter).
- ✓ ***Vesicular*** refers to rocks with round or oval holes, called *vesicles* that resemble the holes in a sponge or Swiss cheese. The holes are bubbles of volcanic gases that bubbled through the lava that cooled to make the rock before the bubbles could escape. Some volcanic rocks have just scattered vesicles, but *pumice* is a rock containing so many vesicles that it floats in water. The vesicles in pumice are tiny glassy bubbles with sharp edges where they break, so pumice is used as an abrasive in polishes and as a cosmetic exfoliant bar to soften skin (pumice stones, Lava™ soap).
- ✓ ***Crystalline*** texture refers to fine- and coarse grained rocks in which the grains are inter-grown mineral crystals that glitter when rotated in bright light. (The light reflects off the flat crystal faces or cleavage surfaces like tiny mirrors.) The crystals may be **hetro-granular** (a mixture of two or more significantly different sizes) or **equi-granular** (all about the same size). The crystals may also be randomly arranged or else *foliated* —a metamorphic texture in which mineral grains have been aligned or layered, causing the rock to break or reflect light in a specific direction like the layered scales on a fish.
- ✓ ***Clastic*** texture means that the rock is mostly made of clasts (fragments; broken pieces) of minerals or other rocks (a rock made mostly of plant fragments or broken or separated bones and shells is called **bioclastic**). The clasts may be **angular** — freshly broken with sharp corners and edges, or **rounded** —having corners and edges worn down from transportation and grain abrasion. Recall that the terms gravel, sand, silt, and clay are also textural terms. **Gravelly** rocks are made mostly of gravel (grains larger than 2 mm; equal to or coarser-grained than aquarium gravel). **Sandy** rocks are mostly made of sand (grains 1/16 to 2

mm in diameter, coarse-grained like sand in a sandbox or a sandy beach). Silty and clayey rocks are fine-grained. The **silty** rocks are mostly made of grains that you can barely see and feel but are too small to identify with a hand lens or your unaided eye. **Clayey** rocks are mostly made of clay, which has grains too small to feel or see (even with a hand lens).

- ✓ ***Layered*** texture. Some rocks have grains arranged in layers that can be observed at more than one scale: over a region, in an outcrop, or in a hand sample. Sedimentary rocks generally have **flat layers** made of either clastic grains (gravel, sand, silt, clay, shells, and plant fragments) or crystals of gypsum, halite, or calcite. Metamorphic rock layers are generally not flat-lying and **foliated** (a metamorphic texture described above in which mineral grains have been aligned or layered, causing the rock to break or reflect light in a specific direction like the layered scales on a fish).

  Metamorphic rock layers may also be **folded,** like you would fold a napkin. If the folds are smooth and unbroken, then the rock must have been soft and ductile (due to high thermal energy) when it was folded. The foliation is due to directed pressure and shearing during metamorphism. Brittle rocks do not fold easily. They tend to fracture (break, form a clastic texture) and move apart along faults.

Part 2.3: Rock Classification

All rocks are classified as igneous, sedimentary, or metamorphic, based on their properties of composition and texture and how they formed. Some properties are characteristic of more than one rock type. For example, igneous, sedimentary, and metamorphic rocks all can be dark, light, or made of mineral particles. Therefore, it is essential to classify a rock based on more than one of its properties.

Igneous Composition and Texture

Recall that igneous rocks form when molten rock (rock liquefied by heat and pressure in the mantle) cools to a solid form (Figure 15). Molten rock exists both below Earth's surface (where it is called *magma*) and at Earth's surface (where it is called *lava*). Igneous rocks can have various textures, including crystalline (hetro-granular), glassy, or vesicular (bubbly). They commonly contain mineral crystals of olivine, pyroxene, or feldspars. Igneous rocks from cooled lava flows may have ropy, streamlined shapes or layers (from repeated flows of lava). Igneous rocks usually lack fossils and organic grains.

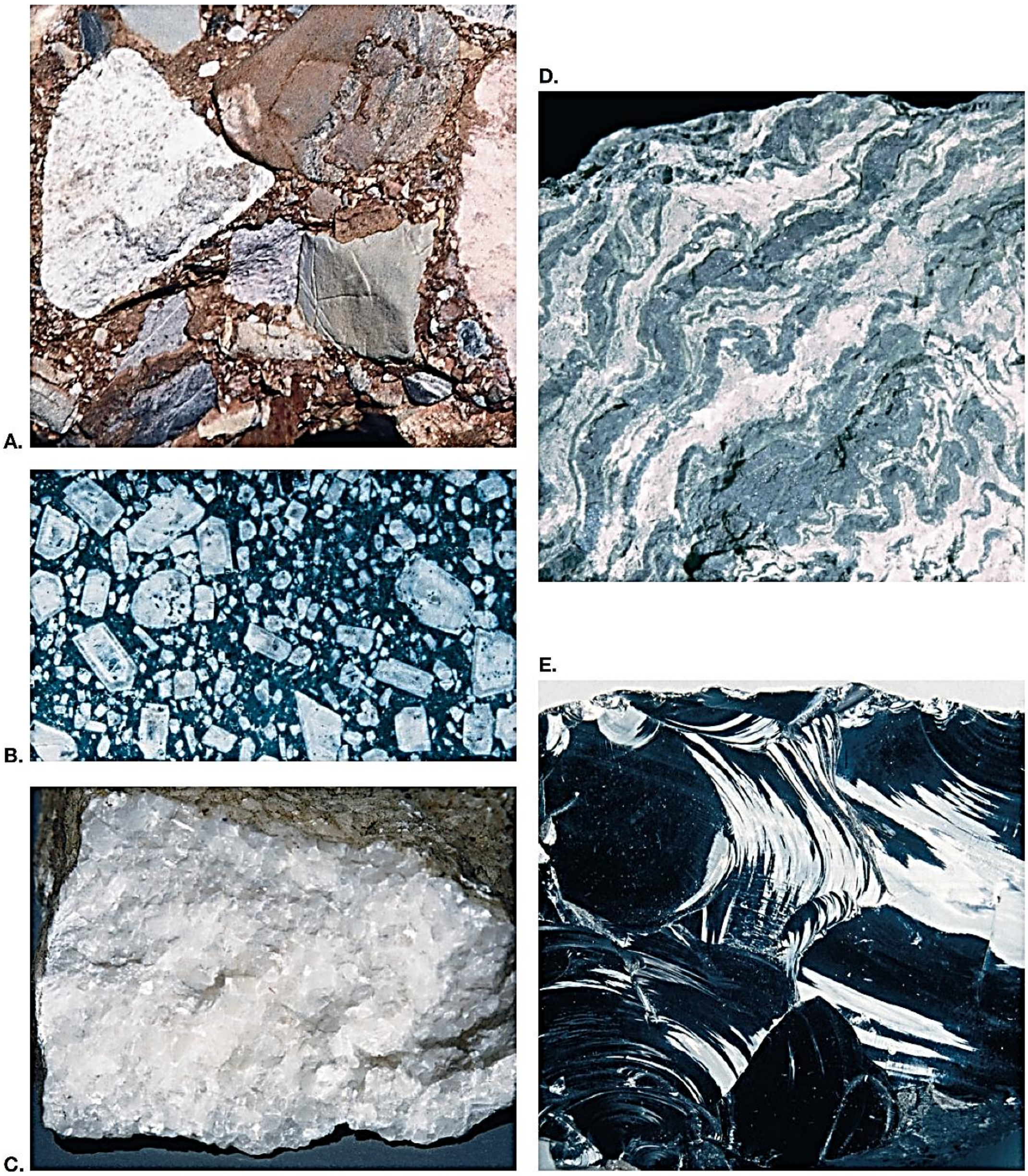


Figure 15

Sedimentary Composition and Texture

Recall that sedimentary rocks form in two ways (Figure 15). **Lithification** is the hardening of sediment—masses of loose Earth materials such as clasts (rock fragments, detrital mineral grains, pebbles, gravel, sand, silt, mud, shells, plant fragments) and products of chemical decay (clay, rust). **Precipitation** produces mineral crystals that collect as *in situ* aggregates, such as the rock salt that remains when ocean water evaporates. The lithification process occurs as layers of sediments are **compacted** (pressure-hardened) or **cemented** (glued together by tiny crystals precipitated from fluids in the pores of sediment).

Thus, most sedimentary rocks are layered and have a **clastic** texture (i.e., are made of grains called *clasts* —fragments of rocks, mineral crystals, shells, and plants—usually rounded into pebbles, gravel, sand, and mud). The sedimentary grains are arranged in layers due to sorting by wind or water. Sedimentary rocks may also include **fossils** —bones, impressions, tracks, or other evidence of ancient life.

The crystalline sedimentary rocks are layered aggregates of crystals precipitated from water. This includes the icicle-shaped stalactites that hang from the roofs of caves. Common minerals of these precipitated sedimentary rocks include calcite, dolomite, gypsum, or halite.

Metamorphic Composition and Textures

Recall that metamorphic rocks are rocks that have been deformed and transformed by intense heat, intense pressure, or the chemical action of hot fluids (Figure 15). Therefore, metamorphic rocks have textures indicating significant deformation (folds, extensive fractures, faults, and foliation). Fossils, if present, also are deformed (stretched or compressed). Metamorphic rocks often contain garnet, tourmaline, or foliated layers of mica. Serpentine, epidote, graphite, galena, and sphalerite occur only in metamorphic rocks. Metamorphism can occur over large regions, or in thin "contact" zones (like burnt crust on a loaf of bread) where the rock was in contact with magma or other hot fluids.

Part 3: Igneous Rocks

3.1. Introduction

Right now, there are more than a hundred volcanoes erupting or threatening to erupt on continents and islands around the world. Some pose direct threats to humans. Others pose indirect threats, such as earthquakes and episodic melting of glaciers. In the oceans, deep under water and far from direct influence on humans, there are likely hundreds more volcanoes. The exact number is unknown, because they are erupting at places on the sea floor that humans rarely see. Most of the world's volcanoes occur along its 260,000 kilometers of linear boundaries between lithospheric plates. The rest are largely associated with hot spots. All of the volcanoes overlie bodies of molten (hot, partly or completely melted) rock called **magma**, which is referred to as **lava** when it reaches Earth's surface at the volcanoes. In addition to their liquid rock portion, or *melt*, magma and lava contain dissolved gases (e.g., water, carbon dioxide, sulfur dioxide) and solid particles. The solid particles may be pieces of rock that have not yet melted and/or mineral crystals that may grow in size or abundance as the magma cools. **Igneous rocks** form when magma or lava cool to a solid state. The bodies of igneous rock may be as large as those in Yosemite Park, where bodies of magma cooled underground to form batholiths of igneous rock, tens of kilometers in diameter. They may be as small as centimeter-thick layers of volcanic ash, which is composed of microscopic fragments of igneous rock (mostly volcanic glass pulverized by an explosive volcanic eruption).

3.2. Mafic and Felsic Rock-Forming Minerals

There are eight silicate minerals that form most igneous rocks. This is because silicon and oxygen are the most common elements in magma and lava. The silicon and oxygen naturally forms silicon-oxygen tetrahedral, in which one silicon atom shares electrons with four oxygen atoms (Figure 16). This creates a silicon-oxygen tetrahedron (four-pointed pyramid) with four electrons too many, so each oxygen atom also shares an electron with another adjacent silicon atom. The simplest ratio of silicon to oxygen is 1:2, written SiO_2 and called **silica.** The mineral quartz is a crystalline form of pure silica. However, with the abundance of other chemicals in magma and lava, silicon-oxygen tetrahedral often bond with other kinds of metal atoms to make the other silicate minerals commonly found in igneous rocks. Although each one has its own unique properties that can be used to identify it, the minerals are also categorized into two chemical groups.

COMPOSITION OF IGNEOUS ROCKS		
Chemical Composition		Physical Composition
Compositional Group Name	Silica % (by weight) in the magma, lava, or rock	**Mafic Color Index (MCI):** Percent of mafic (green, dark gray, and black) mineral crystals in the rock
Felsic (acidic)	above 65%	below 15%
Intermediate	54 – 64%	16 – 45%
Mafic	45 – 53%	46 – 85%
Ultramafic	below 45%	above 85%

Figure 16

Felsic Minerals

The name *felsic* refers to feldspars (*fel*-) and other silica-rich (-*sic*) minerals. The common felsic minerals in igneous rocks are gray translucent *quartz*, light gray opaque *plagioclase feldspar*, pale-orange to pink opaque *potassium feldspar*, and glossy pale-brown to silvery-white *muscovite*. They are all light colored because their chemical composition lacks iron and magnesium.

Mafic Minerals

The name *mafic* refers to minerals with magnesium (*ma* -) and iron (- *fic*) in their chemical formulas, so they are also called *ferromagnesian* minerals. They get their dark color from the abundant proportion of iron and magnesium in their chemical composition. The common mafic minerals in igneous rocks are glossy black *biotite*, dark gray to black *amphibole*, dark green to green-gray *pyroxene*, and olive-green *olivine*.

3.3. Composition of Igneous Rocks

Composition of a rock refers to what it is made of. *Chemical composition* refers to the chemical elements that make up the rock. This determines how the rock will react with materials of different composition, such as whether or not it will react with and decay (tarnish, dissolve, chemically disintegrate) in air or water. It also determines rock color. For example, ferromagnesian-rich rocks (iron and magnesium-rich rocks) generally have a dark color and ferromagnesian-poor rocks generally have a light color. But the chemical elements in a rock are normally bonded together in tangible materials like minerals that, in turn, make up most rocks. So the *physical composition* of rocks is a description of what visible materials they are made of, in whole or part. It is your job as a geologist, using your eyes and simple tools (like a hand magnifying lens), to describe and identify what physical materials igneous rocks are made of.

Chemical Composition—Four Groups

Magmas, lavas, and igneous rocks are composed mostly of the same eight elements that characterize the average composition of Earth's crust. They are oxygen (O), silicon (Si), aluminum (Al), iron (Fe), magnesium (Mg), calcium (Ca), sodium (Na), and potassium (K). All of these elements are cations (positively-charged atoms), except for oxygen (a negatively-charged atom, or anion); oxygen combines with the cations. The most abundant cation is silicon, so silica is the most abundant chemical compound in magmas, lavas, and igneous rocks (Figure 16). Chemical classification of magmas, lavas, and igneous rocks is based on the amount (percentage by weight) of silica they contain, which is used to assign them to one of four chemical **compositional groups**:

1) **Felsic (acidic) Compositional Group**. The name *felsic* refers to feldspars (*fel*-) and other silica-rich (-*sic*) minerals, but it is now also used (in place of "acidic") to describe magmas, lavas, and igneous rocks containing more than 60% silica.
2) **Mafic (basic) Compositional Group.** The name *mafic* refers to minerals with magnesium (*ma*-) and iron (-*fic*) in their chemical formulas (also called *ferromagnesian* minerals), but it is now also used (in place of "basic") to describe magmas, lavas, and igneous rocks containing 45–53% silica.
3) **Ultramafic (ultrabasic) Compositional Group.** As the name implies, this term was originally used to describe igneous rocks made almost entirely of mafic minerals. However, it now also is used (in place of "ultrabasic") to describe magmas, lavas, and igneous rocks containing less than 45% silica.
4) **Intermediate Compositional Group**. This name refers to magmas, lavas, and igneous rocks that contain 54–64 % silica; a composition between mafic and felsic.

Physical Composition

The visible materials that comprise igneous rocks include volcanic glass and **grains** —mineral crystals and other hard discrete particles.

- ✓ **Volcanic glass.** Glass is an amorphous (containing no definite form; not crystalline) solid that forms by cooling viscous molten materials like melted rock (magma, lava) or quartz sand (the main ingredient that is melted to make window glass. Volcanic glass (obsidian) looks and breaks just like window glass, and it is transparent to translucent when held up to a light. It is mostly associated with felsic rocks, because they have a high percentage of silica that can polymerize into glass rather than mineral crystals (Figure 16). It may be tan, gray, black, or red-brown. The black and red-brown varieties get their dark color from the oxidation of minute amounts of iron in the lavas from which they cooled. It takes just a tiny amount of magnetite or hematite to darken the glass.
- ✓ **Mineral grains (crystals).** Most igneous rocks, even pieces of volcanic glass, contain some proportion of mineral crystals—either mafic (dark-colored ferromagnesian minerals) or felsic (light-colored silica-rich minerals). If you have not read Mafic and Felsic Rock-Forming Minerals on page 130, then you should do so now.
- ✓ **Pyroclasts (tephra).** *Pyroclasts* (from Greek meaning "fire broken") are rocky materials that have been fragmented and/or ejected by explosive volcanic eruptions (Figure 17). They include *volcanic ash* fragments (pyroclasts < 2 mm), *lapilli* or *cinders* (pyroclasts 2–64 mm), and *volcanic bombs* or *blocks* (pyroclasts > 64 mm). A mass of pyroclastic debris is called *tephra*.
- ✓ **Xenoliths.** Magma is physically contained within the walls of bedrock (crust, mantle) through which it moves. Fragments of the wall rock occasionally break free and become incorporated into the magma. When the magma cools, the fragments of wall rock are contained within the younger igneous rock as xenoliths.

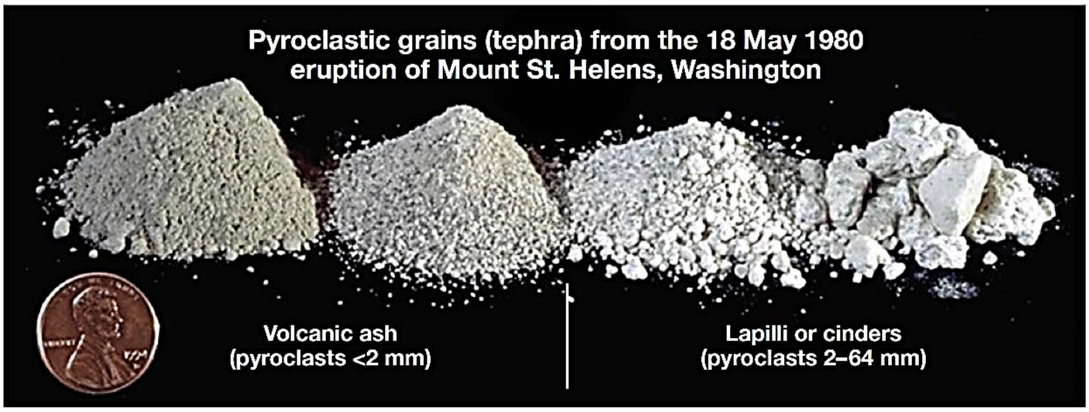


Figure 17

3.4. Textures of Igneous Rocks

Texture of an igneous rock is a description of its constituent parts and their sizes, shapes, and arrangement. You must be able to identify the common textures of igneous rocks described below and understand how they form. Notice the list of textures and their origins in Figure 18. Igneous rocks are also classified into *two textural groups*: intrusive (plutonic) versus extrusive (volcanic).

Intrusive (plutonic) rocks form deep underground, where they are well insulated (take a long time to cool) and pressurized. The pressure prevents gases from expanding, just like carbonation in a sealed soft drink. The cap seals in the pressure—an intrusive process. If you remove the cap, then the carbon dioxide inside the bottle expands and bubbles— an extrusive process. Therefore, **extrusive (volcanic) rocks** form near and on Earth's surface, where the confining pressure is low and gases begin to bubble out of the magma. Cooler surface temperatures also rob thermal energy from magma, so it cools quickly. The size of mineral crystals in an igneous rock generally indicates the rate at which the lava or magma cooled to form a rock and the availability of the chemicals required to form the crystals. Large crystals require a long time to grow, so their presence generally means that a body of molten rock cooled slowly (an intrusive process) and contained ample atoms of the chemicals required to form the crystals. Tiny crystals generally indicate that the magma cooled more rapidly (an extrusive process).

Volcanic glass (no crystals) can indicate that a magma was quenched (cooled immediately), but most volcanic glass is the result of poor nucleation as described below.

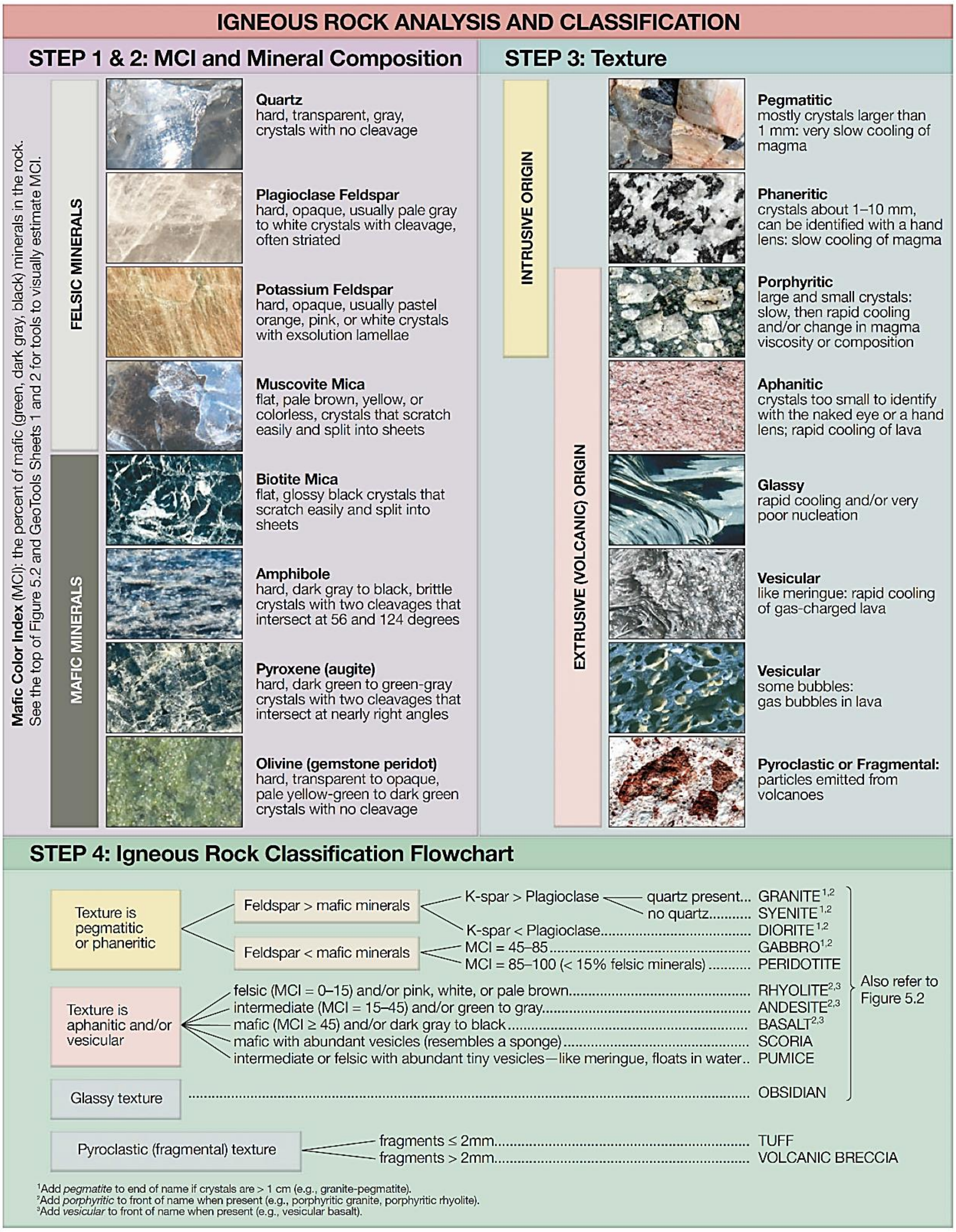


Figure 18

Nucleation and Rock Texture

The crystallization process depends on the ability of atoms in lava or magma to *nucleate*. *Nucleation* is the initial formation of a microscopic crystal, to which other atoms progressively bond. This is how a crystal grows. Atoms are mobile in a fluid magma, so they are free to nucleate. If such a fluid magma cools slowly, then crystals have time to grow—sometimes to many centimeters in length. However, if a magma is very viscous (thick and resistant to flow), then atoms cannot easily move to nucleation sites. Crystals may not form even by slow cooling. Rapid cooling of very viscous magma (with poor nucleation) can produce igneous rocks with a **glassy texture** (see Figure 18), which indicates an extrusive (volcanic) origin.

Textures Based on Crystal Size

Several common terms are used to describe igneous rock texture on the basis of crystal size (Figure 18). Igneous rocks made of crystals that are too small to identify with the naked eye or a hand lens (generally <1 mm) have a very fine-grained **aphanitic texture** (from the Greek word for *invisible*). Those made of visible crystals that can be identified with a hand lens or unaided eye are said to have a **phaneritic texture** (coarse-grained; crystals 1–10 mm) or **pegmatitic texture** (very coarse-grained; >1 cm). Some igneous rocks have two distinct sizes of crystals. This is called **porphyritic texture**. The large crystals are called *phenocrysts*, and the smaller, more numerous crystals that surround them form the *groundmass*, or *matrix*. Porphyritic textures may generally indicate that a body of magma cooled slowly at first (to form the large crystals) and more rapidly later (to form the small crystals). However, recall from above that crystal size can also be influenced by changes in magma composition or viscosity.

Combinations of igneous-rock textures also occur. For example, a *porphyritic-aphanitic* texture signifies that phenocrysts occur within an aphanitic matrix. A *porphyritic-phaneritic* texture signifies that phenocrysts occur within a phaneritic matrix.

Vesicular and Pyroclastic Textures

When gas bubbles get trapped in cooling lava they are called *vesicles,* and the rock is said to have a **vesicular texture**. Scoria is a textural name for a rock having so many vesicles that it resembles a sponge. Pumice has a glassy texture and so many tiny vesicles (like frothy meringue one pie) that it floats in water. Recall that *pyroclasts* (from Greek meaning *fire broken*) are rocky materials that have been fragmented and/or ejected by explosive volcanic eruptions (see Figure 17). They include *volcanic ash* fragments (pyroclasts < 2 mm), *lapilli* or *cinders* (pyroclasts2–64 mm), and *volcanic bombs* or *blocks* (pyroclasts >64 mm). Igneous rocks composed mostly of pyroclasts have a **pyroclastic texture** (see Figure 18).

3.5. How to Identify Igneous Rocks

The identification and interpretation of an igneous rock is based on its composition and texture. ***Follow these steps to classify and identify an igneous rock:***

Steps 1 and 2: Identify the rock's mafic color index (MCI).Then, if possible, identify the minerals that make up the rock and estimate the percentage of each.

- ✓ If the rock is very fine-grained (aphanitic or porphyritic-aphanitic), then you must estimate mineralogy based on the rock's mafic color index. *Felsic* fine-grained rocks tend to be pink, white, or pale gray/brown. *Intermediate* fine-grained rocks tend to be greenish gray to medium gray. *Mafic* and *ultramafic* fine-grained rocks tend to be green, dark gray, or black.
- ✓ If the rock is coarse-grained (phaneritic or pegmatitic), then estimate the mafic color index (MCI) and percentage abundance of each of the specific felsic and mafic minerals. With this information, you can also characterize the rock as felsic, intermediate, mafic, or ultramafic.

Step 3: Identify the rock's texture(s) using Figure 18.

Step 4: Determine the name of the rock using the flowchart in Figure 18.

- ✓ Use textural terms, such as porphyritic or vesicular, as adjectives. For example, you might identify a pink, aphanitic (fine-grained), igneous rock as a rhyolite. If it contains scattered phenocrysts, then you would call it a *porphyritic rhyolite*. Similarly, you should call a basalt with vesicles a *vesicular basalt.*
- ✓ The textural information can also be used to infer the origin of a rock. For example, vesicles (vesicular textures) imply that the rock formed by cooling of a gas-rich lava (vesicular and aphanitic). Pyroclastic texture implies violent volcanic eruption. Aphanitic texture implies more rapid cooling than phaneritic texture.

3.6. Intrusion, Eruption, and Volcanic Landforms

Magma is under great pressure (like a bottled soft drink that has been shaken) and is less dense than the rocks that confine it. Like the blobs of heated "lava" in a lava lamp, the magma tends to rise and squeeze into Earth's cooler crust along any fractures or zones of weakness that it encounters. A body of magma that pushes its way through Earth's crust is called an **intrusion,** and it will eventually cool to form a body of igneous rock. Intrusions have different sizes and shapes. *Batholiths* (Figure 19) are massive intrusions (often covering regions of 100 km^2 or more in map view) that have no visible bottom. They form when small bodies of lava amalgamate (mix together) into one large body. To observe one model of this amalgamation process, watch the blobs of "lava" in alighted lava lamp as they rise and merge into one large body (batholith) at the top of the lamp. Smaller intrusions (see Figure 19) include *sills* (sheet-like intrusions that force their way between layers of bedrock), *laccoliths* (blister-like sills), *pipes* (vertical tubes or pipe-like intrusions that feed volcanoes), and *dikes* (sheet-like intrusions that cut across layers of bedrock). The dikes can occur as *sheet dikes* (nearly planar dikes that often occur in parallel pairs or groups), *ring dikes* (curved dikes that form circular patterns when viewed from above; they typically form under volcanoes), or *radial dikes* (dikes that develop from the pipe feeding a volcano; when viewed from above, they radiate away from the pipe).When magma is extruded onto Earth's surface it is called **lava**. The lava may erupt gradually and cause a blister-like *lava dome* to form in the neck of a volcano or a *lava flow* to run from a volcano. The lava may also erupt explosively to form *pyroclastic deposits* (accumulations of rocky materials that have been fragmented and ejected by explosive volcanic eruptions).All of these extrusive (volcanic) igneous processes present geologic hazards that place humans at risk. When you examine an unopened pressurized bottle of soft drink, no bubbles are present. But when you open the bottle (and hear a "swish" sound), you are releasing the pressure that was containing the drink and allowing bubbles of carbon dioxide gas to escape from the liquid. Recall that magma behaves similarly. When its pressure is released near Earth's surface, its dissolved gases expand and make bubbly lava that may erupt from a volcano. In fact, early stages of volcanic eruptions are eruptions of steam and other gases separated from magma just beneath Earth's surface. If the hot, bubbly lava cannot escape normally from the volcano, then the volcano may explode (like the top blowing off of a champagne bottle).

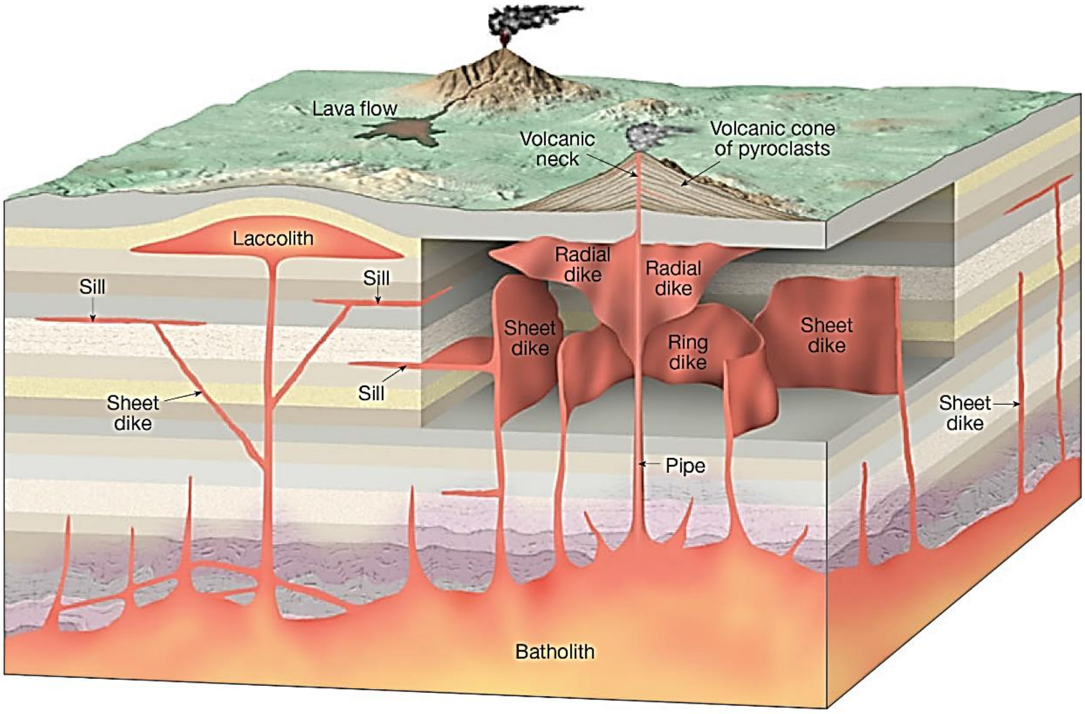


Figure 19

Part 4: Sedimentary Rocks

4.1. Introduction

Sedimentary rocks form when sediments are compressed, cemented, or otherwise hardened together. Some sedimentary rocks form by a process similar to mud hardening in the Sun to form *adobe.* Others form when masses of intergrown mineral crystals precipitate from aqueous (water-based) solutions and lock together to form crystalline rock, like rock salt that remains when ocean water is evaporated. **Sediments** are loose grains and chemical residues of Earth materials, including rock fragments, mineral grains, parts of plants or animals like seashells and twigs, and chemical residues like rust (hydrated iron oxide residue). Grains of sediment are affected by chemical and physical weathering processes until they are buried in a sedimentary deposit or else disintegrate to invisible atoms and molecules dissolved in water(aqueous solutions), like groundwater (water beneath Earth's surface), lakes, streams, and the ocean. The salty taste of ocean water or salty lake water (e.g., Great Salt Lake or the Dead Sea) is a clue that many Earth materials are dissolved into it, but even fresh water has some materials dissolved in it (just not as many). Only distilled water has no materials dissolved in it.

4.2. Sedimentary Processes

Sedimentary processes (Figure 20) include everything from the time and place that sediment forms to the time and place where it is *lithified* (hardened into sedimentary rock).

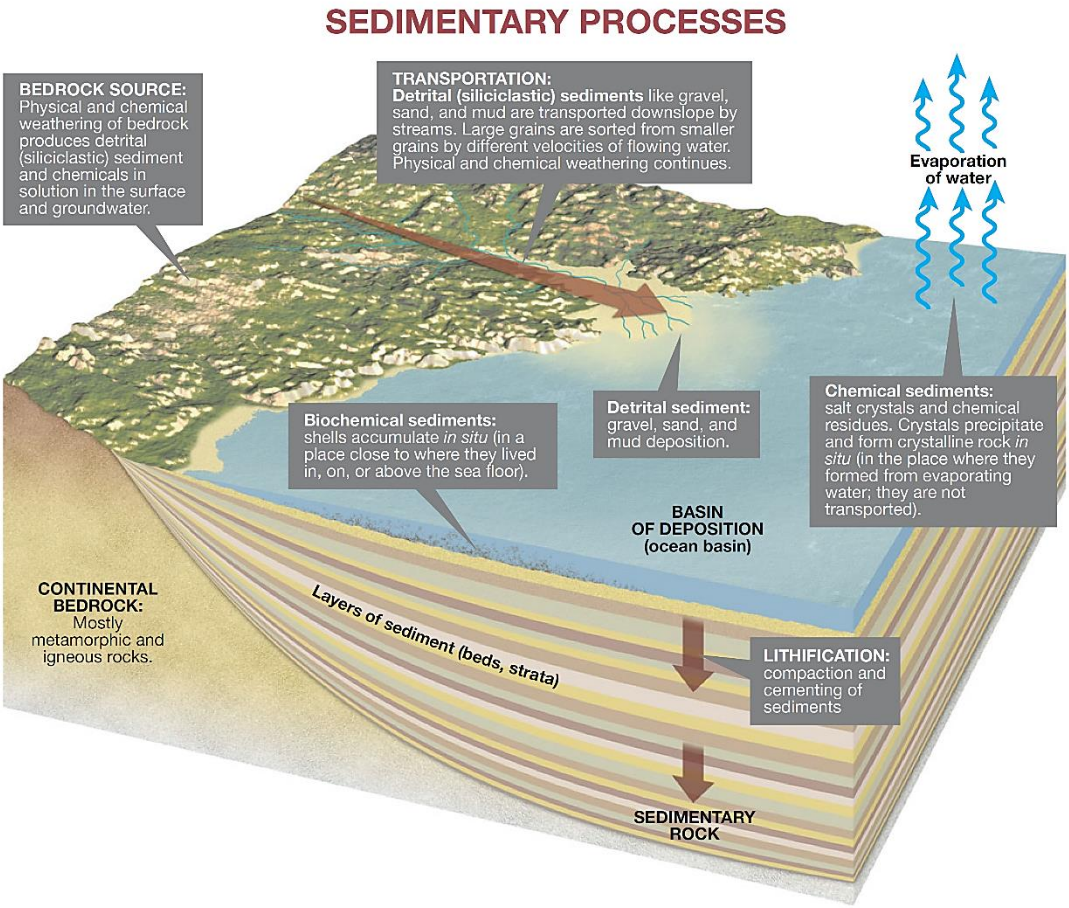


Figure 20

Formation of Chemical Sediment

Water is a *solvent* (a liquid capable of dissolving and dispersing solid materials), so all natural bodies of water are aqueous solutions. This means that they are filled with chemicals that are “in solution,” dissolved and dispersed from the materials over and through which the water has flowed. When water full of dissolved chemicals (an aqueous solution) evaporates, the chemicals in the water combine and precipitate (form solids from the solution) as mineral crystals and chemical residues called **chemical sediment.** Chemical sediment is generally *in situ*, meaning that it formed where it is found. For example, think of the intergrown halite crystals in rock salt that formed in an evaporating sea. The crystals are intergrown and locked together as sedimentary rock as they form. Oxide residues, like rust, are often deposited *in situ* (in place, where the rust formed) as coatings on surfaces of rocks, but they can also form as powdery residues in the water and be carried by the water to new locations. Chemical sediment is the end product of *chemical weathering* —the decomposition or dissolution of Earth materials. For example, feldspars are a group of the most common minerals in Earth's crust. When potassium feldspar decomposes in acidic ground water, it chemically decays to clay minerals (kaolinite) plus chemicals (potassium and silica) in solution. This is the main way that clay forms to make soil. Olivine decomposes to iron and magnesium in solution, and then they combine with oxygen to make oxide residues, like rust. Chemical residues commonly coat the surfaces of visible grains of sediment and either discolor them or serve as a cement to "glue" them together and form sedimentary rock.

Formation of Clastic (Detrital) and Biochemical Sediment

Physical (mechanical) weathering is the cracking, crushing, and wearing away (scratching, abrasion, transportation) of Earth materials. Cracking and crushing processes cause big rocks to be fragmented into *clasts* or *clastic sediment*, including *rock fragments* and *mineral grains* (whole crystals or fragments of crystals). Continental bedrock, rich in silicate minerals, is fragmented into **siliciclastic sediment** made of quartz grains, feldspar grains, and rock fragments. Sediment worn and transported from the land, generally siliciclastic, is also called **detrital sediment.** Rock fragments and mineral crystals broken and transported away from bedrock surfaces (cliffs, valley walls, and other outcrops) are detrital grains comprising detrital sediment. Detrital sediment is not *in situ*; it is transported away from its source. Plants and animals are fragmented into bioclastic **biochemical sediment** made of things like shells, fragmented shells, twigs, and leaves. This kind of sediment is easily broken, worn, and chemically decayed, so it is generally *in situ.* If you find a **fossil** (any evidence of ancient life), then the organism probably lived where it was fossilized.

Erosion, Transportation, and Deposition of Sediment

The place where sediment originates or forms is call edits *source.* Although most biochemical and chemical sediment remains close to where it formed (is *in situ),* detrital sediment is **eroded** (loosened, removed) from its *source* and **transported** (moved, carried) over great distances. Agents of erosion and transportation include wind, water, ice, organisms, and gravity. For example, gravity forces water to flow downhill, and water is a physical agent that picks up and carries sediment. Eventually, the water flows into a *basin* (depression where water and sediment accumulate), becomes part of a lake or ocean, and sediment deposition occurs. **Deposition** is what happens when transportation stops and sediment accumulates by settling out of the water (or air or melting ice) that carried it. (In contrast, chemical and biochemical sediment is usually not transported, so it is deposited *in situ* —where it forms.)

Layering of Sediment

The result of deposition is a **deposit** of sediment. So erosion, transportation, and deposition are a sequence of related events. The events are also episodic (happen infrequently, not continuously). Erosion happens when it rains, transportation happens when it floods, and deposition happens when flood waters accumulate in a lake or ocean and stop moving (and sediment settles out or precipitates out of the water). The net result is, therefore, a layered deposit. Each time a new episode of flood water washes into the lake or ocean, a new layer of sediment is deposited on top of the last (older) one. In between the depositional events, there is *no deposition* (a time during which no deposition occurs). The times of no deposition become surfaces, called **bedding planes,** between the layers of sediment (called **beds, bedding,** or **strata)**.

Lithification of Sediment

Lithification is the process of changing loose particles of sediment (unconsolidated sediment) to solid rock (consolidated sediment). This happens most often when sediment is *compacted* (squeezed together) or *cemented* (glued together by tiny crystals or chemical residues).

4.3. Composition and Textures of Sediments and Sedimentary Rocks

Sediment and sedimentary rocks are described, classified, named, and interpreted on the basis of their composition and textures.

Composition of Sediment and Sedimentary Rocks

The **composition** of a sediment or sedimentary rock is a description of the kinds and abundances of grains that compose it (Figure 21).

Figure 21

Sediments and sedimentary rocks are classified as biochemical (bioclastic), chemical, or detrital (siliciclastic) based on their composition. **Biochemical** sediments and rocks consist of whole and broken **(bioclastic)** parts of organisms, such as shells and plant fragments. **Chemical** sediments and rocks consist of chemical residues and intergrown mineral crystals precipitated from aqueous solutions. The precipitated minerals commonly include gypsum, halite, hematite, limonite, calcite, dolomite, and chert (microcrystalline variety of quartz). **Detrital** sediments and rocks consist of **siliciclastic** grains (rock fragments, quartz, feldspar, clay minerals) that are also *detrital* grains—rock fragments and mineral grains that were worn and transported away from the landscape.

Textures of Sediment and Sedimentary Rocks

Processes of weathering, transportation, precipitation, and deposition that contribute to the formation of a sediment or sedimentary rock also contribute to forming its texture. The **texture** of a sediment or sedimentary rock is a description of its parts and their sizes, shapes, and arrangement (Figure 22). **Grain Size.** The particles that make up sedimentary rocks are called **grains.** Size of the grains is commonly expressed in these *Wentworth classes*, named after C. K. Wentworth, an American geologist who devised the scale in 1922:

1) **Gravel** includes grains larger than 2 mm in diameter (granules, pebbles, cobbles, and boulders).
2) **Sand** includes grains from 1/16 mm to 2 mm in diameter (in decimal form, 0.0625 mm to 2.000 mm).This is the size range of grains in a sandbox. The grains are visible and feel very gritty when rubbed between your fingers.
3) **Silt** includes grains from 1/256 mm to 1/16 mm in diameter (in decimal form, 0.0039 mm to 0.0625 mm). Grains of silt are usually too small to see, but you can still feel them as very tiny gritty grains when you rub them between your fingers or teeth.
4) **Clay** includes grains less than 1/256 mm diameter (in decimal form, 0.0039 mm). Clay-sized grains are too small to see, and they feel smooth (like chalk dust) when rubbed between your fingers or teeth. Note that the word *clay* is used not only to denote a grain size, but also a clay mineral. However, clay mineral crystals are usually clay-sized.

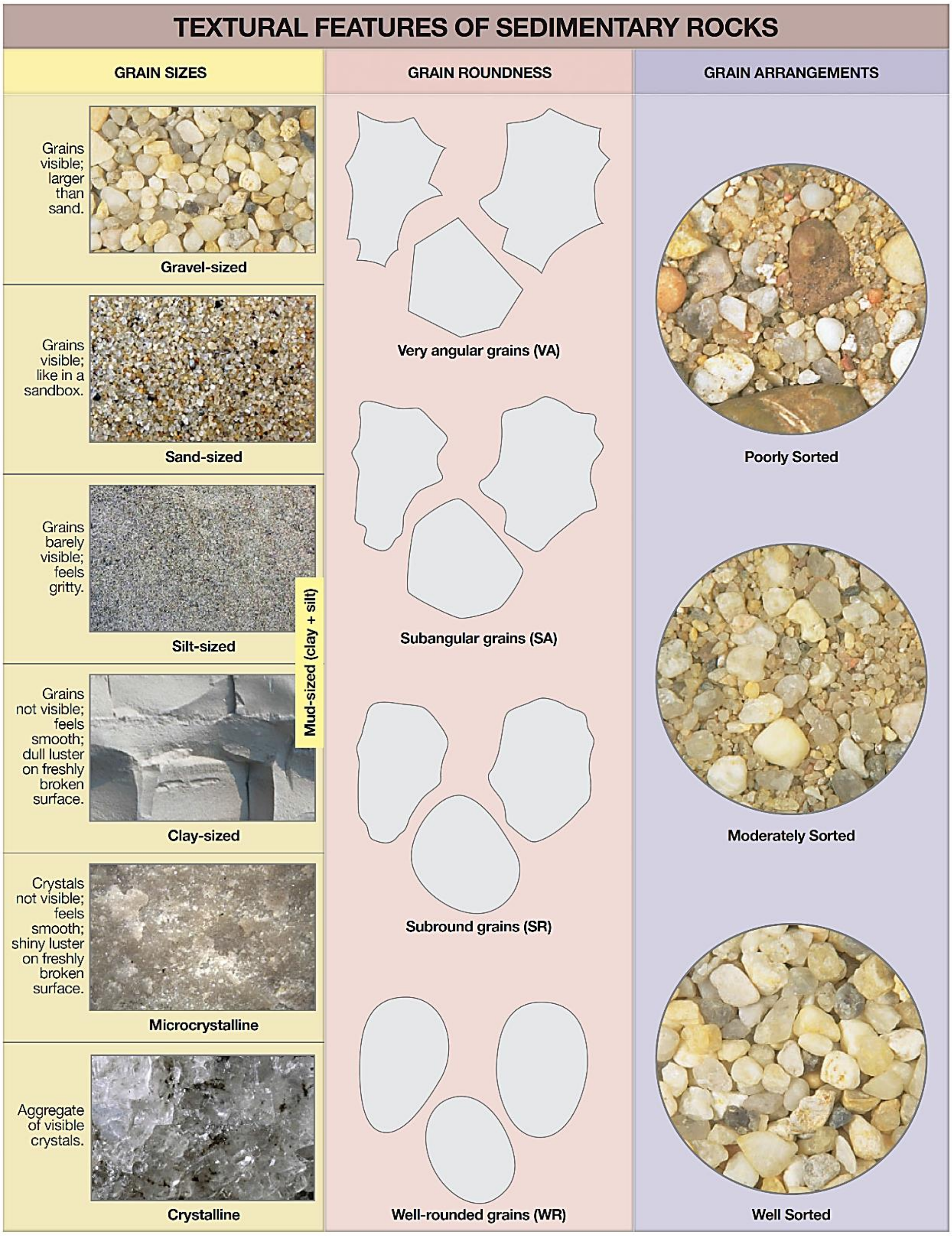


Figure 22

Rounding of Sediment. All sediment has a *source* (place of origin; Figure 21). Sediments deposited quickly at or near their source tend to lack abrasion. Sediments that have been moved about locally (as in waves on a beach) or transported away from their source are abraded (worn). **Roundness** is a description of the degree to which the sharp corners and points of a fragmented grain have been worn away and its profile has become round (Figure 22). A newly formed clast is *very angular*. As itis transported and worn it will become *sub-angular,* then *sub-round,* and then *well rounded.* A freshly broken rock fragment, mineral grain, or seashell has sharp edges and is described as *angular*. The more rounded a grain becomes, the smaller it generally becomes. Gravel gets broken and abraded down into sand, and sand gets broken and abraded into silt and clay-sized grains. When combined, the silt plus clay mixture is called *mud.*

Sorting of Sediment. Different velocities of wind and water currents are capable of transporting and naturally separating different densities and sizes of sediments from one another. **Sorting** is a description of the degree to which one size class of sediment has been separated from the others (Figure 22). *Poorly sorted* sediments consist of a mixture of many different sizes of grains. *Well-sorted* sediments consist of grains that are of similar size and/or density.

Crystalline and Microcrystalline Textures. Sedimentary rocks that form when crystals precipitate from aqueous solutions have a **crystalline texture** (clearly visible crystals; see Figure 22) or **microcrystalline texture** (crystals too small to identify). As the crystals grow, they interfere with each other and form intergrown and interlocking texture that also holds the rock together.

4.4. Formation of Sedimentary Rocks

Lithification is the process of changing loose particles of sediment (unconsolidated sediment) to solid rock (consolidated sediment). Sediment is loose particles such as pebbles, gravel, sand, silt, mud, shells, plant fragments, and mineral crystals. Sediment is lithified when it is **compacted** (pressure-hardened, squeezed: Figure 23) or **cemented** together (glued together by tiny crystals or chemical residues, Figure 23). However, it is also possible to form a dense hard mass of intergrown crystals that lock together directly, as they precipitate from water. Sand (a sediment) can be *compacted* until it is pressure-hardened into sandstone (a sedimentary rock). Alternatively, sandstone can form when sand grains are *cemented* together by chemical residues or the growth of interlocking microscopic crystals in pore spaces of the rock (void spaces among the grains). Rock salt and rock gypsum are examples of sedimentary rocks that form *in situ* by the *precipitation* of aggregates of intergrown and interlocking crystals during the evaporation of saltwater or brine. Ocean water is the most common aqueous solution and variety of salt water on Earth. As it evaporates, a variety of minerals precipitate in a particular sequence. The first mineral to form in this sequence is aragonite (calcium carbonate). Gypsum forms when about50–75% of the ocean water has evaporated, and halite (table salt) forms when 90% has evaporated. Ancient rock salt units buried under modern Lake Erie probably formed from evaporation of an ancient ocean. The salt units were then buried under layers of mud and sand, long before Lake Erie formed on top of them.

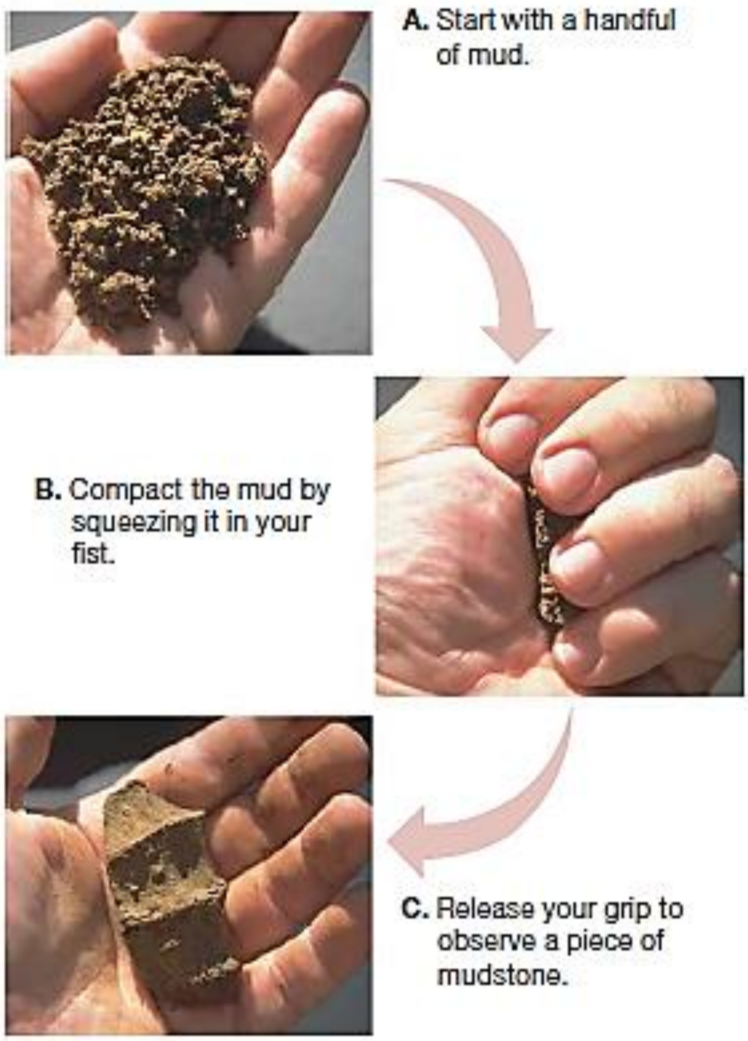


Figure 23

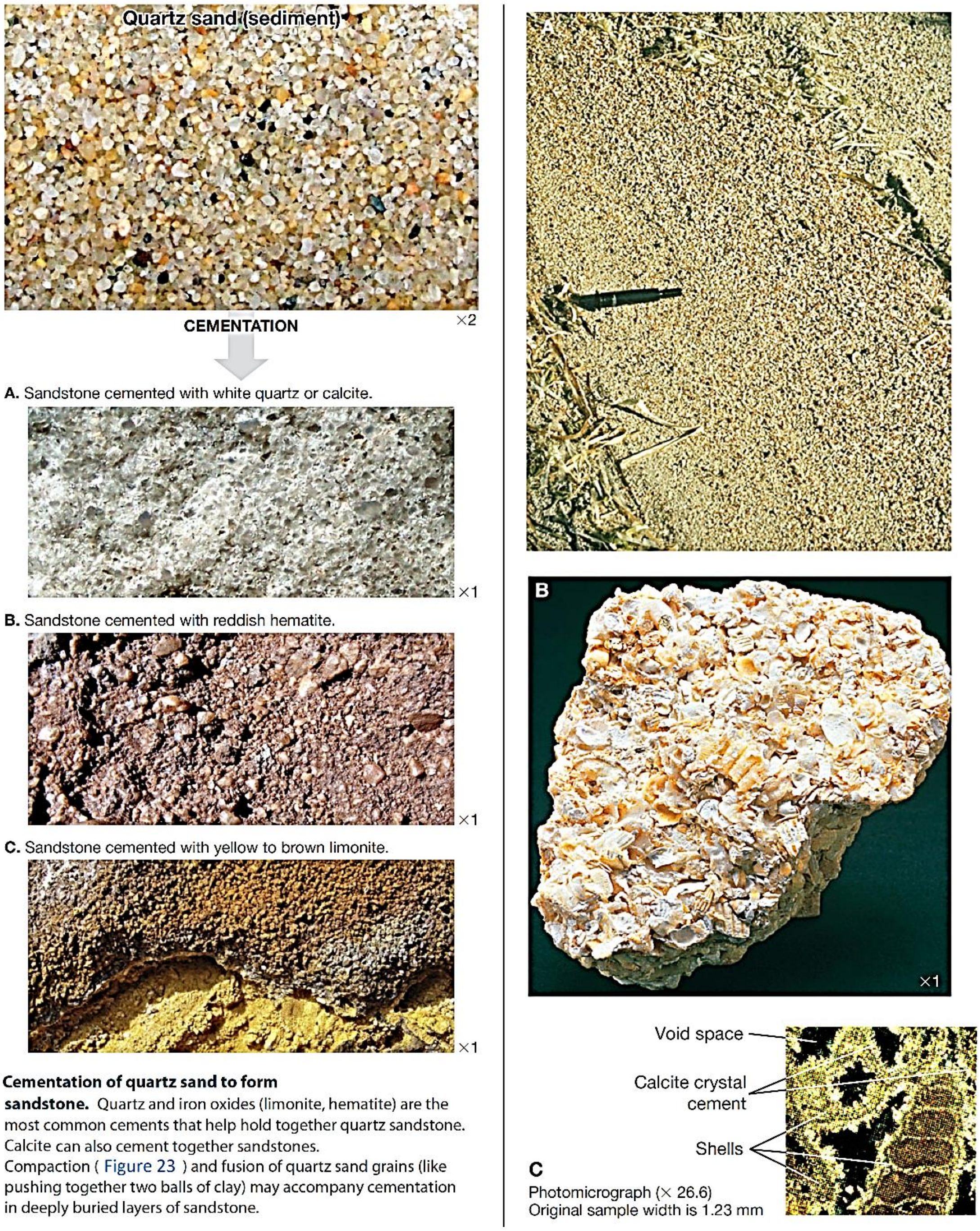


Figure 24

4.5. Classifying Sedimentary Rocks

Geologists classify sedimentary rocks into three main groups (Figure 25): biochemical, chemical (inorganic), and detrital (siliciclastic).

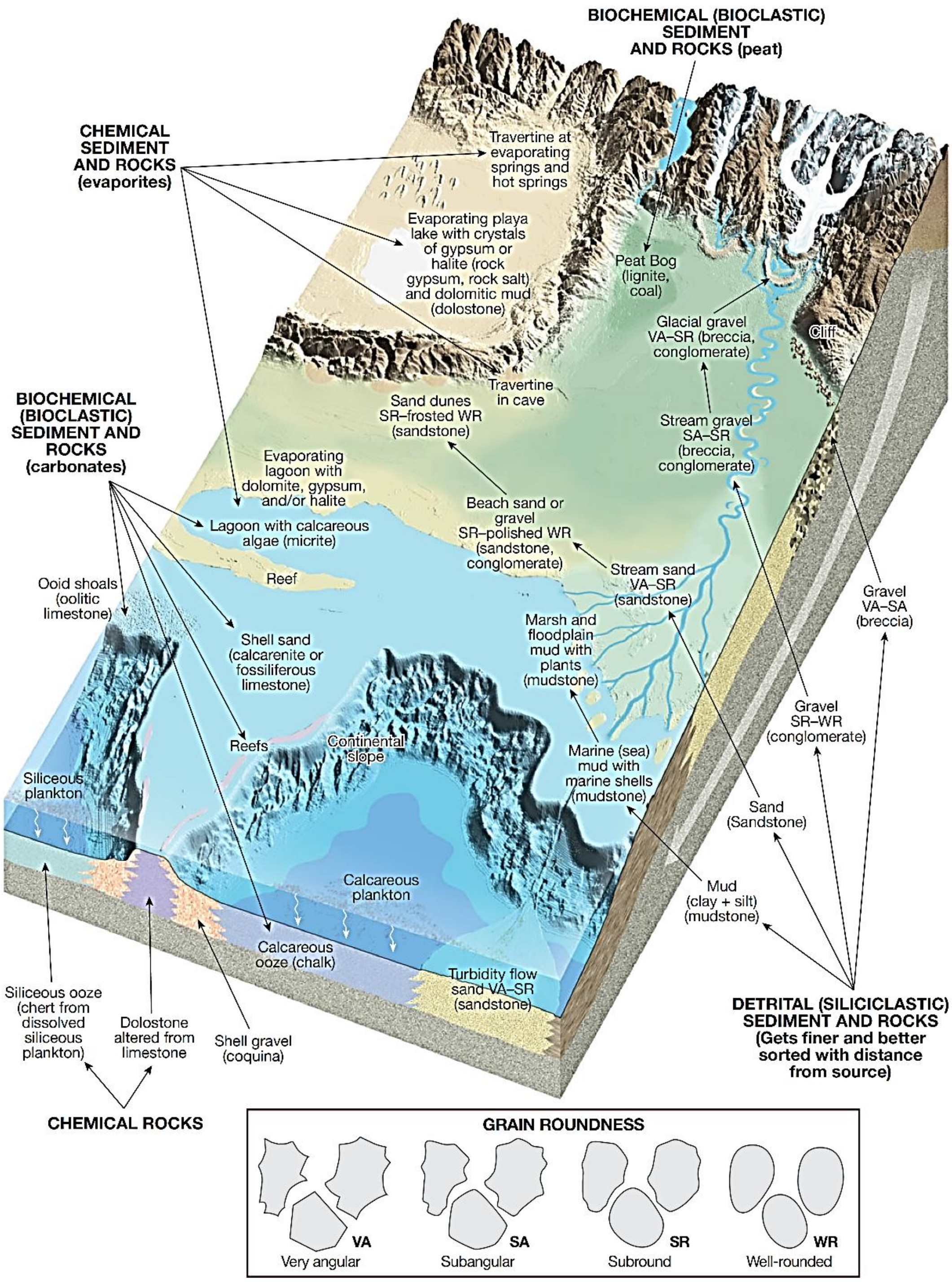


Figure 25

Biochemical Rocks

The main kinds of biochemical (bioclastic) sedimentary rocks are limestone, peat, lignite, and coal. Biochemical limestone is made of broken and whole animal skeletons (usually seashells, coral, or microscopic shells), as in Figure 24. Differences in the density and size of the constituent grains of a biochemical (bioclastic) limestone can also be used to call it a **coquina, calcarenite (fossiliferous limestone), micrite,** or **chalk**. **Peat** is a very porous brown rock with visible plant fragments that can easily be pulled apart from the rock. **Lignite** is brown but denser than peat. Its plant fragments cannot be pulled apart from the rock. **Bituminous coal** is a black rock made of sooty charcoal-like or else shiny brittle layers of carbon and plant fragments.

Chemical Rocks

There are seven main kinds of chemical (inorganic) sedimentary rocks in the classification. **Chemical limestone** refers to any mass of crystalline limestone that has no color banding or visible internal structures. **Travertine** is a mass of intergrown calcite crystals that may have light and dark color banding, cavities, or pores. **Oolitic limestone** is composed mostly of tiny spherical grains (ooids, Figure 21) that resemble beads or miniature pearl sand are made of concentric layers of microcrystalline aragonite or calcite. They form in intertidal zones of some marine regions (see Figure 25) where the water is warm and detrital sediment is lacking. **Dolostone** is an aggregate of dolomite mineral crystals that are usually microcrystalline. It forms in very salty lagoons and desert playa lakes (see Figure 25). Because calcite and dolomite closely resemble one another, the best way to tell them apart is with the “acid test”. Calcite will effervesce (fizz) in dilute HCl, but dolomite will effervesce *only* if it is powdered first. **Rock gypsum** is an aggregate of gypsum crystals, and **rock salt** is an aggregate of halite crystals. Two other chemical sedimentary rocks are **chert** (microcrystalline or even cryptocrystalline quartz) and **ironstone** (rock made mostly of hematite, limonite, or other iron-bearing minerals or chemical residues).

Detrital Rocks

The main kinds of detrital (siliciclastic) sedimentary rocks are mudstone, sandstone, breccia, and conglomerate. It is very difficult to tell the percentage of clay or silt in a sedimentary rock with the naked eye, so sedimentary rocks made of clay and/or silt are commonly called **mudstone.** Mudstone that is *fissile* (splits apart easily into layers) can be called **shale.** Mudstone can also be called siltstone or claystone, depending upon whether silt or clay is the most abundant grain size. Any detrital rock composed mostly of sand-sized grains is simply called **sandstone**; although you can distinguish among *quartz sandstone* (made mostly of quartz grains), *arkose* (made mostly of feldspar grains), *lithic sandstone* (made mostly of rock fragments), or *wacke* (made of a mixture of sand-sized and mud-sized grains). **Breccia** and **conglomerate** are both made of gravel-sized grains and are often poorly sorted or moderately sorted. The grains in breccia are very angular and/or sub angular, and the grains in conglomerate are sub-rounded and/or well rounded.

4.6. Hand Sample Analysis and Interpretation

The complete classification of a sedimentary rock requires knowledge of its composition, texture(s), and other distinctive properties. The same information can be used to infer where and how it formed (see Figure 25). ***Follow these steps to analyze and interpret a sedimentary rock:*** **Step 1:** Determine and record the rock's general composition as *biochemical (bioclastic)*, *chemical*, or *detrital (siliciclastic)* with reference to Figure 21 and Figure 24, and record a description of the specific kinds and abundances of grains that make up the rock. Refer to the categories for composition in the left-hand column of Figure 24. **Step 2:** Record a description of the rock's texture(s) with reference to Figure 22. Also record any other of the rock's distinctive properties as categorized in the center columns of Figure 24. **Step 3:** Determine the name of the sedimentary rock by categorizing the rock from left to right across Figure 24. Use the compositional, textural, and special properties data from Steps 1 and 2 (left side of Figure 24) to deduce the rock name (right side of Figure 24). **Step 4:** After you have named the rock, then you can use Figure 25 and information from Steps 1and 2 to infer where and how the rock formed. See the example for sample X.

4.7. Ancient Environments and Ecosystems

Sediments are deposited in many different environments. Some of these environments are illustrated in Figure 25. Each environment has characteristic sediments, sedimentary structures, and organisms that can become **fossils** (any evidence of prehistoric life). The information gained from grain characteristics, sedimentary structures, and fossils in rocks can be used to infer the ancient environment (**paleo environment)** in which they formed. The process of understanding where and how a body of sediment was deposited depends on the *Principle of Uniformitarianism* —the assumption that processes that shaped Earth and its environments in the past are the same as processes operating today. This principle is often stated as, “the present is the key to the past.” You can think of processes operating in modern ecosystems and then imagine how those same processes may have operated in past ecosystems with different organisms. You can also look at sediment, sedimentary structures, and fossils in a sedimentary rock and infer how it formed on the basis of where such sediment, sedimentary structures, and organisms are found together today.

4.8. Indicators of Ancient Environments

Think of a goldfish. Chances are that your brain put the goldfish into context, and you imagined it in a bowl of water. Now if you saw a goldfish bowl on your neighbor’s kitchen table, you would probably think that the neighbor is getting a goldfish. Whether you think of the goldfish or the bowl, you cannot help but imagine the goldfish in a bowl of water—a gold fish ecosystem. The same process is used to analyze sedimentary rocks and infer how and where they may have formed. If the rock has a fossil of a freshwater fish, then the sediment must have accumulated under water, in a stream or lake. If the rock is made of rounded gravel with pieces of tree bark, then the sediment in the rock must have accumulated in an ecosystem where there were both trees and rounded gravel—like the edge of a river. Fossils and sedimentary structures are good indicators of the paleo environments. It is up to you, the geologist, to place the structures and fossils into context, and infer an environment or ecosystem in which they could have formed together.

Fossils

Fossils are any evidence of ancient life. **Body fossils** are fossils or the body parts of organisms. Soft body parts of organisms (skin, leaves of trees) decay easily, so they are rarely fossilized. Hard body parts like shells and bones are much easier to fossilize. **Trace fossils** are any evidence of the activities of organisms, such as their foot print sand burrows or other structures that they made when living. Both kinds of fossils are useful as clues about the ancient environment of deposition. Trace fossils cannot be transported, so they are *in situ* (formed where they are found). Body fossils, even those of hard shells, are worn away quickly if transported, so they are generally *in situ* as well.

Sedimentary Structures

Sedimentary structures are things like layers of sediment and fossil burrows in the layers. They are structures made of the sediment as it accumulated or after it accumulated (Figures 26 and 27). Some are the result of physical processes, and others are the result of the activities of plants or animals.

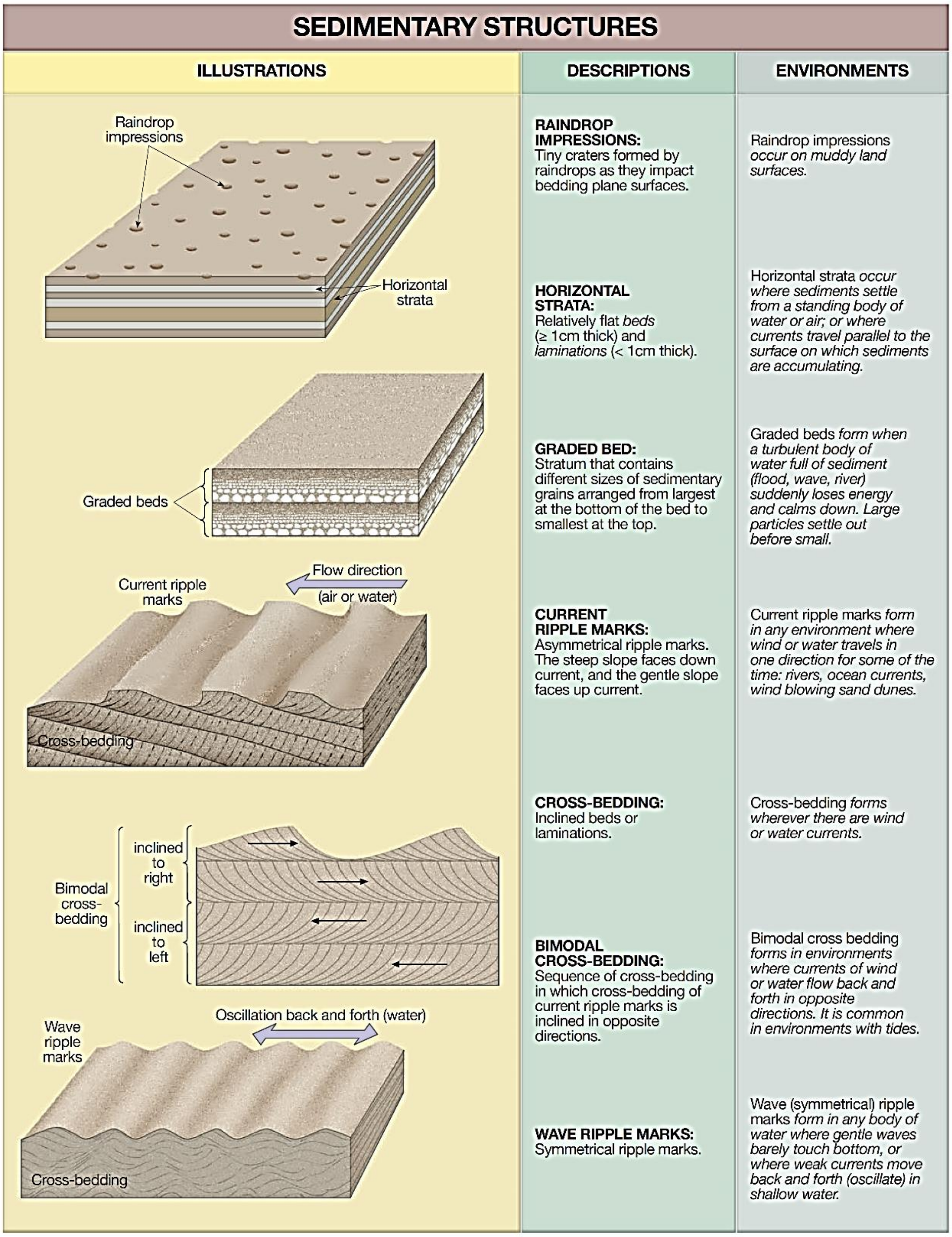


Figure 26

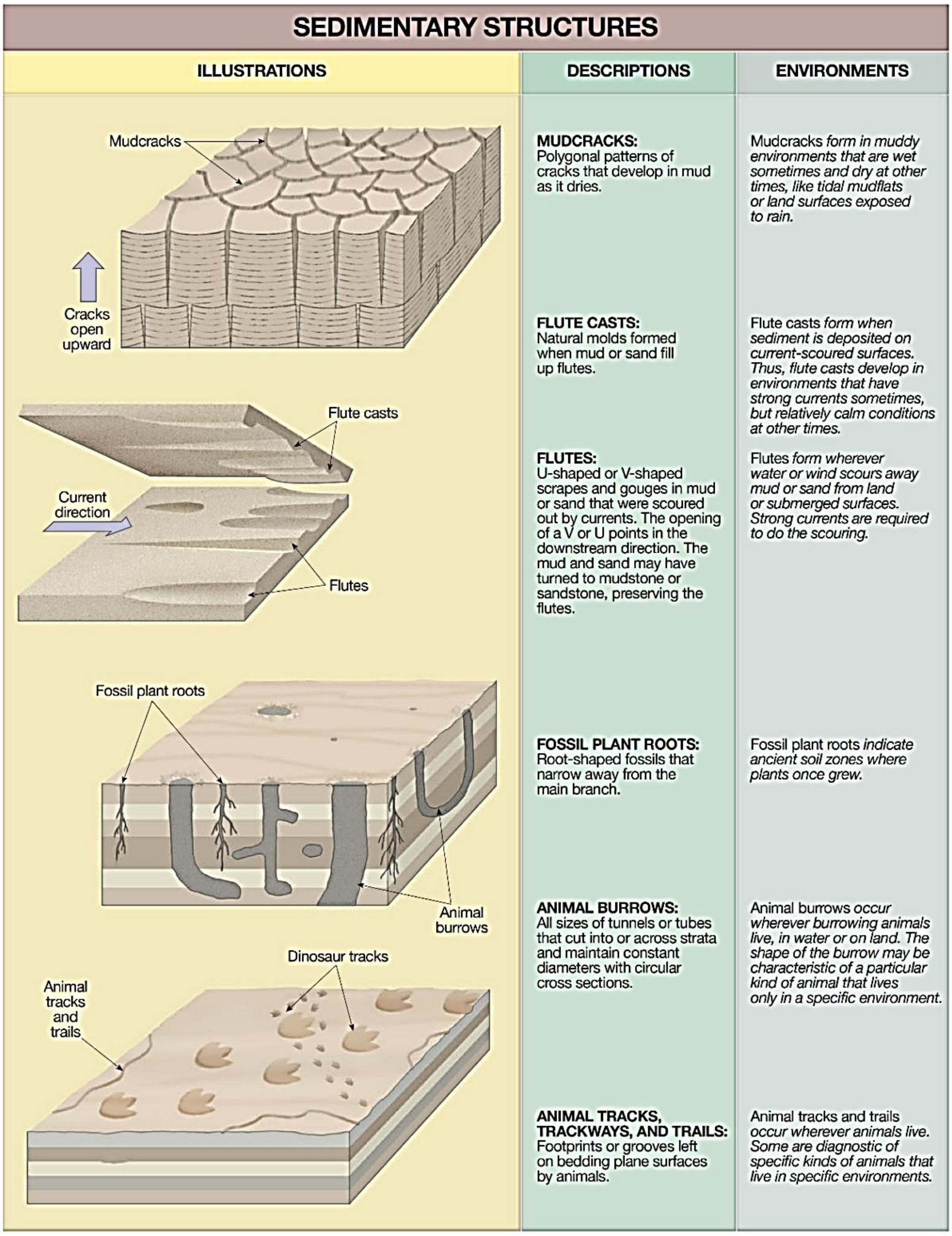


Figure 27

4.9. Stratigraphic Sequences

As sediments accumulate, they cover up the sediments that were already deposited at an earlier (older) time. Environments also change through time, as layers of sediment accumulate. Therefore, at any particular location, bodies of sediment have accumulated in different times and environments. These bodies of sediment then changed into rock units, which have different textures, compositions, and sedimentary structures. An undisturbed succession of beds of rock strata can be divided into units of different color, composition, and texture. The succession of such units, one on top of the other, is called a *stratigraphic sequence.* If you interpret each rock unit of the stratigraphic sequence in order, from oldest (at the base) to youngest (at the top), then you will know what happened over a given portion of geologic history for the site where the stratigraphic sequence is located.

Part 5: Metamorphic Rocks

5.1. Introduction

The word *metamorphic* is derived from Greek and means "of changed form." **Metamorphic rocks** are rocks changed from one form to another (metamorphosed) by intense heat, intense pressure, or the action of watery hot fluids. Think of metamorphism as it occurs in your home. *Heat* can be used to metamorphose bread into toast, *pressure* can be used to compact an aluminum can into a flatter and more compact form, and the chemical action of *watery hot fluids* (boiling water, steam) can be used to change raw vegetables into cooked forms. Inside Earth, all of these metamorphic processes are more intense and capable of changing a rock from one form to another. Thus metamorphism can change a rock's size, shape, texture, color, and/or mineralogy. Every metamorphic rock has a **parent rock** (or *protolith)*, the rock type that was metamorphosed. Parent rocks can be any of the three main rock types: igneous rock, sedimentary rock, or even metamorphic rock (i.e., metamorphic rock can be metamorphosed again), and the degree that a parent rock is metamorphosed can vary. As temperature and pressure increases, so does the metamorphic grade. **Metamorphic grade** refers to the intensity of metamorphism, from low grade (least intense metamorphism) to high grade (most intense metamorphism). Figure 28 is a highly generalized illustration of metamorphism at part of a convergent plate boundary, where rocks were highly compressed at great depths within a mountain belt. A body of granitic magma also intruded part of the region. Note how the rocks were folded and changed. Mafic and ultramafic igneous rocks were metamorphosed to serpentinite. Sedimentary conglomerate, sandstone, and limestone parent rocks were metamorphosed to *meta-conglomerate, quartzite,* and *marble.* Shale was metamorphosed to *slate, phyllite, schist,* and *gneiss,* depending on the grade of metamorphism from low-grade (slate) to medium-grade (phyllite, schist), to high-grade (gneiss). *Hornfels* formed only in a narrow zone of "contact "metamorphism next to the intrusion of magma. Watery hot fluids, called **hydrothermal fluids,** traveled along faults and fractures, where they leached chemicals from the rocks while hot and deposited mineral crystals as they cooled.

5.2. Agents of Metamorphism

Temperature, pressure, and hydrothermal fluids (watery hot fluids) are known as agents of metamorphism. Wherever metamorphism is occurring, one or more of these agents is involved in the metamorphic process.

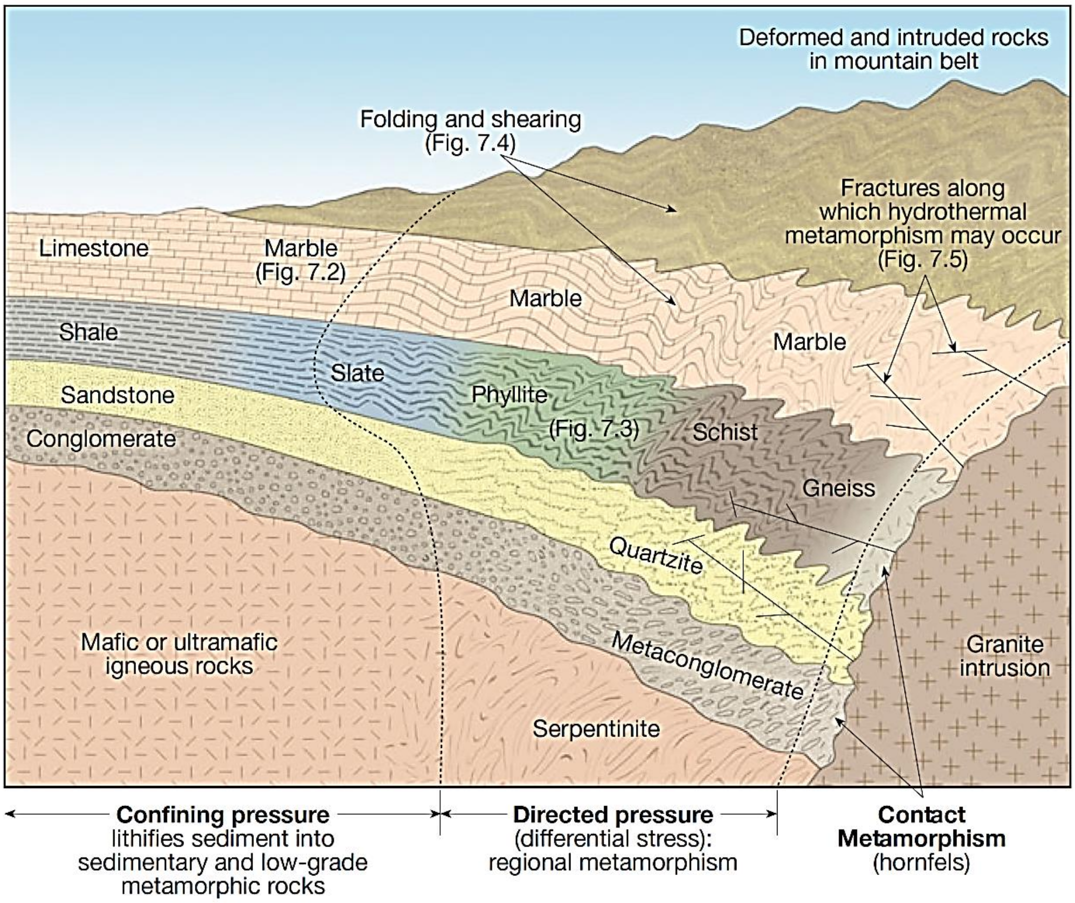


Figure 28

Pressure Effects on Rocks

Confining Pressure is pressure (stress) applied equally in all directions (Figure 29). When you jump into a swimming pool you feel the confining pressure of the water pushing on every part of your body with equal force. If you dive down deep under the water, the pressure increases all around you. The same thing happens with rocks. Confining pressure increases with depth below Earth's surface and is equal in all directions. The deeper the rocks, the greater the confining pressure. This is what compacts rocks from sediment into sedimentary rock. The rock gets denser because it is squeezed into less space. Unequal-sized aragonite seashells or calcite mineral crystals will both recrystallize to a mass of small equal-sized crystals in the metamorphic rock called marble. Quartz sandstone becomes quartzite. **Directed pressure (differential stress)** is pressure that is not equal in all directions. This causes the rock to get more compressed in one direction than any other (Figure 30). If you roll a lump of dough into a ball, then you are rolling and squeezing it equally in all directions to make the ball. But if you place the dough on a table and press on it with your hand, it gets squashed and shortened in the direction of the directed pressure. This causes flat minerals to get **foliated** —flatten out parallel to one another and perpendicular to the stress. Directed stress occurs on a large scale at convergent plate boundaries, where the edges of two plates push together.

Temperature Effects on Rocks

Temperature is a measure of thermal energy. The greater the thermal energy, the higher the temperature and more energized the atoms and molecules are in the rock. When temperature exceeds 200°C (twice the boiling point of water), the molecules get highly energized. If the rock is under directed pressure, then it may fold in a ductile (like plastic) manner and become foliated. Some bonds in the minerals begin to break and reform in more stable configurations. This may cause recrystallization or neo-morphism. **Recrystallization** is a process whereby unequal-sized crystals of one mineral slowly convert to equal-sized crystals of the same mineral, without melting of the rock. The longer the process continues, the larger the crystals become. For example, microscopic calcite crystals in chemical limestone (travertine, as in a cave stalactite) can recrystallize to forma mass of visible calcite crystals in metamorphic marble. Mineral composition of the rock stays the same, but texture of the rock changes.

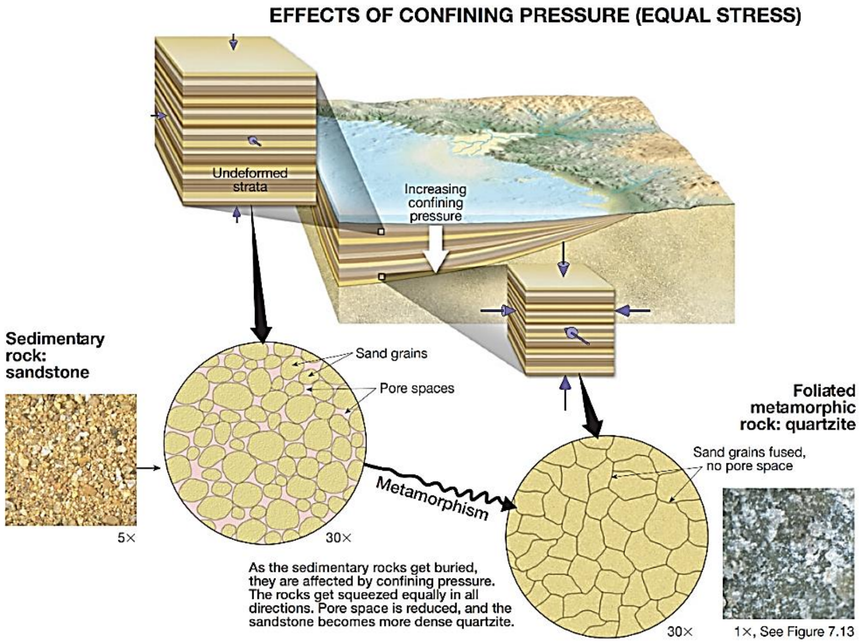


Figure 29

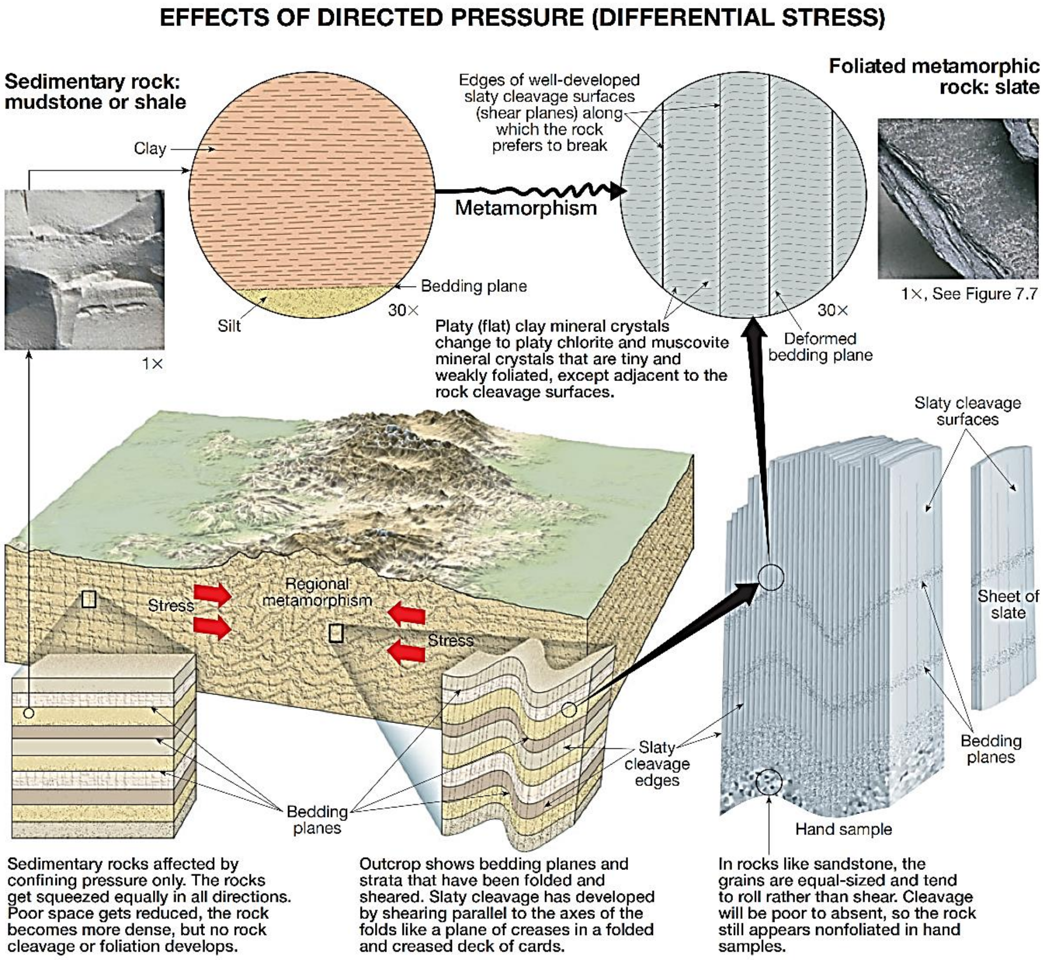


Figure 30

Neo-morphism is a process whereby mineral crystals not only recrystallize but also form different minerals from the same chemical elements. This happens when bonds of the original minerals break, and the chemical elements arrange themselves into different crystalline structure and/or different molecules. For example, shales consisting mainly of clay minerals, quartz grains, and feldspar grains may change to a metamorphic rock consisting mainly of muscovite and garnet.

Hydrothermal Fluid Effects on Rocks

Just as hot water can cook vegetables and remove their color by breaking down molecules within them, it can also change the composition and form of rocks. Thus, water is an important agent of **metasomatism,** the loss or addition of new chemicals during metamorphism. Hornfels sometimes has a spotted appearance caused by the partial decomposition of just some of its minerals. In still other cases, one mineral may decompose (leaving only cavities or molds where its crystals formerly existed) and be simultaneously replaced by a new mineral of slightly or wholly different composition. When the hydrothermal fluids cool, minerals precipitate in the fractures and "heal" them.

5.3. Types of Metamorphism

Metamorphism can occur at different scales and indifferent types of environments. **Burial metamorphism** is the most common type of metamorphism and occurs on a regional scale as rocks form and get buried. The metamorphism is caused by confining pressure. **Regional metamorphism**, as the name implies, occurs on a regional scale, but the term now refers specifically to large-scale metamorphism at convergent plate boundaries, where there is directed pressure (differential stress) and high temperature that causes folding and foliation of the rocks. It is also called dynamo thermal (pressure-temperature) metamorphism. **Contact metamorphism** occurs locally, adjacent to igneous intrusions. It involves conditions of low to moderate pressure and intense heating. The intensity of contact metamorphism is greatest at the contact between parent rock and intrusive magma. The intensity then decreases rapidly over a short distance from the magma or hydrothermal fluids. Thus, zones of contact metamorphism are usually narrow, on the order of millimeters to tens- of-meters thick but some are kilometers wide. The intruding magma thermally metamorphoses the rock in a narrow zone adjacent to the heat source (magma).**Hydrothermal metamorphism** occurs along fractures that are in contact with the watery hot (hydrothermal) fluids. Like contact metamorphism, there is high heat and low pressure. **Dynamic metamorphism** occurs along fault zones where there is local-to-regional shearing and crushing of rocks. If the rocks are brittle, then shearing produces fault breccia. But if the rocks are hot and ductile, then a fine-grained metamorphic rock called mylonite may result. Mylonite is a hard, dense, fine-grained rock that lacks cleavage but may have a banded coloration.

5.4. Minerals of Metamorphic Rocks

The **mineralogical composition** of a metamorphic rock is a description of the kinds and *relative* abundances of mineral crystals that make up the rock. Information about the relative abundances of the minerals is important for constructing a complete name for the rock and understanding metamorphic changes that formed the mineralogy of the rock. Mineralogical composition of a parent rock may change during metamorphism as a result of changing pressure, changing temperature, and/or the chemical action of hydrothermal fluids, and processes like neo-morphism and metasomatism. In general, as temperature and pressure increase, so does the **metamorphic grade** —the intensity of metamorphism, from low grade (least intense metamorphism) to high grade (most intense metamorphism). One group of minerals that was stable at a low temperature and/or pressure will eventually neo-morphose to different minerals at a higher temperature and/or pressure. An **index mineral** is a mineral that is stable under a specific range of temperature and pressure and thus characterizes a grade of metamorphism.

5.5. Textures of Metamorphic Rocks

Texture of a metamorphic rock is a description of its constituent parts and their sizes, shapes, and arrangements. Two main groups of metamorphic rocks are distinguished on the basis of their characteristic textures, *foliated* and *non-foliated.*

Foliated Metamorphic Rocks

Foliated metamorphic rocks (foliated textures) exhibit **foliations** — *layering* and parallel alignment of platy (flat) mineral crystals, such as micas. The foliations form when directed pressure causes the platy (flat) mineral crystals to slide parallel to and past one another (shear). This can happen as they recrystallize. Crystals of minerals such as tourmaline, hornblende, and kyanite can also be foliated because their crystalline growth occurred during metamorphism and had a preferred orientation in relation to the directed pressure. Specific kinds of foliated textures are described below:

- ✓ **Slaty rock cleavage** — *a very flat foliation* (resembling mineral cleavage) developed along flat, parallel, closely spaced shear planes (microscopic faults) in tightly folded clay- or mica-rich rocks (Figure 31). Rocks with excellent slaty cleavage are called *slate*, which is used to make roofing shingles and classroom blackboards. The flat surface of a blackboard or sheet of roofing slate is a slaty cleavage surface.

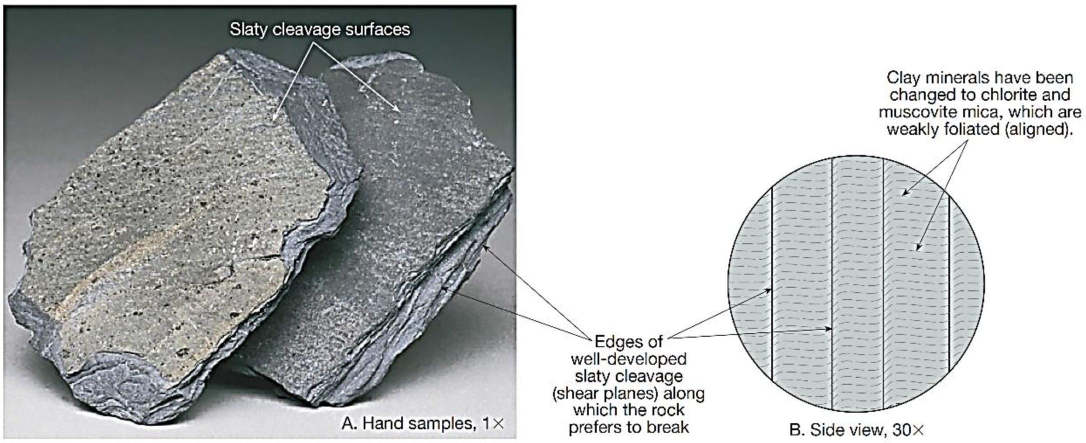


Figure 31

- ✓ **Phyllitic texture** — *a wavy and/or wrinkled foliation* of fine-grained *platy minerals* (mainly muscovite or chlorite crystals) that gives the rock a satiny or metallic cluster. Rocks with phyllite texture are called *phyllite* (Figure 32). The phyllite texture is normally developed oblique or perpendicular to a weak slaty cleavage, and itis a product of intermediate-grade metamorphism.

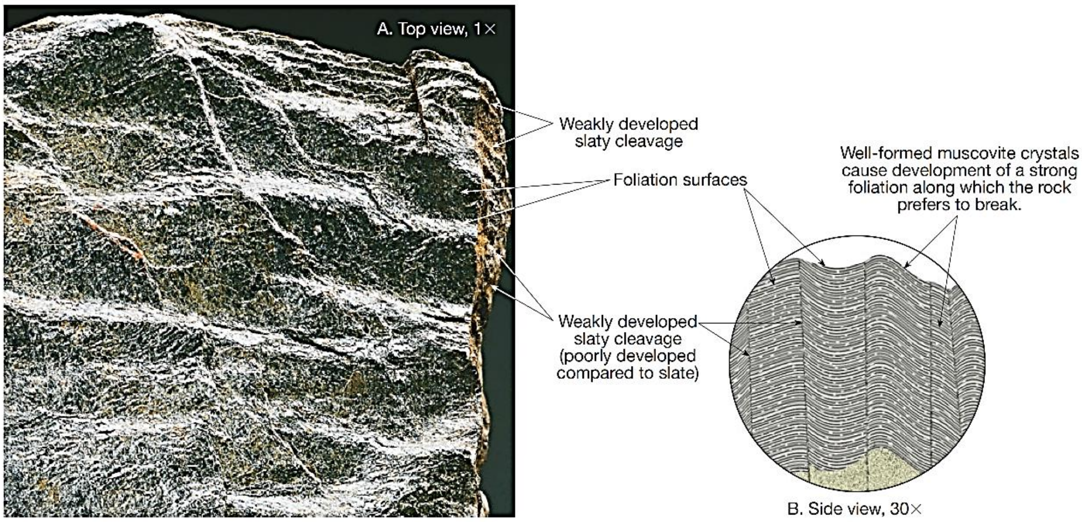


Figure 32

- ✓ **Schistosity** — *a scaly glittery layering* of visible (medium- to coarse-grained) *platy minerals* (mainly micas and chlorite) *and/or linear alignment of long prismatic crystals* (tourmaline, hornblende, and kyanite). Rocks with schistosity break along scaly, glittery foliations and are called *schist* (Figure 33). Schists are a product of intermediate-to-high grades of metamorphism.

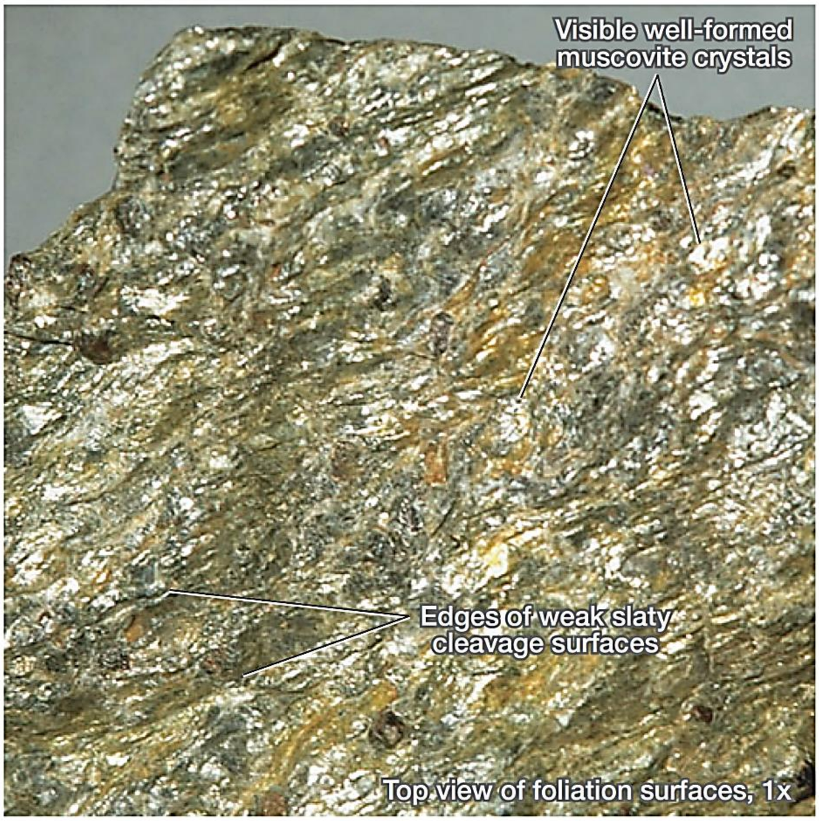


Figure 33

- ✓ **Gneissic banding** — *alternating layers or lenses of light and dark medium- to coarse-grained minerals.* Rock with gneissic banding is called *gneiss* (Figure 34). Ferromagnesian minerals usually form the dark bands. Quartz or feldspars usually form the light bands. Most gneisses form by high-grade metamorphism (including recrystallization) of clay- or mica-rich rocks such as shale, but they can also form by metamorphism of igneous rocks such as granite and diorite.

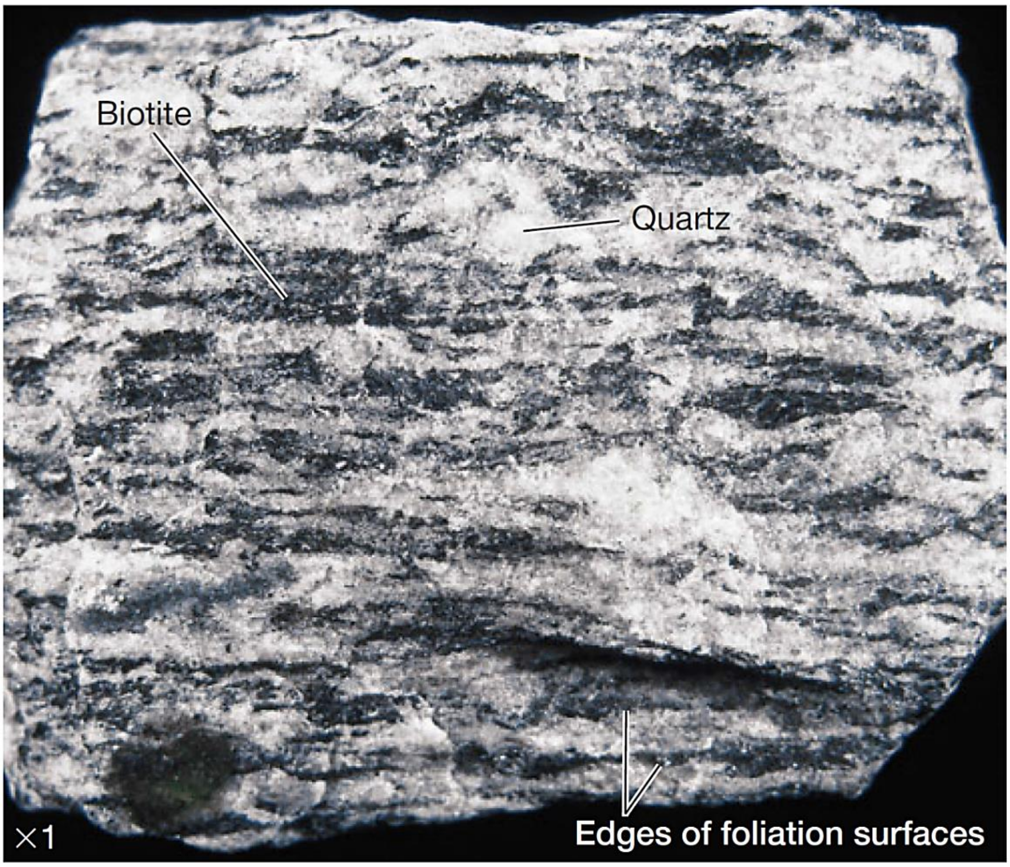


Figure 34

Non-foliated Metamorphic Rocks

Non-foliated metamorphic rocks have no obvious layering (i.e., no foliations), although they may exhibit stretched fossils or long, prismatic crystals (tourmaline, amphibole) that have grown parallel to the pressure field. Non-foliated metamorphic rocks are mainly characterized by the following textures: **Crystalline texture (non-foliated)** —a medium- to coarse-grained aggregate of intergrown, usually equal-sized (equi-granular), visible crystals. *Marble* is a non-foliated metamorphic rock that typically exhibits an equi-granular crystalline texture (Figure 35).

- ✓ **Microcrystalline texture** —a fine-grained aggregate of intergrown microscopic crystals (as in a sugar cube). *Hornfels* is a non-foliated metamorphic rock that has a microcrystalline texture.

Figure 35

- ✓ **Sandy texture** —a medium- to coarse-grained aggregate of fused, sand-sized grains that resembles sandstone. *Quartzite* is a non-foliated metamorphic rock with a sandy texture (Figure 36) remaining from its sandstone parent rock, but the sand grains cannot be rubbed free of the rock because they are fused together.
- ✓ **Glassy texture** —a homogeneous texture with no visible grains or other structures and breaks along glossy surfaces; said of materials that resemble glass, such as *anthracite coal.* Besides the main features that distinguish foliated and non-foliated metamorphic rocks, there are some features that can occur in any metamorphic rock. They include the following:

Figure 36

- ✓ **Stretched or sheared grains** —deformed pebbles, fossils, or mineral crystals that have been stretched out, shortened, or sheared. **Porphyroblastic texture** —an arrangement of large crystals, called *porphyroblasts,* set in a finer-grained groundmass. It is analogous to porphyritic texture in igneous rocks.
- ✓ **Hydrothermal veins** —fractures "healed" (filled) by minerals that precipitated from hydrothermal fluids.
- ✓ **Folds** —bends in rock layers that were initially flat, like a folded stack of paper.
- ✓ **Lineations** —lines on rocks at the edges of foliations, shear planes, slaty cleavage, folds, or aligned crystals.

5.6. Classification of Metamorphic Rocks

Metamorphic rocks are mainly classified according to their texture and mineralogical composition. This information is valuable for naming the rock and determining how it formed from a parent rock. It is also useful for inferring how the metamorphic rock could be used as a commodity for domestic or industrial purposes.

Part 6: Unconformities

6.1. Introduction

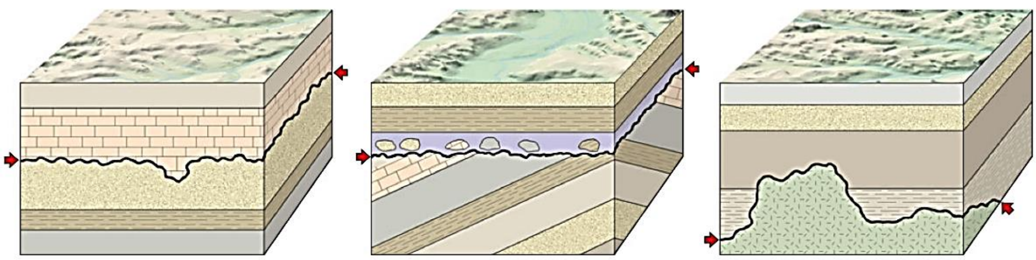
If you could dig a hole deep into Earth's crust, you would encounter the **geologic record,** layers of rock stacked one atop the other like pages in a book. As each new layer of sediment or rock forms today, it covers the older layers of the geologic record beneath it and becomes the youngest layer of the geologic record. Thus, rock layers form a *sequence* from oldest at the bottom to youngest at the top. They also have different colors, textures, chemical compositions, and **fossils** (any evidence of ancient life) depending on the environmental conditions under which they were formed. Geologists have studied sequences of rock layers wherever they are exposed in mines, quarries, riverbeds, road cuts, wells, and mountain sides throughout the world. They have also *correlated* the layers (traced them from one place to another) across regions and continents. Thus, the geologic record of rock layers is essentially a stack of stone pages in a giant natural book of Earth's history. And like the pages in any old book, the rock layers have been folded, fractured (cracked), torn (faulted), and even removed by geologic events. Geologists tell time based on relative and absolute dating techniques. **Relative age dating** (Figures 37-40) is the process of determining when something formed or happened in relation to other events. For example, if you have a younger brother and an older sister, then you could describe your relative age by saying that you are younger than your sister and older than your brother. **Absolute age dating** is the process of determining when something formed or happened in exact units of time such as days, months, or years. Using the example above, you could describe your absolute age just by saying how old you are in years. Geologists "read" and infer Earth's history from rocky outcrops and geologic cross sections by observing rock layers, recognizing geologic structures, and evaluating age relationships among the layers and structures. The so-called *geologic time scale* is a chart of named intervals of the geologic record and their ages in both relative and absolute time. It has taken thousands of geoscientists, from all parts of the world, more than a century to construct the present form of the geologic time scale.

6.2. Relative Age Dating Based on Physical Relationships

A geologist's initial challenge in the field is to subdivide the local sequence of sediments and bodies of rock into mappable units that can be correlated from one site to the next. Subdivision is based on color, texture, rock type, or other physical features of the rocks, and the mappable units are called **formations.** Formations can be subdivided into *members,* or even individual strata. Surfaces between any of these kinds of units are **contacts.**

Unconformities

Surfaces called unconformities represent gaps in the geologic record that formed wherever layers were not deposited for a time or else layers were removed by erosion. Most contacts between adjacent strata or formations are conformities, meaning that rocks on both sides of them formed at about the same time. An unconformity is a rock surface that represents a gap in the geologic record. It is like the place where pages are missing from a book. An unconformity can be a buried surface where there was a pause in sedimentation, a time between two lava flows, or a surface that was eroded before more sediment was deposited on top of it. There are three kinds (Figure 37). A disconformity is an unconformity between parallel strata or lava flows. Most disconformities are very irregular surfaces, and pieces of the underlying rock are often included in the strata above them. An angular unconformity is an unconformity between two sets of strata that are not parallel to one another. It forms when new horizontal layers cover up older layers folded by mountain-building processes and eroded down to a nearly level surface. A nonconformity is an unconformity between younger sedimentary rocks and subjacent metamorphic or igneous rocks. It forms when stratified sedimentary rocks or lava flows are deposited on eroded igneous or metamorphic rocks.

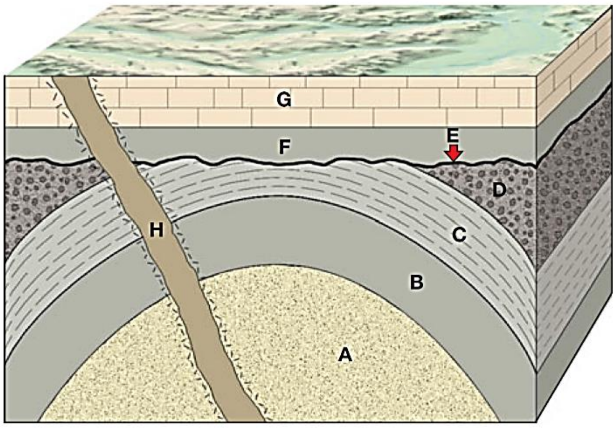


Disconformity
In a succession of rock layers (sedimentary strata or lava flows) parallel to one another, the disconformity surface is a gap in the layering. The gap may be a non-depositional surface where some layers never formed for a while, or the gap may be an erosional surface where some layers were removed before younger layers covered up the surface.

Angular unconformity
An angular unconformity is an erosional surface between two bodies of layered sedimentary strata or lava flows that are not parallel. The gap is because the older body of layered rock was tilted and partly eroded (rock was removed) before a younger body of horizontal rock layers covered the eroded surface.

Nonconformity
A nonconformity is an erosional surface between older igneous and/or metamorphic rocks and younger rock layers (sedimentary strata or lava flows). The gap is because some of the older igneous and/or metamorphic rocks were partly eroded (rock was removed) before the younger rock layers covered the eroded surface.

Figure 37



Law of cross-cutting. The body of igneous rock **H** is the youngest rock unit, because it cuts across all of the others. (When a narrow body of igneous rock cuts across strata in this way, it is called a **dike**.) **A** is the oldest formation because it is at the bottom of the sedimentary rock sequence that is cut by **H.** Folding and erosion occurred after **D** was deposited, but before **F** was deposited. **E** is an angular unconformity.

The sequence of events began with deposition of formations **A** through **D** in alphabetical order and one atop the other. That sequence was folded, and the top of the fold was eroded. Formation **F** was deposited horizontally atop the folded sequence and the erosional surface, which became angular unconformity **E. G** was deposited atop **F.** Lastly, a magma intruded across all of the strata and cooled to form basalt dike **H.**

Figure 38

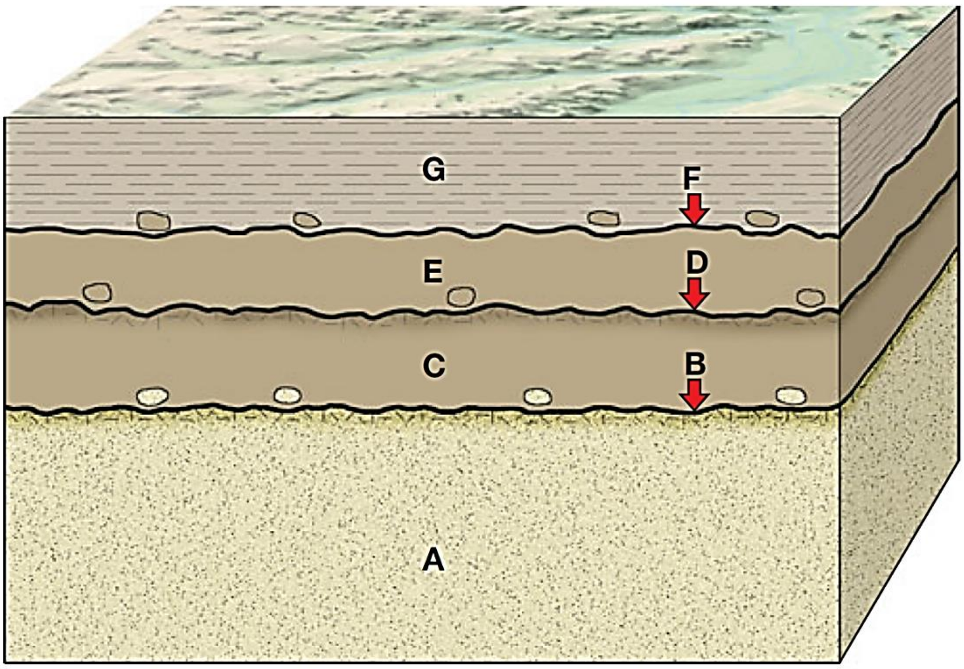


Figure 39

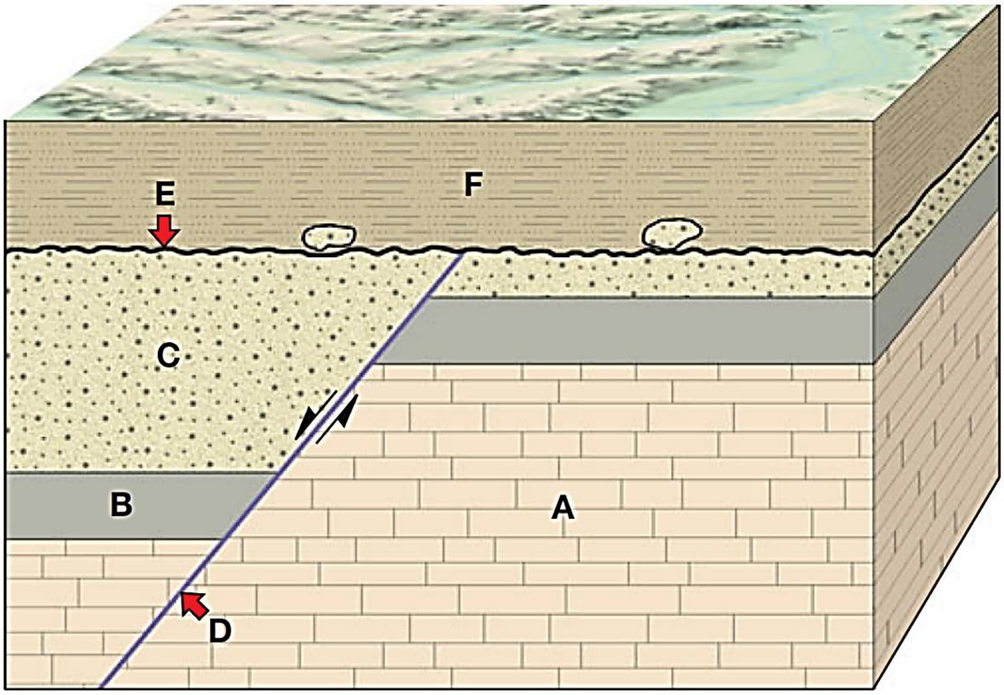


Figure 40

Part 7: Topographic and Geologic Maps

7.1. Introduction

Imagine that you are seated with a friend who asks you how to get to the nearest movie theater. To find the theater, your friend must know locations, distances, and directions. You must have a way of communicating your current location, the location of the Movie Theater, plus directions and distances from your current location to the movie theater. You may also include information about the topography of the route (whether it is uphill or downhill) and landmarks to watch for along the way. Your directions may be verbal or written, and they may include a map, satellite image, or aerial photograph (picture taken from an aircraft). Geologists are faced with similar circumstances in their field (outdoor) work. They must often characterize geologic features, the places where they occur, and their sizes, shapes, elevations, and locations in relation to other features. Satellite images and aerial photographs are used to view parts of Earth's surface from above (Figure 41), and this information is summarized on maps. A **map** is a flat representation of part of Earth's surface as viewed from above and reduced in size to fit a sheet of paper or computer screen. A **plan metric map**

(Figure 41) is a flat representation of Earth's surface that shows horizontal (two-dimensional) positions of features like streams, landmarks, roads, and political boundaries. A **topographic map** shows the same horizontal information as a plan metric map but also includes *contour lines* to represent elevations of hills and valleys. The contour lines are the distinguishing features of a topographic map and make it appear three dimensional. Thus topographic maps show the shape of the landscape in addition to horizontal directions, distances, and a system for describing exact locations. Most United States topographic maps are published by the U.S. Geological Survey (USGS) and available at their US Topo website (http://store.usgs.gov**)**. Canadian topographic maps are produced by the Centre for Topographic Information of Natural Resources Canada (NRCAN: **http://maps.nrcan.gc.ca)**. State and provincial geological surveys, and the national geological surveys of other countries, also produce and/or distribute topographic maps.

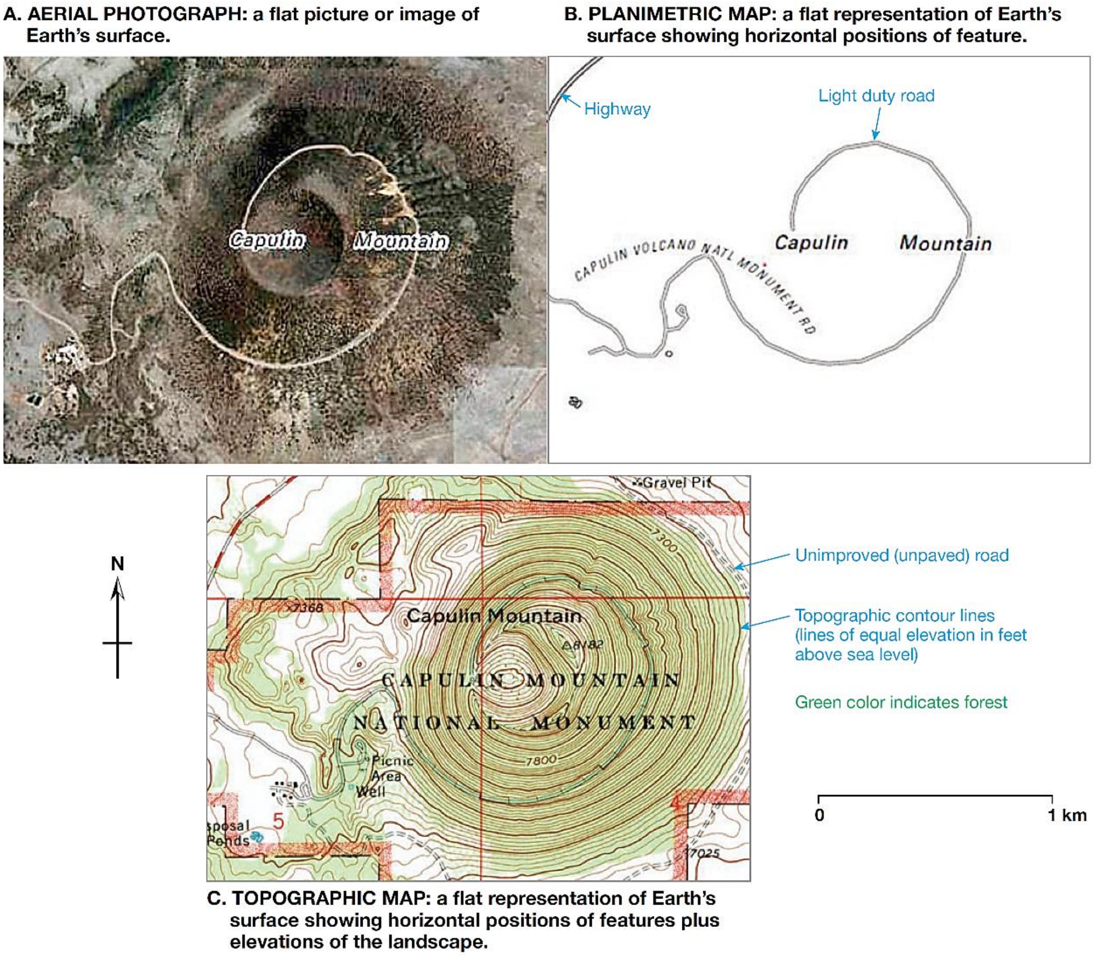


Figure 41

7.2. Latitude-Longitude and Quadrangle Maps

Earth is a spherical body or globe, and specific points on the globe can be defined exactly using a geographic coordinate system in which points are defined by the intersection of imaginary reference lines. The most traditional geographic coordinate system consists of reference lines of geographic latitude and longitude.

Latitude-Longitude Coordinate System

Earth's spherical surface is divided into lines of latitude(*parallels)* that go around the world parallel to the Equator, and lines of longitude (*meridians)* that go around the world from pole to pole (Figure 42). There are360 degrees (360°) around the entire Earth, so the distance from the Equator to a pole (one-fourth of the way around Earth) is 90° of latitude. The Equator is assigned value of zero degrees (0°) latitude, the North Pole is90 degrees north latitude (90°N), and the South Pole is 90 degrees south latitude (90°S). The *prime meridian* is zero degrees of longitude and runs from pole to pole through Greenwich, England. Locations in Earth's Eastern Hemisphere are located in degrees east of the prime meridian, and points in the Western Hemisphere are located in degrees west of the prime meridian. Therefore, any point on Earth (or a map) can be located by its latitude-longitude coordinates. The latitude coordinate of the point is its position in degrees north or south of the Equator. The longitude coordinate of the point is its position in degrees east or west of the prime meridian. For example, point **A** in Figure 42 is located at coordinates of: 20° north latitude, 120° west longitude. For greater detail, each degree of latitude and longitude can also be subdivided into 60 minutes 60′, and each minute can be divided into 60 seconds (60″).

Quadrangle Maps. Most depict rectangular sections of Earth's surface, called quadrangles. A **quadrangle** is a relatively rectangular area of Earth's surface, bounded bylines of latitude at the top (north) and bottom (south) and by lines of longitude on the left (west) and right (east) (Figure 42). A *quadrangle map* is the map of a quadrangle. Quadrangle maps are published in many different sizes but the most common USGS sizes are 15-minute and7.5-minute quadrangle maps. The numbers refer to the amount of area that the maps depict, in degrees of latitude and longitude. A 15-minute topographic map represents an area that measures 15 minutes of latitude by15 minutes of longitude. A 7.5-minute topographic map represents an area that measures 7.5 minutes of latitude by 7.5 minutes of longitude. Therefore, four 7.5-

minutequadrangle maps comprise one 15-minutequadrangle map. Notice its name (Ritter Ridge, CA) and size (7.5 Minute Series, SW 1/4 of the Lancaster 15' Quadrangle) in the upper right and lower right corners of the map, respectively. Also notice that the map has colors, patterns, and symbols that are used to depict water bodies, vegetation, roads, buildings, political boundaries, place names, and other natural and cultural features of the landscape. The lower right corner of the map indicates that the map was originally published in 1958, but it was photo revised in 1974. *Photo revised* means that aerial photographs (from airplanes) were used to discover changes on the landscape, and the changes are overprinted on the maps in a standout color like purple, red, or gray. The main new features shown on this 1974photorevised map are the California Aqueduct (that carries water south, from the Sierra Nevada Mountains to the southern California desert) and several major highways.

7.3. Map Scales

Maps are representations of an area of Earth's surface. The real sizes of everything on a map have been reduced so they fit a sheet of paper or computer screen. So maps are scale models. To understand how the real world is depicted by the map, you must refer to the map scales. Topographic maps commonly have any or all of the following kinds of scales.

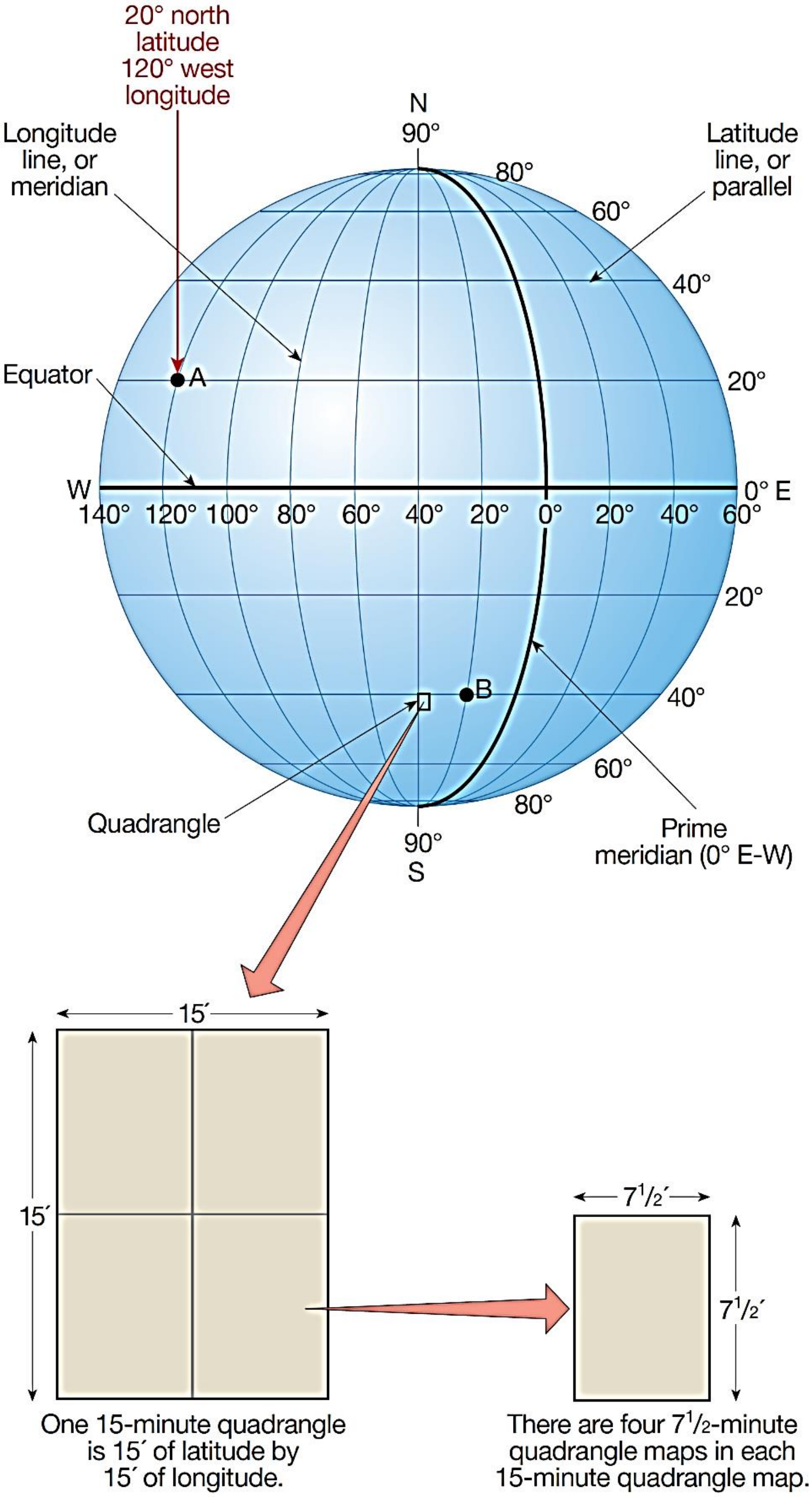

20° north
latitude
120° west
longitude
Longitude
line, or
meridian
N
90°
80°
Latitude
line, or
parallel
60°
40°
Equator
A
20°
W
0° E
140° 120° 100° 80° 60° 40° 20° 0° 20° 40° 60°
20°
B
40°
60°
80°
Quadrangle
90°
S
Prime
meridian (0° E-W)
15′
15′
7½′
7½′
One 15-minute quadrangle
is 15′ of latitude by
15′ of longitude.
There are four 7½-minute
quadrangle maps in each
15-minute quadrangle map.

Figure 42

Bar Scales for Measuring Distances on the Map

The most obvious scales on topographic maps are the **bar scales (graphic scales)** printed in their lower margins. Bar scales are rulers for measuring distances on the map. U.S. Geological Survey topographic maps generally have four different bar scales: miles, feet, kilometers, and meters.

Scales That Tell How the Map Compares to Actual Sizes of Objects

Ratio scales are commonly expressed above the bar scales in the bottom margins of topographic maps and express the ratio of a linear dimension on the map to the actual dimension of the same feature on the ground (in real life). For example, the ratio scale of the map is written as “SCALE 1:24,000.” This indicates that any unit (inch, centimeter, foot, etc.) on the map is actually 24,000 of the same units (inches, centimeters, and feet) on the ground. So 1 cm on the map represents 24,000 cm on the ground, or your thumb width on the map represents 24,000 thumb widths on the ground. The ratio scale can also be interpreted as a **fractional scale,** which indicates how much smaller something is than its actual size on the ground. A map ratio scale of 1:24,000 equals a fractional scale of 1/24,000. This means that everything on the map is 1/24,000 of its actual size on the ground.

Verbal Scales Express Map Proportions in Common Terms

Verbal scales are sentences that help readers understand map proportions in relation to common units of measurement. For example, reconsider the map with “SCALE1:24,000.” Knowing that 1 inch on the map equals 24,000inches on the ground is not very convenient, because no one measures big distances in thousands of inches! However, if you divide the 24,000 inches by 12 to get 2000 ft., then the scale suddenly becomes useful: “1 in. on the map = 2000 ft. on the ground.” An American football field is 100 yards (300 ft.) long, so: “1 in. on the map = 6 23 football fields. “On a map with a scale of 1:63,360, “1 inch equals 63,360 inches” is again not meaningful in daily use. But there are 63,360 inches in a mile. So, the verbal scale, “1 inch equals 1 mile” is very meaningful. A standard1:62,500 map (15-minute quadrangle map commonly used in parts of Alaska) is very close to this scale, so “one inch equals approximately one mile” is often written on such a map. Note that verbal scales are often approximate because their sole purpose is to help the reader make general sense of how the map relates to sizes of real objects on the ground.

7.4. Declination and Compass Bearings

Because longitude lines form the left and right boundaries of a topographic map, north is always at the top of the quadrangle. This is called grid north (GN) and is usually very close to the same direction as *true north* on the actual Earth. Unfortunately, magnetic compasses are not attracted to grid north or true north (the geographic North Pole). Instead, they are attracted to the *magnetic north pole* (MN), currently located northwest of Hudson Bay in Northern Canada, about 700 km (450 mi)from the true North Pole.

What Is Declination?

The trident-shaped symbol on the bottom margin of topographic maps shows the **declination** (difference in degrees) between compass north (MN) and true north (usually a *star* symbol). Also shown is the declination between true north (*star* symbol) and grid north (GN). The magnetic pole migrates very slowly, so the declination is exact only for the year listed on the map. You can obtain the most recent magnetic data for your location from the NOAA National Geophysical Data Center (http://www.ngdc.noaa.gov/geomag-web/#declination).

What Is a Compass Bearing?

A **bearing** is the *compass direction* along a line from one point to another. If expressed in degrees east or west of true north or south, it is called a *quadrant bearing*. Or it may be expressed in degrees between 0 and 360, called an *azimuth bearing*, where north is 0° (or 360°), east is 90°,south is 180°, and west is 270°. Linear geologic features (faults, fractures, and dikes), lines of sight and travel, and linear property boundaries are all defined on the basis of their bearings. But because a compass points to Earth's *magnetic north* (MN) pole rather than the true North Pole, one must correct for this difference. If the MN arrow is to the east of true north (star symbol), then subtract the degrees of declination from your compass reading (imagine that you are rotating your compass counter-clockwise to compensate for declination). If the MN arrow is to the west of true north, then add the degrees of declination to your compass reading (imagine that you rotated your compass clockwise).These adjustments will mean that your compass readings are synchronized with the map (so long as you used the latest declination values obtained from NOAA).

How to Set a Compass for Declination

Some compasses allow you to rotate their basal ring graduated in degrees to correct for the magnetic declination. If the MN arrow is 5° east (right) of true north, then you would rotate the graduated ring 5° east (clockwise, to subtract 5° from the reading). If the MN arrow is 5° west (left) of true north, then you would rotate the graduated ring 5° west (counter-clockwise, to add 5° to the reading).

How to Determine a Compass Bearing on a Map

To determine a compass bearing on a topographic map, follow the directions in (Figure 43). Then imagine that you are buying a property for your dream home. The boundary of the property is marked by four metal rods driven into the ground, one at each corner of the property. The location of these rods is shown on the map in Figure 43 (left side) as points ***A, B, C,*** and ***D.*** The property deed notes the distances between the points *and* bearings between the points. This defines the shape of the property. Notice that the northwest edge of your property lies between two metal rods located at points ***A*** and ***B.*** You can measure the distance between the points using a tape measure. How can you measure the bearing? First, draw a line (very lightly in pencil so that it can be erased) through the two points, ***A*** and ***B.*** Make sure the line also intersects an edge of the map. In both parts of Figure 43, a line was drawn through points ***A*** and ***B*** so that it also intersects the east edge of the map. Next, orient a protractor so that its 0° and 180° marks are on the edge of the map, with the 0° end toward geographic north. Place the origin of the protractor at the point where your line–***B*** intersects the edge of the map. You can now read a bearing of 43° east of north. We express this as a quadrant bearing of "North 43° East" (written N43°E) or as an azimuth bearing of 43°. If you were to determine the opposite bearing, from ***B*** to ***A*** then the bearing would be pointing southwest and would be read as "South 43°, and West," or as an azimuth of 223°. Remember that a compass points to Earth's *magnetic north* pole (MN) rather than true north or grid north (GN). When comparing the bearing read directly from the map to a bearing read from a compass, you must adjust your compass reading to match true north or grid north (GN) of the map, as described above. You also can use a compass to read bearings, as shown in Figure 43 (right). Ignore the compass needle and use the compass as if it were a circular protractor. Some compasses are graduated in degrees, from 0–360, in which case you read an azimuth bearing from 0–360°.Square azimuth protractors for this purpose are provided in Geo-Tools Sheets 3 and 4 at the back of this manual.

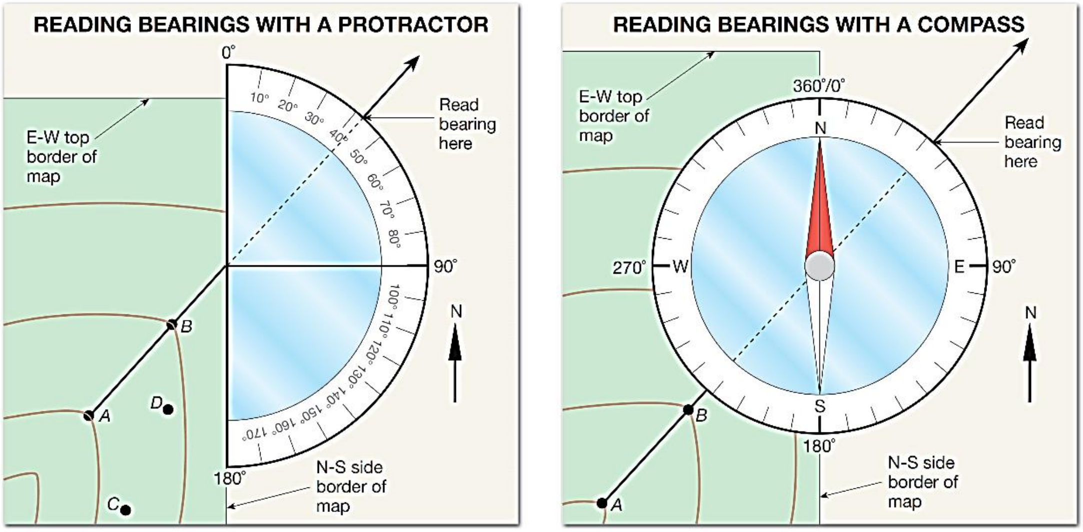


Figure 43

7.5. GPS—Global Positioning System

The Global Positioning System (GPS) is a technology used to make *precise* (exact) and *accurate* (error free) measurements of the location of points on Earth. It is used for geodesy—the science of measuring changes in Earth's size and shape, and the position of objects, over time. GPS technology is based on a constellation of about 30 satellites that take just 12 hours to orbit Earth. They are organized among six circular orbits (20,200 km, or 12,625 mi above Earth) so that a minimum of six satellites will be in view to users anywhere in the world at any time. The GPS constellation is managed by the United States Air Force for operations of the Department of Defense, but they allow anyone to use it anywhere in the world.

How GPS Works

Each GPS satellite communicates simultaneously with fixed ground-based Earth stations and other GPS satellites, so it knows exactly where it is located relative to the center of Earth and Universal Time Coordinated (UTC, also called Greenwich Mean

Time). Each GPS satellite also transmits its own radio signal on a different channel, which can be detected by a fixed or handheld GPS receiver. If you turn on a handheld GPS receiver in an unobstructed outdoor location, then the receiver immediately acquires (picks up) the radio channel of the strongest signal it can detect from a GPS satellite. It downloads the navigational information from that satellite channel, followed by a second, third, and so on. A receiver must acquire and process radio transmissions from at least four GPS satellites to triangulate a determination of its exact position and elevation—this is known as a **fix.** But a fix based on more than four satellites is more accurate. In North America and Hawaii, the accuracy of the GPS constellation is enhanced by WAAS (Wide Area Augmentation System) satellites operated by the Federal Aviation Administration. WAAS uses ground-based reference stations to measure small variations in GPS satellites signals and correct them. The corrections are transmitted up to geostationary WAAS satellites, which broadcast the corrections back to WAAS-enabled GPS receivers on Earth.

GPS Accuracy

The more channels a GPS receiver has, the faster and more accurately it can process data from the most satellites. The best GPS receivers have millimeter accuracy, but handheld WAAS-enabled GPS receivers and smartphones with GPS are accurate to within 3 meters. Receivers lacking WAAS are only accurate to within about 9 meters.

7.6. What Are Topographic Maps?

Topographic maps are miniature models of Earth's three dimensional landscape, printed on two-dimensional pieces of paper or displayed on a flat computer screen. Two of the dimensions are the lengths and widths of objects and landscape features, similar to a plan metric map. But the third dimension, elevation (height), is shown using the *contour lines*, which are lines of equal elevation used to represent hills and valleys. But how are the contour lines determined, and how does one interpret them to "read" a topographic map?

Aerial Photographs and Stereograms

The production of a topographic map begins with overlapping pairs of aerial photographs, called *stereo pairs.* Each stereo pair is taken from an airplane making two closely spaced passes over a region at the same elevation. The passes are flown far enough apart to provide the stereo effect, yet close enough to be almost directly above the land that is to be mapped. Aerial photos commonly are overlapped to form a **stereogram** (Figure 44), which appears three-dimensional (stereo) when viewed through a stereoscope.

Figure 44

Topographic Map Construction

Stereo pairs of aerial photographs are used to build a digital file of terrain elevations that is converted into the first draft of contour lines for the topographic map. Angular distortion is then removed, and the exact elevations of the contour lines on the map are "ground truth" (checked on the ground) using very precise altimeters and GPS. The final product is a topographic map like the one in Figure 45. Notice how the contour lines in Figure 45 occur where the landscape intersects horizontal planes of specific elevations: 0, 50, and 100 feet. Zero feet of elevation is sea level, so it is the coastline of the imaginary island. You can think of the contour lines for 50 and 100 feet above sea level as additional water levels above sea level. An “x” or triangle is often used to mark the highest point on a hilltop, with the exact elevation noted beside it. The highest point on the map in Figure 45 is above the elevation of the highest contour line (100 feet) but below 150 feet (because there is no contour line for 150 feet). In this case, the exact elevation of the highest point on the island is marked by spot elevation (“x” labeled with the elevation of 108 feet).

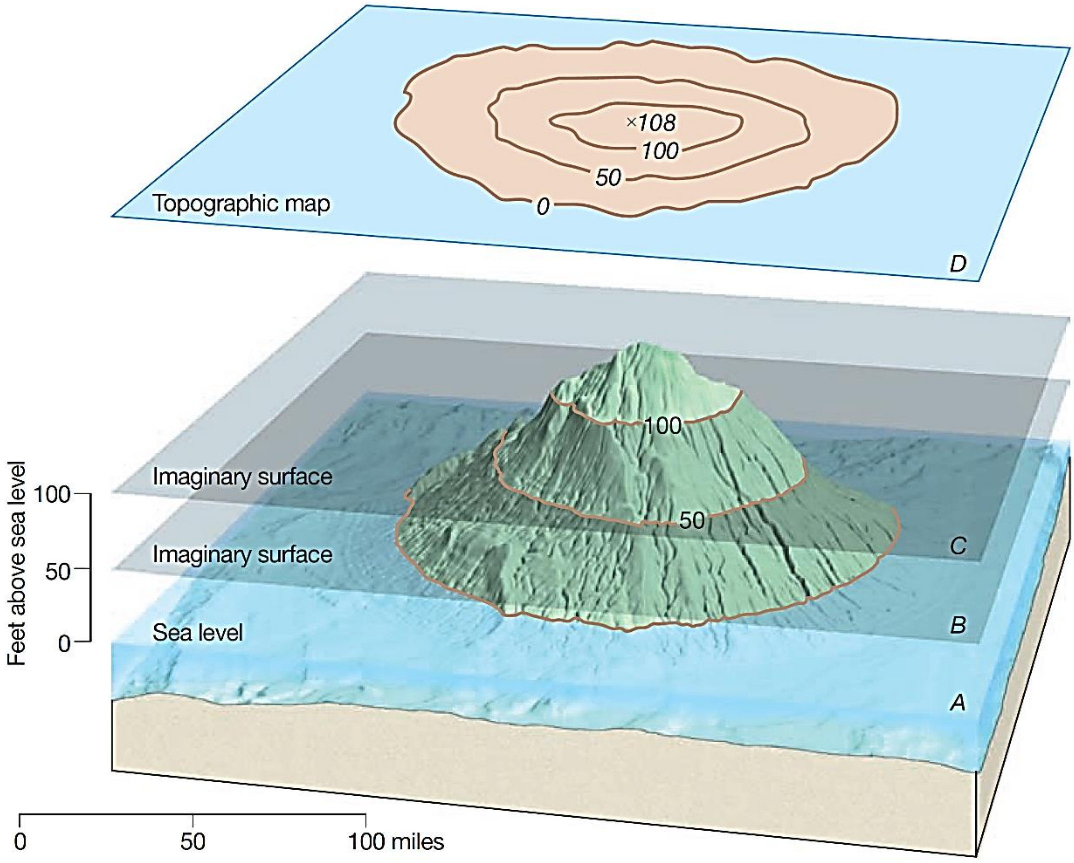


Figure 45

7.7 Rules for Contour Lines

Each **contour line** connects all points on the map that have the same elevation above sea level (Figure 46, rule 1). Look at the topographic map in Figure 41 and notice the light brown and heavy brown contour lines. The heavy brown contour lines are called **index contours,** because they have elevations printed on them (whereas the lighter contour lines do not; Figure 46, rule 6). Index contours are your starting point when reading elevations on a topographic map. For example, notice that every fifth contour line on Figure 41 is an index contour. Also notice that the index contours are labeled with elevations in increments of 200 ft. This means that the map has five contours for every 200 ft. of elevation, or a **contour interval** of 40 ft. This contour interval is specified at the center of the bottom margin of the map (Figure 41). All contour lines are multiples of the contour interval above a specific surface (almost always sea level). For example, if a map uses a 10-ft contour interval, then the contour lines represent elevations of 0 ft. (sea level), 10 ft., 20 ft., 30 ft., 40 ft., and so on. Most maps use the smallest contour interval that will allow easy readability and provide as much detail as possible. Additional rules for contour lines are also provided in Figure 46 and the common kinds of landforms represented by contour lines on topographic maps (Figure 47). Your ability to use a topographic map is based on your ability to interpret what the contour lines mean (imagine the topography).

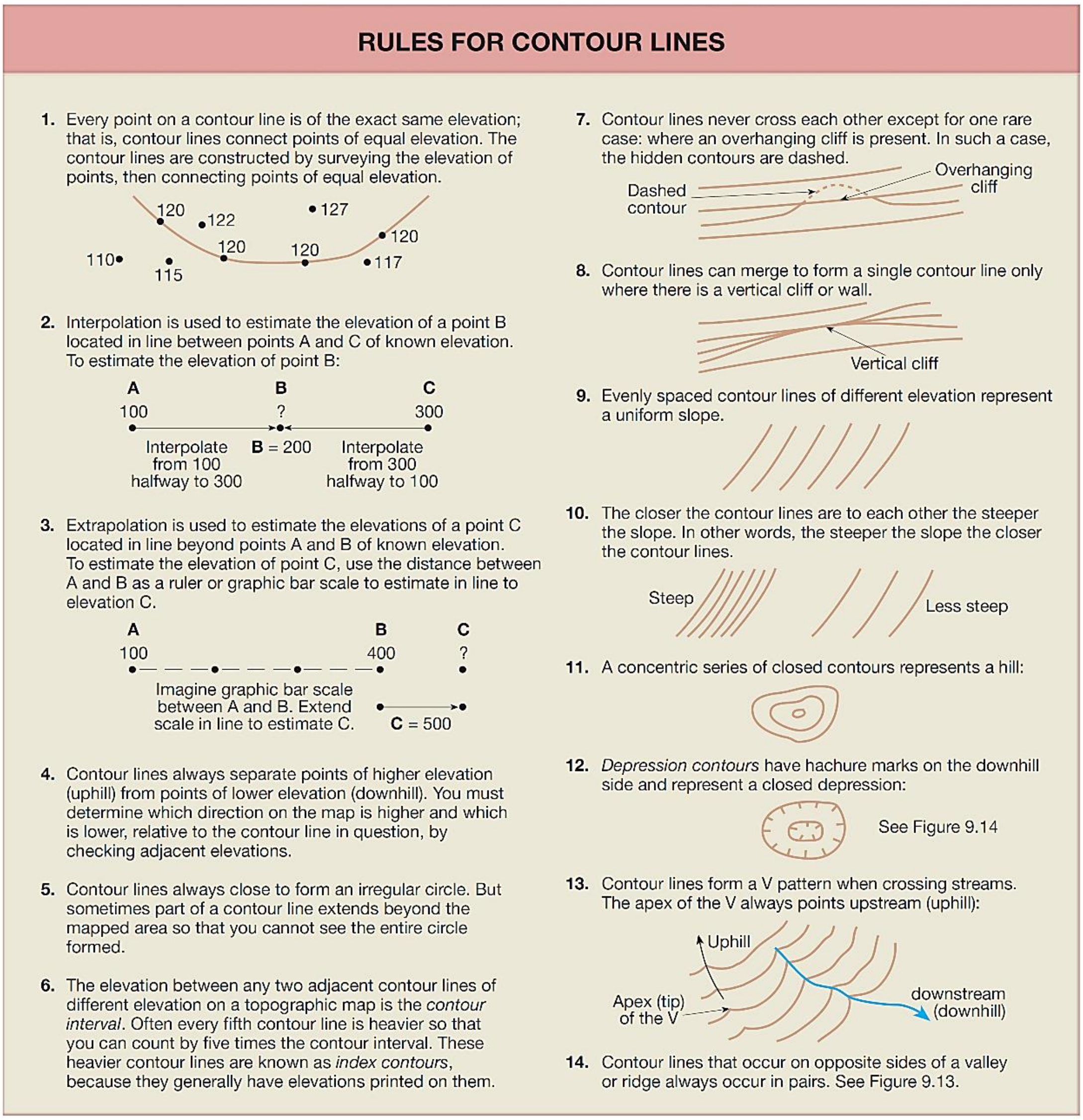


Figure 46

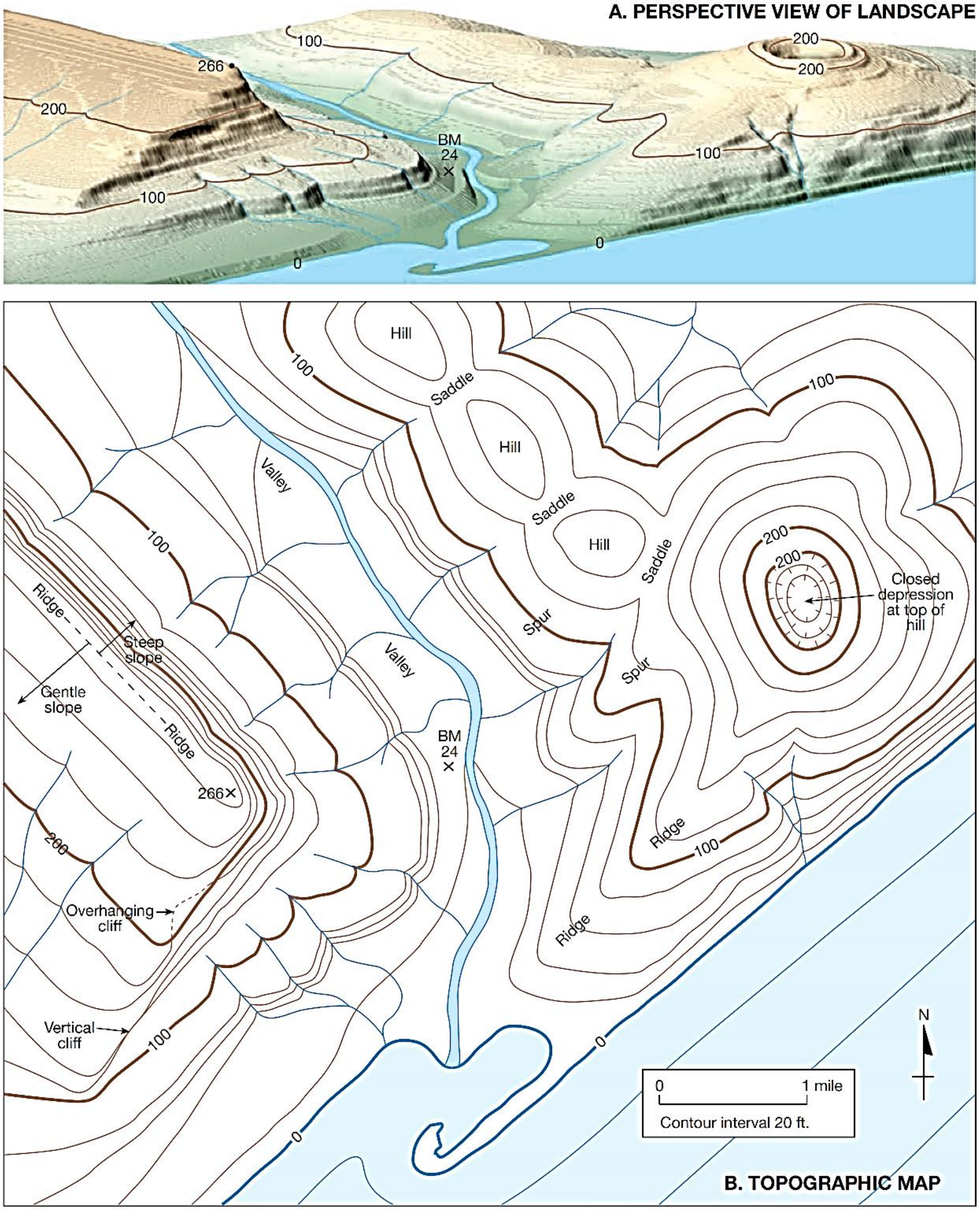


Figure 47

Reading Elevations

If a point on the map lies on an index contour, you simply read its elevation from that line. If the point lies on an unnumbered contour line, then its elevation can be determined by counting up or down from the nearest index contour. For example, if the nearest index contour is 300 ft., and your point of interest is on the fourth contour line *above* it, and the contour interval is 20 ft., then you simply count up by 20s from the index contour: 320, 340, 360, and 380. The point is 380 ft. above sea level. (Or, if the point is three contour lines *below* the index contour, you count down: 280,260, 240; the point is 240 ft. above sea level.)If a point lies between two contour lines, then you must estimate its elevation by interpolation (Figure 46, rule 2). For example, on a map with a 20-ft contour interval, a point might lie between the 340 and 360-ft contours, so you know it is between 340 and 360 ft. above sea level. If a point lies between a contour line and the margin of the map, then you must estimate its elevation by extrapolation (Figure 46, rule 3).

Depressions

Figure 48 shows how to read topographic contour lines in and adjacent to a depression. *Hachure marks* (short line segments pointing downhill) on some of the contour lines in these maps indicate the presence of a closed depression (a depression from which water cannot drain) (Figure 46, rule 12). At the top of a hill, contour lines repeat on opposite sides of the rim of the depression. On the side of a hill, the contour lines repeat only on the downhill side of the depression.

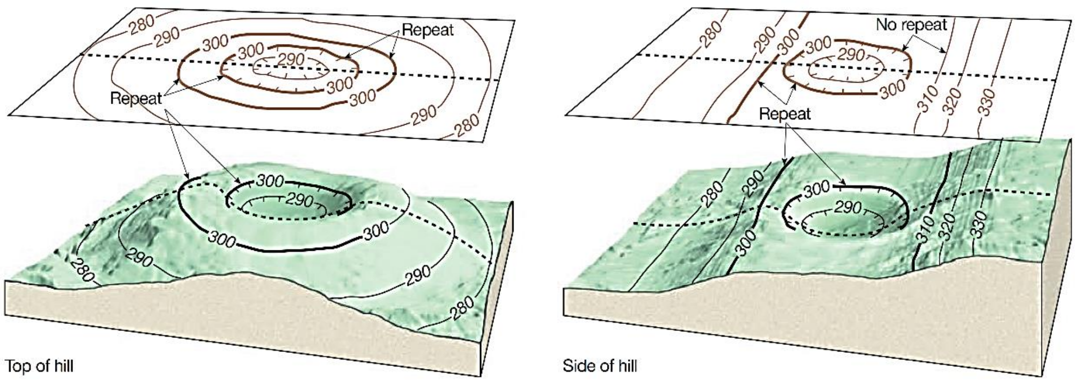


Figure 48

Ridges and Valleys

Figure 49 shows how topographic contour lines represent linear ridge crests and valley bottoms. Ridges and valleys are roughly symmetrical, so individual contour lines repeat on each side (Figure 46, rule 14).To visualize this, picture yourself walking along an imaginary trail across the ridge or valley (dashed lines in Figure 49). Every time you walk up the side of a hill or valley, you cross contour lines. Then, when you walk down the other side of the hill or valley, you re-cross contour lines of the same elevations as those crossed walking uphill.

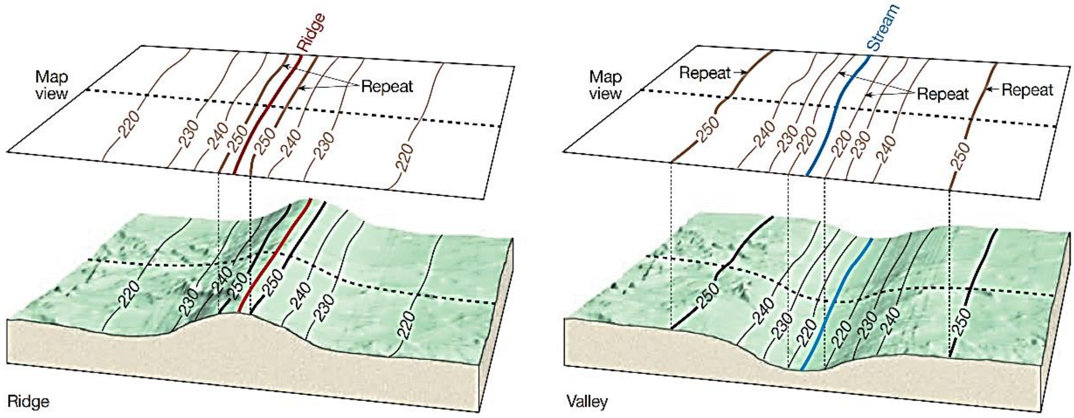


Figure 49

Spot Elevations and Benchmarks

Elevations of specific points on topographic maps (tops of peaks, bridges, survey points, etc.) sometimes are indicated directly on the maps as **spot elevations** beside a small triangle, black dot, or **x** -symbol at the exact spot of the elevation indicated. The elevations of prominent hilltops, peaks, or other features are often identified. For example, the highest point on the ridge in the west central part of Figure 47B has an elevation of 266 ft. above sea level. The notation "BM" denotes a **benchmark,** a permanent marker (usually a metal plate) placed by the U.S. Geological Survey or Bureau of Land Management at the point indicated on the map.

7.8. Relief and Gradient (Slope)

Recall that **relief** is the difference in elevation between landforms, specific points, or other features on a landscape or map. *Regional relief* (total relief) is the difference in elevation between the highest and lowest points on a topographic map. The highest point is the top of the highest hill or mountain; the lowest point is generally where the major stream of the area leaves the map, or a coastline. **Gradient** is a measure of the steepness of a slope. One way to determine and express the gradient of a slope is by measuring its steepness as an angle of ascent or descent (expressed in degrees). On a topographic map, gradient is usually determined by dividing the relief (rise or fall) between two points on the map by the distance (run) between them (expressed as a fraction in feet per mile or meters per kilometer). For example, if points **A** and **B**on a map have elevations of 200 ft. and 300 ft., and the points are located 2 miles apart.

7.9. Topographic Profiles and Vertical Exaggeration

A topographic map provides an overhead (aerial) view of an area, depicting features and relief by means of its symbols and contour lines. Occasionally a cross section of the topography is useful. A **topographic profile** is a cross-section that shows the elevations and slopes along a given line (Figure 50). To construct a topographic profile, follow the steps in Figure 50.

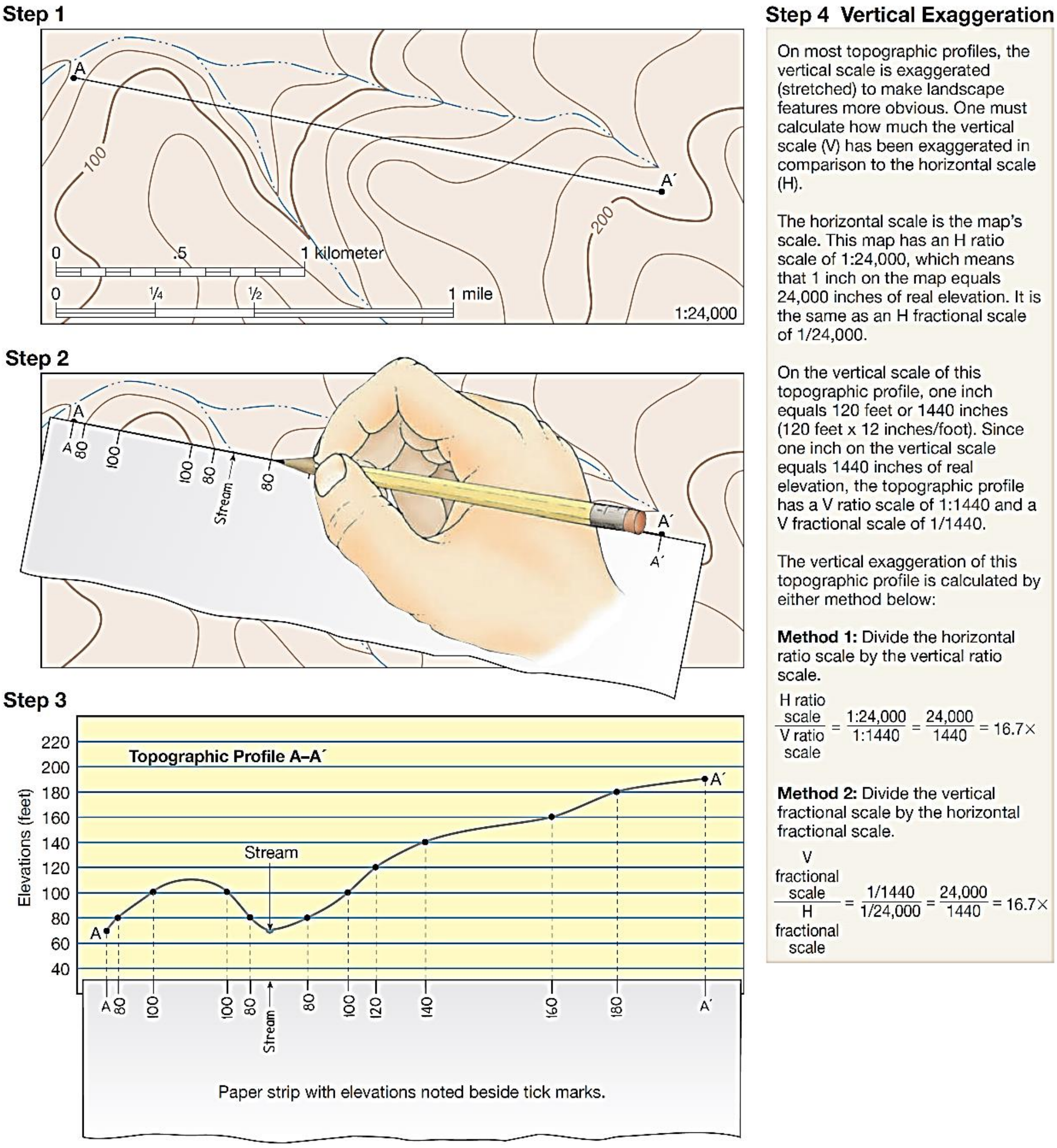


Figure 50

Part 8: Geologic Map – Block Diagram

8.1. Introduction

When two cars collide, their kinetic energy is converted to compressional stresses that force ductile metal and plastic to crumple and brittle glass to fracture and shatter. When lithospheric plates collide, pull apart, or slide past one another, a similar crumpling, fracturing, and shattering of rock occurs. However, the process is accompanied by hazardous earthquakes, may last for tens-of-millions of years, and can affect rocks over hundreds to thousands of square kilometers. Structural geology is the study of rock **deformation** (change in position, volume or shape of a body of rock) and **geologic structures** (fractures, faults, and folds that result from deformation).Structural geology relies on the Laws of Original Horizontality and Lateral Continuity, which state that sediment and lava are deposited in relatively flat, continuous, horizontal layers called *beds* or *strata* (plural of stratum) like a layer cake. Wherever strata are folded (no longer relatively flat), tilted (no longer horizontal), or fractured apart (no longer continuous), they have been deformed. Structural geologists must decipher the shapes and internal characteristics of geologic structures to help locate the mineral, energy, and water resources hidden within them and to be sure that dams, power plants, and other structures are safely constructed on stable ground. Interpreting geologic structures requires knowledge of stress–strain relationships and the nature of the rocks themselves.

8.2. Stress and Strain

Stress is the amount of pressure or force acting on a unit surface area, like pounds per square inch or kilograms per square meter. Strain (deformation) occurs when the rock yields (gives in) to the stress. In other words, stress (pressure, force) acts on a body of rock and causes it to deform, or strain. **Confining pressure** is pressure (stress, force) applied equally in all directions and shown by the red arrows in Figure 51**.** It is like the water pressure you feel all over your body when you dive to the bottom of a swimming pool. The deeper you go, the more confining is the water pressure you feel. The same thing happens with rocks. Confining pressure is equal in all directions and increases with depth below Earth's surface. Under low confining pressure, rocks remain *brittle,* which means that they tend to fracture and shatter when they yield to stress. Under high confining pressure, they undergo *dilation* (decrease in volume). This is what compacts sediment into more dense sedimentary rock (and eventually metamorphic rock). Rocks under high confining pressure also lose their brittle nature and, instead, become *ductile* —capable of plastic flow and folding if the confining pressure is accompanied by directed pressure.

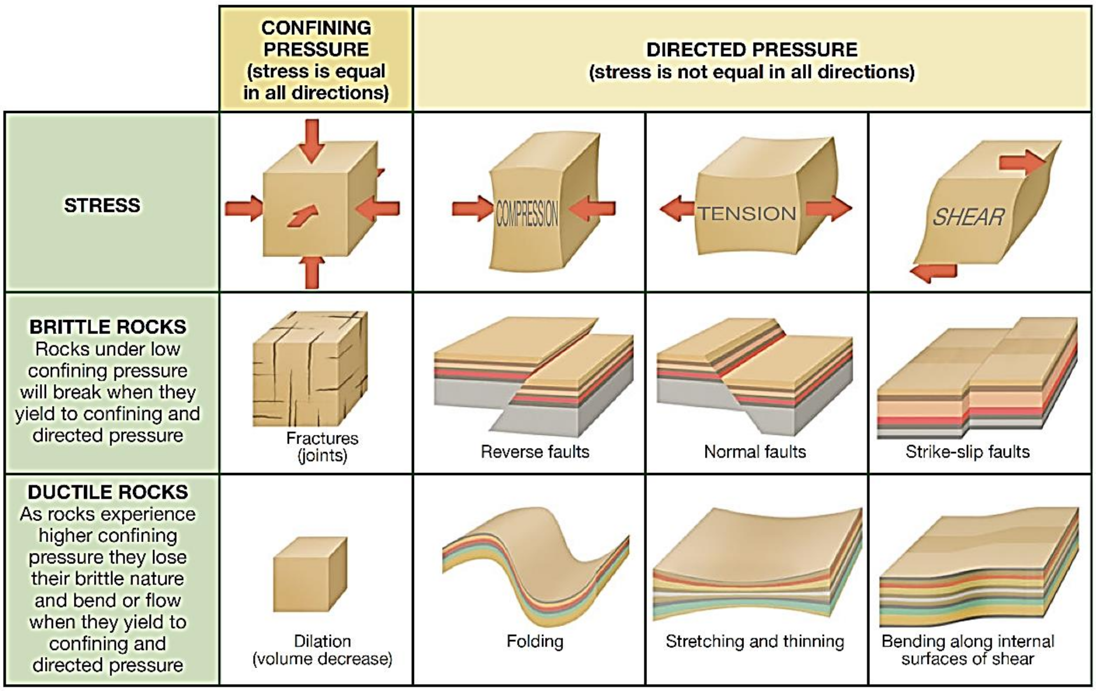


Figure 51

Directed pressure occurs when the stress is unequal—greater in one direction than another (while the rocks are also under some amount of confining pressure). The vector directions of directed stress are indicated with arrows in Figure 51. Stress arrows pointed directly at one another indicate **compressional stresses** —opposing stresses that push and squeeze rocks (shorten them parallel to the fractures and faults as the rocks yield to compressional stress. Stress arrows pointing directly away from one another indicate **tensional stresses** —stresses that pull rocks apart (lengthen them parallel to the arrows). Brittle rocks develop faults and ductile materials stretch (become elongated along the axis of the tensional stresses). Stress arrows pointing past one another indicate **shear stresses** —stresses that cause parts of the body of rock to slide past one another in opposite directions and parallel to the surface between them. Brittle rocks develop faults and ductile materials bend.

8.3. Formations, Geologic Maps, and Block Diagrams

Geologists can see how bodies of bedrock or sediment are positioned three dimensionally where they *crop out* (stick out of the ground as an outcrop) at Earth's surface. The outcrops are classified into mappable units, called *formations*.

Formations

Formations are mappable rock units (Figure 52). This means that they can be distinguished from one another "in the field" and are large enough to appear on geologic maps (which usually cover a 712-minute quadrangle).The surfaces between formations are called **formation contacts** and appear as black lines on geologic maps and cross sections. Formations may be subdivided into mappable *members* composed of *beds* (individual strata, layers of rock or sediment). **Bedding plane contacts** are surfaces between individual beds within a formation. Individual beds/strata are rarely mapped because they are not wide enough to show up on a typical 712-minutequadrangle map (where a pencil line equals about 6meters, 20 ft.). Geologists assign each formation a formal name, which is capitalized (e.g., Yellow Formation or Yellow Fm in Figure 52) and published with a description of its distinguishing features and a "type locality" upon which the name and distinguishing features are based. The formal name can include the word "formation" or the name of the rock type that makes up the formation. For example, the Dakota Formation is also formally called the Dakota Sandstone.

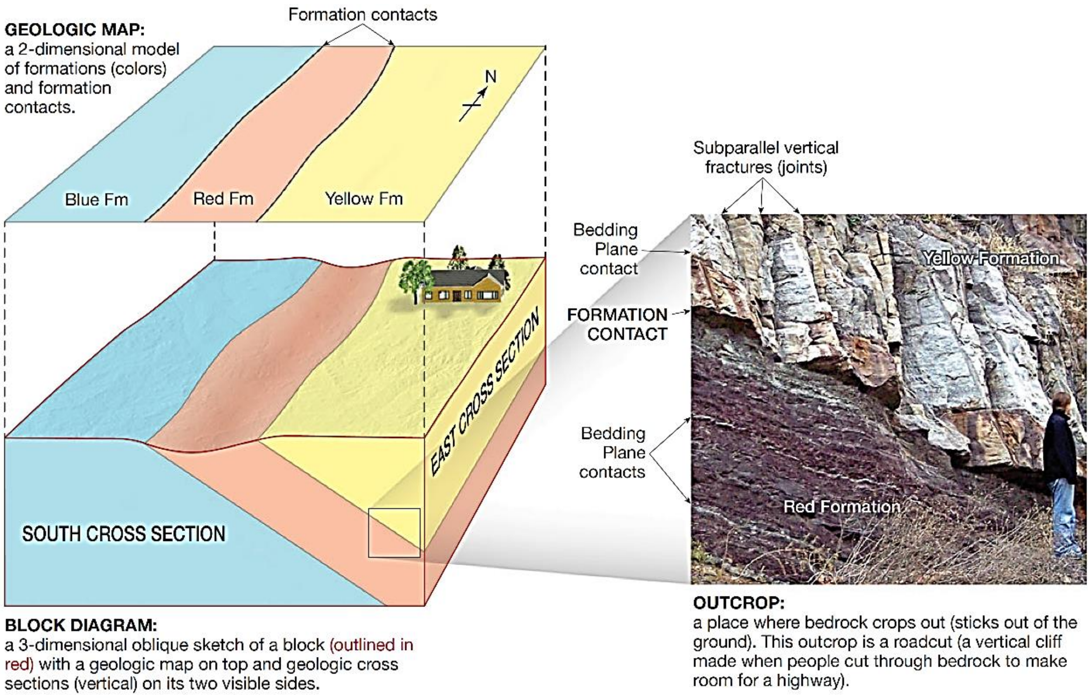


Figure 52

Geologic Maps

Geologic maps are flat (two-dimensional, like a sheet of paper or computer display) models of Earth's surface, viewed from directly above, that use different colors and symbols to represent the locations of formations (Figure 52). You can search for U.S. geologic maps and formation descriptions with the National Geologic Map Database and Geologic Names Lexicon (http://ngmdb.usgs.gov). This site also has links to state geologic maps.

Block Diagrams

The widths of formations vary in outcrops and on maps because of variations in formation thickness, angle of tilting, and the angle of the land surface at which they crop out. To visualize this, geologist's use block diagrams. A **block diagram** is an oblique sketch of a block of Earth's lithosphere, like a block of cake cut from a sheet cake and viewed from one corner, just above the level of the table on which the cake is sitting. It has a geologic map on top and a geologic cross section on each of its visible sides (Figure 52). Notice how the block diagram in Figure 52 gives you a three-dimensional perspective of how the formations are oriented.

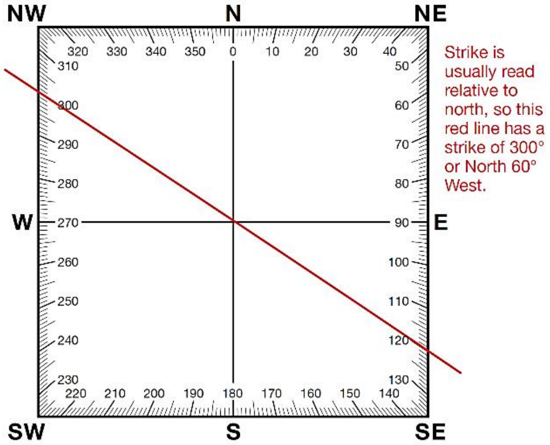
8.4. Attitude—Strike and Dip

The geologic map and block diagram in Figure 52 shows where each formation occurs but it does not yet include any information about its three-dimensional orientation. The block diagram in Figure 52 shows the three- dimensional orientation of each formation, but it is an oblique view in which angles are distorted. Therefore, geologists must measure the orientation of formations, and then record the orientation data on maps and block diagrams using symbols.

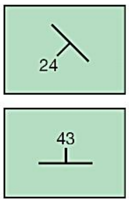
What Is Attitude?

Attitude is the orientation of a rock unit, surface (contact), or line relative to horizontal and/or a compass direction. Geologists have devised a system of strike and-dip for measuring and describing the attitude of tilted rock layers or surfaces, so they can visualize how they have been deformed from their original horizontality (Figure 53). Strike and dip are usually measured directly from an outcrop using a compass and clinometer (device for measuring the angle of inclined surfaces). However, they can be measured or estimated by the shapes of landforms observed from a distance or on aerial photographs, ortho-images, and satellite images (Figure 54).

STRIKE AND DIP ON MAPS AND IMAGES OF LANDSCAPES

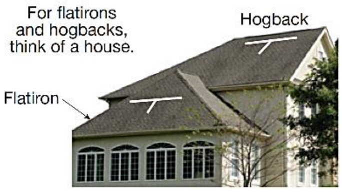


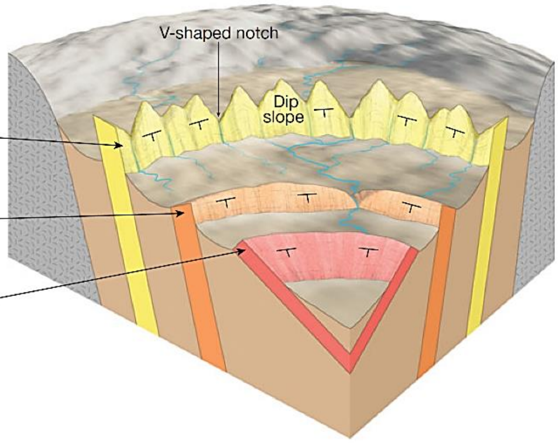
Examples of how to read strike-and-dip symbols. Notice how strike is normally expressed relative to north:



Quadrant: North 45° West (or South 45° East), 24° Southwest
Azimuth: Strike = 315° (or Strike = 135°), Dip = 24° @ 245°

Quadrant: North 90° East (or South 90° West), 43° North
Azimuth: Strike = 090° (or Strike = 270°), Dip = 43° @ 000°



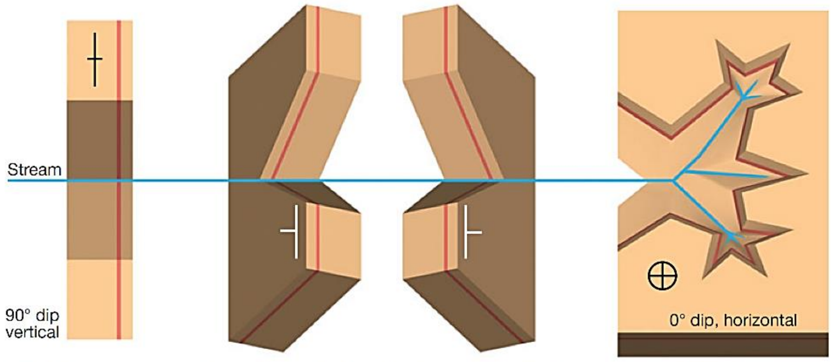


Flatiron–a triangular ridge of steeply dipping resistant rock between two V-shaped notches (cut by streams) and resembling the flat pointed end of a clothing iron or a triangular roof (above). A jagged ridge of flatirons is parallel to strike, and the flatiron surfaces are dip slopes.

Hogback–a sharp-crested ridge of resistant rock that slopes equally on both sides, so it resembles the back of a razorback hog. The ridge crest is parallel to strike and dip is > 30°.

Cuesta–a ridge or hill of resistant rock with a short steep slope on one side (scarp) and a long gentle dip slope on the other side. The ridge is parallel to strike and the long gentle slope is a dip slope. Dip is < 30°.

RULE OF Vs FOR FINDING DIP DIRECTION



Vertical strata: No V-shapes in the rock layers or contacts can be seen on orthoimages and maps.

Tilted strata: Streams cut V-shapes into the rock layers and contacts that point in the direction of dip (except in rare cases when the slope of the stream bed is greater than the dip of the strata).

Horizontal strata: Streams cut V-shapes into the rock layers and contacts that point upstream and form a characteristic dendritic drainage (streams branching like a plant).

Figure 53

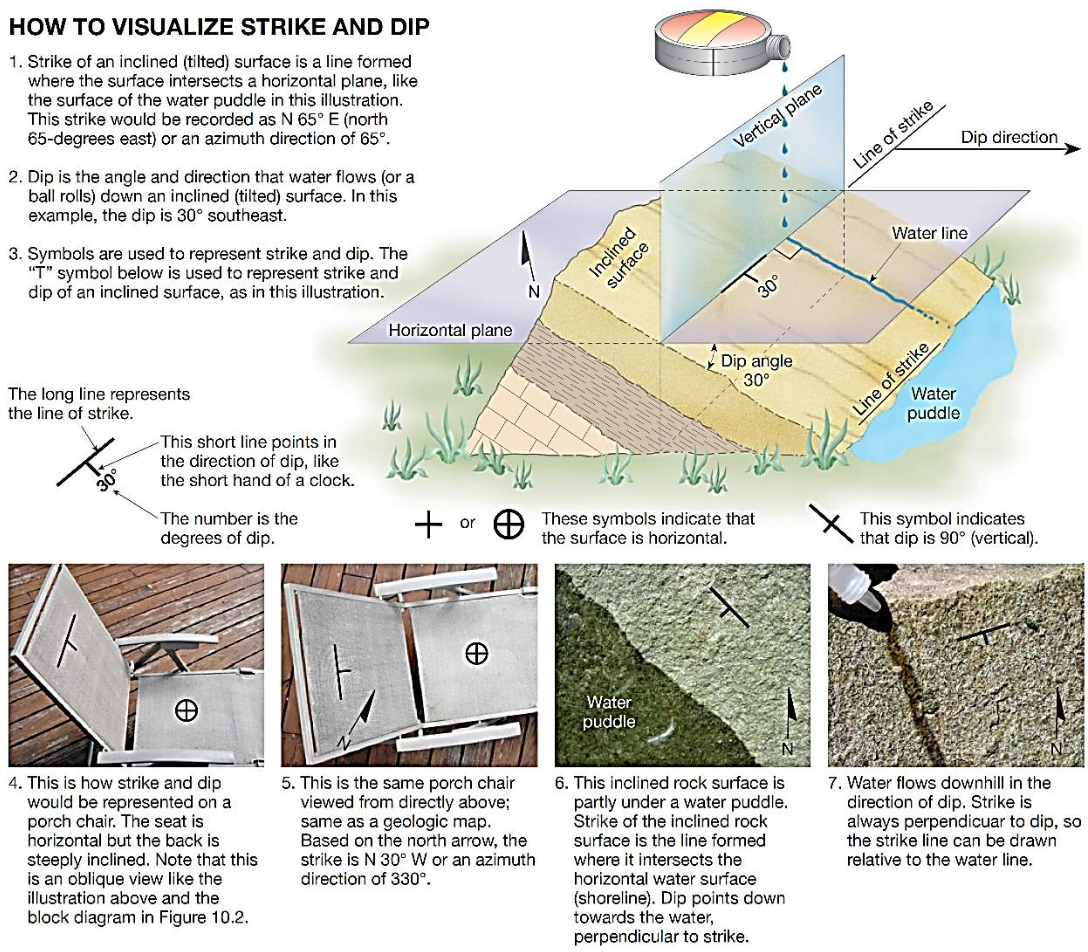


Figure 54

What Is Strike?

Strike is the *compass bearing* (line of direction or trend) of a line formed by the intersection of a horizontal plane, such as the surface of a lake, and an inclined surface (contact) or rock layer such as a bed, stratum, or formation (Figure 53).When the strike is expressed in degrees east or west of true north or true south, it is called a *quadrant bearing*. However, it is more common to express strike as a three-digit *azimuth bearing* in degrees between 000 and 360. In azimuth form, north is 000° (or 360°), east is 090°, south is 180°, and west is 270°. Because the azimuth data represents directions with a number, instead of letters and numbers, it is easier to enter it into spreadsheets for numerical analysis. Strike is usually expressed relative to north (Figure 54).

What Is Dip?

Dip is the *angle* between a horizontal plane and an inclined (tilted) surface, measured perpendicular to strike. The surface may be a formation contact, bedding plane contact, fault, or fracture. As you can see in Figure 53, a thin stream of water poured onto an inclined surface always runs downhill along the **dip direction,** which is always perpendicular to the line of strike. The inclination of the water line, compared to a horizontal plane, is the **dip angle.** Dip is always expressed in terms of its dip angle and dip direction. The dip angle is always expressed in degrees of angle from 0 (horizontal) to 90(vertical). The dip direction can be expressed as a three-digit azimuth direction or as a quadrant direction.

Strike-and-Dip Symbols

A strike-and-dip symbol consists of a long line showing the orientation of strike, plus a short line for the direction of dip. Note that the dip direction is always perpendicular to strike and points *down dip* —the direction that drops of water would flow or a ball would roll. Accompanying numerals indicate the dip angle in degrees. See Figure 54 for examples of how to read and express strike and dip in quadrant or azimuth form. Also note that special symbols are used for horizontal strata (rock layers) and vertical strata (Figure 55).

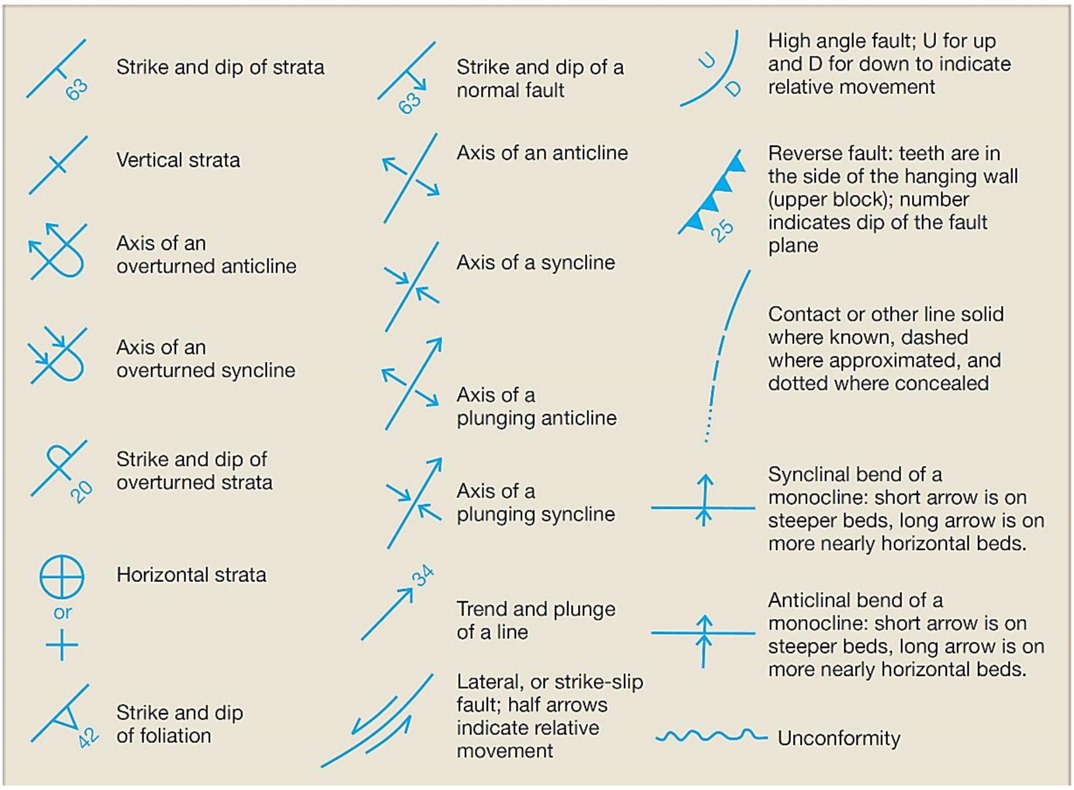


Figure 55

8.5. Constructing Geologic Cross Sections

Geologic maps contain evidence of the surface locations and orientations of formations and the structures into which they have been deformed. To help visualize the geologic structures, geologists convert this surface information into vertical geologic cross sections like the sides of the block diagram in Figure 52. Geologic cross sections are often drawn perpendicular to strike, so you can see the dip of the rocks more exactly. Most are drawn beneath a topographic profile (Figure 56), so you can see the topographic expression of the formations and geologic structures. However, some geologic cross sections are just rectangular cross-sections that do not show the topography. Once you have constructed a topographic profile (or drawn a rectangular space) for the map line segment of the cross section (Figure 56), then follow the directions in Figure 56 to add the geologic information. You will need to use a pencil (with a good eraser), protractor, ruler, and colored pencils and be very neat and exact in your work.

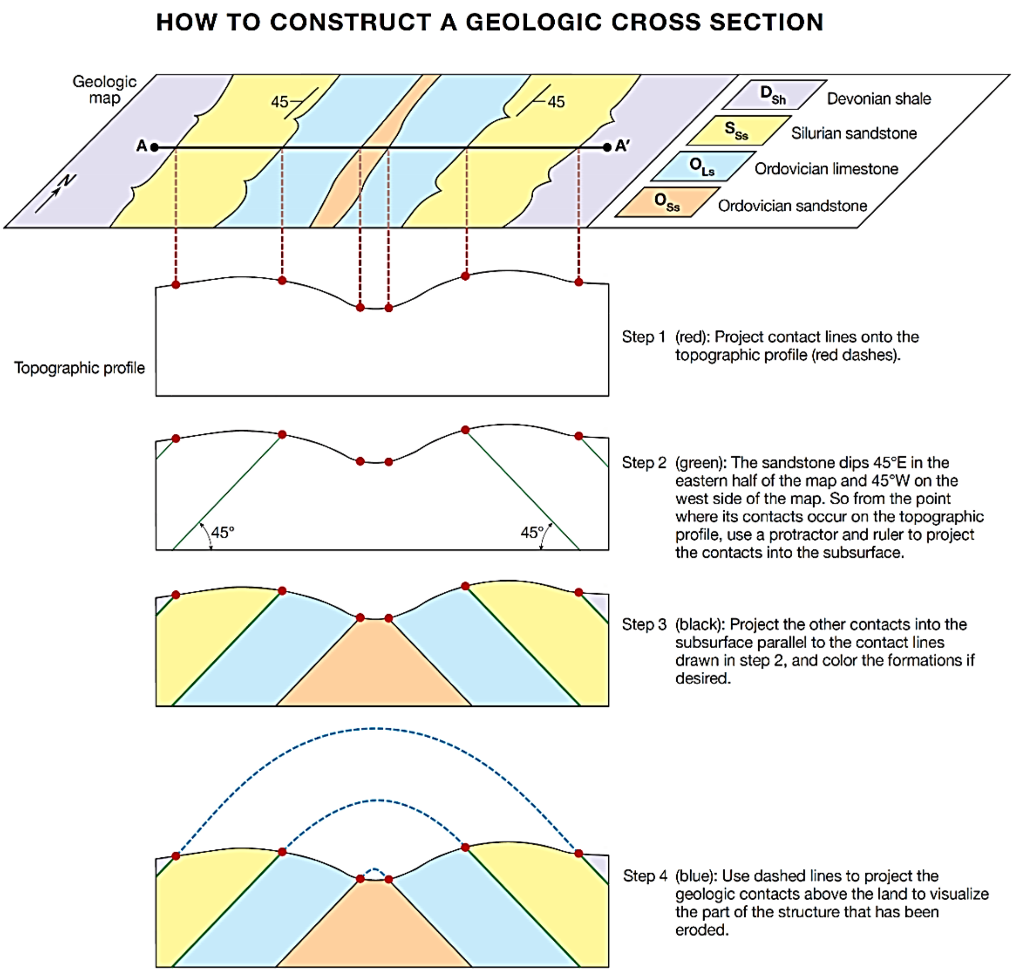


Figure 56

8.6. Fractures and Faults

Brittle deformation is said to occur when rocks **fracture** (crack) or **fault** (slide in opposite directions along a crack in the rock). Motion and scraping of brittle rocks along the fault surfaces causes development of *slickensides*, polished surfaces with lineation and step-like linear ridges that indicate the direction of movement along the fault (Figure 57). If you gently rub the palm of your handback and forth along the slickensides, then one direction will seem smoother (down the step like ridges) than the other. That is the relative direction of the side of the fault represented by your hand. Faults form when brittle rocks experience one of these three kinds of directed pressure (stress): *tension* (pulling apart or lengthening), *compression* (pushing together, compacting, and shortening), or *shear* (smearing or tearing). The three kinds of stress produce three different kinds of faults: normal, reverse/thrust, and strike-slip (Figure 57). Normal and reverse/thrust faults both involve vertical motions of rocks. These faults are named by noting the *sense of motion* of the top surface of the fault (top block) relative to the bottom surface (bottom block), regardless of which one actually has moved. The top surface of the fault is called the **hanging wall** and is the base of the **hanging wall** (top) **block** of rock. The bottom surface of the fault is called the **footwall** and forms the top of the **footwall block.** Whenever you see a fault in a vertical cross section, just imagine yourself walking on the fault surface. The surface that your feet would touch is the footwall.

Normal Faults

Normal faults are caused by tension (rock lengthening).As tensional stress pulls the rocks apart, gravity pulls down the hanging wall block. Therefore, normal faulting gets its name because it is a normal response to gravity. You can recognize normal faults by recognizing the motion of the hanging wall block relative to the footwall block. First, imagine that the footwall block is stable (has not moved).If the hanging wall block has moved downward in relation to the footwall block, then the fault is a normal fault.

Reverse Faults

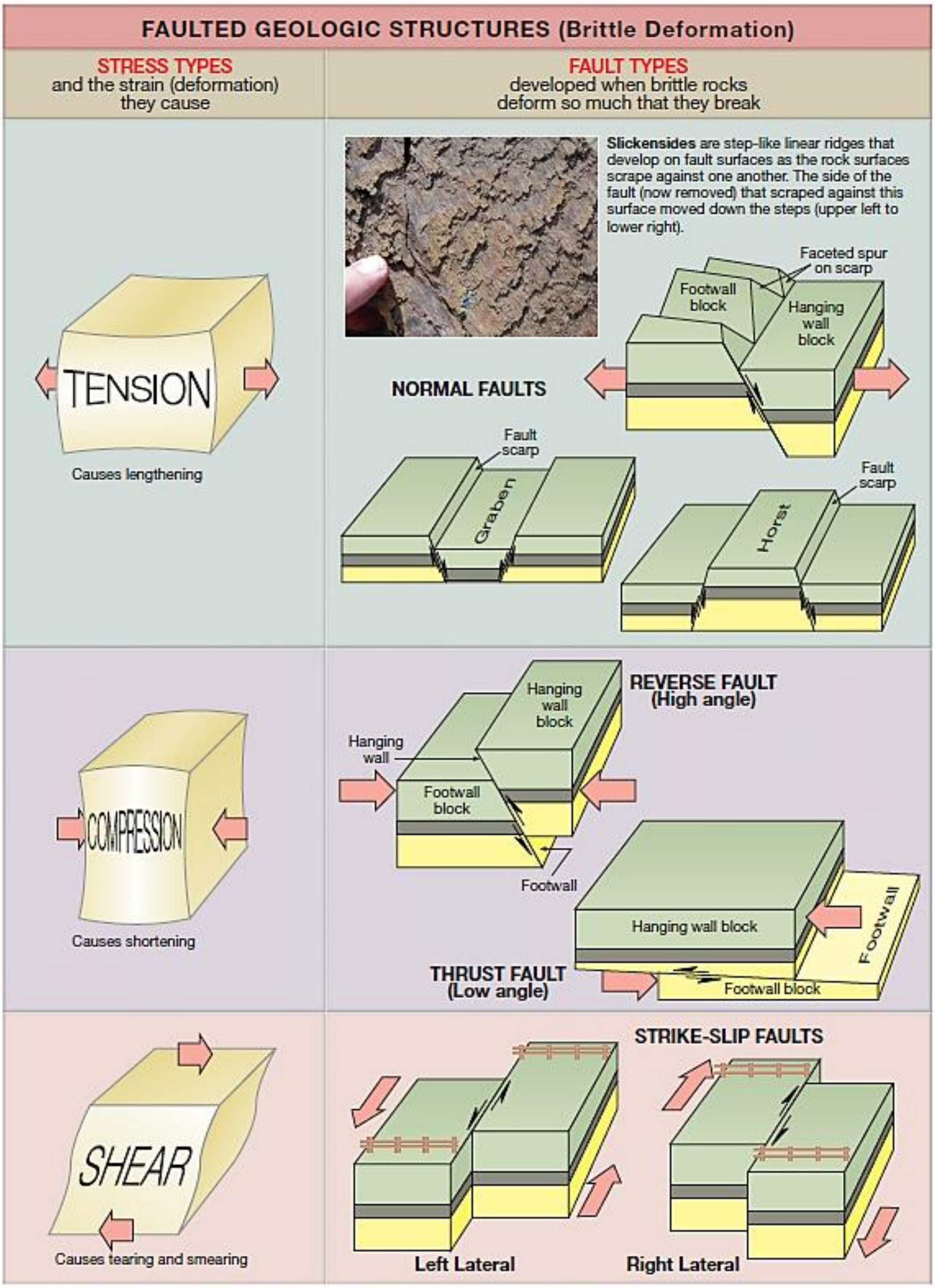
Reverse faults are caused by compression (rock shortening). As compressional stress pushes the rocks together, one block of rock gets pushed atop another. You can recognize reverse faults by recognizing the motion of the hanging wall block relative to the footwall block. First, imagine that the footwall block is stable (has not moved).If the hanging wall block has moved upward in relation to the footwall block, then the fault is a reverse fault. **Thrust faults** are reverse faults that develop at a very low angle and may be very difficult to recognize (Figure 57). Reverse faults and thrust faults generally place older strata on top of younger strata.

Strike–Slip Faults

Strike–slip faults (lateral faults) are caused by shear and involve horizontal motions of rocks (Figure 57). If you stand on one side of a strike–slip fault and look across it, then the rocks on the opposite side of the fault will appear to have slipped to the right or left. Along a *right-lateral (strike–slip) fault*, the rocks on the opposite side of the fault appear to have moved to the right. Along a *left-lateral (strike–slip) fault*, the rocks on the opposite side of the fault appear to have moved to the left.

8.7. Folded Structures

Folds are upward, downward, or sideways bends of rock layers. **Synclines** are “down folds” or “concave folds,” with the *youngest* rocks in the middle (Figure 58). **Anticlines** are “up folds” or “convex folds” with the *oldest* rocks in the middle. In a fold, each stratum (rock layer) is bent around an imaginary axis, like the crease in a piece of folded paper. This is the **fold axis** (or **hinge line)**. For all strata in a fold, the fold axes lie within the **axial plane** of the fold. The axial plane divides the fold into two **limbs**. For symmetric anticlines and synclines, the fold axis is vertical, but most anticlines and synclines are asymmetric. The axial plane of asymmetric folds is leaning to one side or the other, so one limb is steeper and shorter than the other. The fold axis may not be horizontal, but rather it may plunge into the ground. This is called a **plunging fold**. **Plunge** is the angle between the fold axis and horizontal. The **trend** of the plunge is the bearing (compass direction), measured in the direction that the axis is inclined downward. You can also think of the trend of a plunging fold as the direction a marble would roll if it were rolled down the plunging axis of the fold. If a fold is tilted so that one limb is upside down, then the entire fold is called an **overturned fold**. **Monoclines** have two axial planes that separate two nearly horizontal limbs from a single, more steeply inclined limb. **Domes** and **basins** are large, somewhat circular structures formed when strata are warped upward, like an upside-down bowl (dome) or downward, like a bowl (basin). Strata are oldest at the center of a dome, and youngest at the center of a basin (Figure 59).



Faults (brittle deformation). Three classes of faults result from three kinds of directed pressure (stress: tension, compression, shear) applied to brittle rocks.

Figure 57

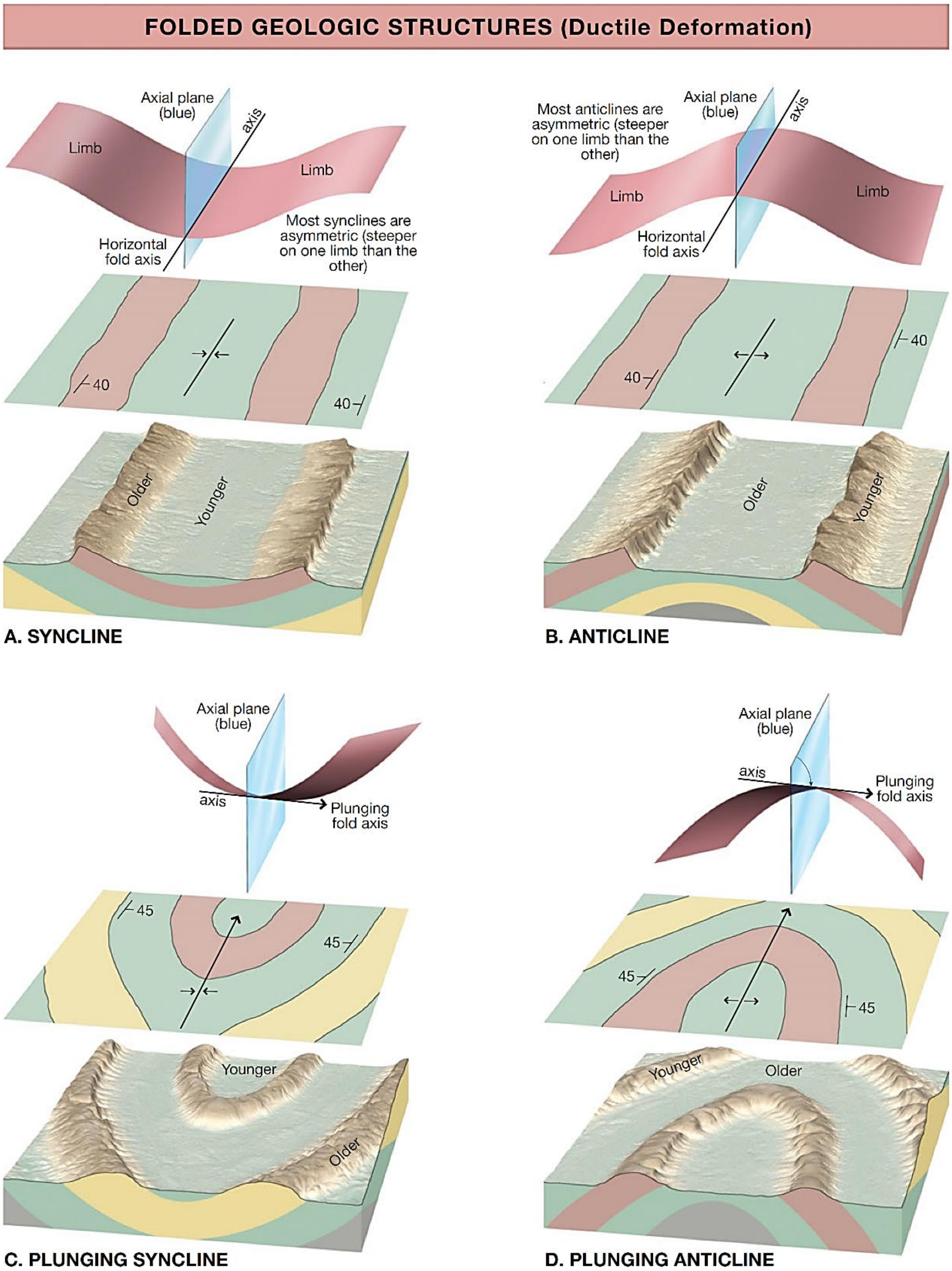

FOLDED GEOLOGIC STRUCTURES (Ductile Deformation)
Axial plane (blue)
axis
Limb
Limb
Horizontal fold axis
Most synclines are asymmetric (steeper on one limb than the other)
40
40
Older
Younger
A. SYNCLINE
Most anticlines are asymmetric (steeper on one limb than the other)
Axial plane (blue)
axis
Limb
Limb
Horizontal fold axis
40
40
Older
Younger
B. ANTICLINE
Axial plane (blue)
axis
Plunging fold axis
45
45
Younger
Older
C. PLUNGING SYNCLINE
Axial plane (blue)
axis
Plunging fold axis
45
45
Younger
Older
D. PLUNGING ANTICLINE

Figure 58

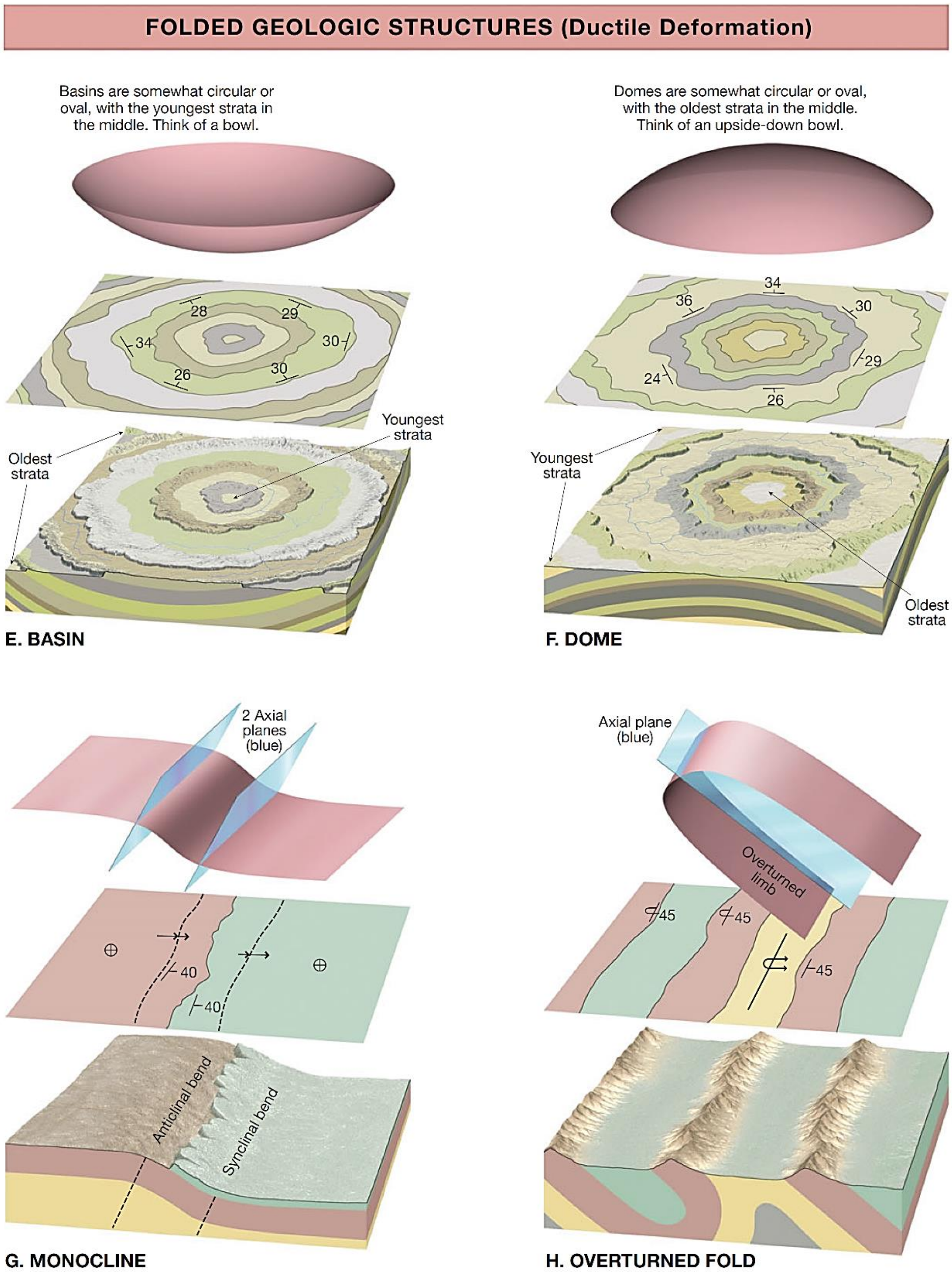

FOLDED GEOLOGIC STRUCTURES (Ductile Deformation)
Basins are somewhat circular or oval, with the youngest strata in the middle. Think of a bowl.
Domes are somewhat circular or oval, with the oldest strata in the middle. Think of an upside-down bowl.
28
29
34
30
26
30
Youngest strata
Oldest strata
34
36
30
29
24
26
Youngest strata
Oldest strata
E. BASIN
F. DOME
2 Axial planes (blue)
40
40
Anticlinal bend
Synclinal bend
G. MONOCLINE
Axial plane (blue)
Overturned limb
45
45
45
H. OVERTURNED FOLD

Figure 59

9. References

(1) The American Geological Institute & the National Association of Geoscience Teachers. (2015). *Laboratory manual in physical geology*. 10th edition, Edited by: Richard M. Busch, (editor: West Chester University of Pennsylvania); illustrated by Dennis Tasa, Tasa Graphic Arts, Inc.

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(3) Greg P. Gardiner. (2011). *Introductory Physical Geology: Laboratory Manual for Distance Learning.* Coastline Community College, Coast Learning Systems. Kendall/Hunt Publishing Company. USA.
ISBN-13: 978-0-7575-6320-1

ACTIVITY 1 Spheres of Matter, Energy, and Change

Name: ____________________ **Course/Section:** ____________________ **Date:** ____________

A. Complete the table below.

State of Matter	Sphere	What is the main source of energy that powers the sphere (Sun or geothermal energy)?	Give examples of named parts of this sphere that you have personally encountered.
GAS: What is a gas?	What sphere is made mostly of gases?		
LIQUID: What is a liquid?	What sphere is made mostly of liquid water?		
	What subsphere of Earth in Figure 1.8 is a mostly liquid rock?	Geothermal energy	Not encountered by humans.
SOLID: What is a solid?	What subsphere is made mostly of water ice?		
	What sphere is made mostly of solid rock (besides water ice)?		
SOLIDS, LIQUIDS, AND GASES	What sphere consists of living parts containing solids, liquids, and gases?		

COMMON PROCESSES OF CHANGE

Process	Kind of Change	Example
Melting	Solid phase changes to liquid phase.	Water ice turns to water.
Freezing	Liquid phase changes to solid phase.	Water turns to water ice.
Evaporation	Liquid phase changes to gas (vapor) phase.	Water turns to water vapor or steam (hot water vapor).
Condensation	Gas (vapor) phase changes to liquid phase.	Water vapor turns to water droplets.
Sublimation	Solid phase changes directly to a gas (vapor) phase.	Dry ice (carbon dioxide ice) turns to carbon dioxide gas.
Deposition	The laying down of solid material as when a gas phase changes into a solid phase or solid particles settle out of a fluid.	Frost is the deposition of ice (solid phase) from water vapor (gas). There is deposition of sand and gravel on beaches.
Dissolution	A substance becomes evenly dipersed into a liquid (or gas). The dispersed substance is called a solute, and the liquid (or gas) that causes the dissolution is called a solvent.	Table salt (solute) dissolves in water (solvent).
Vaporization	Solid or liquid changes into a gas (vapor), due to evaporation or sublimation.	Water turns to water vapor or water ice turns directly to water vapor.
Reaction	Any change that results in formation of a new chemical substance (by combining two or more different substances).	Sulfur dioxide (gas) combines with water vapor in the atmosphere to form sulfuric acid, one of the acids in rain.
Decomposition reaction	An irreversible reaction. The different elements in a chemical compound are irreversibly split apart from one another to form new compounds.	Feldspar mineral crystals decompose to clay minerals and metal oxides (rust).
Dissociation	A reversible reaction in which some of the elements in a chemical compound are temporarily split up. They can combine again under the right conditions to form back into the starting compound.	The mineral gypsum dissociates into water and calcium sulfate, which can recombine to form gypsum again.
Chemical precipitation	A solid that forms when a liquid solution evaporates or reacts with another substance.	Salt forms as ocean water evaporates. Table salt forms when hydrochloric acid and sodium hydroxide solutions are mixed.
Photosynthesis	Sugar (glucose) and oxygen are produced from the reaction of carbon dioxide and water in the presence of sunlight (solar energy).	Plants produce glucose sugar and oxygen.
Respiration	Sugar (glucose) and oxygen undergo combustion (burning) without flames and change to carbon dioxide, water, and heat energy.	Plants and animals obtain their energy from respiration.
Transpiration	Water vapor is produced by the biological processes of animals and plants (respiration, photosynthesis).	Plants release water vapor to the atmosphere through their pores.
Evolution	Change over time (gradually or in stages).	Biological evolution, change in the shape of Earth's landforms over time.
Crystallization	Atoms, ions, or molecules arrange themselves into a regular repeating 3-dimensional pattern. The formation of a crystal.	Water vapor freezes into snowflakes. Liquid magma cools into a solid mass of crystals.
Weathering	Materials are fragmented, worn, or chemically decomposed.	Rocks break apart, get worn into pebbles or sand, dissolve, rust, or decompose to mud.
Transportation	Materials are pushed, bounced, or carried by water, wind, ice, or organisms.	Sand and soil are blown away. Streams push, bounce, and carry materials downstream.
Radiation	Transfer of energy through space; not via materials.	Sunlight radiates from the Sun to Earth.
Conduction	Transfer of energy by direct contact between molecules of two stationary materials.	A pan conducts heat from the hot stove top that it sits on.
Convection	Transfer of energy in moving molecules of flowing materials.	Thermal energy in lava is transferred as the lava flows from a volcano.
Convection cycling	Cyclic current motion (and heat transfer) within a flowing body of matter due to unequal heating and cooling. As part of the material is heated and rises, a cooler part of the material descends to replace it (whereupon it is reheated and rises again to form a convection cell.	Warm air in the atmosphere rises and cooler air descends to replace it; water boiling in a pot.

FIGURE 1.1 Some common processes of change on Earth.

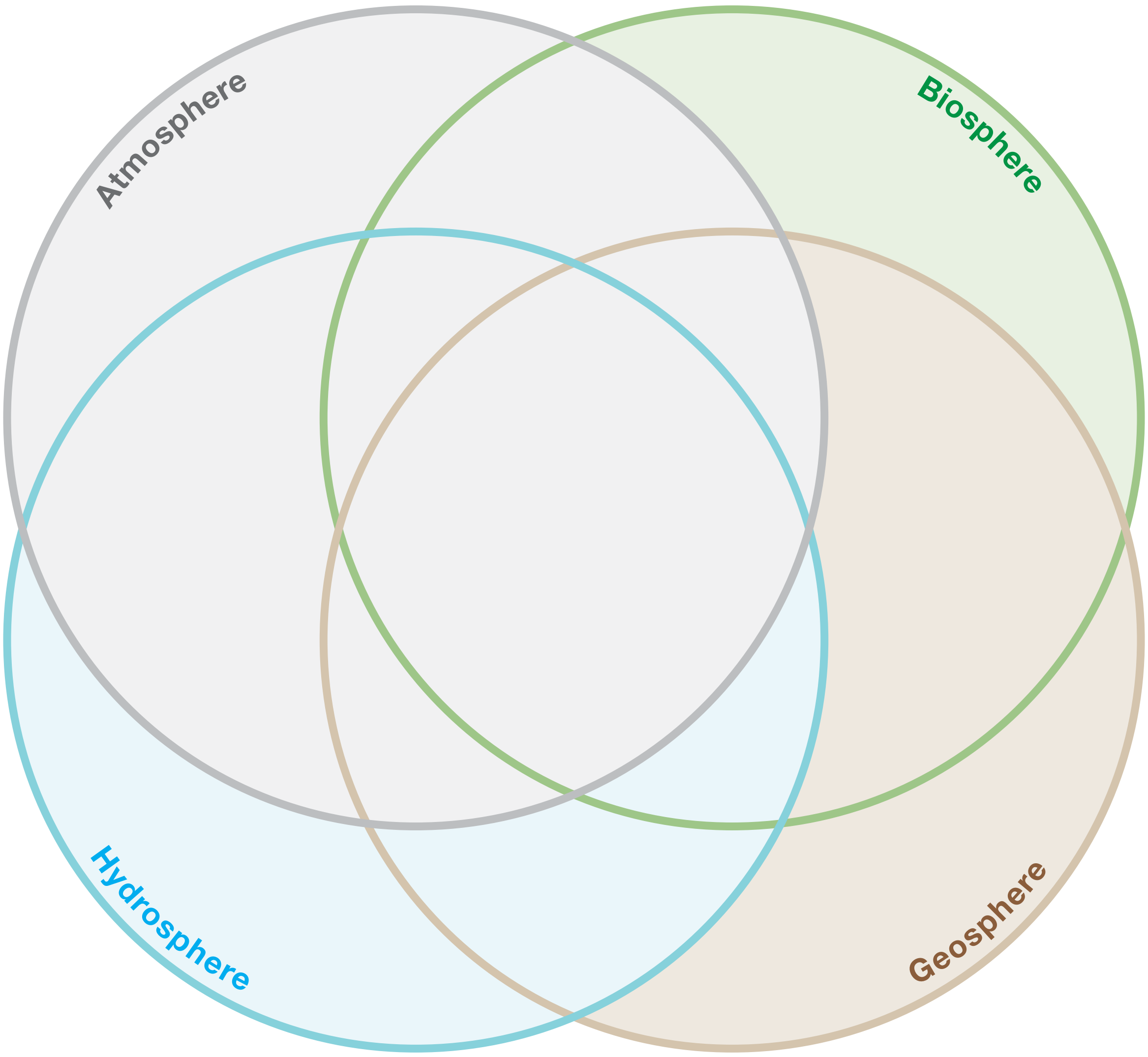
B. Study the processes of change in **FIGURE 1.1**, then complete the table below as done for deposition.

Process of Change	Sphere(s) involved in the process or product	Give an example of how you observed the process happening or how you encountered the result of the process	What caused the process to happen?
Deposition	atmosphere geosphere	I saw frost crystals on cold metal surfaces and windows of my car last winter.	The temperature of the metal was so cold that water vapor in the air formed ice crystals on contact with the metal.
	hydrosphere geosphere atmosphere	At the seashore, sand covered up my feet as waves crashed onto the beach where I was standing.	Wind caused waves. Waves carried the sand. When waves broke, they lost energy and the sand settled out.
Evaporation			
Condensation			
Decomposition reaction			
Dissolution			
Chemical precipitation			

C. Many of Earth's physical environments and ecosystems (communities of organisms and the physical environments in which they live) occur at the boundary between, or at intersection among, two or more spheres.

1. Add the following environments and ecosystems to the correct field of the Venn diagram below.

Surface of a leaf	Surface of an ocean, lake, stream	Lava flowing over a forest
Beach	Moldy brick basement walls	Bottom of ocean, lake, stream
Phytoplankton floating at the surface of the ocean	Surface of a glacier	Seafloor rock with attached oysters
	Soil	



2. In the four sphere fields above (labeled atmosphere, hydrosphere, geosphere, and biosphere) add an "S" for solar energy and a "G" for geothermal energy to indicate which kind of energy *primarily* powers it. Where two of the fields overlap, write an "SS" or "SG" to indicate the sum of energies that power the field. Use the same convention with three letters to indicate the sum of energy sources where three fields overlap.

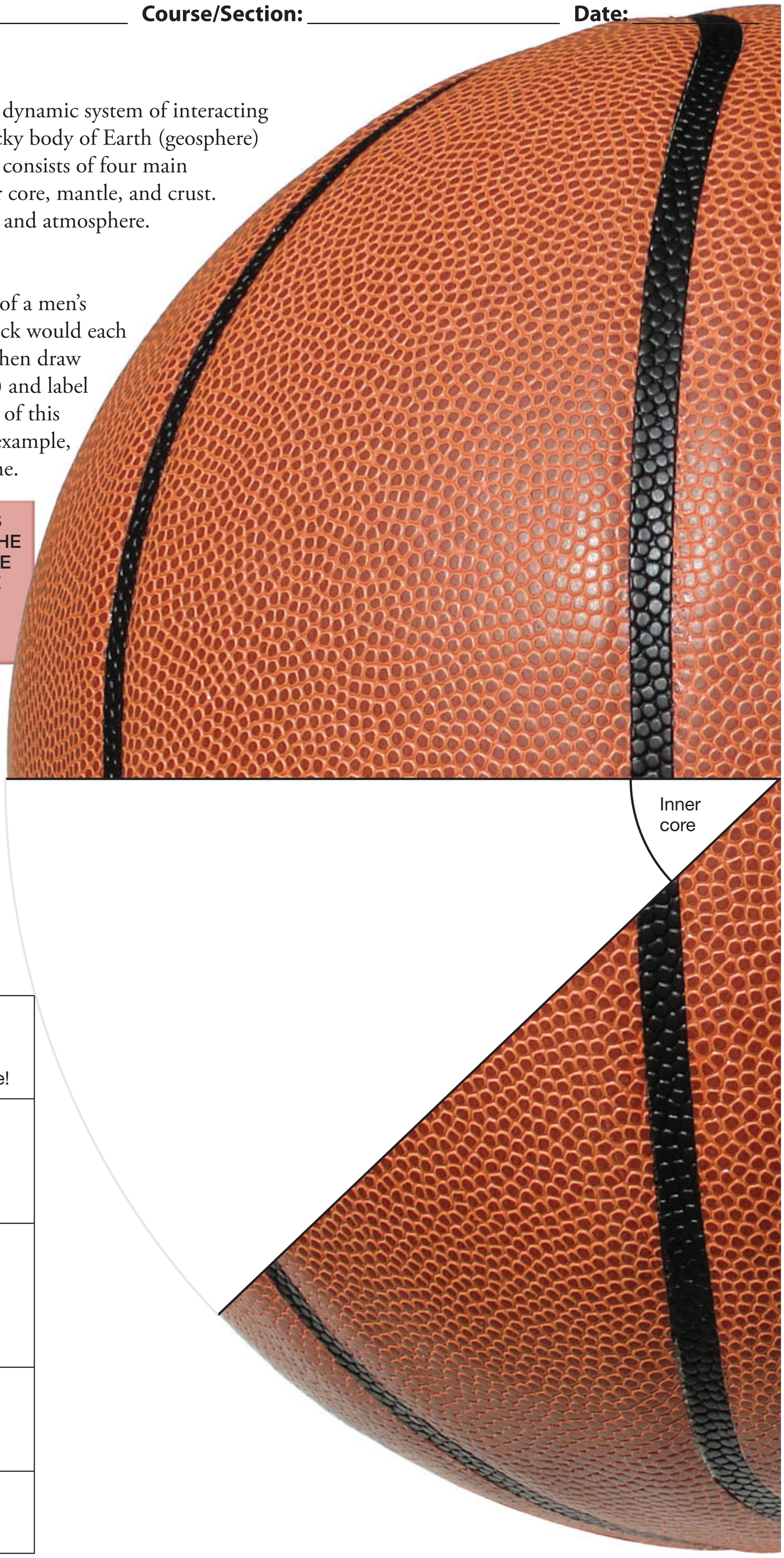
ACTIVITY 2 Modeling Earth Materials and Processes

Name: ______________________ **Course/Section:** ______________ **Date:** ________

A. Geoscientists conceptualize Earth as a dynamic system of interacting material spheres (subsystems). The rocky body of Earth (geosphere) has an average radius of 6371 km and consists of four main compositional layers: inner core, outer core, mantle, and crust. These are overlain by the hydrosphere and atmosphere.

1. If Earth's geosphere had the radius of a men's basketball (119 mm), then how thick would each sphere be? Fill in the chart below, then draw (with a ruler and drafting compass) and label each sphere on the pie-shaped slice of this basketball. Label each sphere. For example, the inner core has already been done.

SPHERE	ACTUAL THICK-NESS	THICKNESS IN MM, IF THE GEOSPHERE IS THE SIZE OF A BASKET-BALL
Atmosphere: mostly nitrogen (N), oxygen (O), and argon (Ar) gases in air. Nearly all of the materials in air occur in a sphere just 16 km (10 mi) thick (troposphere). "Space" (no air) begins about 1000 km above sea level.	16 km	
Hydrosphere: mostly water (H_2O, ocean) in a liquid state.	3.7 km	Draw in blue!
Crust: mostly oxygen (O), silicon (Si), aluminum (Al), and iron (Fe).	25 km	
Mantle: mostly oxygen (O), silicon (Si), magnesium (Mg), and iron (Fe) in a solid state.	2900 km	
Outer Core: mostly iron (Fe) and nickel (Ni) in a liquid state.	2250 km	
Inner Core: mostly iron (Fe) in a solid state	1196 km	22.3 mm



2. Recall that Earth's actual average radius is 6371 km (6,371,000 meters) and that the radius of the basketball is only 119 mm (0.119 meters). Calculate the fractional scale (show your work) and ratio scale of the basketball model.

Fractional scale: **Ratio scale:**

B. MODELING LANDSLIDE HAZARDS

1. Place a ruler flat on a table in front of you. Place a coin in the center of the ruler. What happens if you lift one end of the ruler?

2. The coin did not slide off of the ruler at the very second you started to lift one end of the ruler. Why?

3. Why did the coin start sliding when it did?

3 Measuring and Determining Relationships

Name: ____________________ **Course/Section:** ____________________ **Date:** ____________

A. Make the following unit conversions using the Mathematical Conversions chart on page xii.

1. 10 mi = ____________ km **3.** 16 km = ____________ m **5.** 25.4 mL = ____________ cm^3

2. 1 ft = ____________ m **4.** 25 m = ____________ cm **6.** 1.3 liters = ____________ cm^3

B. Write these numbers using scientific notation

1. 6,555,000,000 = ____________________ **2.** 0.000001234 = ____________________

C. Using a ruler, draw a line segment that has a length of exactly 1 cm (1 centimeter). A line occupies only one dimension of space, so a line that is 1 cm long is 1 cm^1.

D. Using a ruler, draw a square area that has a length of exactly 1 cm and a width of exactly 1 cm. An area occupies two dimensions of space, so a square that is 1 cm long and 1 cm wide is 1 cm^2 of area $(1\ \text{cm} \times 1\ \text{cm} = 1\ \text{cm}^2)$.

E. Using a ruler, draw a cube that has a length of 1 cm, width of 1 cm, and height of 1 cm. This cube made of centimeters occupies three dimensions of space, so it is 1 cm^3 (1 cubic centimeter) of volume.

F. Explain how you could use a small graduated cylinder and a gram balance to determine the density of water (ρ_{water}) in g/cm^3. Then use your procedures to calculate the density of water as exactly as you can. Show your data and calculations.

G. Obtain a small lump of clay (grease-based modeling clay) and determine its density (ρ_{clay}) in g/cm^3. There is more than one way to do this, so develop and apply a procedure that makes the most sense to you. Explain the procedure that you use, show your data, and show your calculations.

H. Reconsider your answers to items **F** and **G** and the fact that modeling clay sinks in water.

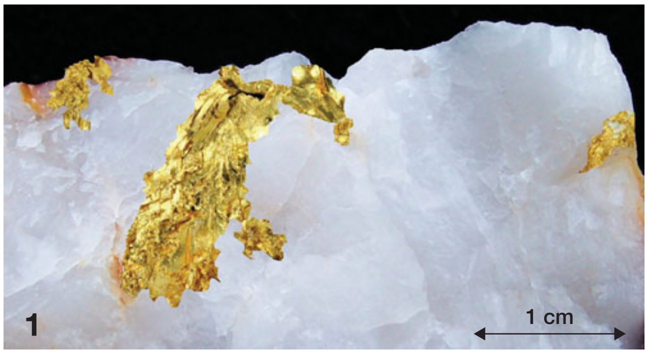
1. Why does modeling clay sink in water?

2. What could you do to a lump of modeling clay to get it to float in water? Try your hypothesis and experiment until you get the clay to float.

ACTIVITY 4 Mineral and Rock Inquiry

Name: ______________________ **Course/Section:** ______________ **Date:** ________

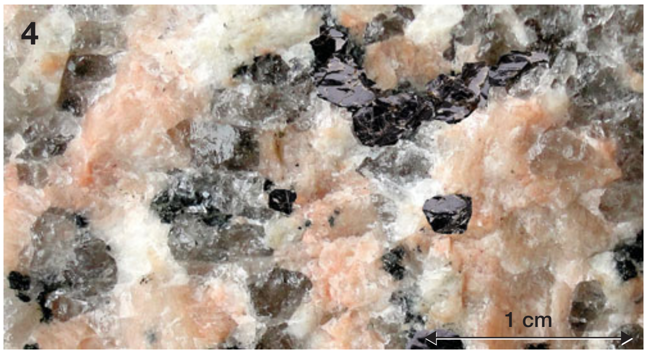
A. All of the samples below are rocks from Earth's crust. Record how many crystals you see in each sample (Write 1, 2, 3, or many). Then make a numbered list of how many different kinds of minerals are in the sample and describe each one in your own words. Complete parts **B** and **C**.



How many **crystals** do you see in this sample? _____
List the number of different **minerals** in the sample and give a description of each one.

How many **crystals** do you see in this sample? _____
List the number of different **minerals** in the sample and give a description of each one:

How many **crystals** do you see in this sample? _____
List the number of different **minerals** in the sample and give a description of each one:



How many **crystals** do you see in this sample? _____
List the number of different **minerals** in the sample and give a description of each one:

B. Which of these samples seems to have crystals of a valuable chemical element? _______ What element? _______

ACTIVIT

5 Mineral Properties

Name: ______________________ **Course/Section:** ______________ **Date:** ________

A. Indicate whether the luster of each of the following materials looks metallic (M) or nonmetallic (NM):

1. a mirror: ________ **2.** butter: ________ **3.** ice: ________ **4.** a rusty nail: ________

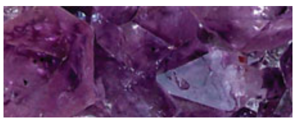
B. What is the streak color (i.e., color in powdered form) of each of the following substances?

1. salt: ____________ **2.** wheat: ____________ **3.** pencil lead: ______________

C. What is the crystal form of the:

1. quartz____________ **2.** native copper ____

D. Look up quartz in the Mineral Database
to find a list of the varieties (var.) of quartz. Then identify each quartz variety below, and write its name beneath the image.



var. ____________

var. ____________

var. ____________

var. ____________

E. A mineral can be scratched by a masonry nail or knife blade but not by a wire (iron) nail

1. Is this mineral hard or soft? ____________

2. What is the hardness number of this mineral on Mohs Scale? ________

3. What mineral on Mohs Scale has such a hardness? ______________

F. A mineral can scratch calcite, and it can be scratched by a wire (iron) nail.

1. What is the hardness number of this mineral on Mohs Scale? ________

2. Which mineral on Mohs Scale has this hardness? ______________

G. Analyze each crystalline household material pictured below and identify which crystal system it belongs to. (Use a hand lens or microscope to observe actual samples of the materials if they are available.)

1. Sucrose (table sugar) belongs to the ______________________________________ crystal system.
How can you tell?

2. Epsomite (epsom salt) belongs to the ______________________________________ crystal system.
How can you tell?

3. Halite (table salt) belongs to the ______________________________________ crystal system.

ACTIVITY 6 Determining Specific Gravity (SG)

Name: ______________________ **Course/Section:** ______________________ **Date:** ____________

A. Imagine that you want to buy a box of breakfast cereal and get the most cereal for your money. You have narrowed your search to two brands of cereal that are sold in boxes of the exact same size and price. The boxes are made of opaque cardboard and have no labeling of weight. Without opening them, how can you tell which box contains the most cereal?

B. Like the cereal boxes above, equal-sized samples of different minerals often have different weights. If you hold a mineral sample in one hand and an equal-sized sample of a different mineral in the other hand, then it is possible to act like a human balance and detect that one may be heavier than the other. This is called **hefting**, and it is used to estimate the relative densities of two objects. Heft the three mineral samples provided to you, then write sample numbers/letters on the lines below to indicate the sample densities from least dense to most dense.

(Least dense) ______________ ______________ ______________ (Most dense)

C. In more exact terms, **density** is a measure of an object's mass (weighed in grams, g) divided by its volume (how much space it takes up in cubic centimeters, cm^3). Scientists use the Greek character rho (ρ) to represent density, which is always expressed in g/cm^3. What is the density of a box of cereal that is 20 cm by 25 cm by 5 cm and weighs 0.453 kg? Show your work.

D. Mineralogists compare the relative densities of minerals according to their **specific gravity (SG)**: the ratio of the density of a mineral divided by the density of water. Since water has a density of 1 g/cm^3, and the units cancel out, specific gravity is the same number as density but without any units. For example, the density of quartz is 2.6 g/cm^3, so the specific gravity of quartz is 2.6.

Return to the three mineral samples that you hefted above, and do the following:

1. First (while they are still dry), determine and record the mass (weight) of each sample in grams.
2. Use the water displacement method to measure and record the volume of each sample Recall that one fluid milliliter (mL or ml on the graduated cylinder) equals one cubic centimeter.
3. Calculate the specific gravity of each sample.
4. Identify each sample based on the list of specific gravities of some common minerals.

Sample	Mass in Grams (g)	Volume in Cubic cm (cm^3)	Specific Gravity (SG)	Mineral Name

SG OF SOME MINERALS	
2.1	Sulfur
2.6–2.7	Quartz
3.0–3.3	Fluorite
3.5–4.3	Garnet
4.4–4.6	Barite
4.9–5.2	Pyrite
7.4–7.6	Galena
8.8–9.0	Native copper
10.5	Native silver
19.3	Native gold

Name: ____________________ Course/Section: ____________________ Date: ____________________

Sample Letter or Number	MINERAL DATA CHART						
	Luster*	Hardness	Color / Streak	Cleavage / Fracture	Other notable properties; tenacity, magnetic attraction, reaction with acid, specific gravity, smell, etc	Name (Fig. 3.18, 3.19, or 3.20) and chemical composition (Fig. 3.21)	How do you depend on this mineral or elements from it? (Fig. 3.21)

*M = metallic or submetallic, NM = nonmetallic

Name: ____________ Course/Section: ____________ Date: ____________

MINERAL DATA CHART

Sample Letter or Number	Luster*	Hardness	Color / Streak	Cleavage / Fracture	Other notable properties; tenacity, magnetic attraction, reaction with acid, specific gravity, smell, etc	Name (Fig. 3.18, 3.19, or 3.20) and chemical composition (Fig. 3.21)	How do you depend on this mineral or elements from it? (Fig. 3.21)

*M = metallic or submetallic, NM = nonmetallic

Name: ____________ Course/Section: ____________ Date: ____________

MINERAL DATA CHART

Sample Letter or Number	Luster*	Hardness	Color / Streak	Cleavage / Fracture	Other notable properties; tenacity, magnetic attraction, reaction with acid, specific gravity, smell, etc	Name (Fig. 3.18, 3.19, or 3.20) and chemical composition (Fig. 3.21)	How do you depend on this mineral or elements from it? (Fig. 3.21)

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Name: ______________ Course/Section: ______________ Date: ______________

MINERAL DATA CHART

Sample Letter or Number	Luster*	Hardness	Color / Streak	Cleavage / Fracture	Other notable properties; tenacity, magnetic attraction, reaction with acid, specific gravity, smell, etc	Name (Fig. 3.18, 3.19, or 3.20) and chemical composition (Fig. 3.21)	How do you depend on this mineral or elements from it? (Fig. 3.21)

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ACTIVITY 8 What Is Rock Texture?

Name: ______________________ **Course/Section:** ______________________ **Date:** ____________

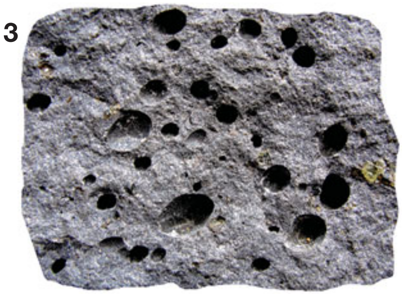
A. Review the following list of textures on page 117. Below each sample, write the name of every one of these textures it contains. Be prepared to compare your observations with the observations of the other geologists. (All samples x1.)

Glassy	Fine-grained	Crystalline (heterogranular)	Clastic (angular)	Layered (flat)
Vesicular	Coarse-grained	Crystalline (equigranular)	Clastic (rounded)	Layered (foliated)
			Bioclastic	Layered (folded)
			Clastic (gravely, sandy, silty, clayey)	

1

2

3



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