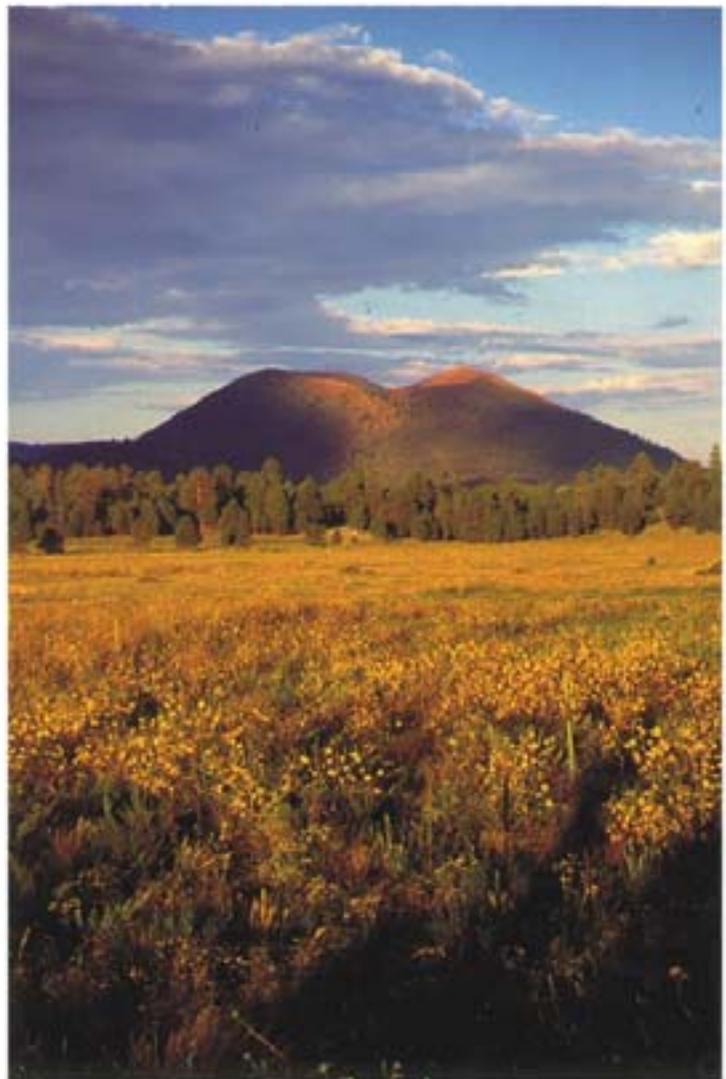
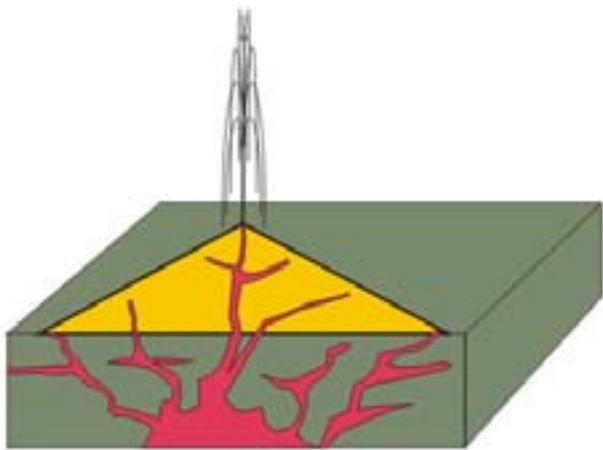
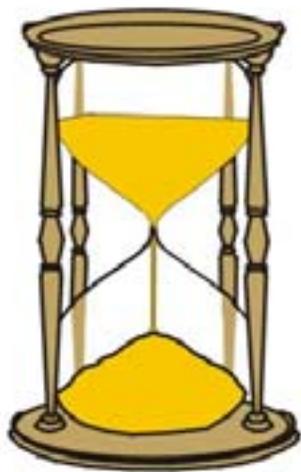


# SUNSET CRATER VOLCANO NATIONAL MONUMENT

*Geology*

*Training*

*Manual*



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# **SUNSET CRATER VOLCANO NATIONAL MONUMENT**

## ***Geology Training Manual***

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### **PREFACE**

This manual is an overview of concepts important to understanding the geology of Sunset Crater Volcano National Monument. It is intended as part of the training of permanent, seasonal, and volunteer National Park Service interpreters. The manual is written primarily for non-geologists, to give them grounding in basic geologic concepts; the concepts discussed are those that will help explain Sunset Crater and its environs to park visitors.

Sunset Crater is an exciting place to “seize the moment,” to help visitors learn while they are relaxed, on vacation in a beautiful and fascinating place. When people think of geology, their imaginations are often stirred by images of bulky dinosaurs or fiery volcanoes. At Sunset Crater, you often see excitement on visitors’ faces when they realize that, for the first time, they are walking on young lava flows. We don’t have dinosaurs at Sunset Crater, but we do have the opportunity to educate the public on the various types of volcanoes, the products of volcanic eruptions, and how volcanoes affect people.

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# INTRODUCTION

## WHY MAKE A BIG DEAL ABOUT GEOLOGY?

**Geology** is the study of the Earth. It incorporates more than just the identification of a bunch of rocks. Geology involves the study of processes occurring within or on the Earth that make the Earth come alive. Processes within the Earth include those responsible for **earthquakes, volcanoes**, and the formation of **mountain ranges**. The actions of wind, water, and ice occur at Earth's surface, resulting in **erosion, exposure of older rocks**, and the **deposition of sediment**. Park rangers can observe features at Earth's surface and explain them to the public in terms of Earth's internal and external processes.

**Sunset Crater Volcano** is a pile of airborne volcanic particles (a **cinder cone**) that extruded tongues of dark, fluid lava from its base. It rests on older volcanic deposits that cover still older sedimentary layers. The national monument lies on the southwestern edge of the Colorado Plateau, a broad region that has recently elevated to over 6000 feet (2000 meters). It's also near the Basin and Range Province, where the North American continent is being ripped apart.

## PRESENTING SUNSET CRATER GEOLOGY TO PARK VISITORS

Background in two areas of Geology is important to appreciate Sunset Crater Volcano National Monument: tectonics and volcanism. **Tectonics** is the study of large features on Earth's surface and of the processes within the Earth that resulted in their formation. A modern view of tectonics is that Earth's outer shell is rigid and is broken into large plates that move about relative to each other (hence, **plate tectonics**). Knowledge of plate tectonics helps park rangers understand forces responsible for the geology and landforms of Northern Arizona, including uplift of the Colorado Plateau and the earthquakes and volcanism accompanying continental rifting in the Basin and Range Province.

**Volcanism**, the melting of rocks and extrusion of magma at Earth's surface, commonly occurs at the boundaries of moving plates. Sunset Crater is part of the San Francisco Volcanic Field that has been propagating westward as continental rifting of the Basin and Range Province eats away at the edge of the Colorado Plateau. **From vistas along the Lava Flow Trail, rangers can point out a variety of volcanoes and volcanic landforms in the surrounding countryside.** With this background it is easier to understand the nature of the cinders and lava flows found along the trail, and to compare them with volcanic features found in other national parks.

Presentation of the two areas of Geology begins with a discussion of the types of plate boundaries and of features that form along the boundaries. Special emphasis is given to processes that lead to volcanism and to the rifting and uplift of broad regions of a continent. An overview of the tectonics of the southwestern United States follows, then details of the geology in and around Sunset Crater Volcano National Monument.

## **What to Present?**

The geology of Sunset Crater Volcano National Monument lends itself to presentations on two different scales. At scenic viewpoints one can see the surrounding countryside for miles around, including numerous cinder cones, lava domes, and the highest point in Arizona (Mt. Humphreys within San Francisco Peaks). These features originate from processes that occurred on a very large scale, the scale of plate tectonics. ***On a clear day, park rangers can have visitors gaze to the west and imagine San Francisco Peaks as one towering mountain, more than 3,000 feet (1,000 meters) higher than it is today. Perhaps similar to the recent eruption of Mt. St. Helens, the summit and eastern flank of the Peak were blasted away in a violent explosion half a million years ago.*** On a more local scale, visitors can examine the cinders and lava flows that surround Sunset Crater Volcano, and envision fountains and tongues of fluid lava forming these features just 900 years ago.

## **Ten Questions about the Geology of Northern Arizona and Sunset Crater**

The types of questions one is able to ask can gauge mastery of a subject. As interpreters we know this - we've done our job well if visitors ask us to expand upon what we've said. Below is a list of questions about northern Arizona and the development of cinder cones and other volcanic features. The purpose of this manual is to give interpreters enough background in the two areas of geology so that they can ask similar questions. Details explaining the brief answers constitute the rest of the manual.

### **1. *How did Sunset Crater Volcano form?***

Fluid lava erupted out of a long fissure in the year 1064, forming the Cinder Hills. It culminated as a giant fountain that fell into a pile of volcanic cinders known as Sunset Crater Volcano. Tongues of lava oozed out of the base of the cinder cone, cooling as the dark-colored Bonita and Kana-a flows.

### **2. *How is it possible to so precisely date the initial eruption of Sunset Crater Volcano?***

Geologic dating methods commonly have errors associated with them. For rocks several hundred years old, one might expect the error to be, at best, plus or minus tens of years. Dendrochronology, a method used to date events in northern Arizona, is unique, in that it can yield an exact year. A pattern of tree ring growth for the region has been established. Near Sunset Crater Volcano National Monument, trees that survived the eruption show a normal pattern of growth right up to the year 1064. For several decades after that the pattern is irregular, because the trees were stressed due to the cover of ash and cinders.

### **3. *Why is tectonic activity concentrated over such narrow zones on Earth's surface?***

Tectonic activity (earthquakes, volcanic eruptions, the formation of mountains) is associated with the movement of large plates of Earth's outer, rigid shell, called the lithosphere. Most of the activity is due to interactions along the boundaries of plates, or because a plate moves over a hotspot rising from Earth's deep interior.

### **4. *What cause volcanic activity?***

Volcanic activity occurs above places in the Earth where pressure and temperature conditions conspire to melt rock. There are two main ways to melt solids: 1) take a cold

solid and heat it up; 2) take a hot solid that is under pressure and suddenly release the pressure. Volcanism is common in three tectonic settings: a) where plates of Earth's outer shell converge; b) where plates diverge; c) where a plate rides over a hotspot. Converging plates illustrate the first way we normally view melting. As one plate "subducts" beneath the other, the crust on its surface heats up to a point where hot fluids are released. The fluids rise, melting rock in their path. At diverging plate boundaries (mid-ocean ridges; continental rift zones) and hotspots, deep mantle material is hot but remains solid because it is under great pressure. As the hot mantle rises, the sudden drop in pressure causes melting, much like taking the lid off a pressure cooker causes super-heated water to flash to steam.

**5. *Why is there volcanic activity in northern Arizona?***

There is no clear evidence of a plate boundary or hotspot to explain the volcanic activity in Northern Arizona. One possibility is that continental rifting of the Basin and Range Province has been extending westward, eating away at the edge of the Colorado Plateau. Another is that the North American plate has been drifting eastward over a stationary hotspot.

**6. *What is the timing and pattern of volcanic activity in northern Arizona?***

Volcanism started near the town of Williams about 6 million years ago. It has propagated roughly in an eastward direction, forming San Francisco Peaks about 2 million years ago, then the cinder cones and lava flows of the Sunset Crater region.

**7. *Why is there a variety of volcanoes and volcanic products in northern Arizona?***

Unless it can find clear conduits, magma must melt its way through a significant thickness of continental crust in order to reach the surface of the Colorado Plateau. Crustal melting enriches the silica (silicon and oxygen) content of the magma, forming pasty lava that cools as light-colored rocks (rhyolite, dacite, and andesite) and steep-sided lava domes and composite volcanoes. Magma that is not as enriched in silica results in more fluid eruptions of dark-colored lava (basalt) that spread out as low-profile shield volcanoes and fountains that rain down to form cinder cones.

**8. *Is there likely to be a volcanic eruption in the Sunset Crater region in our lifetime?***

A conservative estimate is that, over the last 6 million years, there have been about 600 episodes of volcanic eruptions in northern Arizona. The average time (or recurrence interval) between eruptions is thus about 10,000 years. Sunset Crater Volcano was the site of the last eruption, about 900 years ago. It is unlikely that such a long-lasting and prolific geologic feature like the San Francisco Volcanic Field will suddenly shut off. Volcanic activity will almost certainly continue in Northern Arizona. Given the 10,000 year recurrence interval, an eruption probably won't happen in our lifetime, but there's no guarantee!

**9. *Why are the lava-flow rocks around Sunset Crater Volcano so dark and heavy?***

The lava that flowed out of the base of the cinder cone is relatively low in the elements silicon and oxygen (which bond together as "silica"), and high in iron and magnesium. Silica is the same material that makes window glass; rocks that are high in silica are light-colored and light-weight. High amounts of iron and magnesium (at the expense of silica) in the lava flows from Sunset Crater, result in the dark, heavy rock called basalt.

### 10. ***How have/will eruptions of Sunset Crater Volcano affect plants and people?***

Northern Arizona is a very dry climate, so that water typically runs off the surface of hard rock before it can help to develop soil and thus support life. Initial eruptions of the Cinder Hills and Sunset Crater Volcano in 1064 were actually beneficial to plant life and people in some areas. Where deposits of fine-grained cinders and ash were just a few inches thick (as in Wapatki National Monument), the material acted as a mulch, trapping moisture. For about 200 years soil conditions were ideal for certain crops, and Native American people flourished.

## **What Should Interpreters Know About Geology? What Should Interpreters Explain to Visitors?**

The level of technical detail presented in this manual is that thought appropriate for the geology background of Park Service interpreters. The information will help interpreters design their own programs on the tectonic history and volcanism of Sunset Crater Volcano National Monument. The detail of programs, however, might be at a level somewhat different than that presented here. So design a program with language and explanations the public can understand, but have in your toolbox more in-depth information from the manual.

### ***DOs and DON'Ts***

#### DOs:

- Present information at a level the public understands.
- Talk about things you truly understand.
- Talk about things that the people are actually seeing, on hiking trails, at the Visitor Center, and on slides during evening programs.

#### DON'Ts:

- Use "buzzwords."
- Talk over people's heads.
- "Parrot" information or concepts you don't really understand.
- Talk about things the visitors aren't looking at.

### ***About "Buzzwords"***

Technical terms, or "buzzwords," are both a godsend and a curse. They are useful because they are concise; they can convey a lot of information with a minimum of verbiage. For example, instead of "the relatively soft part of Earth's mantle, between about 100 and 400 miles depth, sandwiched between harder mantle above and below," we might just say "asthenosphere." Buzzwords are not useful, however, when the intended audience does not have sufficient technical background to understand them. How many people know what Earth's mantle is, much less that it has a relatively soft zone called the "asthenosphere?" Park Service interpreters should be familiar with buzzwords, because they enable the interpreter to explore concepts in greater depth when communicating with experts or researching material for programs. When explaining things to the public, however, it may be best to avoid buzzwords. Why not explain the concept in simple English, even if it takes a few more words? At the very least, define a buzzword the first time you use it in a program, and give a real-life analogy (preferably one involving food!).

### ***Talk about things people are seeing!***

When presenting talks it is advisable to talk about things the visitors are looking at. If those things aren't actually there, then you need to "bring them along," in the form of props or illustrations. Some examples:

1. On national parkland, you can't simply take out a hammer and whack off a piece of rock! A suggestion would be to take along rock samples with fresh faces exposed, to show visitors during the program.
2. On the lower portion of the Lava Flow Trail, one can point out detailed features within the lava flows and look back at the cinder cone shape of Sunset Crater Volcano. But the overall volcanic activity of northern Arizona, as well as discussion of different types of volcanoes, are best presented at the upper portion of the trail, where the dramatic landscape is in full view.
3. Plate tectonic theory is background information critical to understanding how and where various types of rocks and landscapes form. It is not easily and effectively worked into programs at Sunset Crater, however, because the volcanism in northern Arizona does not fit into a simple tectonic setting, and because there is no viewpoint that makes the overall tectonics clear. Discussion of plate tectonics should therefore be limited to responses to specific questions from visitors, or for evening programs, when there is time to develop concepts and illustrate them with maps and slides.

### ***Developing a Knowledge Gap***

Interpretation is possible when your general knowledge of a park resource is somewhat more than that of a typical visitor. The "knowledge gap" does not have to be great! If you know some basic geologic concepts and familiarize yourself with the tectonic setting of the park and a few specific observations within the park, then you can begin to relate geology to the public. Even more important is that you know enough to explain how geology relates to plants, people, and other things that visitors see in the park. This Geology Training Manual contains information and insight to help you expand the knowledge gap between you and the visitors.

## **GEOLOGIC TIME**

Table 1 is the geologic time scale, showing the names of the divisions of geologic time as well as the span of years represented by each division. The divisions generally relate to forms of life that occurred at various times in the geologic past. The 4.6 billion years of Earth history are first broken into four **eons**. In the Hadean and Archean eons, spanning nearly half of geologic time (from 4.6 to 2.5 billion years ago), there were only very primitive bacteria and algae. The Proterozoic Eon, from 2.5 billion to 570 million years ago, saw the development of primitive aquatic plants. In the Phanerozoic Eon, beginning 570 million years ago, life suddenly flourished and evolved to the complex plants and animals we know today. The Phanerozoic Eon is broken into finer divisions called **eras**, in turn divided into **periods** and **epochs**. The first period of the Phanerozoic Eon is the Cambrian. Rocks older than the Phanerozoic (that is, older than the Cambrian Period) are thus collectively termed **Precambrian**.

At the beginning of the Paleozoic Era (meaning "time of early life") marine invertebrates suddenly flourished, followed progressively by the development of fish and early land plants. In the Mesozoic Era ("middle life") trees appeared, along with dinosaurs and the first birds and

mammals. The Cenozoic Era (“modern life”) saw the rise of mammals and, very recently, humans.

## **Vastness of Earth History**

The great length of geologic time is difficult to appreciate, given that the span of a human life is only a few decades. For perspective, consider that by some accounts, based on cultural and religious beliefs, the Earth is only about 6,000 years old. Geology’s most important contribution to human thought may be that, according to scientific observation, the Earth is about 4.6 billion years old. Consider that 4.6 billion years is about **one million** times as long as 6,000 years. With only 6,000 years available it is necessary to call upon processes that happen very quickly in order for continents, oceans, mountains, valleys, and other features to form. With a million times as much time to work with, however, these same features could develop through slow processes that act for long periods of time. Whether one accepts that Earth is very old (4.6 billion years) or relatively young (6,000 years), the controversy affects thinking far beyond geology and other sciences. The debate encompasses history, philosophy, and religion, involving ideas at the very heart of the nature of people and the universe.

The enormous span of geologic time, and where our own lives fit in, can be visualized by putting the 4.6 billion years between the goal lines of a 100-yard long football field. The span of only very primitive life (Precambrian) stretches all the way across mid-field to the opponents 12 yard line! Extinction of the dinosaurs (end of the Cretaceous, 63 million years ago) would be between the 1 and 2 yard lines. The appearance of the earliest human ancestors (5 million years ago) would be 4 inches from the goal line. The beginning of recorded history (about 5,000 years ago) would be 4 one-thousandths of an inch (.004 inch) from the goal line, less than the width of the “dimples” on the leather ball. Now consider where the eruptions that built Sunset Crater Volcano, about 900 years ago, fit in (diameter of a grain of chalk dust marking the line?).

## **Geologic Events In Northern Arizona: Evidence of the Past**

The very young lava flows and cinders on the surface at Sunset Crater Volcano National Monument are some of the most recent of a sequence of events that shaped the landscape of northern Arizona. Earlier history, involving shallow seas and wind-blown deserts, are represented by the sequence of sedimentary rocks exposed in the Grand Canyon. Since then, throughout a region called the Basin and Range Province, the North American continent has been ripping apart. At the same time, the adjacent Colorado Plateau has been slowly rising, accompanied by volcanic activity along its edges.

### ***Sequence of Rocks in the Grand Canyon***

The very oldest rocks in the Grand Canyon formed nearly 2 billion years ago, during the early part of the Proterozoic Eon. They were buried deeply within the Earth and subjected to extreme heat and pressure so that they metamorphosed to the rock known as the Vishnu Schist. In places the schist was intruded by magma that cooled beneath the surface as the Zoroaster Granite. The region was uplifted and shallower rocks eroded away, so that these very old rocks were exposed at the surface. Shallow seas periodically invaded the continent during the Paleozoic Era, depositing sedimentary layers of sandstone, limestone, and shale over the schist and granite. The limestone layers, formed primarily from dissolved pieces of shellfish,

are evidence that the North American continent was much farther south, where ocean waters are warm. The continent has since drifted slowly northward.

### ***Continental Rifting in the Basin and Range Province***

Much of the western part of the North American continent, including all of Nevada and portions of surrounding states, has been ripping apart for the past 20 million years. The upper, brittle part of the crust has cracked along a series of block faults, forming long mountain ranges with valleys (“basins”) in between; the region is thus called the Basin and Range Province. The continental rifting is accompanied by volcanic activity, commonly as sticky lavas forming steep, explosive volcanoes, followed by fluid lava that erupts as fountains of cinders and dark flows forming broad, gently-sloping volcanoes.

### ***Volcanism and Uplift of the Colorado Plateau***

Starting about 6 million years ago a broad region, roughly centered on the four-corners region of Utah, Colorado, New Mexico, and Arizona, has slowly uplifted as a huge piece of the continent known as the Colorado Plateau. The Colorado River has been eroding downward, exposing the spectacular sequence of Paleozoic strata and older rocks in the Grand Canyon. At the same time, volcanic activity has been occurring along the western, southern, and eastern edges of the Colorado Plateau. In northern Arizona, eruptions began about 6 million years ago, in the transition zone between the Basin and Range Province and the Plateau. The volcanic activity has since progressed eastward, forming the San Francisco Peaks and, very recently, the Cinder Hills and Sunset Crater Volcano. The volcanic rocks at Sunset Crater Volcano National Monument were therefore erupted at high elevation, resting upon the Paleozoic sedimentary strata on top of the Colorado Plateau. It is quite likely that their origin relates to continental rifting, as the Basin and Range volcanism appears to be encroaching on the edges of the Plateau.

## **TYPES OF ROCKS**

Virtually all the rocks found in Sunset Crater Volcano National Monument are ***igneous***, one of the three basic kinds of rocks. “Volcanic” refers to igneous rocks that solidified from molten magma that poured out onto Earth’s surface. The cooled lava and other volcanic material rest on older layers of ***sedimentary*** rock, the same sequence exposed in the walls of the Grand Canyon. Still older rocks that are exposed at the bottom of the Grand Canyon were subjected to high temperature and pressure, and are thus ***metamorphic***.

***Petrology*** is the study of rocks and the processes that form them. Like earthquakes, volcanoes, and mountain ranges, most rocks are products of processes that occur at the boundaries of lithospheric plates. Such boundaries are generally where: 1) heating or decompression generates magma that forms igneous rocks; 2) erosion and deposition result in sedimentary rocks; and 3) increases in temperature and pressure cause existing rocks to re-crystallize as metamorphic rocks.

## **Rocks and Minerals**

Sometimes the terms “rock” and “mineral” are confused. A ***mineral*** is a substance that has the following properties.

1. It is a naturally-occurring, inorganic solid.
2. It has a definite chemical composition (or a specific range of compositions).
3. It has a specific internal (crystalline) structure.
4. It has definite physical properties that result from the chemical composition and crystalline structure.

Take for example, the mineral **quartz**. Its chemical composition is  $\text{SiO}_2$ , meaning the molecules have two atoms of oxygen (O) for every one atom of silicon (Si). Quartz forms long, six-sided crystals that come to a point. One of its physical properties is that it has a hardness of 7, meaning that it can scratch the mineral orthoclase (hardness 6), but not topaz (hardness 8).

A **rock** is an aggregate (consolidated mixture) of minerals. Generally (but not always), a rock has more than one kind of mineral. The mineral grains are held together as a rigid solid; either they become interlocked as they form, or the particles are cemented together in some natural way. For example, after sediment is deposited and buried, silicon and oxygen atoms can precipitate from groundwater, gluing grains of quartz and other minerals together as **sandstone**.

### **Three Basic Types of Rocks**

Rocks are generally classified according to the way they formed. An **igneous rock** is an aggregate of interlocking minerals, formed by the cooling and solidification of molten magma. A **sedimentary rock** is an aggregate of fragments eroded from older rocks, or minerals precipitated through chemical or biological activity. A **metamorphic rock** is an aggregate of interlocking minerals, formed by re-crystallization of some or all of the minerals in an existing rock. The re-crystallization occurs when the rock is subjected to elevated temperature or pressure, but while the rock is still in a solid state.

#### ***Igneous Rocks***<sup>1</sup>

Igneous rocks solidify from **magma**, which is molten rock that may contain gasses and suspended solid material. The terms “magma” and “lava” are often used interchangeably, but have important differences. All melted Earth material is magma, while **lava** is magma that poured out on Earth’s surface, forming **extrusive** (or **volcanic**) rocks. When magma solidifies below Earth’s surface, **intrusive** rocks result.

Igneous rocks are classified according to two parameters, texture and chemistry (Table 2). **Texture** refers to the **size of the mineral grains**, which is a function of how quickly the magma cooled. Intrusive rocks are coarse-grained because they cooled very slowly within the Earth, where mineral crystals had time to develop. Magma that encounters air or water at Earth’s surface cooled very quickly, so that extrusive (volcanic) rocks have fine-grained minerals that you generally cannot see with your naked eye. Magma may cool so fast that there is no time for crystals to form; instead atoms remain in a random state, forming volcanic glass, known as **obsidian**.

The **chemistry** of igneous rocks is commonly related to the **amount of silica** (silicon and oxygen) contained in the rock minerals (Table 2). Silica is the same material that makes up window glass and, in its pure form, is the mineral quartz ( $\text{SiO}_2$ ). Rocks with high silica content thus tend to be light-weight and light in color. Coarse-grained (intrusive) **granite** and fine-grained (extrusive) **rhyolite** are thus pink-to-white-colored igneous rocks that are high in silica

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<sup>1</sup>See also Appendix A.

(≈ 70% of the total rock mass). As the silica content goes down, minerals generally have higher percentages of heavier elements like iron and magnesium. With decreasing silica content, igneous rocks therefore tend to be heavier and darker. Intermediate-silica (≈ 60%) rocks are coarse-grained **diorite** and fine-grained **andesite** that are commonly gray in color. Low-silica (≈ 50%) igneous rocks tend to approach black in color, as intrusive **gabbro** and extrusive **basalt**. When rock is very low in silica (< 40%) it has a lot of iron and magnesium, so that it forms olive-green colored **peridotite**, the very heavy, coarse-grained rock that makes up Earth's mantle. Crustal material isn't as heavy as mantle because crust has more silica and less iron and magnesium. Oceanic crust, made of gabbro and basalt, is somewhat heavier than continental crust, which has rocks closer to the composition of granite.

Most of the igneous rocks found in Sunset Crater Volcano National Monument, including lava flows and cinders, have the chemistry of basalt. The low-silica and high-iron content combine to make the lava flows dark and heavy. In places normally dark-colored cinders turned red when the iron reacted with hot fluids to form rust (iron oxide). O'Leary Peak is an exception. It developed from pasty magma, forming a small, steep-sided volcano called a lava dome. The rocks on O'Leary Peak are **dacite**, a light-weight, light-colored rock with silica-content between that of andesite and ryholite.

### **Sedimentary Rocks**

Most sedimentary rocks form through the cycle of: 1. erosion, chemical, or biological activity that forms particles (sediment); 2. transportation of the sediment by water, wind, or ice; 3. deposition of the sediment in oceans, lakes, or streams; 4. compaction and cementation of the sedimentary particles as they are buried beneath more sediment.

Types of sedimentary rocks are best understood by imagining their environments of deposition. Gravel is found on the beds of fast-moving mountain streams. When buried and cemented, it forms the sedimentary rock **conglomerate**. **Sandstone** is made of sand-size grains, mostly quartz, that were deposited in stream beds or on beaches. In lakes or deeper parts of the ocean, where water is quieter, finer particles of silt and mud accumulate. Burial, compaction, and cementation turns these materials into **siltstone** and **shale**. In warm climates shell fragments of marine organisms dissolve in seawater, precipitating out as calcium carbonate. This fine lime mud eventually turns into the sedimentary rock **limestone**.

Sedimentary rocks at Sunset Crater Volcano National Monument are buried beneath volcanic deposits. Portions of the same sequence of rocks, mostly sandstone, shale, and limestone, however, can be studied in nearby Wapatki and Walnut Canyon national monuments, as well as in Grand Canyon National Park. These strata provide clues to the geologic history of northern Arizona prior to the volcanic activity that formed the San Francisco Volcanic Field.

### **Metamorphic Rocks**

There are three general factors that determine what type of metamorphic rock forms: 1) the original ("parent") rock; 2) the heat and pressure the rock endured, and 3) the presence (or absence) of fluids within the rock. The classification of metamorphic rocks is thus extensive and technical. Metamorphism, nonetheless, can be understood on a simple level if one imagines what happens to a specific parent rock as it is buried deeper and deeper within the Earth (that is, as it encounters increases in temperature and pressure). For example, as the sedimentary rock shale is initially buried, it begins to compress and heat up, forming the low-grade metamorphic rock **slate**. With deeper burial larger crystals develop (especially the flaky

mineral mica), forming intermediate-grade **schist**. Finally, at great depth where the temperature and pressure are very high, large crystals of blocky minerals like quartz and feldspar form a high-grade metamorphic rock called **gneiss**. If the rock is buried deeper it becomes so hot that it melts, forming magma.

Northern Arizona is covered extensively by sedimentary and volcanic strata, so that not a lot of metamorphic rock is exposed at the surface. Metamorphic rocks do occur in some mountain ranges where deep layers were uplifted during structural deformation, and at the bottom of the Grand Canyon, where the Colorado River has cut entirely through the overlying strata. The only metamorphic rocks found at Sunset Crater National Monument are a special kind formed near lava flows, where high temperatures have “baked” the underlying rocks.





## Chapter 1

# **PLATE TECTONICS: EARTHQUAKES, VOLCANOES, AND MOUNTAIN RANGES**

The term **tectonics** originates from the Greek word "tektōn," referring to a builder or architect. **Plate tectonics** suggests that large-scale features on Earth's surface, such as continents, ocean basins, and mountain ranges, result from interactions along the edges of large plates of Earth's outer shell, or **lithosphere** (Greek "lithos," hard rock). The plates, comprised of Earth's crust and uppermost mantle, ride on a warmer, softer layer of the mantle, the **asthenosphere** (Greek "asthenos," lacking strength). Earth's lithosphere is broken into a mosaic of seven major and several minor plates. Relative motions between plates define three types of boundaries: **divergent**, where plates rip apart, creating new lithosphere; **convergent**, where one plate dives beneath the other and lithosphere is destroyed; **transform**, where plates slide past one another, neither creating nor destroying lithosphere. Another large-scale feature is a **hotspot**, where a plate rides over a fixed "plume" of hot mantle, creating a line of volcanoes. Distinct patterns of mountains, earthquakes, and volcanoes are associated with each type of plate boundary and with hotspots.

Areas are designated as National Park Service lands because of their special historical significance or natural beauty. The later category commonly includes areas of mountains, valleys, seashores, or rock formations, features that commonly form along plate boundaries or hotspots. Understanding plate tectonic processes therefore establishes a framework that helps us understand the inspiring landscapes that attract us to national parks.

## **THE WHOLE EARTH**

Soon after it formed 4.6 billion years ago, the molten Earth settled into three layers (left side, Fig. 1.1). Dense material, mostly iron, fell toward the center to form the **core**. Lighter compounds of silicon and oxygen (silicates) remained closer to the surface. Silicates rich in iron and magnesium formed the **mantle**, overlain by a thin **crust** of silicates containing light elements (aluminum, calcium, potassium, and sodium). This classical division, based on chemical composition, was discovered in the early 1900's by analyzing earthquake seismic waves that penetrated the entire Earth.

By the mid 20<sup>th</sup> Century detailed seismic observations made it possible to study Earth's interior in finer detail. In modern times the three chemical layers are differentiated into five zones based on physical state (right side, Fig. 1.1). Changes in physical state occur because both temperature and pressure increase downward in the Earth. Temperature is hot enough at depths of 2900 to 5100 kilometers (1800 to 3200 miles) that the iron of the **outer core** is liquid. Below that, however, to a depth of 6400 kilometers (4000 miles) at Earth's center, pressure is so great that the **inner core** is solid. The iron/magnesium silicates of the mantle also show stratification due to the increasing temperature and pressure (Fig. 1.2). The outermost mantle and crust are cold and hard (like butter in a freezer), forming the rigid **lithosphere**. Below about 150 kilometers (100 miles) depth the mantle is warmer, so that the **asthenosphere** is a softer solid (like butter left on a dinner table). Still deeper, between about

700 and 2900 kilometers (400 and 1800 miles), pressure is so great that the lower mantle (**mesosphere**) is a harder solid. These changes in strength of the mantle create a unique situation where plates of lithosphere can ride over the softer zone of asthenosphere, similar to sliding a hard Oreo<sup>®</sup> Cookie over the creamy filling.

Blocks of crust actually ride passively at the top of plates of lithosphere, 75 to 200 kilometers (50 to 120 miles) thick, composed mostly of mantle (Fig. 1.2). There are two types of crust: relatively high-silica **continental crust**, about 20 to 75 kilometers (10 to 50 miles) thick, and lower-silica, 2 to 8 kilometer (1 to 5 mile) thick **oceanic crust**. The underlying mantle is denser than both continental and oceanic crust; crustal blocks can thus be thought of as “floating” on the denser mantle, much as icebergs on water (Fig. 1.3). Continental crust is more buoyant than oceanic crust, mainly because it is thicker. The effects of the buoyancy difference between the two types of crust can be envisioned by considering a tennis ball and a soccer ball in a swimming pool (Fig. 1.4). The balls are about the same density, but the soccer ball sticks farther out of the water because it is bigger and hence more buoyant. Areas underlain by thick continental crust likewise stand above sea level, while those with thin oceanic crust sag below. A swimmer can easily bring the tennis ball to the bottom of the pool, but might have difficulty doing that with the more buoyant soccer ball; lithosphere with thin oceanic crust is readily consumed (“subducted”) where plates converge, while buoyant continental crustal blocks collide rather than subduct.

## CONTINENTAL DRIFT AND THE DEVELOPMENT OF PLATE TECTONIC THEORY

Ever since the first maps of the Atlantic Ocean were made in the 16<sup>th</sup> Century people noticed how Africa and South America fit together like pieces of a giant jigsaw puzzle. The fit is even more impressive if continents are joined together at the edges of their continental shelves (Fig. 1.5). That huge landmass, called **Pangea**, represents only a brief glimpse in time, about 250 million years ago. At that time, during the Permian Period, most of the continental crust happened to be joined together. Prior to that time the continents were apart; since then they have drifted apart (imagine bumper cars being stuck together for a while, then flying apart). This theory, called **continental drift**, was viewed with skepticism in the early 20<sup>th</sup> Century. It was thought impossible for blocks of crust to plow their way over mantle, which was known to be much more rigid and dense than crust.

Two situations resulted in new information critical to acceptance of continental drift and plate tectonics. First, the topography of the ocean floor was mapped in great detail during and after World War II (Fig. 1.6). It was discovered that the floors of the ocean basins are not flat. A continuous mountain chain circumscribes the globe near the center of oceans and, in places, the ocean floor descends abruptly into deep trenches. Secondly, a network of seismographs was installed around the world in the early 1960’s, to detect nuclear tests during the Cold War. It was then possible to accurately locate earthquakes and to map the speed at which seismic waves pass through various regions of the Earth. The seismic data revealed startling observations.

- 1) Earthquakes are not scattered throughout the oceans, but instead are confined to narrow, rather continuous bands (Fig. 1.7).
- 2) Only shallow earthquakes occur along the mid-ocean ridges, but they extend along dipping zones from the surface downward at deep-sea trenches.
- 3) Within the upper mantle, there is a zone where seismic waves travel slowly (that is, the asthenosphere).

The last observation is the “Rosetta Stone” for plate tectonic theory. It provides a means by which continents can drift apart. Instead of having to plow their way through stronger mantle, the continents are passive “passengers” at the tops of plates comprised mostly of stiff mantle (lithosphere). The plates of crust and stiff mantle move about on the softer mantle beneath (asthenosphere, Figs. 1.1, 1.2). The observations of narrow zones of earthquakes and their depths provide clues to the distribution of deforming, brittle lithosphere, and thus outline the plate boundaries (Figs. 1.8, 1.9). 18

## THINGS THAT HAPPEN AT PLATE BOUNDARIES AND HOTSPOTS

Tectonic activity, including earthquakes, volcanism, and the formation of mountains, commonly occurs along plate boundaries or at hotspots. The pattern of earthquakes in Fig. 1.7 can be used to delineate the boundaries of lithospheric plates (Fig. 1.8), showing regions where plates rip apart (***divergent plate boundaries***, Fig. 1.9a); where they slide past one another (***transform plate boundaries***, Fig. 1.9b); and where they come together (***convergent plate boundaries***, Fig. 1.9c). Lines of volcanoes in the interiors of plates reveal ***hotspots***, where a plate rides over a plume of hot mantle material (Fig. 1.9d).

### Earthquakes

There are two conditions necessary for earthquakes to occur: 1) motion within the Earth so that material is stressed beyond its breaking point (or “elastic limit”); and 2) material that deforms in a sudden (***brittle***), rather than flowing (***ductile***), manner. Practically the only region of the Earth that can produce earthquakes, therefore, is the lithosphere (Fig. 1.9). In fact, earthquakes are generally confined to the cold, upper portion of lithospheric plates, which can break like peanut brittle. The lower, warmer regions of plates tend to bend easily without breaking. Earthquakes at divergent, transform, and hotspot settings are therefore only shallow, within the upper 30 or so kilometers (20 miles) of Earth’s surface (Fig. 1.9 a, b, d).

Shallow earthquakes also occur due to compression and other stresses at convergent plate boundaries (Fig. 1.9c). If plate convergence is fast enough, however, the plate remains cold and brittle to considerable depth, much like a cube of ice remains cold and brittle for some time when it is pushed to the bottom of a cup of hot coffee. Earthquakes therefore can occur to considerable depths (down to 700 km; 400 miles) as the rigid top portion of the downgoing plate is stressed and contorted. The biggest earthquakes ever recorded, beneath Chile in 1961 and Alaska in 1964, occurred in regions where one converging plate had been locked against the other plate for some time, building enormous stress.

There are several regions of the United States that are prone to earthquake activity. The magnificent landscapes characteristic of many national parks result, in part, from hundreds to thousands of movements along fault zones, accompanied by earthquakes. The Basin and Range Province, a rift in the continent that is developing into a divergent plate boundary, has shallow earthquakes that shake areas like Great Basin National Park and Death Valley National Monument. Along the San Andreas Fault in California, a transform plate boundary, shallow earthquakes shake Channel Islands National Park and Golden Gate National Recreation Area. In southern Alaska the Pacific and North American plates converge, forming a subduction zone under Alaska. The 1964 Great Alaska Earthquake shook Katmai, Lake Clark, Denali, Kenai Fjords, and Wrangell-St. Elias national parks. In the Pacific Northwest, the Juan de Fuca plate is subducting beneath the North American Plate. Although small-to-moderate

size, shallow earthquakes have occurred in historic time, it is thought that the plates have been locked together since the last large earthquake, 300 years ago. When the plates can no longer stand the accumulated stress they will suddenly snap along their boundary, causing a large earthquake that may devastate the region, which includes Olympic, Mount Rainier, Crater Lake, Redwoods, and Mount Lassen national parks.

## **Volcanism**

**Volcanism** refers to the fiery action at Earth's surface that some believe is caused by the Roman god *Volcanus*. The source of volcanism is **magma**, which is molten rock that may contain gas and suspended solid material. When magma cools slowly below Earth's surface, coarse-grained **intrusive** (or **plutonic**) rocks form (from *Pluto*, Roman god of the underworld). **Lava** is magma that pours out on Earth's surface, forming finer-grained, **extrusive** (or **volcanic**) rocks (Fig. 1.10).

Contrary to popular conceptions, magma does not originate from the molten core of the Earth. The source of almost all magma is much shallower, at depths of the lower crust and upper mantle (Fig. 1.11). The melting of rock occurs under two circumstances:

- 1) material that was cold and solid near Earth's surface is pushed to depths where it is much hotter (Fig. 1.11a); and
- 2) hot material that was solid because of enormous pressure rises and decompresses (Fig. 1.11b,c).

The first situation is the normal way we envision melting. At room temperature and pressure, for example, putting a match to plastic will cause it to melt. The top of a lithospheric plate "sweats" fluids as it encounters higher temperature during subduction. The second situation can be understood in the context of a pressure cooker. Under high pressure, water in the cooker remains liquid at temperatures considerably above its normal boiling point (212°F; 100°C). Removing the lid from the cooker suddenly releases the pressure, causing the hot water to flash to steam. Similarly, hot mantle material that is solid under high pressure will begin to melt ("flash to liquid") when the material rises and decompresses at divergent plate boundaries and hotspots.

Where plates converge the cold sediments and crust on top of the downgoing plate are heated as they subduct into the mantle (Fig. 1.11a). The plate thus "sweats" hot fluids, primarily water. As the fluids rise, they melt mantle and crustal materials in their paths. High-silica minerals are incorporated into the magma first, because they have lower melting temperatures than low-silica minerals. Magmas at convergent plate boundaries may thus be enriched in silica, forming intrusive rocks with compositions from **diorite** (~ 60% silica) to **granite** (~ 70% silica) and extrusive (volcanic) rocks ranging from **andesite** (~ 60% silica) to **rhyolite** (~ 70% silica). In some situations, rocks with lower (~ 50%) silica can also occur (intrusive **gabbro**; extrusive **basalt**).<sup>2</sup> Convergent boundary (subduction zone) volcanoes are present in national parks in southern Alaska (Katmai, Lake Clark, Kenai Fjords) and the Pacific Northwest (Mount Rainier, Crater Lake, Mount Lassen).

At divergent boundaries hot asthenosphere rises as the plates rip apart (Fig. 1.11b). The asthenosphere is part of the mantle, which is made mostly of iron and magnesium, with about 40% silica, comprising the rock **peridotite**. Under pressure, the peridotite of the asthenosphere is solid. As it rises and the pressure drops, however, the asthenosphere begins to melt. The magma that "bleeds off" the hot mantle is richer in silica (totaling about 50%), so

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<sup>2</sup>See Appendix A and Table 2 for more detailed discussion of igneous rocks and magmas.

that it forms ***gabbro*** and ***basalt***. A similar decompression of hot mantle occurs at hotspots (Fig. 1.11c); Hawaii Volcanoes and Haleakala national parks thus have enormous outpourings of basalt. Where thin (and relatively low-silica) oceanic crust caps plates in divergent or hotspot settings (that is, at mid-ocean ridges or oceanic hotspots), the magma does not have to melt much crustal material; the basalt/*gabbro* composition thus remains intact. In continental rift or continental hotspot settings, rising magma intrudes thicker continental crust, so that silica enrichment occurs, and rocks up to granite/*rhyolite* composition form. In the Basin and Range continental rift zone, Great Basin National Park and Death Valley National Monument have both low-silica basalt and higher-silica dacite and rhyolite. Isle Royal National Park in Michigan and St. Croix National Scenic River on the Wisconsin/Minnesota border have layers of basalt that formed when the Keweenaw Rift tried to rip the continent apart 1.1 billion years ago.

Where plates slide past one another, materials do not deepen or shallow appreciably (Fig. 1.11d). There is no significant heating of cold crust, nor decompression of hot mantle, that would induce melting. Volcanism is therefore not common at transform plate boundaries. Along the San Andreas Fault in California, an active transform plate boundary, Channel Islands National Park and Pinnacles National Monument do not have young volcanic rocks.

## **Formation Of Mountains**

Mountain ranges generally form due to volcanism and/or deformation of the crust. The type of volcanism (and hence type of volcanoes) depends on the type of plate boundary (or hotspot) and type of crust (oceanic or continental) on each plate involved. Likewise, forces that deform the crust into mountains depend on the type of plate boundary present, and whether oceanic or continental crust caps the plates involved.

### ***Mountains and Mountain Ranges formed by Volcanism***

The style of volcanic eruptions and the type of volcanoes formed relate to the amount of silica present in the erupting lava (Fig. 1.12). Silica tends to be a thickening agent, much like flour added to pancake batter.<sup>3</sup> The term ***viscosity*** refers to how a material resists flowing. Lava that is high in silica is thick and pasty (that is, it has *high viscosity*; Fig. 1.12a), while a low-silica lava is thin and runny (*low viscosity*; Fig. 1.12b).

Low-silica lavas seem to flow like water over long distances, so that the resulting volcanoes are broad, with gentle topographic slopes (Fig. 1.13a). From the air these volcanoes look like giant warrior's shields, so they are called ***shield volcanoes***. Shield volcanoes are predominately lava flows of basalt; the high amounts of iron and magnesium result in a dark, black landscape. The largest single mountain on Earth is the island of Hawaii (Fig. 1.12a). Starting from a depth of 5500 meters (18,000 feet) below sea level, this island of huge shield volcanoes rises to elevations over 4000 meters (13,000 feet), as the peaks Mauna Loa ("Long Mountain," Fig. 1.14a) and Mauna Kea ("Big Mountain"). Kilauea Volcano, in Hawaii Volcanoes National Park, is on the south flank of Mauna Loa.

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<sup>3</sup> *Growing up in the Cajun Country of south Louisiana, I was exposed to some of the most delicious food in the world. My mother and grandmother made some of the most tasty gumbos and étouffees you can imagine – muuuuuuh, ummmmm! They always started by making a roux, a mixture of hot grease and flour. The more flour added, the thicker and more pasty the roux. Magma is similar, only the thickening agent is silica.*

A **cinder cone** is a small volcano that forms from basaltic lava with high gas content (Fig. 1.13b). The lava is so fluid that the escaping gases result in fountains of hot liquid erupted through long fissures or central vents. As the material begins to cool and solidify, it falls to earth as particles, commonly sand-to-gravel sized cinders. The pile of cinders steepens until it reaches a certain angle (the angle of repose), much like sand falling in an hourglass. The cinder cone can continue to grow, but the angle of repose (commonly about 30°) remains the same. Sunset Crater Volcano National Monument, Capulin Volcano National Monument, and Wizard Island in Crater Lake National Park (Fig. 1.14b) are all cinder cones that formed in the past 6,000 years.

Where lava is thick and pasty, gases may be trapped under high pressure, sometimes resulting in explosive eruptions like Mount St. Helens in 1980 (Fig. 1.12b). Such high-silica volcanoes have not only lava flows, but also stratified layers of ash, cinders, pumice, mud, and other materials; they are thus called **composite volcanoes** (or **strato-volcanoes**). The sticky lavas do not flow easily, so that steeper volcanoes result (Figs. 1.13c, 1.14c). Composite volcanoes in national parks include Aniakchak, Mount Rainier, Mount Mazama (which collapsed and is filled with Crater Lake), and Lassen Peak.

When sticky lava concentrates in a small area, its high viscosity (that is, high resistance to flow) tends to make small volcanoes with steep, rounded shapes (Figs. 1.13d, 1.14d). **Lava domes** are distinct by their light color, due to volcanic rocks with very high silica content (dacite ~ 65% silica, to rhyolite ~ 70% silica). O'Leary Peak, near Sunset Crater Volcano National Monument, is a lava dome (Fig. 1.14d).

Considering Earth's topography both above and below the sea, most mountain ranges result from volcanic activity. Chains of steep-sided volcanoes, such as the Cascade Range in the Pacific Northwest (Fig. 1.15a), form on the overriding plate where one plate "subducts" beneath another (Fig. 1.11a). The chains of volcanoes are often curved, so that they are called **volcanic arcs** (for example, notice the Andes Mountains and Aleutian chain in Figs. 1.6 and 1.8). The national parks on the Alaska Peninsula and in southern Alaska, as well as those in the Cascade Mountains in the Pacific Northwest, are primarily there to showcase large composite volcanoes that are parts of volcanic arcs formed by subduction. Plate divergence produces vast amounts of magma (Fig. 1.11b), creating interlocking shield volcanoes that form long, submerged mountain chains (Mid-Atlantic Ridge; Fig. 1.15b). The system of mid-ocean ridges is, in fact, the longest mountain range on Earth (~ 60,000 kilometers, or 35,000 miles long; Fig. 1.6). The Hawaiian Islands and their sub-sea extension, the Emperor Seamount Chain (Fig. 1.15c), are a classic example of volcanic mountains developed over a hotspot (Fig. 1.11c). Hawaii Volcanoes and Haleakala national parks thus show different stages of volcanic activity related to the northwestward movement of the Pacific Plate over the hotspot.

### ***Mountains and Mountain Ranges formed by Crustal Deformation***

*Earth scientists had just discovered something fascinating about the continent Pally Keene was standing on, incidentally. It was riding on a slab about forty miles thick, and the slab was drifting around on molten glurp. And all the other continents had slabs of their own. When one slab crashed into another one, mountains were made. (Breakfast of Champions by Kurt Vonnegut, Jr., © 1973, Delacorte Press).*

Mountain ranges form in several ways through deformation of Earth's crust. Two types of geologic structures, faults and folds, are important components in the development of structural mountain ranges. Isostatic uplift, which results from changes in crustal or lithospheric thickness, is another important component. Different types of faults, folds, and

isostatic uplift occur due to different types of forces acting at plate boundaries and hotspots.

**Faults.** A **fault** is a break between two blocks of rock, along which there is relative movement between the blocks. Faulting is **brittle** deformation of rock, occurring primarily in the cold, upper portion of the crust. The warmer, lower crust, like the asthenosphere, tends to fail in a **ductile** fashion, slowly flowing rather than breaking.

There are three main types of faults, described by how one fault block moves relative to the other. The type of faulting can be described by envisioning the layers of rock before and after faulting (Fig. 1.16). In the 19<sup>th</sup> Century, coal miners in Pennsylvania recognized faults offsetting the strata along the walls of mine shafts. They described the type of fault motion by standing across the sloping fault surface. The block in back of their head they called the **hanging wall**, at their feet the **foot wall**. A fault where the hanging wall block moved downward, relative to the foot wall, was termed a **normal fault** (Fig. 1.16a). A **reverse fault** occurred where the hanging wall moved upward, relative to the foot wall (Fig. 1.16b). A special kind of reverse fault, where the fault surface slopes at a low angle, is called a **thrust fault**. The term **strike-slip fault** was later applied to the situation where one block slid laterally past the other (Fig. 1.16c).

Normal, reverse, and strike-slip faults form due to specific kinds of stresses, which generally relate to the three types of plate boundaries (Fig. 1.9). When a block of rock is subjected to **tension**, as at divergent plate boundaries, it is pulled apart along normal faults. At convergent plate boundaries, where there is **compression**, blocks are pushed (or thrust) over other blocks, forming reverse faults. There are **shearing stresses** concentrated along transform plate boundaries, so that faults are predominately strike-slip. While this simple pattern relating the kind of faulting to the type of plate boundary generally rings true, it should be noted that stress patterns are often complex; all three types of faults may be found in various places along a given plate boundary.

**Folds.** A **fold** is the bending of rock layers along a recognizable pattern. Folding can occur where rocks are cold and brittle, accompanied by cracks and small faults that allow the rocks to bend. Folds also form in hot, ductile rock, as the rock flows and bends instead of cracking.

As with faults, it is informative to envision rock layers before and after folding (Fig. 1.17). In a normal sequence of rocks, the older layers are at the bottom, the youngest on top. An **anticline** is where the layers are folded upward; after some surface erosion, the older layers are at the center of the anticline, the younger ones toward the flanks (Fig. 1.17a). Where rock is bent downward, at a **syncline**, the younger layers appear at the center (Fig. 1.17b). Rock layers are often buckled into a **series of anticlines and synclines** (Fig. 1.17c). In some places, such as the Valley and Ridge Province of the Appalachian Mountains, rock layers are folded in a more complex fashion, forming **plunging anticlines and synclines** (Fig. 1.17d). After erosion, distinct “V-shaped” patterns develop on the ground surface. At a **plunging anticline** the “V’s” point in the direction the structure plunges, while the opposite is true of a **plunging syncline**.

**Isostatic Uplift.** Where low-density material is present at the level normally occupied by the upper mantle, a broad region of high topography uplifts to compensate (Fig. 1.18). The situation can be envisioned by taking a beach ball into a swimming pool. A beach ball placed under your belly lifts just enough of your body out of the water to weight down the ball.

There are two situations where broad mountain ranges form to compensate low-density

material at depth. Where the crust is thick, a low-density root sticks downward into the denser mantle (Fig. 1.18a). The resulting buoyancy causes uplift of the crust until just enough topography is created to weight down the root. At divergent plate boundaries, where the lithosphere is thin, the underlying asthenosphere is shallow (Fig. 1.18b). Shallow asthenosphere has relatively low-density because it is hot, expanded mantle. The buoyancy that causes the high topography at mid-ocean ridges and continental rift zones is thus similar to a hot-air balloon inflating beneath the thin lithospheric plates.

Structural Mountain Ranges at Plate Boundaries. Crustal deformation occurs in all tectonic settings. Where plates diverge the cold, brittle part of the crust can fracture due to tensional stresses, forming a series of normal faults. **Fault-block mountains** thus form, each of the blocks separated by normal faults (Fig. 1.18b). The Basin and Range Province in the United States and Mexico is an example of block faulting in a continental rift setting (Fig. 1.19a). The rift valleys (or “basins”) are down-dropped, hanging wall blocks, while the mountain ranges are foot wall blocks (Fig. 1.16a).

Sediments and crust can be scraped off the cold portion of the downgoing oceanic plate at a convergent boundary. The material is squeezed upward by compression between the two plates, resulting in a structural mountain range parallel to the chain of composite volcanoes. The overall shape is that of a wedge that is attached, or “accreted,” to the crust of the overriding plate. Such a structural mountain range, consisting of numerous folds and reverse (thrust) faults, is thus called an **accretionary wedge** (Fig. 1.19b).

The highest elevations on Earth occur in **collisional mountain ranges** that form when an ocean basin closes due to plate convergence (Fig. 1.18a). Compression uplifts and thrusts sediments and hard crust over one continent, as occurs today in the Himalayas, where India is colliding with Asia (1.19c). A broad, very high region, the Tibetan Plateau, forms when one block of thick continental crust (India) is pushed beneath another (Asia). As in an accretionary wedge, the collision zone consists of numerous folds and thrust faults. Flying over portions of the Appalachian mountains, an ancient continental collision zone that has been heavily eroded in the last 300 million years, one sees spectacular examples of plunging anticlines and synclines (Fig. 1.19d; compare to Fig. 1.17d).

At transform plate boundaries, mountains rise as the plates slide by one another and material is squeezed upward. The San Andreas Fault in California thus reveals mountain ranges of complex structure due to shearing action as the Pacific Plate moves north-northwest relative to the North American Plate.

## GENERAL TECTONIC SETTINGS IN THE UNITED STATES

Table 3 lists National Park Service lands that lie within specific tectonic settings. The term **tectonic setting** refers to the factors responsible for the topography and rocks of a region. Structures and processes at each setting are products of: 1) relative motions between lithospheric plates at their boundaries; and 2) the kind of crust. The tectonic setting for a park is thus classified according to whether the park is near a divergent, convergent, or transform plate boundary or a hotspot, and whether thick continental or thin oceanic crust caps each of the plates involved.

Much of this work presents the landscapes of National Parks in a sequence known as the “Wilson Cycle,” whereby ocean basins open and close through time (Fig. 1.20). In a

complete Wilson Cycle, divergent plate motions rip away at a continent, forming a continental rift zone. An ocean basin then forms, with passive continental margins on its edges and a mid-ocean ridge creating new oceanic lithosphere at the divergent boundary. The basin eventually closes through convergent plate motion as oceanic lithosphere is consumed at a subduction zone. A collisional mountain range forms when blocks of thick, buoyant continental crust along the margins of the ocean enter the subduction zones.

The shaded, raised-relief map of the United States highlights regions according to their tectonic settings (Fig. 1.21). Active continental rifting is evident from the block-faulting that results in the Basin and Range Province. The Rio Grande Rift is an extension of the rifting through New Mexico and southern Colorado. Passive continental margins along the Atlantic and Gulf coasts occur in the transition from continental to oceanic crust, evident from the map as the coastal plains onshore and continental shelves offshore.

Topography of a subduction zone is shown by the deep-blue trench offshore of the volcanic mountain chain in the Aleutian Islands, Alaska Peninsula, and southern Alaska. In the Pacific Northwest the coast ranges (accretionary wedge) are the structural mountain range parallel to the composite volcanoes of the Cascade Range (volcanic arc). A low region between the two mountain ranges, characteristic of subduction zones, is the Puget Sound area of Washington and Willamette Valley in Oregon. In California, topography of past subduction is still evident, as the Coast Range (structural mountain range), Sierra Nevada Mountains (eroded volcanic range), and intervening Great Valley. Sheared and compressed mountain ranges near the coast represent current transform plate motion along the San Andreas Fault.

High mountains that may have resulted from low-angle subduction run all along the front ranges of the Rocky Mountains, through west Texas, New Mexico, Colorado, Wyoming, and Montana. Areas of complex, accreted terrains are west of the frontal ranges, from interior Alaska southward all the way into Mexico.

The Appalachian Mountains in the eastern United States and Canada represent the collision of continents 300 to 500 million years ago. In their prime these mountains were probably as high as the mountains in the continental collision zone stretching from the Himalayas through the Alps. Since that time, the Atlantic Ocean opened up and the mountains eroded down, mere shadows of their former selves. The zone of continental collision continues southwestward, but young sediments of the Gulf coastal plain mostly cover it. It does surface, as small mountains, the Ouachitas of western Arkansas and southeastern Oklahoma, and the Marathon Mountains in the Big Bend area of west Texas. Another, younger zone of continental collision is the Brooks Range, stretching west-to-east across northern Alaska.

Two hotspot tracks appear on the map, one where a plate with oceanic crust is involved, and one with continental crust. The Hawaiian Islands are broader and higher on the southeast, becoming lower and smaller to the northwest. This pattern continues far beyond the islands as submerged seamounts. The Hawaiian Island – Emperor Seamount chain suggests that the Pacific Plate has been moving over a hotspot, first in a northerly direction, then northwestward. On the North American continent the Snake River Plain of southern Idaho connects the Columbia Plateau region of southeastern Washington and northeastern Oregon with Yellowstone National Park in the northwest corner of Wyoming. This feature has been interpreted as due to the movement of the North American continent over a hotspot.

The topography of two regions of the map is not easily associated with plate boundaries or hotspots. The Colorado Plateau, centered on the Four-Corners region of Arizona, New Mexico, Colorado, and Utah, is relatively stable, experiencing only broad, regional uplift. The

stable craton refers to most of the continental interior of Canada and the United States.  
Plate tectonic processes are evident in the topography of areas surrounding the craton, but the craton itself has not experienced significant tectonic activity in hundreds of millions of years.

**Table 3. Classification of National Park Service lands according to tectonic setting.** The setting depends on the type of plate boundary and crust present during formation of the rocks and landscapes in each park. Areas were selected if a significant amount of the material presented to park visitors relates to the geology of the region. NP = National Park; NM = Nat. Monument; NS = Nat. Seashore; NLS = Nat. Lake Shore; NRA = Nat. Recreation Area; NSR = Nat. Scenic River; NHP = Nat. Historic Park; WSR = Wild and Scenic River; NST = Nat. Scenic Trail; NRR = Nat. Recreation River.

## **1. DIVERGENT PLATE BOUNDARIES**



### **A) CONTINENTAL RIFTS**

#### **Basin and Range Province (Active)**

Great Basin NP, NV	Saguaro NM, AZ
Death Valley NM, CA	Joshua Tree NM, CA
Timpanogos Cave NM, UT	Organ Pipe Cactus NM, AZ
Lake Mead NRA, CA	Grand Canyon NP, AZ
Lava Beds NM, CA	Crater Lake NP, OR
Devils Postpile NM, CA	Sunset Crater NM, AZ

#### **Rio Grande Rift (Active)**

White Sands NM, NM	Capulin Volcano NM, NM
Bandelier NM, NM	

#### **Keweenawan Rift (Ancient)**

Isle Royale NP, MI	Pictured Rocks NLS, MI
Grand Portage NM, MN	St. Croix NSR, MN/WI
Apostle Island NLS, WI	

### **B) PASSIVE CONTINENTAL MARGINS**

#### **Atlantic Coast**

Acadia NP, ME	Assateague Island NS, MD
Biscayne NP, FL	Cape Hatteras NS, NC
Fire Island NS, NY	Cape Lookout NS, NC
Gateway NRA, NJ	Cumberland Island NS, GA
Cape Cod NS, MA	Canaveral NS, FL

#### **Gulf of Mexico Coast**

Everglades NP, FL	Big Thicket N Pres, TX
Gulf Islands NS, FL/MS	Padre Island NS, TX
Jean Lafitte NHP & Pres, LA	

### **C) MID-OCEAN RIDGES**

**(None)**

## 2. CONVERGENT PLATE BOUNDARIES



### A) OCEAN-OCEAN SUBDUCTION ZONES

**Aleutian Islands/Alaska  
Pen.**  
Aniakchak NM & Pres, AK

**Western Pacific**  
NP of American Samoa, Am Sam

### B) OCEAN-CONTINENT SUBDUCTION ZONES

#### **Coast Ranges (Accretionary Wedge)**

Olympic NP, WA  
Redwood NP, CA

Oregon Caves NM, OR

#### **Alaska (Active Volcanic Arc)**

Katmai NP & Pres, AK  
Lake Clark NP & Pres, AK

Kenai Fjords NP, AK

#### **Cascade Mountains (Active Volcanic Arc)**

Mount Rainier NP, WA  
Crater Lake NP, OR

Lassen Volcanic NP, CA

#### **Sierra NV Mountains (Ancient Volcanic Arc)**

Yosemite NP, CA  
Kings Canyon NP, CA

Sequoia NP, CA

#### **Laramide Uplifts (Low-Angle Subduction)**

Glacier NP, MT  
Grand Teton NP, WY  
Rocky Mountain NP, CO  
Wind Cave NP, SD  
Carlsbad Caverns NP, NM  
Guadalupe Mountains NP, TX

Bighorn Canyon NRA, MT  
Mount Rushmore NM, SD  
Jewel Cave NM, SD  
Great Sand Dunes NM, CO  
Florissant Fossil Beds NM, CO

### C) COLLISIONAL MOUNTAIN RANGES

#### **Appalachian Mountains**

Shenandoah NP, VA  
Great Smoky Mountains NP, NC/TN  
Blue Ridge Parkway, VA/NC  
Appalachian NST, GA to ME  
Delaware Water Gap NRA, PA  
Gauley River NRA, West VA

New River Gorge NR, West VA  
Bluestone NSR & RA, KY  
Big South Fork NR & RA, KY/TN  
Obed WSR, TN  
Russell Cave NM, AL  
Chattahoochee River NRA, GA

**Ouachita Mountains**

Hot Springs NP, AR  
Chickasaw NRA, OK

**Marathon Mountains**

Big Bend NP, TX  
Rio Grande WSR, TX

**Brooks Range**

Gates of the Arctic NP&Pres, AK  
Noatak NP & Pres, AK

Cape Krusenstern NP & Pres, AK

**D) ACCRETED TERRAINS****North American Cordillera**

Denali NP, AK  
Wrangell-St. Elias NP & Pres, AK  
North Cascades NP, WA

Yukon-Charley Rivers N Pres, AK  
Ross Lake NRA, WA

**3. TRANSFORM PLATE BOUNDARIES****San Andreas Fault**

Channel Islands NP, CA  
Point Reyes NS, CA  
Muir Woods NM, CA  
Golden Gate NRA, CA

Pinnacles NM, CA  
Santa Monica Mountains NRA, CA  
Cabrillo NM, CA

**Southeast Alaska**

Glacier Bay NP & Pres, AK

**Caribbean**

Virgin Islands NP, U. S. VI  
Buck Island Reef NM, U. S. VI

**4. HOTSPOTS ←←←****A) OVER OCEANIC CRUST****Hawaii - Emperor**

HI Volcanoes NP, HI

Haleakala NP, HI

**B) OVER CONTINENTAL CRUST****Yellowstone-Snake River Plain-Columbia Plateau**

Yellowstone NP, WY/ID/MT  
Craters of the Moon NM, ID

Sunset Crater Volcano NM, AZ?  
Capulin Volcano NM, NM?

## **5. AREAS NOT EASILY ASSOCIATED WITH PLATE BOUNDARIES OR HOTSPOTS**

### **Colorado Plateau**

Grand Canyon NP, AZ  
 Zion NP, UT  
 Bryce Canyon NP, UT  
 Petrified Forest NP, AZ  
 Capital Reef NP, UT  
 Arches NP, UT  
 Mesa Verde NP, CO  
 Walnut Canyon NM, AZ

Wapatki NM, AZ  
 Sunset Crater Volcano NM, AZ  
 Natural Bridges NM, UT  
 Cedar Breaks NM, UT  
 Glen Canyon NRA, UT  
 Dinosaur NM, UT/CO  
 Black Can of the Gunnison NM, CO  
 Curecanti NRA, CO

### **Stable Craton**

Theodore Roosevelt NP, ND  
 Badlands NP, SD  
 Voyageurs NP, MN  
 Mammoth Cave NP, KY  
 Agate Fossil Bed NM, NB  
 Scotts Bluff NM, NB  
 Missouri NRR, SD/NB  
 Lake Meredith NRA, TX  
 MS NR & RA, MN  
 Pipestone NM, MN

Effigy Mounds NM, IA  
 Ozark NSR, MO  
 Buffalo NR, AR  
 Poverty Point NM, LA  
 Natchez-Trace Pky & NST,  
 MS/AL/TN  
 Sleeping Bears Dunes NS, MI  
 Mound City Group NM, OH  
 Indiana Dunes NLS, IN

## Chapter 2

# TECTONICS OF THE SOUTHWESTERN UNITED STATES

The large-scale topography and other geologic features in the southwestern United States result, to a large degree, from activity in three different tectonic settings (Figs. 2.1, 2.2). The **Basin and Range Province**, including all of Nevada and the western and southern portions of Arizona, is an active continental rift. The **San Andreas Fault** in southern California is a transform plate boundary, along which the Pacific Plate is moving north-northwest, relative to the North American Plate. A region of broad, gradual vertical uplift, centered around the Four Corners area of Arizona, Utah, Colorado, and New Mexico, is the **Colorado Plateau**. Sunset Crater Volcano National Monument lies on the southwestern edge of the Colorado Plateau, near the transition to the Basin and Range Province. The volcanism of northern Arizona does not lend itself to any simple explanation. It may be due to 1) eastward propagation of continental rifting in the Basin and Range Province; 2) westward movement of the North American Plate over a hotspot; 3) uplift of the Colorado Plateau; 4) remnant of a subducted mid-ocean ridge; or 5) some combination of those factors.

### BASIN AND RANGE PROVINCE (CONTINENTAL RIFT)

Continental rift zones form during divergent plate motion as thick continental crust rips apart. Where plates move away from one another the lithosphere thins, so that the underlying, buoyant asthenosphere elevates a broad region (Fig. 2.3). The elevated regions are **continental rift zones** or **mid-ocean ridges**, depending on whether they have continental or oceanic crust.

Tensional forces that produce fissures, block faulting, and rift valleys characterize **continental rift zones** (Fig. 2.3a). If a continent completely rips apart, the two fragments drift away as parts of different lithospheric plates (Fig. 2.3b). New oceanic lithosphere is created between the continents, at a **mid-ocean ridge**. If the process continues long enough, a large ocean basin forms (Fig. 2.3c). The plate boundary is then at the mid-ocean ridge, far from the margins separating continental from oceanic crust; such margins are termed **passive continental margins**.

As a continent rips apart it stretches, thinning the crust and entire lithosphere (Fig. 2.3a). The region is raised to high elevation because the underlying asthenosphere is hot and buoyant. The upper part of the crust deforms in a cold, brittle fashion, causing earthquakes and mountain ranges that are separated by down-dropped valleys. These **rift valleys** fill with up to 5 miles (8 kilometers) of sedimentary and volcanic deposits as they subside, forming basins. The broad region of continental rifting in western North America, including all of Nevada and portions of Oregon, Idaho, California, Utah, Arizona, New Mexico, west Texas, and Mexico, is thus termed the **Basin and Range Province** (Fig. 2.1).

Fig. 2.4 shows stages of divergent plate boundary development in northeast Africa and Saudi Arabia. Active continental rifting (Fig. 2.3a) is occurring in East Africa. Many of the rift valleys have lakes because the valley floors are dropping faster than sediment can fill them. In

fact, most of the world's deep lakes form in continental rift valleys, including Lake Baikal in Siberia (deepest: 5369 feet, 1637 meters), Lake Tanganyika in East Africa (2<sup>nd</sup> deepest: 4708 feet, 1435 meters), Lake Malawi in East Africa (4<sup>th</sup> deepest: 2316 feet, 706 meters), Issyk Kul in central Asia (5<sup>th</sup> deepest: 2297 feet, 700 meters), and Lake Tahoe in the Basin and Range Province (8<sup>th</sup> deepest: 1685 feet, 514 meters).<sup>4</sup> The Red Sea is an early-stage ocean basin (Fig. 2.3b), with passive continental margins bordering Africa and Saudi Arabia and a mid-ocean ridge down the center. The adjacent Gulf of Aden is more advanced (Fig 2.3c), including a mid-ocean ridge that extends into the Indian Ocean.

## **Structure of the Basin and Range Province**

The Basin and Range Province (Fig. 2.1) is a classic example of fault-block mountains (Figs. 1.19a, 2.2), the basins (rift valleys) separated from the mountain ranges by normal faults (Fig. 1.16a). Great Basin National Park, in Nevada near the Utah border, lies in a mountain range adjacent to a rift valley (Fig. 2.5a). The uplifted fault block is the Snake Range, including prominent mountains like Wheeler Peak (13,863 feet; 3,982 meters) where older sedimentary, igneous, and metamorphic rocks are exposed. The adjacent basin is the Snake Valley, filled with young sedimentary deposits from rivers and lakes, as well as lava flows.

From Crater Lake National Park in southern Oregon, you can look to the south and see the Klamath Basin, a rift valley on the northwestern edge of the Basin and Range Province (Fig. 2.5b). The valley floor is flat, covered in part by the Klamath Lakes. The regular occurrence of earthquakes demonstrates that normal faults bounding the basin are active. Sedimentary strata deposited in the lakes and along streams, as well as lava flows, fill the basin as the valley floor drops along the faults.

## **Volcanism in the Basin and Range Province**

Continental rift zones commonly exhibit two-stage (“bimodal”) volcanism (Fig. 2.6): 1) an early stage, where ascending magma melts a lot of continental crust, producing high-silica (rhyolitic) volcanism; and 2) an advanced stage, where magma comes more directly from the asthenosphere, producing lower-silica (basaltic) volcanism. The later stage may evolve to a mid-ocean ridge (Fig. 2.3). Examples of continental rift volcanism include Mt. Kenya and Mt. Kilimanjaro in the East African rift system (Fig. 2.4).

Although recent volcanic activity occurs over much of the Basin and Range Province, it is generally concentrated along the edges. In southern Oregon, volcanism shows an age progression toward the western edge of the Province. At the Steens Mountains in the southeastern corner of the state, the lava flows are 10 million years old. They become younger and younger westward, to Newberry Crater, an active shield volcano south of Bend.

A similar pattern occurs in northern Arizona (Fig 2.1). Bill Williams Mountain, near Williams, is a 6 million-year-old lava dome. The volcanism progresses eastward, to the 2 to ½ million-year-old San Francisco Peaks composite volcano, then the active basaltic cinder cones and lava flows around Sunset Crater Volcano National Monument. A possible interpretation is

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<sup>4</sup>Most of the other deep lakes in the world are in the remains of deep glacial valleys. A notable exception is Crater Lake in Oregon, the world's 7<sup>th</sup> deepest (1,932 feet, 589 meters). It partially fills the large, vertical-walled hole (“caldera”) that resulted from the eruption and collapse of a composite volcano.

that Basin and Range volcanism is propagating eastward across northern Arizona, encroaching on the edge of the Colorado Plateau.

## **COLORADO PLATEAU (GRADUAL VERTICAL UPLIFT)**

The Colorado Plateau is a large block of the North American continent that has been gradually uplifting for about the past 6 million years. The coincidence in timing with the volcanic activity in northern Arizona might suggest that the two are related, although it is not clear exactly how.

One way to view the incredibly deep and broad Grand Canyon is to imagine what would happen if the Colorado River eroded downward about as fast as the Colorado Plateau moved upward. There would be no real change in elevation of the river; instead, the land would slowly move upward around the river. The effect would be the river remaining at about 2000 feet (600 meters) elevation as the plateau moved upward about one mile (1.6 kilometers).

Erosion has exposed the entire stratigraphic section in the Grand Canyon. These are essentially the same layers that the volcanic rocks of Sunset Crater Volcano rest upon. The upper layers of the section are exposed nearby at Walnut Canyon and Wapatki national monuments.

As at the Basin and Range Province to the west and south, uplift of the Colorado Plateau may be due to shallowing of the asthenosphere. Asthenosphere is hot mantle, so as it rises it expands like a hot-air balloon (Fig. 1.18b). The region of hot mantle might extend beyond the boundaries of the Basin and Range Province, uplifting a large part of western North America. If so, then this may support the idea that Basin and Range continental rifting is eating away at the Colorado Plateau. The rising and expansion of the asthenosphere would lead to decompression melting (Figs. 1.11b, 2.6), which could explain the volcanism in northern Arizona over the last 6 million years.

## **SAN ANDREAS FAULT (TRANSFORM PLATE BOUNDARY)**

Where plates slide horizontally past one another, lithosphere is neither created nor destroyed. Such boundaries are called "transform" because they connect other plate boundaries in various combinations, transforming the site of plate motion. Common examples are the offsets connecting segments of a mid-ocean ridge (Fig. 1.8). Prominent transform plate boundaries that extend on land include the Anatolian Fault in Turkey and the Alpine Fault of New Zealand. The San Andreas Fault, extending from the Gulf of California to north of San Francisco, accommodates the current motion between the Pacific and North American plates (Fig. 2.1). Prior to 20 million years ago, however, the entire western margin of North America was a convergent plate boundary. Coming in from the west, the so-called **Farallon Plate**, along with a mid-ocean ridge along its western boundary, have since been consumed by subduction beneath North America.<sup>5</sup> There is some speculation that volcanic activity in northern Arizona reflects continued activity of the mid-ocean ridge underneath the continent.

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<sup>5</sup>*The Juan de Fuca Plate to the north is a small remnant of the Farallon Plate.*

## **Earlier Subduction Zone in California**

Where lithospheric plates converge, the plate with thinner, less buoyant crust commonly descends beneath the other plate (Fig. 2.7). The region where a lithospheric plate descends deeply within the mantle is called a **subduction zone**. Prior to about 20 million years ago, the continental margin of California was part of a subduction zone, with oceanic crust of the Farallon Plate subducting beneath the continental crust of North America. A divergent plate boundary (mid-ocean ridge, Fig. 2.3c) separated the Farallon Plate from the Pacific Plate. About 20 million years ago, the mid-ocean ridge entered the subduction zone. The Pacific and North American plates were then in contact, so that the San Andreas Fault now manifests the north-northwest, transform plate boundary motion. The earlier plate convergence and subduction of the oceanic ridge may have influenced the crustal structure and volcanism in northern Arizona.

Continental crust is thicker, and therefore more buoyant, than oceanic crust; a plate with oceanic crust will subduct beneath one capped by continental crust (Fig. 1.4). Two chains of mountains, one structural and one volcanic, form parallel to the **deep-sea trench** at the surface juncture of the plates (Fig. 2.7). Just landward of the trench, where the top of the plate is shallow and cold, some of the sediments and underlying rock are scraped off and deformed into a wedge-shape. These materials attach (or "accrete") to the overriding plate; portions of this **accretionary wedge** may rise above sea level as the sediments and rock are compressed, folded, and faulted, forming long ridges and valleys (Fig. 1.19b).

Farther from the trench the top of the descending plate may reach depths of 100 to 150 km (60 to 100 miles), where it is so hot that fluids are driven from its crust. The fluids rise, melting silicate minerals from the mantle and crust of the overriding plate. Magma that makes it to the surface erupts as a (straight or curved) chain of volcanoes, called a **volcanic arc**. The volcanoes build up on the continental crust, because that crust caps the overriding plate. The low area between the accretionary wedge and volcanic arc, which often accumulates sediments, is a **forearc basin**.

Ocean-continent subduction zones are often called "convergent" or "**active**" **continental margins**. Examples include Japan, western South America, and the Pacific Northwest of the United States. For the latter, the accretionary wedge includes the coastal ranges of Washington, Oregon and northern California (Fig. 2.9). The volcanic arc is the Cascade Mountains, and the intervening forearc basin is the Great Valley, Willamette Valley and Puget Sound. The Sierra Nevada Mountains in northern California are the roots of the volcanic arc; the volcanoes have eroded away, exposing granitic rocks of the cooled magma chambers.

## **Current Transform Plate Boundary**

About 20 million years ago, the mid-ocean ridge separating the Farallon Plate from the Pacific Plate reached the subduction zone. In other words, that part of the Farallon Plate was completely subducted, so that the Pacific Plate was in direct contact with the North American Plate. The San Andreas Fault now accommodates the transform motion between the Pacific and North American plates, of about 1.5 inches (4 centimeters) per year. It is not clear what happens after a mid-ocean ridge is subducted. Some people speculate that motion continues, so that a "slab window" opens. If so, then that might explain the eastward propagation of volcanic activity in Arizona.

## WESTWARD MOVEMENT OF NORTH AMERICAN PLATE OVER A HOTSPOT?

Some volcanic chains lie within the interiors of lithospheric plates, rather than along the edges (Fig. 1.9d). Commonly, the volcanoes get progressively older away from the largest and most active volcanoes. The volcanoes are thought to form over narrow "plumes" of heat that rise from deep within Earth's mantle. A **hotspot** is a region in the mantle where magma forms above a plume. A chain of volcanoes develops as a lithospheric plate moves over a hotspot, much like a line of melted wax forms as a sheet of waxed paper is pushed over a burning candle. Examples of such hotspot tracks include the Hawaiian Islands within the Pacific Plate, and the Columbia Plateau - Snake River Plain - Yellowstone area of Washington, Oregon, Idaho, and Wyoming (Fig. 2.9).

Hotspots provide a framework to track the motion of lithospheric plates over deeper portions of the mantle (Fig. 1.11c). Mantle plumes and associated hotspots are thought to be fixed relative to the deep mantle, as well as to one another. One volcano after another forms as a plate moves over a hotspot. The resulting chain of volcanoes is: 1) parallel to the direction of plate motion; and 2) older in a direction away from the hotspot. By mapping the changing age of volcanism, the speed and direction of movement of the lithospheric plate over the deeper mantle can be calculated. A hotspot thus provides a framework through which the **absolute motion** of a plate can be determined. That is important because, at plate boundaries, only the **relative motion** of one plate compared to the other can be determined.

The type of volcanism that occurs above a hotspot depends on the volume of magma surfacing as well as the type of crust that must be penetrated by the magma. As at divergent plate boundaries, hotspot magma forms due to a drop in pressure as hot mantle material rises (Fig. 1.11). The fluid that initially bleeds off the partially melted mantle is thus relatively low-silica basalt.

Hotspot volcanism can occur where either oceanic or continental crust is on the overriding plate. Hotspot magma intruding only thin oceanic crust, as in Hawaii, results in fluid lava of basaltic composition, forming shield volcanoes (Figs. 1.12a, 1.14a). The Pacific Northwest of the United States reveals a region where continental lithosphere has been moving over a hotspot (Fig. 2.9). Southeast Washington and northeast Oregon are dominated by layers of basalt, comprising the Columbia Plateau. This massive volume of rock resulted from mantle-derived lava that extruded 15 to 18 million years ago. Along the Snake River Plain in Idaho, lavas are progressively younger from west to east, ending where there is active volcanism in Yellowstone National Park. Hotspot lava thus originally surfaced in Oregon and Washington 18 million years ago. As the North American Plate moved westward over the hotspot, lavas erupted in a narrow, steady stream across southern Idaho to Yellowstone. Some of the later volcanism produced rhyolite, because the magma became enriched in silica as it ate its way through continental crust.

Northern Arizona volcanism might be due to westward movement of the North American plate over a stationary hotspot for the past 6 million years (Fig. 2.1). The rate of movement can be calculated by taking the distance from the oldest eruptions (Bill Williams Mountain) to the most recent (Sunset Crater-Cinder Hills), which is about 60 miles. The average rate of movement of the plate over the hotspot would be about 10 miles (16 kilometers) per million years, or 0.6 inches (1.6 centimeters) per year. The motion is thus roughly equivalent to the rate that the North American plate has been moving over the Yellowstone Hotspot.

## Chapter 3

# GEOLOGY IN AND AROUND SUNSET CRATER VOLCANO NATIONAL MONUMENT

The geology of Sunset Crater Volcano National Monument has three aspects (Fig. 2.1):

- 1) uplift of the Colorado Plateau over the past 6 million years (the overall tectonic setting);
- 2) coincident volcanic deposits that erupted through, and rest upon, the sedimentary strata covering the Plateau (the regional geologic setting); and
- 3) very recent volcanism that resulted in Sunset Crater Volcano and the adjacent Cinder Hills (the local geologic setting).

The coincident uplift and volcanism may have the same cause. Eastward propagation of continental rifting in the Basin and Range Province would result in the asthenosphere rising and partially melting, uplifting the topography of the Colorado Plateau (Fig. 2.1).

Uplift of the Colorado Plateau resulted in rivers cutting deep canyons, thereby exposing the Paleozoic sedimentary strata and Precambrian igneous and metamorphic rocks in the Grand Canyon (Fig. 3.1). The same rock layers, as well as younger, Mesozoic sediments like those exposed nearby in Wapatki National Monument, are probably beneath the volcanic deposits at Sunset Crater. In addition to the very young cinders and lava flows, the volcanic deposits may include underlying deposits from the explosion of San Francisco Peak about 300,000 years ago.

From vantage points along the **Lava Flow Trail**, several exciting geologic observations can be pointed out to visitors. On the upper part of the trail, a spectacular view of the nearby and surrounding landscape provides examples of three of the four kinds of volcanoes (Figs. 1.13, 1.14) and their eruptive products. Looking back, you can see that Sunset Crater Volcano is a cinder cone, formed when fluid lava erupted as a fountain of cinders and piled up like sand in an hourglass (Fig. 1.14b). The oozing of black, basaltic lava (Bonita Flow) extends like a giant tongue out of the base of the cone. Looking downhill in the foreground, the very gentle slope of the surface of the flow is apparent; had enough of this low-silica lava erupted, a broad shield volcano might have resulted (Fig. 1.14a). The two types of high-silica volcanoes can be seen on the skyline. Straight to the west, the steep slopes of San Francisco Peaks represent the remnants of a composite volcano. Just to the north, the light-colored rocks and steep, rounded slopes of O'Leary Peak are characteristic of a lava dome.

Some general characteristics of a basaltic lava flow are apparent at various places along the trail. Fissures opened on the cooled crust of the flow as it was "inflated" by magma from below. Within some of the fissures are pieces of sedimentary rocks, called xenoliths, that were caught in the rising lava and survived the trip to the surface. Small holes within the lava are solidified gas bubbles; large bubbles, up to three feet across, represent inflation on the thin, outermost skin of the lava, much like bubble gum. The surface of the lava is commonly composed of sharp, broken and tumbled blocks called aa. Spatter cones are hollow, cone-shaped mounds that represent the splashing of liquid lava around gas vents on the lava surface, much like bubbles popping and spattering spaghetti sauce. Fins of semi-solid lava oozed upward through fissures, like toothpaste, forming squeeze-ups. An ice cave extending about 600 feet (200 meters) laterally may be a lava tube resulting from the subterranean "plumbing system" of the flow, or simply the "roofing over" of a fissure by a younger lava flow.

## **GEOLOGIC HISTORY**

The combination of several geologic events has resulted in the rocks that occur at and below the surface of Sunset Crater Volcano National Monument, as well as the topography and overall elevation of the park. The events include:

- 1) deposition of Paleozoic and Mesozoic sedimentary strata on the North American Continent, followed by
- 2) continental rifting of the Basin and Range Province and
- 3) uplift of the Colorado Plateau with concurrent volcanism along its edges.

### **Local Sedimentary Geology**

The thick deposits of lava flows and cinders in Sunset Crater Volcano National Monument cover the sedimentary strata of the Colorado Plateau (Fig. 3.1). Some of the strata are exposed in the other two national monuments in the Flagstaff area, Wapatki and Walnut Canyon. In the Grand Canyon the entire sedimentary section is exposed, as well as underlying igneous and metamorphic rocks. Knowledge of the local sedimentary geology is useful, for appreciation of the older geologic history of the area, and because magma had to work its way through the sequence of sedimentary layers to get to the surface. In fact, foreign rocks (or “xenoliths”) found in fissures along the lava flow trail are probably pieces of the Kaibab limestone, the hard layer at the top of the Grand Canyon.

### ***Paleozoic Strata at Walnut Canyon and Wapatki National Monuments***

The spectacular ruins at Walnut Canyon National Monument, 5 miles east of Flagstaff, were built on cliff faces of the upper (Permian age) layers of Paleozoic rocks (Fig. 3.1). At the bottom of Walnut Canyon, there are fabulous cross-bedded layers of Coconino Sandstone. The cross-bedding results from the sand layers accumulating along the sides of dunes in an ancient desert. A softer, more shaley layer, the Toroweap Formation, has eroded into more gentle slopes in the middle portion of the Canyon. Hard layers of the Kaibab Limestone at the top of the canyon form the vertical cliffs that served as both the walls and building blocks of the ancient dwellings (Fig. 3.2a).

The same sequence of rocks is exposed at Wapatki National Monument, 20 miles from Sunset Crater, where additional sandstone and shale of the early Mesozoic (Triassic age) Moenkopi Formation overlie the Kaibab Limestone. The shale layers form gentle slopes, while harder sandstone is more resistant to erosion, forming steep cliffs and capping mesas. Native Americans took advantage of some unique properties of the sandstone and built dwellings on the tops or sides of mesas, as at Crack-in-Rock (Fig. 3.2b). The flat layers of sandstone cracked along vertical surfaces, called **joints**, during uplift of the Colorado Plateau. The joints developed along two prominent directions, perpendicular to one another. Sides of mesas thus erode away as rectangular slabs break away along the vertical joints. The remaining vertical walls served as ready-made walls for pueblos, and as huge canvases for the magnificent rock art preserved at the sites. Also, because the eroded rock slabs have three perpendicular faces, two along the vertical joints and the other along the bedding surface, they are natural bricks that were used to construct the remaining walls of pueblos.

## **San Francisco Volcanic Field**

Uplift of the Colorado Plateau, which began about 6 million years ago, was accompanied by volcanic activity along its edges (Fig. 2.1). The San Francisco Volcanic Field in northern Arizona extends eastward for about 60 miles (100 kilometers), from near Williams to Roden Crater, about 10 miles beyond Sunset Crater. It covers about 2000 square miles (5000 square kilometers) and includes both high-silica (andesite/dacite/rhyolite) and low-silica (basalt/basaltic andesite) eruptions.

### ***High-Silica Eruptions***

Regions of high-silica magma in the San Francisco Volcanic Field include a large composite volcano that is currently several mountain tops collectively called “San Francisco Peaks,” as well as lava domes comprising Bill Williams Mountain, Mt. Elden near Flagstaff, and O’Leary Peak just north of Sunset Crater.

Composite Volcanoes. There is speculation that the ridge and individual summits known as ***San Francisco Peaks*** were once one large composite volcano (Fig. 3.3). The strata of San Francisco Peaks include pyroclastic deposits (cinders, bombs, scoria, pumice), ash, mudflows, and fiery ashflows. Rocks are commonly of andesite to dacite composition, but with some rhyolite, basaltic andesite, and basalt. Eruptions forming the mountain lasted from about 2.8 million years ago, up until when a huge blast may have destroyed the mountain about 300,000 years ago.

From the upper portion of the Lava Flow Trail, there’s a fabulous view of the eastern side of San Francisco Peaks (Fig. 3.3a). Using a little imagination, the slopes of the mountain can be extended upward to a point at about 16,000 feet elevation. One can make a wonderful analogy with Mount St. Helens in Washington state (Fig. 3.3b). In 1980, high-silica magma migrated upward, causing a bulge on the north side of Mount St. Helens. Gases trapped under high pressure suddenly exploded, blasting away 1200 feet (350 meters) from the top of the mountain and forming a breached crater about 1½ miles (2½ kilometers) wide. A lava dome of sticky dacite has since formed inside the crater. A lateral blast on the east flank of San Francisco Mountain, about 200,000 to 400,000 years ago, may have been even bigger. If so, the mountain may have lost 3,000 to 4,000 feet (1000 to 1200 meters) of its height. The breached crater (called the “Inner Basin”) is about 5 miles (8 kilometers) across. A dacite lava dome, called Sugarloaf, then developed at the mouth of the basin about 200,000 years ago. Deposits from the east flank explosion of San Francisco Peaks may lie underneath younger volcanic material at Sunset Crater.

Humphreys Peak, the tallest of the San Francisco Peaks, is also the highest point in Arizona at 12,633 feet (3,851 meters). It’s summit is about one mile above the surrounding terrain, about the same relief as the Grand Canyon. If it were indeed 16,000 feet (3,851 meters) elevation in the past, then San Francisco Peaks would have been about 9,000 feet (3 kilometers) above the surrounding terrain.

Lava Domes. Lava domes in the San Francisco Volcanic Field can be up to 2,000 feet (600 meters) tall. One of these, ***O’Leary Peak*** (Fig. 3.4a) can be viewed from the upper part of the Lava Flow Trail. If you ignore the black colors, which are cinders blown by the wind from Sunset Crater, you notice that the hard rock of the dome is a brown to whitish color, indicating high-silica dacite and rhyolite. O’Leary Peak was active about 170,000 to 40,000 years ago. Other lava domes include ***Sugarloaf*** (formed about 200,000 years ago) at the mouth of the Inner Basin of San Francisco Peaks (Fig. 3.4b), ***Elden Mountain*** (active 570,000 to 490,000

years ago) on the east side of Flagstaff, **Kendrick Peak** (2.7 to 1.4 million years), and **Bill Williams Mountain** (4.2 to 2.8 million years). Lava cooling near the surface of a lava dome can develop into a rigid shell. As more magma is injected, inflating the dome like a giant balloon, the shell may crack, littering the area with slabs of rock.

### **Low-Silica Eruptions**

During the past 6 million years, the San Francisco Volcanic Field has produced about 120 cubic miles (500 cubic kilometers) of lava flows, cinders, ash, and other eruptive materials. This volume was estimated by assuming that an average of about 300 feet (100 meters) of volcanic material overlies the field's 2000 square miles (5000 square kilometers). Most of the material is of low-silica (basaltic) composition, erupted from about 600 different volcanic vents. Consider that if the volcanism were evenly distributed throughout the field, then the time between eruptive episodes would be about 10,000 years (6,000,000 years/600 eruptions). The average area covered by a single vent is about 3 square miles (2000 square miles/600 vents), or 8 square kilometers (5000 square kilometers/600 vents).

Interpreters should keep the above numbers in mind when contemplating the volcanic deposits at Sunset Crater Volcano National Monument. The approximately 4 square miles (10 square kilometers) covered by Sunset Crater Volcano and the associated Bonita and Kana-a lava flows is not so unusual. Furthermore, it may be quite reasonable to assume that the average thickness of the volcanic materials is about 300 feet (100 meters), although they are undoubtedly thicker in places.

Shield Volcanoes. Low-silica eruptions yield fluid lava flows and fissure eruptions. Shield volcanoes develop where there is a large enough volume of magma to build the layers of basalt and cinders into a sizable pile. In northern Arizona there wasn't enough basaltic lava in any local area to build big shield volcanoes (remember the average thickness is only about 300 feet, or 100 meters). The Bonita and Kana-a lava flows, though, show very gentle surface slopes that, with continued eruptions, would have eventually developed into a broad shield volcano. There is one small shield volcano in the area, **Hart Prairie Volcano**, on the western flank of San Francisco Peaks.

Cinder Cones. A cinder cone generally develops during one eruptive episode, perhaps lasting a few years to a couple of hundred years. Cinder cones form as blobs of magma erupt high into the air. During flight the blobs cool and form solid particles, called cinders. If the wind is not too strong, the cinders rain straight back down, forming a cone. If there is no wind, the eruptive spray falls straight down, building a symmetrical cinder cone like **Sunset Crater Volcano** and **SP Crater** to the northwest, across Highway 89. Where the lava fountain sprays downwind, an asymmetrical cone develops, such as **Red Mountain**, 22 miles northwest of Flagstaff, off Highway 180.

Cinder cone development is similar to sand falling in an hourglass (Fig. 3.5). A small cone forms. It gradually gets steeper until it reaches a certain angle, the **angle of repose**. It then continues to grow, but the angle remains the same. A pile of sand grains has internal friction. The friction holds the grains together, but when the surface slope is greater than the angle of repose, the grains slip. The angle of repose is thus maintained as the cone gets bigger.<sup>6</sup>

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<sup>6</sup>There are two real-life examples of "angle of repose."

- a) The stock market; if it rises too fast, beyond its angle of repose, it collapses back to a less precarious slope.
- b) There is a book titled "Angle of Repose," about personal relationships. A relationship well

Looking at the slope of Sunset Crater Volcano on the skyline, the angle of repose appears to be about 30 degrees. The cinder cone is about 1000 feet (300 meters) high, the top at 8,029 feet (2,447 meters) elevation. The crater on top is about 2,000 feet (600 meters) wide and 300 feet (100 meters) deep. Until the 1970's people could climb Sunset Crater. This caused problems. The people were walking up a cone of loose cinders that is at the angle of repose. They were essentially walking on ball bearings; each step would cause material to slide downslope. Deep gullies thus formed in the sides of the mountain, some up to 6 feet (2 meters) deep!

Volcanic cinders are red or black, sand to gravel-sized particles that rain down during an eruption. They are black because the lava was high in iron and magnesium; red because some of the iron combines with oxygen to form rust (iron oxide). In some northeastern states, salt is used for traction on snowy roads. This can be very bad, because salt makes cars rust; pretty soon, to stop you simply drag your feet on the ground, like in one of those Flintstone cars! In Arizona, cinders are very plentiful and are used on roads instead of salt. One can see that rusting is prominent near the top of Sunset Crater, where there were hot gases and fluids present during the eruption. Since the eruption, interaction was only with cold fluids in a dry climate. There has not been much oxidation, so that the cinders on most of the mountain remain black. Putting cinders on roads is therefore far kinder than using salt!

### **Cinder Hills Fissure Eruption and Sunset Crater**

The eruptions that formed Sunset Crater Volcano were thought to have begun in the year 1064 or 1065, just prior to the Battle of Hastings that culminated in the Norman Conquest of England. Such a precise date may at first appear suspect, because geologic dating methods normally involve uncertainties of many years. The date for Sunset Crater is determined, however, by **dendrochronology**, whereby annual growth rings of trees are compared to a standard growth-ring pattern for a region. The technique is analogous to the "bar code" found on items purchased in a supermarket. The bands have a unique pattern indicative of a specific product. Similarly, the pattern of summer growth and winter dormancy results in a distinct pattern representing the weather that occurred in a region for a particular number of years. Researchers can thus look at the ring pattern and determine the exact year represented by any ring. Some nearby Ponderosa Pine trees survived the Sunset Crater eruption in areas that were covered by ash and cinders. Native Americans used these trees as beams for their Pueblo and pit houses. The trees show normal growth ring patterns up to the year 1064, but much thinner rings for several years afterward, suggesting severe stress due to the cover of ash and cinder.

The recent eruptions began along a 6-to-9 mile (10-to-15 kilometer) long fissure in the Cinder Hills region east of Sunset Crater. The fluid lava produced a long "curtain of fire" (Fig. 3.6), eventually confined to a central vent at Sunset Crater Volcano. The material shot up into the air as fluid lava, cooling and raining down as solid particles of cinder. Characteristic of cinder cones, not much of the heavy lava made it up the throat of the volcano. Instead, it flowed out of the base of the cone through the weak cinders (Fig. 3.7). Two such "tongues" of basaltic lava, the Kana-a and Bonita flows, erupted out of the east and west sides of the cone, respectively.

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*beyond the angle of repose is too hectic; much less than the angle of repose is boring; right at the angle of repose is exciting, yet manageable.*

At the earliest stages, starting about 1064 A.D., cinder and ash erupted in the area of Sunset Crater Volcano and the Kana-a lava flow, from fissures on its east base. Cinder and ash continued building Sunset Crater Volcano, covering much of the Kana-a flow. Around 1180 A.D. the Bonita flow erupted from the west base of the Sunset Crater cinder cone. Sections of the cone were rafted on top of the flow. Cinder and ash continued to erupt, eventually developing the symmetric profile of the cone we see today. Hot vapors oxidized iron around the vent, turning them a rusty red. Looking up at the volcano, one sees the black background of the cinder cone, with greens and yellows from the vegetation and red cinders on top; the overall effect is like the setting sun, hence "**Sunset Crater.**"

## **VOLCANIC FEATURES IN SUNSET CRATER VOLCANO NATIONAL MONUMENT**

Sunset Crater Volcano National Monument contains spectacular examples of fluid (basaltic) lava eruptions. There are two prominent cinder cones, one older (Lenox Crater) and one quite recent (Sunset Crater). The external profiles of both, as well as the craters at their summits, are well preserved because of the dry climate in northern Arizona. Likewise, features within and on the surface of lava flows probably remain much as they appeared just a few weeks after they formed.

### **Bonita Park**

Near Flagstaff, **parks** are grassy meadows surrounded by volcanic hills. They are simply flat areas that were excluded from recent volcanic activity. **Bonita Park**, at the west entrance to Sunset Crater Volcano National Monument, is such an area (Fig. 3.8). It was covered by cinders and ash carried by wind and washed in by streams. The ash and cinders are probably very thick and porous. Consequently, the re-establishment of plants is very slow, hence the open parkland.

### **Cinder Cones**

#### ***Why is there a Cone?***

A cinder cone forms when low-silica magma contains a lot of gas. Rather than flow out as liquid on the surface, the gasses cause the fluid lava to spray out as fountains along long fissures or central vents. The lava drops begin to cool in the air, raining down as solid particles, ranging from watermelon-sized **bombs** to sand-sized **cinders**. "*Like sands in the hourglass, so are the days of our lives,*" and so are the cones of cinders around vents (Fig. 3.5). As discussed earlier, sides of cinder cones steepen until they reach the angle of repose for cinders. After that, there is slip between individual cinder grains; the cone becomes larger, but the angle of repose stays the same.

#### ***Why is there a Crater?***

Rather than a crater forming within a cinder cone, think about the surrounding crater rim forming. Material initially fountains upward, like a giant fire hose. The material cannot easily fall back into the center of the fountain; instead it's deposited in a ring-shaped mound about the vent. As the cone grows, both the rim (the ring-shaped mound) and the bottom of the

vent rise in elevation, but the rim is always higher. A crater shape is thus developed and maintained throughout the eruption.

### ***Lava Flows from Cinder Cones***

Lava flows from the base of a cinder cone due to a combination of several factors (Fig. 3.7). First, low-silica (basaltic) lava is heavy (high density); if it doesn't have enough gas to propel it, it has difficulty getting all the way up the throat of the cone. Second, the pile of cinders is porous and is therefore light weight (low density). Third, the cinders are not very well compacted. The combination of low density and poor compaction makes the pile of cinders very weak. Finally, the basaltic lava is very fluid; when it rises to the base of the weak cinders, it breaks through, oozing outward. Extensive flows from craters at the tops of cinder cones are therefore rare. Instead it is common to see black "tongues" of basaltic lava extruding from the bases of cinder cones (For example, look at Wizard Island in Fig. 1.14b). In the vicinity of Sunset Crater, there are numerous cinder cones, most with such tongues. Examples are the flow from the base of S.P. Crater, as well as the Kana-a and Bonita flows from Sunset Crater.

### ***Sunset Crater Volcano***

Sunset Crater Volcano is one of the best examples in the world of a cinder cone. Many other volcanoes of northern Arizona can be seen from the upper portion of the Lava Flow Trail. Sunset Crater is about 1,000 feet (300 meters) high, the top at an elevation of 8,029 feet (2,447 meters), just 20,999 feet lower than Mt. Everest! The crater on top is about 300 feet (100 meters) wide, the width about 2,000 feet (600 meters) on the rim. Near and in the National Monument, the best views of the nearly-perfect cone shape are from the Bonita Park pullout (Fig. 3.8) and on the beginning part of the Lava Flow Trail. The crater itself can be viewed by taking the three-mile, four-wheel drive, road up nearby O'Leary Peak (Fig. 3.7b).

### ***Lenox Crater***

Many visitors are at first disappointed when told they cannot climb to the top of Sunset Crater, then delighted when informed that there's a moderately-difficult trail up nearby Lenox Crater. Though older (formed about 100,000 years ago), Lenox Crater preserves classic features of a cinder cone because of the dry climate. Walking up the trail, one experiences three of these features.

- 1) The ground is a loose pile of cinders, like walking up ball bearings!
- 2) There's a tendency to slide backward with each step, because overall slope is near the angle of repose.
- 3) Even after 100,000 years vegetation is sparse, because water percolates quickly through the coarse cinders.

Approaching the top, one might again feel disappointed, because "there couldn't possibly be much of a crater up here." Delightment once again sets in, however, when the rim is reached and the broad, 100 foot (30 meter) deep crater emerges into view.

### **Features At and Near the Surface of Flows**

There are several interesting and educational features on the surface of lava flows at Sunset Crater Volcano National Monument. These features form in various ways: as the magma forces its way upward; as it flows out onto the surface; and as it cools and hardens.

## **Cooling and Hardening of the Surface**

When lava is low in silica it is very runny. It can therefore flow for several miles, developing a thin crust on top. When the crust remains more or less together or in large blocks, it has a smooth or ropy texture and is called **pahoehoe lava** (pronounced “puh-hoy-hoy,” Fig. 3.9a). If the lava continues flowing underneath, however, the crust may break into smaller, sharp blocks, forming **aa lava** (“ah-ah,” Fig. 3.9b). Most of the lavas at Sunset Crater Volcano have sharp, blocky surfaces and are thus aa flows.

## **System of Fissures**

The surface of a lava flow cools first, because it is in contact with the cold air. A hot, expanded material shrinks as it cools, subjecting the solidified material to tension. The tension thus forms a series of **fissures** at the surface of the lava flow, much as cracks form in mud as it dries. Many of the fissures at Sunset Crater are several feet wide, such as the one spanned by the bridge on the Lava Flow Trail (Fig. 3.10a). Such large fissures form after crust develops on a lava flow, but while lava still flows beneath. Local areas are “inflated” by the flow of lava, bulging the surface upward. At the top of the bulge the crust extends and cracks open along the wide fissures.

## **Xenoliths**

Fissures allow us to look inside a lava flow. In one of the fissures on the Lava Flow Trail there are light-colored rocks that contrast with the dark, basaltic lava (Fig. 3.10b). These rocks hint at the manner in which magma makes its way to Earth’s surface. Magma does not just ooze through open fissures. It may also “eat” its way through the rock layers, a process called **stoping**. The magma may reach the surface and cool before all of the rock fragments had time to melt. Such fragments preserved in the solidified magma are called **xenoliths** (xeno = “foreign;” lith = “rock”). The white-to-brown colored rocks found in the fissure along the Lava Flow Trail are probably part of the Kaibab Limestone, the same rock layer that forms the upper portion of the Grand Canyon (Fig. 3.1).

## **Squeeze-ups**

As fissures open on the surface of an active flow, molten lava may extrude outward like soft plastic. Such “fins” sticking up through fissures are called **squeeze-ups** (Fig. 3.11). Long, deep grooves on the surfaces of some squeeze-ups show that the near-solid lava was rubbing against adjacent rock as it moved upward through the fissure.

## **Gas Bubbles**

Basalt flows often have holes, from sand grain to pebble size. The holes, called **vesicles**, result from bubbles of gas that were trapped in the lava as it cooled. If the rock has holes about the size and shape of almonds, it is called **amygdaloidal basalt**.

Very near the surface of hot lava flows a skin, just a few inches thick, may form. Like the surface of hot plastic (or bubble gum), the skin may inflate with gas. On the lower Lava Flow Trail, the large blisters are up to three feet across (Fig. 3.12). Some have remnants of lava that dripped from under the surface of the bubble and hardened, similar in appearance to ice sickles or stalactites on the roof of a limestone cave.

## **Spatter Cones**

Anyone who has cooked spaghetti sauce understands how a **spatter cone** forms. Air bubbles pop at the surface, spattering bright orange-colored sauce on your white stovetop. Similarly, gasses within lava can cause bubbles that pop, spattering hot magma around the exploded bubble. On the upper Lava Flow Trail, you can see a line of spatter cones formed along the backbone of the Bonita Lava Flow (Fig. 3.13). These features are labeled “Hornito’s,” from the Spanish word for “small oven.”

### ***Ice Cave (Lava Tube?)***

Fluid, basaltic lava does not flow only on the surface. The surface of a flow cools and crusts over, but the lava may continue to flow underneath. A series of underground channels can thus form. Some of the passages may eventually drain, leaving a hollow pipe, or **lava tube** (Fig. 3.14). Lava tubes are commonly long and straight, with arched roofs and flat floors, like subway tunnels. In some instances small amounts of lava can continue to flow along the edges of the floors, leaving long grooves; in places lava tubes thus look like “underground bowling alleys.” A single tube can carry lava for months or even years, as the solidified rock above and below acts as an insulator. The lava can thus remain hot and fluid and travel for several miles, as occurs today on Kilauea Volcano in Hawaii Volcanoes National Park.

The **Ice Cave**, located on the upper part of the Lava Flow trail, may be a lava tube. Unlike well-developed lava tubes, however, it is crooked and there is lots of rubble strewn about, so that identification is uncertain.<sup>7</sup> **Lava River Cave**, however, 20 miles northwest of Flagstaff, is a well developed lava tube that is open to the public. It lies within a flow that erupted from Hart Prairie shield volcano.

## **HOW SUNSET CRATER VOLCANO AFFECTS PEOPLE**

Native American dwellings (called **pit houses**) were found beneath cinder deposits near Sunset Crater Volcano. No human bodies have been found, and it appears that the people had time to abandon their houses before the eruptions. The people may have been warned by events that precede volcanic eruptions, such as swarms of earthquakes due to magma moving beneath the surface. People soon came back to the area, however, as pit houses were built on top of the cinders.

### **Earthquakes As Precursors To Volcanic Eruptions**

Magma gradually moves toward the surface before an eruption. Blocks of rock crack and are shoved aside to accommodate the rising magma, causing earthquakes days to months before the actual eruption. As the magma rises, earthquakes are originally deep, but become shallow over time. Peculiar kinds of earthquakes called **harmonic tremors** occur, shaking the Earth for several minutes as the magma moves in pulses. The combination of upward-migrating earthquakes and harmonic tremors is strong evidence of an impending eruption.

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<sup>7</sup> *The long openings in the lava at the beginning portion of the Lava Flow Trail (Fig. 3.10a) are not collapsed lava tubes. They are most likely fissures due to flow inflation beneath the hardened crust of the flow. (See above section on “System of Fissures”).*

## **Potential for Future Volcanic Eruptions in Northern Arizona**

An often-asked question during Ranger Programs is “Will there be another volcanic eruption at Sunset Crater?” Before answering that question, consider that volcanism has been occurring for the past 6 million years in northern Arizona. It started near Williams and progressed eastward, across the San Francisco Peaks to the Sunset Crater area. In this region, collectively called the San Francisco Volcanic Field, there are approximately 600 different volcanoes of various types. As a conservative estimate, consider that there were at least 600 major eruptions over the 6 million-year interval. This would suggest that the average time between major eruptions is 6,000,000 years divided by 600 eruptions, or **10,000 years**. It is clear that the “**geologic climate**” of northern Arizona is that of volcanic activity.

Consider an analogy with the “**weather climate**.” For several centuries now, northern Arizona has had dry, desert conditions, with monsoons in late summer. We expect to have monsoons next year, and that the pattern will probably continue throughout our lifetime. There is no reason to suspect that the region will suddenly change to a tropical rain forest! So too, the “geologic climate.” There have been periodic volcanic eruptions in northern Arizona for the past 6 million years and it seems inevitable that there will be more.

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## **APPENDIX A**

### **Classification of Igneous Rocks**

(Detailed Explanation of Table 2)

**Table 2** illustrates the classification of igneous rocks according to silica content (**chemical composition**) and texture (**grain size**). The rock names are a rough guide because igneous rocks commonly have compositions falling between the silica and heavy mineral percentages shown. Properties of the igneous rocks and the magmas that form them also exhibit gradations between the rock types.

The terms “magma” and “lava” are often used interchangeably, but they have important differences. **Magma** is melted Earth material. In addition to liquid, magma can contain gasses and dissolved or suspended solid material. **Lava** is magma that has flowed out onto the surface of the Earth. Magma can turn into rock either above or below the surface of the Earth. An **intrusive** igneous rock forms from magma that solidified within the Earth; it is also referred to as **plutonic**, after *Pluto*, the Roman god of the underworld. An **extrusive** igneous rock forms from magma that solidified at Earth’s surface; it is thus **volcanic**, after *Volcanus*, the Roman god of fire.

#### **Silica [SiO<sub>2</sub>] Content**

Silica is the stuff that makes common window glass. An example of a mineral that is pure silica is quartz [chemical formula SiO<sub>2</sub>]. Common minerals found in igneous rocks that are high in silica include: quartz; feldspars [orthoclase or potassium feldspar, KAlSi<sub>3</sub>O<sub>8</sub>]; albite or sodium plagioclase feldspar [NaAlSi<sub>3</sub>O<sub>8</sub>]; and micas [muscovite, KAl<sub>3</sub>Si<sub>3</sub>O<sub>10</sub>(OH)<sub>2</sub>; biotite, K(Mg,Fe)<sub>3</sub>Si<sub>3</sub>O<sub>10</sub>(OH)<sub>2</sub>]. Common minerals in igneous rocks low in silica are amphibole [hornblende, NaCa(Mg,Fe)<sub>5</sub>AlSi<sub>7</sub>O<sub>22</sub>(OH)<sub>2</sub>]; olivine [(Mg,Fe)<sub>2</sub>SiO<sub>4</sub>]; calcium plagioclase feldspar [CaAl<sub>2</sub>Si<sub>2</sub>O<sub>8</sub>]; and pyroxene [Ca,Fe,Mg-Silicate].

The percentage of silica is an important factor in the properties of magma. As magma cools, the silica begins to form molecules while the magma is still liquid. This early bonding of silica tends to make the magma more **viscous** (that is, more sticky), like grease or molasses. Magmas high in silica thus tend to flow sluggishly, while those with lower silica content flow more freely, like fountains or rivers of water. High-silica minerals also tend to have lower melting temperatures than those with low silica, so that when rocks begin to melt, magmas with high silica content form before those low in silica.

When magma cools to rock, the amount of silica helps determine the minerals formed, hence affecting the rock's physical properties. High-silica minerals tend to be light in color and weight; the rocks formed commonly have a pink-to-white appearance and low density (granite, rhyolite). When rocks are low in silica, they have a larger proportion of heavy, dark minerals that are high in iron and magnesium; those rocks are therefore high density and are generally dark brown, dark green, or black (basalt, gabbro, peridotite).

#### **Size of Mineral Grains ("Texture")**

As magma cools, mineral crystals begin to form. If the rock cools quickly, the crystals

are so small that they cannot be seen with the naked eye. Slow cooling, however, gives crystals enough time to grow large. Igneous rocks are thus classified as fine-grained (or **aphanitic**, from Greek "invisible," or course-grained (or **phaneritic**, from Greek "visible").

Texture can be used to help understand the genesis of an igneous rock. Fine-grained igneous rocks result from magma that cooled at or near Earth's surface, forming extrusive ("volcanic") and shallow intrusive rocks. Magma that cooled slowly, deep within the Earth, formed coarse-grained intrusive ("plutonic") rocks. Under special circumstances, magma may cool so fast that crystals do not have time to develop; volcanic glass, or obsidian, then develops.

### **Description of Igneous Rocks**

The descriptive classification scheme below relates to **Table 2** as follows:

- Capital letters refer to the texture ("grain size") of the rock.
    - A)** Coarse (phaneritic).
    - B)** Fine (aphanitic).
  - Numbers correspond to the chemical composition:
    - 1)** High silica content (granite/rhyolite).
    - 2)** Intermediate silica content (diorite/andesite).
    - 3)** Low silica content (gabbro/basalt).
    - 4)** Extremely low silica content (peridotite).
- A) Phaneritic (Coarse Grained) Textures:
- 1) **Granite. (~70% silica)**
    - a) Most common minerals:
      - potassium (K) feldspar (orthoclase);
      - quartz;
      - some sodium (Na) feldspar (albite);
      - minor amounts of mica (muscovite/biotite), which stand out as clear or black flakes.
    - b) Light colored (generally pink).
    - c) Relatively low density (~2.6 to 2.8 g/cm<sup>3</sup>).
    - d) Common in middle and upper portions of continental crust.

(A coarse-grained igneous rock with silica content between that of granite and diorite is called **granodiorite**).
  - 2) **Diorite. (~60% silica)**
    - a) Most common minerals:
      - sodium-calcium feldspar (plagioclase);
      - only minor amounts of quartz;
      - dark minerals amphibole and pyroxene.
    - b) Grayish color (looks like "salt and pepper").
    - c) Density between granite and gabbro (~2.8 g/cm<sup>3</sup>).
    - d) Common in the mid-crust beneath volcanic arcs.
  - 3) **Gabbro. (~50% silica)**
    - a) Most common minerals:
      - calcium-rich feldspar (plagioclase);
      - pyroxene;

- minor amounts of olivine;

4) **Peridotite. (~40% silica)**

a) Mostly composed of:

- olivine and pyroxene;
- perhaps some calcium-rich feldspar.

b) Dark green color.

c) Very high density (3.3 to 3.4 g/cm<sup>3</sup>).

d) Not common in the crust, but forms the mantle part of the lithosphere:

- generally formed from magmatic differentiation as hot asthenosphere rises at a mid-ocean ridge:
  - low-silica magma cools first, crystallizing as the heavy minerals pyroxene and olivine (the rock peridotite);
  - the remaining magma has more silica and is thus lighter, so it moves upward to form the crust (gabbro and basalt).

B) Aphanitic (Fine Grained) Textures:

1) **Rhyolite. (~70% silica)**

(a), (b), and (c) same as for granite.

d) Occurrence:

- generally occurs as volcanic eruptions on continental crust, where magma intruded and re-melted silica-rich minerals.
- not much found in ocean crust;

(A fine-grained igneous rock with silica content between that of rhyolite and andesite is called **dacite**).

2) **Andesite. (~60% silica)**

(a), (b), and (c) same as for diorite.

d) Common in volcanic rocks at convergent plate boundaries:

- the downgoing ocean crust and sediments are heated, releasing fluids;
- the fluids work their way to the surface, partially melting mantle and crust of the overriding plate;
- silica-rich minerals have lower melting temperatures, enriching silica content of the resulting magma.

(A fine-grained igneous rock with silica content between that of andesite and basalt is called **basaltic andesite**).

3) **Basalt. (~50% silica)**

(a), (b), and (c) same as for gabbro.

d) Originates from cooling lava flows, commonly at divergent plate boundaries:

- upper part of ocean crust;
- continental rift zones.

4) Fine-grained equivalents to peridotite are very rare.

- too dense to extrude through the crust;
  - normally, only the coarse-grained (peridotite) forms, because it cools slowly at depth, within the mantle;
- the rare examples, called **komatiites**, are very old rocks, formed when the Earth was much hotter.

### **Properties of Magma**

The physical properties of magma depicted in **Table 2** depend, to a large degree, on the silica content of the magma.

**Color.** The less silica, the more dark colored minerals. Low-silica magmas therefore form igneous rocks that are dark green to black, while lighter colors (pink to white) occur as silica content increases.

**Density.** The less silica, the more heavy minerals (like those with iron and magnesium); the magma and resulting igneous rocks are thus more dense.

**Melting (Solidification) Temperature.** The more silica, the lower the melting temperature. As rock melts, high-silica magmas generally come out first. Likewise, as magma cools, lower silica minerals solidify first, followed progressively by those with higher and higher silica.

**Viscosity (Resistance to flow; "stickiness").** Silica molecules (tetrahedra) begin to form while the magma is still liquid. High-silica magmas (rhyolite/andesite) are therefore more paste-like than low-silica magmas (basalt), which tend to erupt like fountains of water and flow like rivers.

**Extent of Lava Flows.** The viscosity determines how easily (and how far) lava is likely to flow. Low-viscosity magmas (those with low silica) will therefore flow much farther (and are much thinner) than those with high-viscosity (high silica).

**Percent Volatiles.** **Volatiles** (water vapor and carbon dioxide) escape easily from fluid magmas, but are trapped when magmas are sticky. Low-viscosity (low-silica) magmas therefore have a much lower percentage of trapped gasses than high-viscosity (high-silica) magmas.

**Types of Volcanic Eruptions.** As magma rises and cools, gasses escape from free-flowing, low-silica magma, but are trapped (under high pressure) within sticky, high-silica magma. Sudden release of pressure causes violent eruption of magmas with andesite to rhyolite composition.

**Types of Volcanoes.** Low-viscosity magmas (basalt) flow freely, forming volcanoes with gentle slopes of less than 8° (**shield volcanoes**). Gas within the fluid magma causes it to spray like a fire hose, forming **cinder cones**. High-viscosity magmas (andesite to rhyolite) stick to the sides of volcanoes, making the volcanoes much steeper (10° - 15° slopes; **composite volcanoes**). Local eruptions of high-silica lava may pile up as steep-sided **lava domes**.

### **Tectonic Setting**

Numbers on **Table 2** refer to the tectonic settings where specific igneous rocks commonly occur (Chapter 1). Lower case letters indicate where the magma solidified within the crust or mantle. The occurrence for each rock type is a rough guide, indicating settings where

substantial amounts of that rock form.

## **ACKNOWLEDGEMENTS**

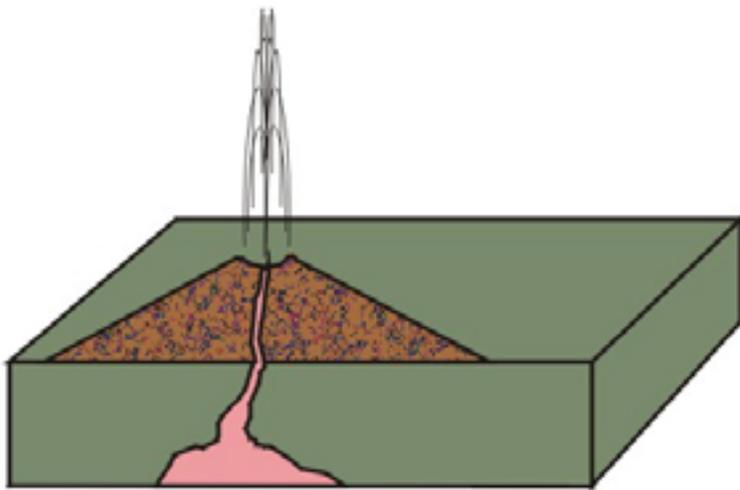
I'm thankful to many individuals for their help and encouragement during my stay at Sunset Crater Volcano National Monument. Anita Davis and SuZan Pearce arranged for my visit and made me feel at home. Staff members, including John Bland, Katie Hassler, Floy Healer, Bill Lee, Suzanne Morrison, Michael Stuckey, and Johnny Turner provided valuable help and discussion on the practical aspects of presenting natural science to Park visitors. They were also fun to work with! Judy Geniac of the National Park Service, *Geologist-in-the-Parks Program*, made my visit to Sunset Crater possible.

I'm also grateful to Melanie Moreno of the U. S. Geological Survey for helpful discussions on the writing and illustration of National Park Geology, and for providing maps and other material used in the manual. Reviews by Wendell Duffield of Northern Arizona University and Judy Geniac and Diann Gese of the *Geologist-in-the-Parks Program* were extremely helpful in improving the manual.

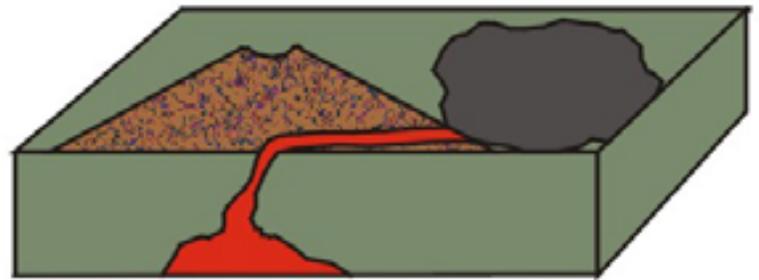
Finally, the smell of coffee and the background noise of colorful people often inspire writing. I am grateful to *Macy's European Coffee House*, *Campus Coffee Bean*, *Late for the Train*, and *Jitters* for making my stay in the Flagstaff area all the more pleasant!

**a**

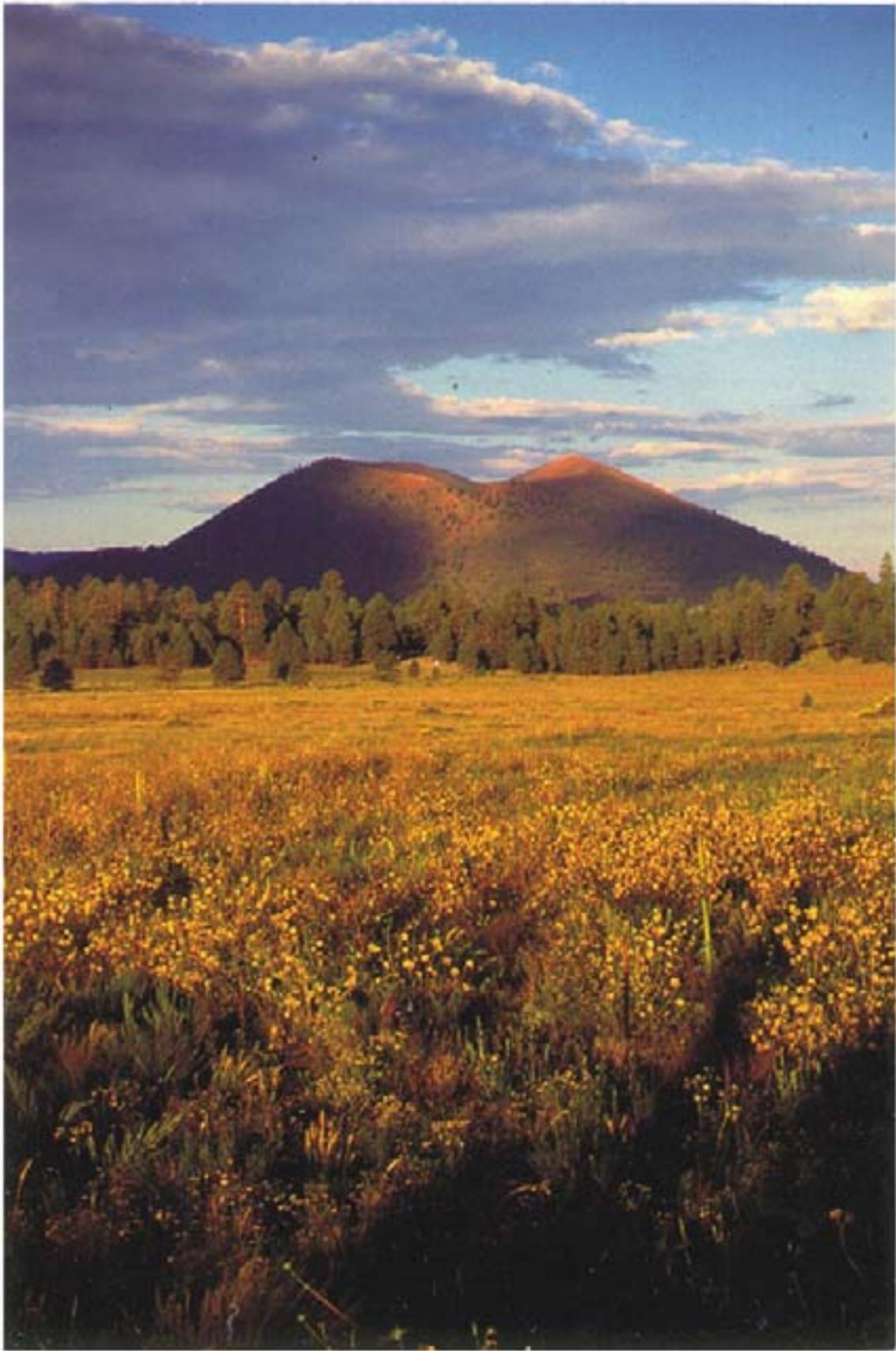
Magma with high gas content shoots upward like a "fire hose," spraying cinders out of the vent at the summit.



Magma low in gas is heavier. It breaks through the pile of loose cinders, erupting out of the base of the cone.

**b**

**Fig. 3.7. "Tongue" of lava extruding from the base of a cinder cone.** a) Schematic illustration showing that the dense, basaltic lava flows out of the base of the cinder cone, rather than fight gravity to the crater at the summit. The cinder cone is weak because it's a loose pile of material, and low density because there's a lot of pore space between the cinder particles. b) Bonita Lava Flow at the base of Sunset Crater Volcano. (Photo by R. J. Lillie).

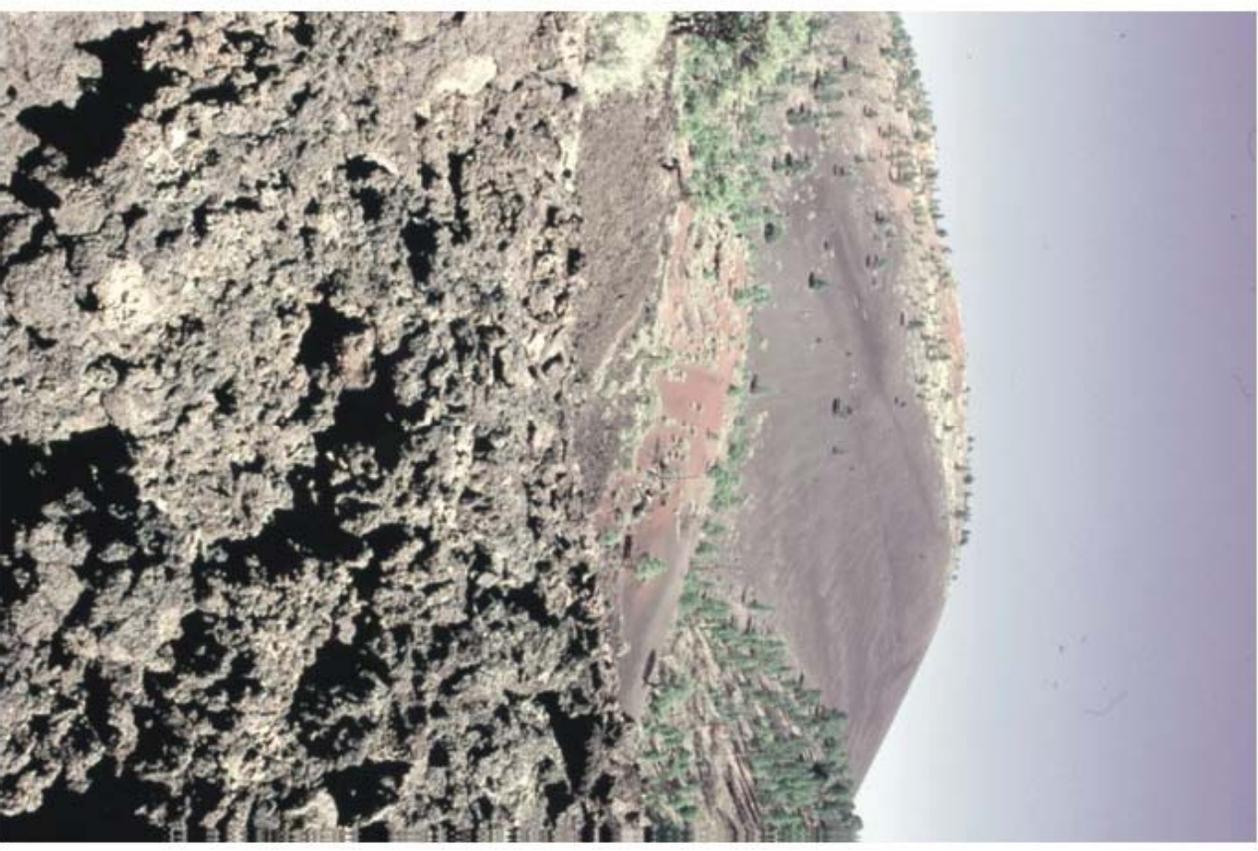


*Fig. 3.8. Bonita Park is a flat area that was excluded from fairly recent volcanic activity. Sunset Crater Volcano is in the background. (Photo by R. J. Lillie.)*

a



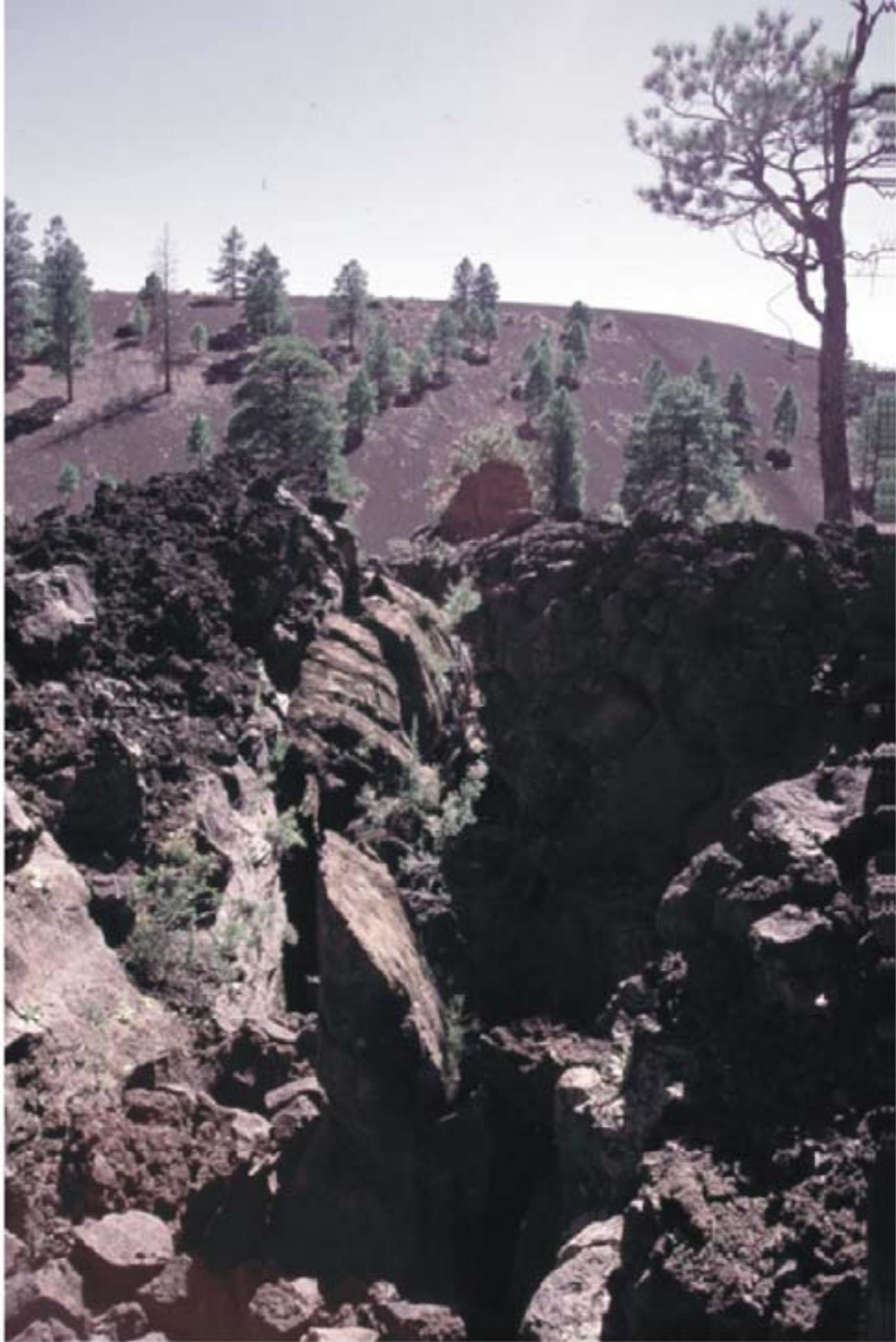
b



*Fig. 3.9. Surfaces of lava flows. (Photos by R. J. Lillie). a) Pahoehoe, from 1996 eruption at Hawaii Volcanoes National Park. b) Aa, from Lava Flow Trail, Sunset Crater Volcano National Monument.*

**a****b**

***Fig. 3.10. Cracks form on the surface of lava as it cools and contracts; wide fissures open where lava “inflates” the hard surface, causing it to bulge upward and expand. a) Fissure on the lower part of the Lava Flow Trail. b) Closeup of a xenolith exposed along the wall of the fissure in (a).***



*Fig. 3.11. Squeez-ups are "fins" of lava extending from fissures, as along the central portion of the Lava Flow Trail. (Photo by R. J. Lillie).*



**Fig. 3.12. Bubbles form from expanding gas near the surface of a lava flow.** The large "blister" seen near the bridge on the lower Lava Flow Trail is much like the result of blowing "bubble gum." (Photo by R. J. Lillie).



Fig. 3.13. **Spatter Cone on the upper portion of the Lava Flow Trail.** (Photo by R. J. Lillie).

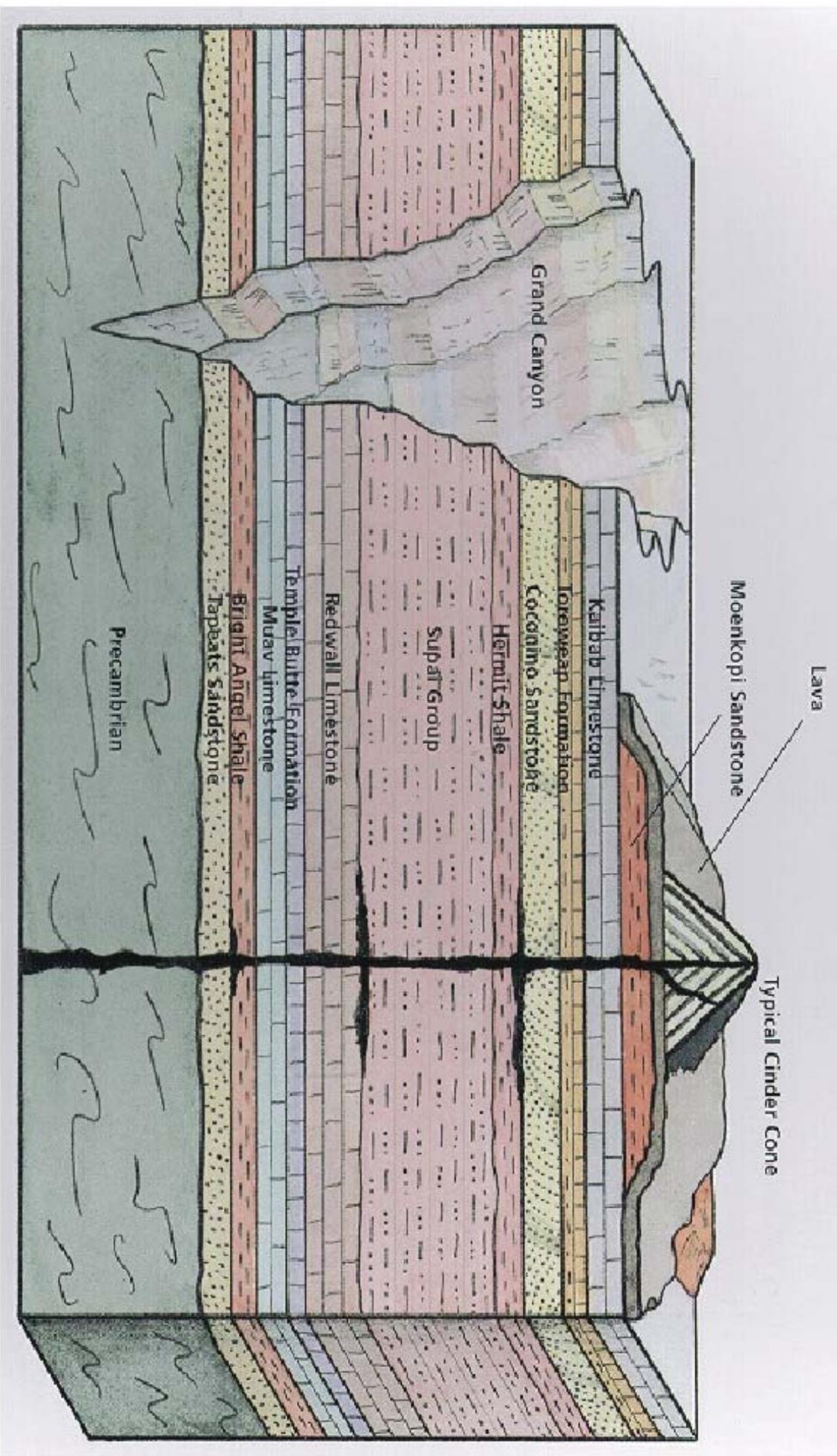
**a****b****c**

*Fig. 3.14. **Lava tubes.** (Photos by R. J. Lillie). a) Entrance to a lava tube at MacKenzie Pass, Cascade Mountains, Oregon. b) Inside of Ape Cave, a lava tube near Mount St. Helens, Washington. Note the long, flat floor and "gutters" that create the sensation of an "underground bowling alley." c) Entrance to the Ice Cave at the upper portion of the Lava Flow Trail, Sunset Crater Volcano National Monument, Arizona.*

<i>EON ERA</i>		<i>PERIOD</i>		<i>EPOCH</i>		<i>Present</i>
<b>Phanerozoic</b>	<b>Cenozoic</b>	Quaternary		Holocene		<i>Present</i>
				Pleistocene		<i>0.01</i>
		Tertiary	Neogene	Pliocene		<i>1.6</i>
				Miocene		<i>5.3</i>
				Oligocene		<i>23.7</i>
				Eocene		<i>36.6</i>
			Paleocene		<i>57.8</i>	
			Cretaceous		<i>66.4</i>	
			Jurassic		<i>144</i>	
	Triassic		<i>208</i>			
	<b>Paleozoic</b>	Carboniferous	Permian		<i>245</i>	
			Pennsylvanian		<i>286</i>	
			Mississippian		<i>320</i>	
		Devonian		<i>360</i>		
		Silurian		<i>408</i>		
Ordovician		<i>438</i>				
Cambrian		<i>505</i>				
<b>Precambrian</b>		Proterozoic		<i>570</i>		
	Archean		<i>2500</i>			
	Hadean		<i>3800</i>			
						<i>4550</i>

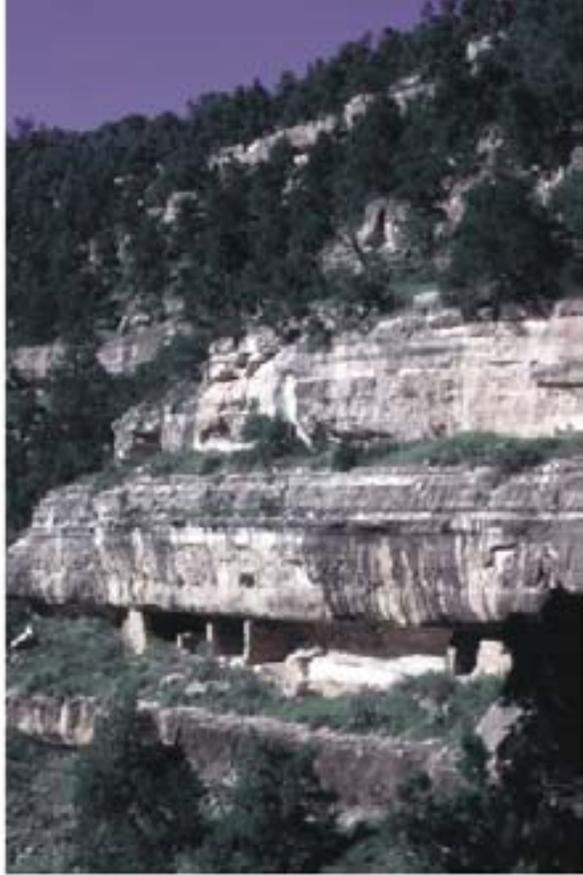
*AGE (Millions of Years before Present)*

*Table 1. Geologic Time Scale. From Decade of North American Geology (DNAG), 1983. Figure courtesy United States Geological Survey.*



**Fig. 3.1. Stratigraphic sequence underlying Sunset Crater Volcano.** (From Duffield, 1997). The older rocks (Paleozoic sedimentary strata and Precambrian igneous and metamorphic rocks) are probably the same layers that are exposed 100 miles away in the Grand Canyon. A younger, Mesozoic layer (Moenkopi Sandstone) occurs locally, overlain by volcanic deposits from the San Francisco Peaks region, then cinders and lava flows from the recent eruptions of Sunset Crater and the Cinder Hills.

*a*

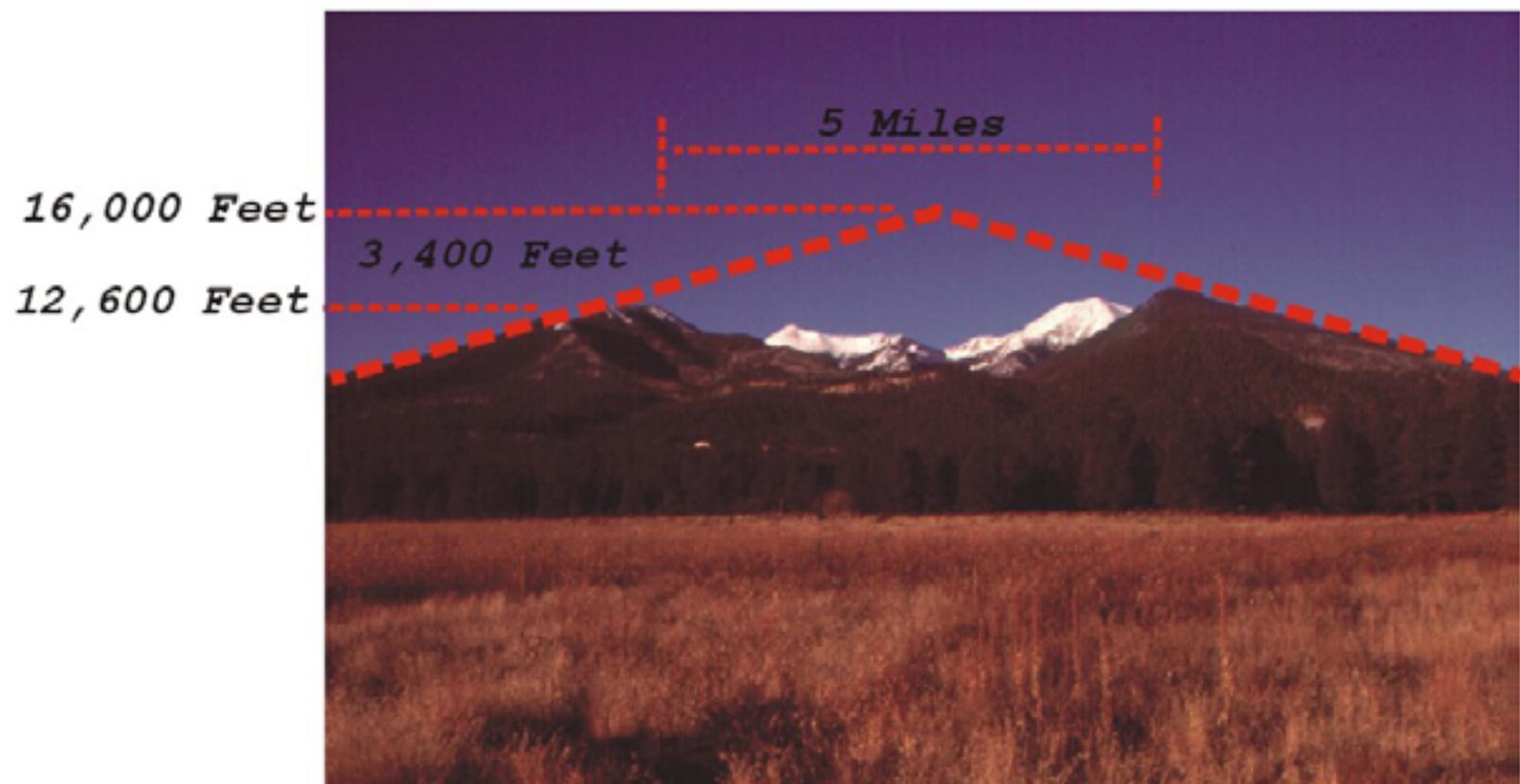


*b*

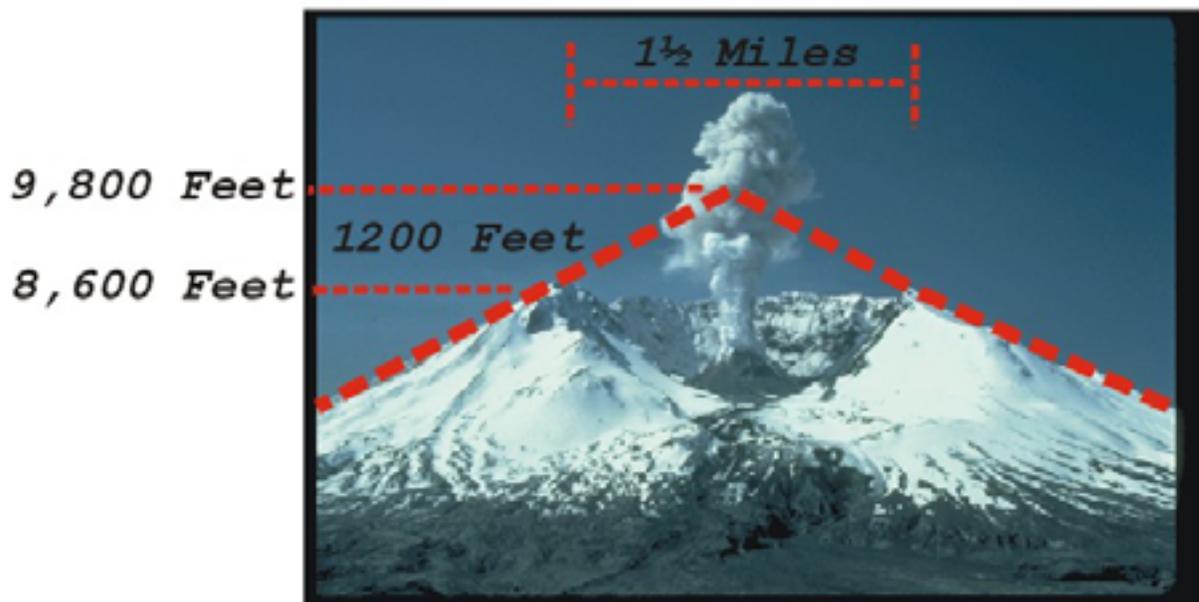


*Fig. 3.2. Vertical joints in sedimentary rock layers in Flagstaff area National Monuments. (Photographs by R. J. Lillie) a) Slabs of rock broke along joints in Kaibab Limestone layers at Walnut Canyon National Monument. The resulting vertical faces were used as walls for ancient dwellings. b) Joints formed in Meonkopi Sandstone layers at Wapatki National Monument. At Crack-in-Rock, the smooth, vertical faces were used as canvas for rock art, in addition to dwelling walls. Rectangular slabs of rock that broke off along the vertical joints*

## a) San Francisco Peaks



## b) Mount St. Helens



**Fig. 3.3. Photographs of the eastern side of San Francisco Peaks (a) and the blasted out, north side of Mount St. Helens (b).** Mount St. Helens lost about 1,200 feet of its height, compared to over 3,000 feet that may have been lost by San Francisco Peaks during a similar explosion. The breached crater ("Inner Basin") on San Francisco Peaks is also much wider (~5 miles) than the one on Mount St. Helens (~1½ miles). Photo in (a) by R. J. Lillie; (b) courtesy U. S. Geological Survey.

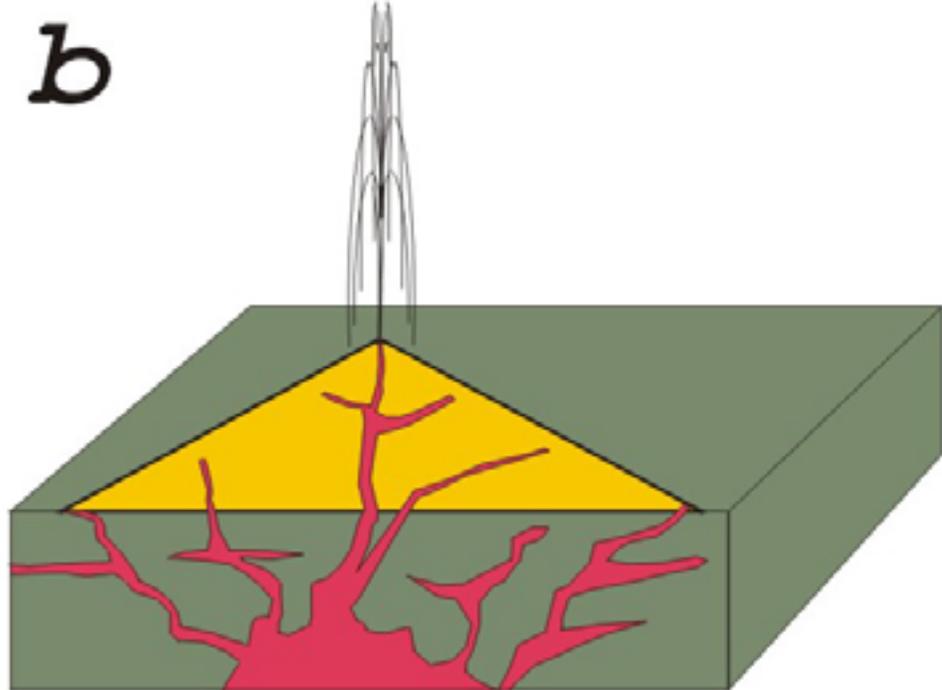
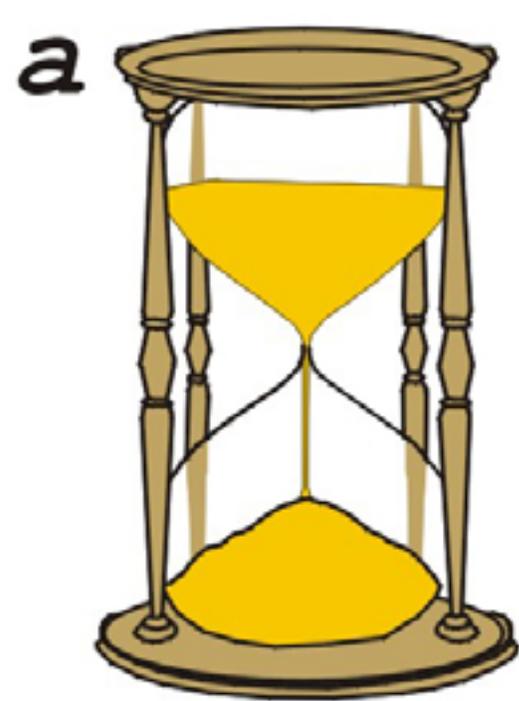
a) *O'Leary Peak*



b) *Sugarloaf*



**Fig. 3.4. Lava domes near Sunset Crater Volcano National Monument.**  
(Photographs by R. J. Lillie). a) *O'Leary Peak*, from Lava Flow Trail. b) *Sugarloaf*, from Inner Basin of San Francisco Mountain. (Sunset Crater Volcano is the cinder cone to upper right of Sugarloaf).



**Fig. 3.5. Cinder cone formation.** a) Sand falling in an hourglass builds a cone that steepens until it reaches the angle of repose. The cone then gets bigger, but the slope remains at that angle. b) A cinder cone is similar, reaching the angle of repose then simply getting bigger as it maintains that profile. c) Paricutin Volcano in Mexico is a large cinder cone formed during eruptions in the 1940's. d) Capulin Volcano, a cinder cone in Capulin Volcano National Monument, New Mexico. (Photo by R. J. Lillie).



*Fig. 3.6. "Curtain of fire" eruption of fluid (basaltic) lava through a fissure on the flanks of Heimaeý Volcano in Iceland.*

**Table 2**

CLASSIFICATION and PROPERTIES of IGNEOUS ROCKS and MAGMAS

		CHEMICAL COMPOSITION				Cooling History		
GRAIN SIZE	Fine Grained	Rhyolite	Andesite	Basalt		Rate	Position	Rock Type
	Coarse Grained	Granite	Diorite	Gabbro	Peridotite	Fast	Above Surface	Extrusive (Volcanic)
						Slow	Below Surface	Intrusive (Plutonic)
<b>% Silica</b>		<b>70%</b>	<b>60%</b>	<b>50%</b>	<b>40%</b>			
% Dark (Heavy) Minerals		30%	40%	50%	60%			
Names of Common Minerals		K-Feldspar Quartz	Plag.-Feld. Amphibole	Plag.-Feld. Pyroxene	Olivine Pyroxene			
Color		Light	Intermed.	Black	Dark Green			
Density (gram/cc)		2.7	2.8	2.9	3.3			
Melting Temp. (deg. C)		800	950	1100	1400			
Viscosity of Magma		High	Interm.	Low				
Extent of Lava Flows		Small Area		Large Area				
% Volatile Fluids		10%	5%	1%				
Type of Eruptions		Explosive	Explosive	Quiet				
Types of Volcanoes		Composite Lava Dome	Composite	Shield Cinder Cone				
<b>Tectonic Setting:</b>								
1. Continental Rift								
2. Mid-Ocean Ridge		Rhyolite	Andesite	Basalt				
3. Subduction Zone								
4. Hot Spot		1a, 3a, 4a	3a	1a, 2a, 3a, 4a				
5. Continental Collis.								
<b>Where Solidified:</b>								
a. Upper Crust		Granite	Diorite	Gabbro	Peridotite			
b. Mid-to-Lower Crust								
c. Mantle		3b, 5b	3b	1b, 2b, 4b	2c			

***Table 2***



**Table 3.** Classification of National Park Service lands according to tectonic setting. The setting depends on the type of plate boundary and crust present during formation of the rocks and landscapes in each park. Areas were selected if a significant amount of the material presented to park visitors relates to the geology of the region. NP = National Park; NM = Nat. Monument; NS = Nat. Seashore; NLS = Nat. Lake Shore; NRA = Nat. Recreation Area; NSR = Nat. Scenic River; NHP = Nat. Historic Park; WSR = Wild and Scenic River; NST = Nat. Scenic Trail; NRR = Nat. Recreation River.

## **1. DIVERGENT PLATE BOUNDARIES**



### **A) CONTINENTAL RIFTS**

#### **Basin and Range Province (Active)**

<p>Great Basin NP, NV          Death Valley NM, CA          Timpanogos Cave NM, UT          Lake Mead NRA, CA          Lava Beds NM, CA          Devils Postpile NM, CA</p>	<p>Saguaro NM, AZ          Joshua Tree NM, CA          Organ Pipe Cactus NM, AZ          Grand Canyon NP, AZ          Crater Lake NP, OR          Sunset Crater NM, AZ</p>
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#### **Rio Grande Rift (Active)**

<p>White Sands NM, NM          Bandelier NM, NM</p>	<p>Capulin Volcano NM, NM</p>
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#### **Keweenawan Rift (Ancient)**

<p>Isle Royale NP, MI          Grand Portage NM, MN          Apostle Island NLS, WI</p>	<p>Pictured Rocks NLS, MI          St. Croix NSR, MN/WI</p>
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### **B) PASSIVE CONTINENTAL MARGINS**

#### **Atlantic Coast**

<p>Acadia NP, ME          Biscayne NP, FL          Fire Island NS, NY          Gateway NRA, NJ          Cape Cod NS, MA</p>	<p>Assateague Island NS, MD          Cape Hatteras NS, NC          Cape Lookout NS, NC          Cumberland Island NS, GA          Canaveral NS, FL</p>
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#### **Gulf of Mexico Coast**

<p>Everglades NP, FL          Gulf Islands NS, FL/MS          Jean Lafitte NHP &amp; Pres, LA</p>	<p>Big Thicket N Pres, TX          Padre Island NS, TX</p>
---	--

### **C) MID-OCEAN RIDGES**

**(None)**

## 2. CONVERGENT PLATE BOUNDARIES



### A) OCEAN-OCEAN SUBDUCTION ZONES

**Aleutian Islands/Alaska  
Pen.**

Aniakchak NM & Pres, AK

**Western Pacific**

NP of American Samoa, Am Sam

### B) OCEAN-CONTINENT SUBDUCTION ZONES

**Coast Ranges (Accretionary Wedge)**

Olympic NP, WA

Redwood NP, CA

Oregon Caves NM, OR

**Alaska (Active Volcanic Arc)**

Katmai NP & Pres, AK

Lake Clark NP & Pres, AK

Kenai Fjords NP, AK

**Cascade Mountains (Active Volcanic Arc)**

Mount Rainier NP, WA

Crater Lake NP, OR

Lassen Volcanic NP, CA

**Sierra NV Mountains (Ancient Volcanic Arc)**

Yosemite NP, CA

Kings Canyon NP, CA

Sequoia NP, CA

**Laramide Uplifts (Low-Angle Subduction)**

Glacier NP, MT

Grand Teton NP, WY

Rocky Mountain NP, CO

Wind Cave NP, SD

Carlsbad Caverns NP, NM

Guadalupe Mountains NP, TX

Bighorn Canyon NRA, MT

Mount Rushmore NM, SD

Jewel Cave NM, SD

Great Sand Dunes NM, CO

Florissant Fossil Beds NM, CO

### C) COLLISIONAL MOUNTAIN RANGES

**Appalachian Mountains**

Shenandoah NP, VA

Great Smoky Mountains NP, NC/TN

Blue Ridge Parkway, VA/NC

Appalachian NST, GA to ME

Delaware Water Gap NRA, PA

Gauley River NRA, West VA

New River Gorge NR, West VA

Bluestone NSR & RA, KY

Big South Fork NR & RA, KY/TN

Obed WSR, TN

Russell Cave NM, AL

Chattahoochee River NRA, GA

**Ouachita Mountains**

Hot Springs NP, AR  
Chickasaw NRA, OK

**Marathon Mountains**

Big Bend NP, TX  
Rio Grande WSR, TX

**Brooks Range**

Gates of the Arctic NP&Pres, AK  
Noatak NP & Pres, AK

Cape Krusenstern NP & Pres, AK

**D) ACCRETED TERRAINS****North American Cordillera**

Denali NP, AK  
Wrangell-St. Elias NP & Pres, AK  
North Cascades NP, WA

Yukon-Charley Rivers N Pres, AK  
Ross Lake NRA, WA

**3. TRANSFORM PLATE BOUNDARIES****San Andreas Fault**

Channel Islands NP, CA  
Point Reyes NS, CA  
Muir Woods NM, CA  
Golden Gate NRA, CA

Pinnacles NM, CA  
Santa Monica Mountains NRA, CA  
Cabrillo NM, CA

**Southeast Alaska**

Glacier Bay NP & Pres, AK

**Caribbean**

Virgin Islands NP, U. S. VI  
Buck Island Reef NM, U. S. VI

**4. HOTSPOTS ←←←****A) OVER OCEANIC CRUST****Hawaii - Emperor**

HI Volcanoes NP, HI

Haleakala NP, HI

**B) OVER CONTINENTAL CRUST****Yellowstone-Snake River Plain-Columbia Plateau**

Yellowstone NP, WY/ID/MT  
Craters of the Moon NM, ID

Sunset Crater Volcano NM, AZ?  
Capulin Volcano NM, NM?

## **5. AREAS NOT EASILY ASSOCIATED WITH PLATE BOUNDARIES OR HOTSPOTS**

### **Colorado Plateau**

Grand Canyon NP, AZ  
 Zion NP, UT  
 Bryce Canyon NP, UT  
 Petrified Forest NP, AZ  
 Capital Reef NP, UT  
 Arches NP, UT  
 Mesa Verde NP, CO  
 Walnut Canyon NM, AZ

Wapatki NM, AZ  
 Sunset Crater Volcano NM, AZ  
 Natural Bridges NM, UT  
 Cedar Breaks NM, UT  
 Glen Canyon NRA, UT  
 Dinosaur NM, UT/CO  
 Black Can of the Gunnison NM, CO  
 Curecanti NRA, CO

### **Stable Craton**

Theodore Roosevelt NP, ND —  
 Badlands NP, SD  
 Voyageurs NP, MN  
 Mammoth Cave NP, KY  
 Agate Fossil Bed NM, NB  
 Scotts Bluff NM, NB  
 Missouri NRR, SD/NB  
 Lake Meredith NRA, TX  
 MS NR & RA, MN  
 Pipestone NM, MN

Effigy Mounds NM, IA  
 Ozark NSR, MO  
 Buffalo NR, AR  
 Poverty Point NM, LA  
 Natchez-Trace Pky & NST,  
 MS/AL/TN  
 Sleeping Bears Dunes NS, MI  
 Mound City Group NM, OH  
 Indiana Dunes NLS, IN