GEOLOGIC PROCESSES

By Susan Pater, Kim McReynolds, and Kristine Uhlman

"Eventually, all things merge into one, and the river runs through it. The river was cut by the world's great flood and runs over rocks from the basement of time. On some of the rocks are timeless raindrops, under the rocks are the words, and some of the words are theirs. I am haunted by the waters." --Norman MacLean, from *A River Runs Through It*

INTRODUCTION

Watersheds are made up of many ingredients, but most important among them are water, rocks and soil. The common element influencing all of these is **geology**. Geology is the study of planet Earth, its rocky exterior, its history, and the processes that act upon it. The word geology comes from the Greek *geo,* "earth," and *logia,* "the study of." Geologists seek to understand how the earth formed and evolved into what it is today. Geologists study the changes that the Earth has undergone during its 4.5 billion year history. Geology is one of the key foundations for understanding watershed processes.

In this section you will learn about:

- Basic geological concepts & processes.
- How geology influences topography.
- How geology influences watersheds.
- How water influences geology.
- How water quality is influenced by geology.

An Exercise

Take a stroll along your local wash, lake or stream. At any given point, stop and look around you, starting first with the water body or stream channel (if it is a dry wash at this point in the year).

- Notice the rocks and/or soil along the banks. Look upstream and downstream. Are there differences in the color, shape or size of this material? Can you guess where these soils or rocks came from? If you notice smooth stones, what might have shaped their contours?
- Note differences in the type of soil or depth near and away from the water body. Why would there be differences?
- Look up the horizon of your watershed. Do you notice any hills, canyons or mountains in the distance? What formed them? Do you see evidence of volcanic activity around you anywhere?
- How steep is the land on which you stand? How would this influence the water body or even the whole watershed?
- Does your water body flow from a higher point in the landscape? Why?
- If you are near a road, do you see any cuts into the sides of these geologic formations? What can you observe in these cross-sections of the earth?
- Pick up a rock near you and observe its color, texture and weight. What is it made of?
- Grab a handful of soil by the side of the stream, farther upland and at the top of the watershed. What is different about it's texture, particle size or moisture levels?

Remember that all around you are the processes of geologic change—and these processes intimately influence the formation of your watershed. We will explore the basics of geology in greater detail below.

BASIC BUILDING BLOCKS: MINERALS AND ROCKS

The study of geology means understanding the crust of the Earth. That crust consists of rocks and **minerals**. Rocks are a mixture of minerals. A single rock may not have the same mixture of minerals all the way through, and the size of the mineral crystals may change too. Characteristics that define minerals include:

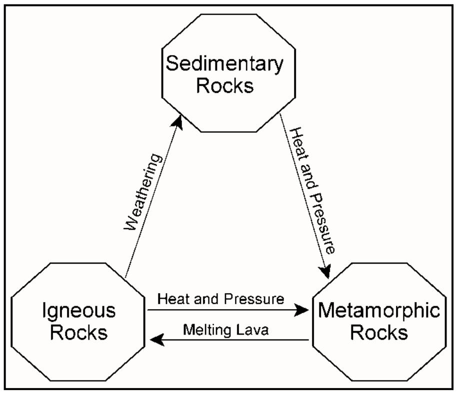

Figure 1. The Rock Cycle.

1) The elements in a mineral are bound together in a repeating pattern that determines the specific shape of a mineral crystal.
2) Minerals have a distinct inorganic chemical composition. Most minerals are compounds of several elements.
3) Minerals are nonliving, although minerals may be concentrated by living organisms, such as calcium in our bones and mineral enrichment zones around deep oceanic volcanic vents that support bacterial colonies rich in zinc and other heavy metals.
4) Minerals occur in a solid state at room temperature.
5) Minerals occur naturally on Earth.
6) Minerals have distinct physical properties.

The identification of minerals is like being a detective. Through a series of basic tests, the properties of the mineral are determined, and possibilities are eliminated one by one until the mineral is identified. The properties of minerals commonly tested for with a mineral test kit are:

Color—some minerals have a characteristic identifying color.

Luster—a description of the way a mineral's surface looks in reflected light. Is it pearly, metallic, or dull?

Shape—the specific shape of a mineral crystal is characteristic of its component elements.

Hardness—most mineral test kits use the Mohs Hardness Scale. The Mohs scales runs from 1 (talc) to 10 (diamond).

Specific gravity—this is the comparison of a mineral's weight to the same volume of water. Specific gravity does not change.

Streak—this is the color a mineral makes when scratched on a rough white porous ceramic surface.

Cleavage—The shape a mineral takes when it is broken.

Unusual properties—include taste, such as in salt; odor, such as in sulfur; florescence under an ultraviolet light; or magnetism. Vinegar is used for testing lime minerals such as calcite because the acid reacts with the carbonate, causing the surface to fizz and bubble.

A rock, in a geological sense, is the material that forms an essential part of the Earth's crust and includes loose (unconsolidated) masses such as beds of sand, clay, gravel, or volcanic ash as well as the very firm, hard, and solid (consolidated) masses of granite, sandstone, limestone, etc. Most rocks are aggregates of one or more minerals, but some are composed of remelted minerals to form glass such as obsidian, perlite, and pumice. Arizona is rich in copper and is famous for its turquoise, azurite, and malachite, copper-bearing minerals valued for their beautiful shades of green and blue.

Rocks vary greatly in composition, and geologists have established several classifications of them. Some rocks are large masses of a single mineral; quartzite's are composed almost entirely of quartz. Other rocks are composed of a mixture of minerals, as for example, granite, conglomerate, gneiss, and schist.

Properties of rocks, such as the characteristics of their minerals and crystals, provide important clues about how they were formed. Rocks are formed through the actions of powerful geologic processes. Three of the most important processes that shape the Earth's crust and create different kinds of rocks and minerals are: **volcanism**; **erosion** and **sedimentation**; and **metamorphism**. Each of these processes leads to the formation of a different type of rock as shown in Figure 1. The rocks are accordingly classified into three major categories: **igneous**, **sedimentary**, and **metamorphic**.

The word igneous means "fire formed" and refers to those rocks, formed through volcanism—in which molten material from the Earth's mantle rises up through the crust, where it later cools and solidifies. Molten material that cools after spilling out onto the Earth's surface forms <u>extrusive</u> igneous rocks (like ryholite, basalt, obsidian, and pumice). Quick cooling tends to form an igneous rock that is composed of very small mineral particles and may be even glassy in texture. Molten material that cools below the Earth's surface forms <u>intrusive</u> igneous rocks (like granite). Slow cooling tends to form igneous rocks having larger mineral particles. Igneous rocks have interlocking grains with angular, sharp shapes.

Sedimentary rocks (layered rocks) are those that have been deposited from water, wind, or ice (glaciers). The particles that make up a sedimentary rock may come from destruction of some previously existing source material (clastic sedimentary rocks – such as sandstone and shale) or they may be chemically precipitated from water (chemical sedimentary rocks – such as limestone). Sedimentary rocks may have rounded, grains that may look layered; the silt, sand, and/or clay may have differing levels of compaction and or cementation to form rock. Some sedimentary rocks can be readily taken apart with your fingernail, whereas other sedimentary rock can be as resistant to erosion as the metamorphic or igneous rocks.

Metamorphic rocks (changed rocks) form as a result of recrystallization of a previously existing rock. These form where igneous and sedimentary rocks are buried to such great depths that the heat and pressure of the Earth's interior cause the minerals to recrystallize and react to form different rocks. By this process, heat and pressure transform limestone to marble and shale to slate. Metamorphic rocks may have a sheet-like texture; they may be compact and banded, and are very hard.

STRUCTURE OF THE EARTH

Let's take a step up in scale now—looking at the whole planet. Earth's interior is made up of three main layers. These are the **crust**, the **mantle**, and the **core** (Figure 2). Each of these layers may be divided into smaller layers by their specific properties.

The crust is the outer layer, similar to the shell of an egg. Like an eggshell, the crust is thin compared to the thickness of the mantle and core. The crust ranges in thickness from as little as 4 miles (6 km) thick beneath the oceans to more than 50 miles (80 km) thick under continental mountains. The mantle is directly beneath the crust, similar to the white of an egg. It is a pliable layer of rock that is denser than the crust because it contains more iron and manganese. The core of the Earth is similar to the yolk of an egg. It is composed of an iron-nickel alloy and is nearly twice as dense as the mantle. The outer core is a thick liquid, approximately 1,800 miles deep with a thickness of 1,400 miles. The inner core is solid, due to the intense pressure at this depth. As Earth rotates, the liquid outer core slowly flows, creating Earth's magnetic field.

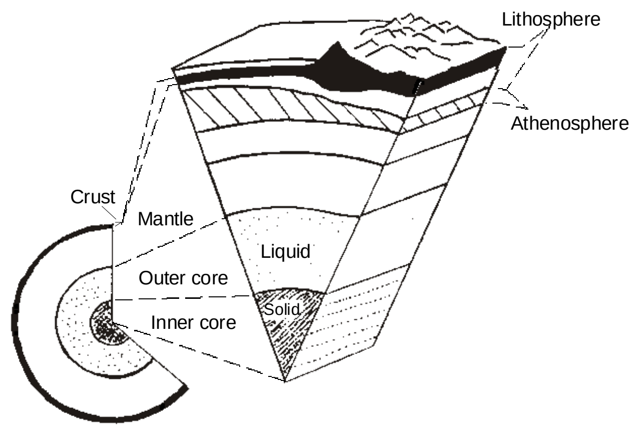

Figure 2. The Earth's Interior.

The **lithosphere** is made up of the crust and the upper or outer most part of the mantle. It is composed of a dozen or more plates that move relative to one another as they ride atop hotter, more mobile materials. The plates move at average speeds of a few inches per year.

A **tectonic plate** is a massive, irregular slab of solid rock. Tectonic plates have drifted around on the surface of the Earth throughout geologic time, breaking apart, crunching together, and/or sliding past or under one another. Plates are divided into two types, oceanic and continental plates, based on their physical properties. The difference in density of the oceanic and continental plates is important in understanding how the plates behave when they come together.

Continental plates have a thick crust composed of granitic rocks, which are made up of relatively lightweight minerals such as quartz and feldspar. By contrast, **oceanic plates**, which are denser and heavier, have a crust composed of iron-rich basaltic rocks. The crust under continents is on average around 20 miles thick. The crust under oceans generally is only about 3 miles thick. Oceanic plates are created along oceanic ridges where mantle material rises and spreads, forming the thin oceanic crust.

The place where the two plates meet is called a plate boundary. Boundaries have different names depending on how the two plates are moving in relationship to each other. As the edge of the

North American continental plate has moved west, it has ridden over the heavier Pacific oceanic plate. The oceanic plate is moving downward into the mantle in an offshore subduction zone (the location where sinking of a plate occurs). This is a convergent plate boundary, where crust is destroyed as one plate dives under another, and is one of three types of tectonic plate boundaries. The other two types of plate boundaries are: **divergent boundaries**, where new crust is generated as plates pull away from each other; and **transform boundaries**, where crust is neither produced nor destroyed as plates slide horizontally past each other.

Convergent plate boundaries can occur in one of three ways: (1) between oceanic and continental plates, (2) between two oceanic plates, and (3) between two continental plates. Convergent boundaries are associated with subduction zones, where crust on one side is being destroyed. They are also associated with large-scale volcanic and seismic (earthquake) activity. The crust and the lithosphere material melts under great pressure as it enters the asthenosphere. Some of this melted material rises to feed the magma chambers of volcanoes. Mountain building takes place at convergent boundaries. The creation and destruction of lithospheric plates happens very slowly.

The western coast of North America exhibits land forms resulting from all three types of tectonic plate boundaries. In the Pacific Northwest, the Pacific oceanic plate is subducted beneath the North American Plate, forming the chain of active volcanoes approximately 50 miles inland from the plate boundary. As subduction pulls the oceanic plate beneath the continental plate, sediments eroded from the continental plate are pulled down within the subduction zone, remelted, and mixed within immense magmatic chambers feeding the volcanoes. Mt. Baker, Mt. Rainier, Mt. St. Helens – all the way south through California to Mt. Shasta and Mt. Lassen – are all active volcanoes fed by the subduction zone.

The San Andreas Fault is a transform boundary where the Pacific oceanic plate is slipping past the North American Plate, generating significant seismic activity as the Pacific plate is pushed north, eventually to be subducted beneath the Oregon and Washington coast.

Along the Baja California portion of the plate boundary, the Pacific Plate has been diverging from the continental plate, stretching the continental plate and forming the equivalent of stretch marks in the earth's crust, nearly parallel to the strike (direction) of the plate boundary. This stretching is evident in the alignment of mountain peaks and valleys in a general northwest – southeast alignment pattern, referred to geologically as **lineation**. As the earth's crust is stretched, blocks of crust break and drop in a pattern of valley basins and high peak ranges, and is known as the Basin and Range Province within Arizona and other regions of Mexico and the western United States. Observation of high-altitude aerial photographs or topographic maps of the region show obvious lineations within the Basin and Range. The vertical displacement between the base of the basin and mountain peak may exceed 10,000 feet, but over time the basin fills with sediments eroded from the mountains, with some basins filling with alluvium over nearly 7,000 feet in thickness. The sedimentary material within the Basin and Range valley **alluvium** forms the major aquifers of the arid west.

Observation of the landforms across the North American continent makes it obvious that the behavior of the tectonic plate boundary has evolved over geologic time, with the Basin and Range Geologic Province evident as far north as Idaho.

GEOLOGIC TIME

Arizona's geography and topography are the result of millions of years of geological and meteorological forces. Volcanoes, plate tectonics, folding, faulting, sediment deposition, weathering and erosion have in turn built up, and then worn down the land (see Part II for more information on how water influences these processes). These continual changes take place not only on the surface (crust) where people can observe them, but also deep inside the Earth. Crustal rock recycles into subduction zones to be remelted and recreated as new crust.

The functions of biotic (living) organisms are influenced by abiotic (non-living) factors such as the Earth's geologic make-up, air, water and soil. Living organisms also use non-living resources, chiefly soil, in environments that have been formed over long periods. Geologic resources (rocks and minerals) and the Earth's physical characteristics (mountains, canyons, and valleys) are the result of past events (earthquakes, volcanic eruptions, erosion and deposition). Because of the long time frames and the processes involved, geologic resources are generally considered non-renewable. A non-renewable resource cannot be replaced once it is used or consumed. For example, once copper is removed from the Earth, more copper does not "re-form" to replace the extracted ore. There is a finite amount of non-renewable resources. Non-renewable resources may eventually become depleted.

The continental crust of Arizona has been evolving in many ways over the past 4 billion years. The rock record informs us of many episodes of volcanism, and formation of shallow seas, and coastal sand dunes. Before that time, this area was defined by sea floor rocks resting beneath an ancient ocean. Arizona's geologic history can be divided into five grand rock cycles as shown in Table 1. Each cycle contained some erosion, sedimentation, volcanism, mountain building, and had very different, unique climates.

Figure 3. The Grand Canyon and Colorado River. Courtesy Philip Fortnam, Central Arizona Project.

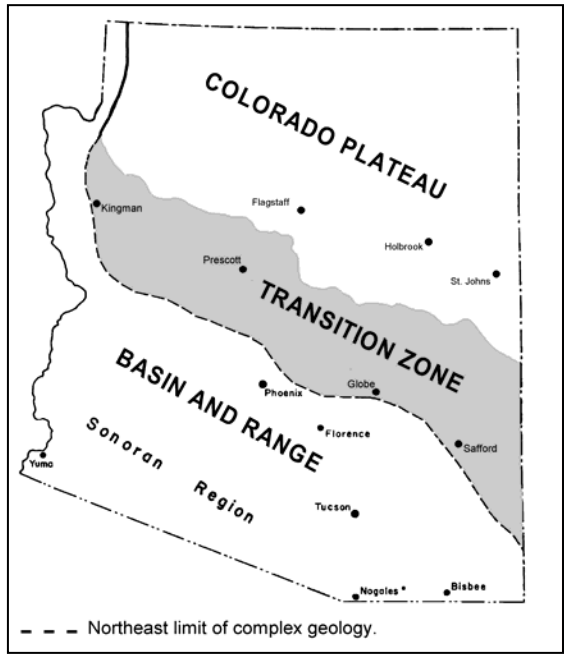

Figure 4. Arizona's Geologic Provinces.

Table 1. Arizona Geologic History.

Time	Era	Life Forms	Rocks Produced
0 - 65 million years before present	Cenozoic	mammals, apes, man, grasses, grazing animals	Two grand volcanic cycles. Formation of the Basin and Range Province, which extends from southern Idaho to central Mexico. Uplift of the Colorado Plateau. Extinction of dinosaurs 58-66 million years ago.
65 - 250 million years before present	Mesozoic	dinosaurs, shrews, flowering plants, first birds	Intermittent volcanic activity and fault movement. Sandstones, shale, coal beds, creation of ore deposits, and shallow lakes. Most of Arizona was a low relief plain, like Texas today.
250 - 600 million years before present	Paleozoic	age of invertebrates, trilobites, reptiles, amphibians, first land plants - ferns, cycads, conifers	Limestone and sandstone of Grand Canyon deposited during this time, while most of state under shallow seaways. Coral islands, broad sandy beaches. Vast coastal sand dunes, lagoons. Arizona resembled the modern landscapes of Florida and the Bahamas.
600 - 1400 million years before present	Younger Precambrian	worms, jellyfish, stromatolytes, sponges	Sedimentary rocks exposed in the Sierra Ancha near Roosevelt Lake formed under shallow ocean with some western continental partner attached near Yuma.
1400 - 1850 million years before present	Older Precambrian	bacteria, cyano-bacteria, protozoans	Arizona started out as submarine sea floor, then a volcanic complex like Japan, then continental collisions welded the islands onto the continent. A final catastrophic collision metamorphosed all the rocks and produced mighty mountains.

Arizona's final chapter of geologic history resulted in the formation of three geologic provinces: the Colorado Plateau, the Transition Zone, and the Basin and Range Province (Figure 4). An uplift of the Mountain highlands elevated the Mogollon Rim Plateau region. Horizontal extension of the Earth’s crust caused an uplift of the mountains and a subsidence of basins that produced the basin and range topography characteristic of southern and western Arizona.

The northeastern Colorado Plateau Province consists of broad plateaus and mesas, separated by deep canyons, the deepest of which is the Grand Canyon. The southern boundary of the Colorado Plateau is the Mogollon Rim formed by erosion following the Colorado Plateau uplift and Basin and Range formation. Large recent volcanoes, such as the San Francisco Peaks and the White Mountains are present along the edge of the Plateau.

The Transition Zone in central Arizona separates the Basin and Range Province and the Colorado Plateau with geologic characteristics intermediate between the two. It is intermediate in overall elevation and contains highlands cut by major canyons and some sediment-filled valleys such as the Verde Valley.

The Basin and Range Province of southern and western Arizona is an area where the Earth's crust has been stretched and broken by numerous faults so that mountain ranges and basins (broad valleys) have formed by the vertical motion of large crustal blocks. The valleys are generally underlain by thick (up to 7,000 ft.) sequences of gravel, sand, and silt that are the main aquifers for the region. The major cities (Phoenix and Tucson) and farmlands in the state are located in these valleys.

An important consideration within the Basin and Range Province is how these tectonic forces have influenced the quality of water held within the aquifers. As Basins formed, many could not be drained due to either insufficient rainfall or geologic barriers to flow. Drainage systems formed, but could not reach the sea, generating large inland seas – such as the Great Salt Lake – that concentrated the salts leached from the geologic material as water evaporated. Large evaporite deposits of salt are common within valley aquifers within the Basin and Range province, and elevated concentrations of chemical constituents such as boron, sodium chloride (salt) and calcium sulfate (gypsum) are often found in the deeper alluvium of the basin aquifers. As the Basins filled with sediment and drainage features formed that were able to eventually discharge to the sea, water quality improved as salts were flushed from the drainage system. In the arid west, however, there is a delicate balance between salt concentrations by evaporation and flushing of dissolvable salts from the soils and aquifer, and all is dependent on climate.

SOME FINAL THOUGHTS ON ARIZONA GEOLOGY

Our geologic history has created the diversity of topography and soil parent materials found in Arizona. The distribution of rock types, their mineral components, and resultant landforms - provide constraints on the distribution of ALL necessities, and comforts for our lives: energy minerals, water, metals, petroleum products - all from extractive mining of non- renewable natural resources. Underground water is distributed according to strict geological rules - the more porous the rock, the more water it holds.

An important example of how critical geology can be for water is the contrast between Tucson and Nogales, Arizona. Tucson is one of the largest cities in the U.S. to survive on 100% groundwater from aquifers until the recent introduction of Central Arizona Project (CAP) water. Nogales, Arizona draws much of its water from much shallower aquifers along the Santa Cruz River. The rock that fills the Nogales aquifer is not as deep as the rock in Tucson. It is also younger and less porous. This means that Tucson has more underground storage for groundwater while Nogales has far less. The size of the cities is dramatically different partly as a result of the limits of their water resources—and ultimately, their different underlying geology.

Geologic forces determine local and global topography, thus determining the climate of various regions. The constant change of environmental factors due to geologically driven forces - climate change, change of elevation, etc., demand all life forms to do one of three things—migrate to a more favorable region, adapt to the changes, or to go extinct.

TAKING ACTION: OTHER ACTIVITIES YOU CAN DO

- Explore your local watershed's geology on a hike or drive. Good field guides to bring with you include: *Roadside Geology of Arizona, Field Geology Illustrated,* or *Geology of Arizona*.
- Take a mine tour. Many local mine operations, including historic and modern-day mines, will offer tours to groups or individuals who make appointments.
- Visit the offices or website of the Arizona Geologic Survey to learn more about Arizona's unique geology. The AZGS is located at: 416 W. Congress St., Suite 100, Tucson, Arizona 85701; (520) 770-3500; http://www.azgs.state.az.us/
- The Arizona Department of Mines and Mineral Resources also is a good place to begin any exploration of Arizona geology. The ADMMR is located at: 1502 West Washington, Phoenix, Arizona 85007-3210**;** 1-800-446-4259; http://www.admmr.state.az.us/
- Visit a gem or mineral show. Every February, Tucson hosts one of the world's largest. A list of mineral shows throughout the state can be found by visiting the Arizona Department of Mines and Mineral Resources website: http://www.admmr.state.az.us/showlst.htm
- Museums with large mineralogical collections include:
    - Arizona-Sonora Desert Museum
    - University of Arizona Mineral Museum and Flandrau Science Center
    - Jerome Mining Museum
    - Department of Mines and Mineral Resources
    - Bisbee Mining and Historical Museum
    - Museum of Northern Arizona
- Join a local geologic society. A complete listing of groups is located at:

http://www.admmr.state.az.us/clubs.htm

WORDS TO KNOW

Alluvium – the deposits of clay, silt, sand and gravel, or other particulate material that has been deposited by a stream or other body of running water in a streambed, on a floodplain, delta or at the base of a mountain.

Continental plate – the tectonic plate that supports the major land masses.

Core – the superheated, metallic portion at the center of the Earth.

Crust - the cooled surface of the Earth, composes our landscape.

Deposition – the act of depositing materials; in geology refers to materials that have been moved by some mechanical, biological, or other physical process.

Divergent boundary – a geologic boundary between tectonic plates where new crust is generated as the plates pull away from each other.

Elements – one of the most basic building blocks for all physical matter in the universe.

Erosion – the wearing away and removal of materials of the Earth's crust by natural means; includes weathering, solution, corrosion, and transportation.

Geology - the study of the planet Earth, its rocky exterior, its history, and the processes that act upon it.

Igneous rock – rock formed by volcanic action.

Lineation - stretching of the Earth's surface resulting in mountain chains and valleys aligning along a common parallel direction.

Lithosphere – the crust and the upper or outer most part of the Earth's mantle.

Mantle –the hot portion of crust of the Earth.

Metamorphic rock – previously formed rock that has been transformed by physical processes such as great heat or pressure.

Mineral – a naturally occurring mixture of tightly bound, crystallized, inorganic elements that forms material with unique physical properties.

Ocean plate – a large tectonic plate that supports one of more of the Earth's oceans.

Rock - a basic geologic material made up of different minerals in hard or crystallized form.

Sediment - geologic deposits from water; mineral particles derived from soil, alluvial or rock materials moved by water; sediment also refers to material in suspended in water or recently deposited from suspension.

Sedimentary rock – rock composed of mineral particles derived from soil, alluvial or rock materials moved by water, ice and other physical or chemical means.

Sedimentation – the process of depositing sediment from suspension in water.

Tectonic plate - a massive, irregular slab of solid rock. Tectonic plates have drifted around on the surface of the Earth throughout geologic time.

Transform boundary - a geologic boundary between tectonic plates where new crust is generated as the plates slide horizontally past each other.

Tributary - a stream which joins another stream or body of water; in Arizona a tributary may contribute even minute or intermittent amounts of water to the main waterbody.

Volcanism – pertaining to volcanic events.

Weathering – the process of removing particles of a material—usually rock—through mechanical, biological or other physical processes (such as through the action of wind and water).

SOURCES

Chronic, Halka. 1983. *Roadside Geology of Arizona*, Mountain Press Publishing Company, Missoula, Montana.

Kamilli, R.J. and S.M. Richard, editors. 1998. *Geologic Highway Map of Arizona*. Tucson, Arizona Geological Society and Arizona Geological Survey.

Leopold, Luna B. M. Gordon Wolman and John P. Miller. 1992. *Fluvial Processes in Geomorphology*. New York, NY: Dover Publications, Inc.

Maley, Terry S. 2003. *Field Geology Illustrated.* Boise, Idaho: Mineral Land Publications

Nations, Dale and Edmund Stump. 1996. *Geology of Arizona, Second Edition.* Dubuque, Iowa: Kendall/Hunt Publishing Company.

Ohio Department of Natural Resources Water Division. 1998. Stream Management Guide No. 3.

Oregon State University Extension Service. 2002 Watershed Stewardship: A Learning Guide. Oregon State University, Corvallis, Oregon.

Rosgen, Dave. 1996. *Applied River Morphology.* Pagosa Springs, Colorado: Wildland Hydrology.

Scarbrough, Bob. 1998. *Geology Fact Sheets* from the Natural Resources Conservation Workshop for Arizona Youth.

Skinner, Quentin D., Kelly K. Crane, Joseph G. Hiller, and J. Daniel Rodgers. 2000. *Wyoming Watersheds and Riparian Zones.* Laramie, WY: University of Wyoming Cooperative Extension Service.

Thompson, V. 2000. Oregon 4-H Earth Science Project Leader Guide. Oregon State University Extension Service.

Document Revised 9/19/05