

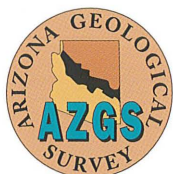
# *A Guide to the* **Geology** *of the* **Flagstaff Area**



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*Down-to-Earth 14*



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# Contents

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|   |    |
|---|----|
| Acknowledgments.....  | 3  |
| Introduction.....   | 9  |
| General Geology.....  | 11 |
| Geologic Features North and Northeast of Flagstaff                            |    |
| Feature 1    San Francisco Volcanic Field.....                                | 15 |
| Feature 2    Lava Dome: Mount Elden.....                                      | 17 |
| Feature 3    Stratovolcano: San Francisco Mountain.....                       | 18 |
| Feature 4    Glacial features: Cirques, Moraines,<br>and U-shaped Valley..... | 21 |
| Feature 5    Young Cinder Cones and Lava Flows: Sunset<br>and SP Craters..... | 23 |
| Feature 6    Squeeze-up: Bonito Flow.....                                     | 27 |
| Feature 7    Cinder Dunes and Ventifacts.....                                 | 28 |
| Feature 8    Moenkopi Formation: Wupatki National Monument.....               | 30 |
| Feature 9    Blowhole: Wupatki National Monument.....                         | 31 |
| Feature 10   Fault-aligned Cinder Cones:<br>Wupatki National Monument.....    | 32 |
| Feature 11   Sinkhole: Wupatki National Monument.....                         | 34 |
| Feature 12   Graben: Wupatki National Monument.....                           | 36 |
| Feature 13   Folding: Black Point Monocline.....                              | 37 |
| Feature 14   Entrenched Meanders: Walnut Canyon<br>National Monument.....     | 39 |
| Feature 15   Kaibab Formation: Walnut Canyon<br>National Monument.....        | 41 |
| Feature 16   Coconino Sandstone: Walnut Canyon<br>National Monument.....      | 43 |
| Feature 17   Stream Displaced by a Lava Flow: Grand Falls.....                | 44 |
| Feature 18   Meteor Impact Crater: Barringer Meteor Crater.....               | 46 |
| Feature 19   Laccolith: White Horse Hills (Marble Mountain).....              | 48 |
| Feature 20   Anatomy of a Cinder Cone: Red Mountain.....                      | 50 |
| Feature 21   Tafoni: Red Mountain.....  | 51 |
| Feature 22   Hoodoos (Demoiselles): Red Mountain.....                         | 52 |
| Feature 23   Lava Tube: Lava River Cave.....                                  | 53 |

|                             |    |
|-----------------------------|----|
| Suggested Readings. . . . . | 54 |
|-----------------------------|----|

## List of Figures

|             |   |    |
|-------------|---|----|
| Figure A    | Index map and location of geologic features and access roads in the Flagstaff area. . . . .                                       | 8  |
| Figure B    | Geology of the Flagstaff area with inset map of the Colorado Plateau. . . . .   | 10 |
| Figure C    | Geologic cross-section of the Flagstaff area. . . . .   | 12 |
| Figure 1.1  | Satellite image of the eastern San Francisco volcanic field. . . . .  | 14 |
| Figure 1.2  | Volcanic fields of the southern Colorado Plateau. . . . .   | 14 |
| Figure 2.1  | Aerial photograph of Mount Elden. . . . .   | 16 |
| Figure 2.2  | The Mount Elden dome formed by the injection of dacitic lava. . . . .   | 17 |
| Figure 3.1  | San Francisco Mountain with dashed lines showing the possible maximum elevation of the stratovolcano. . . . .                     | 18 |
| Figure 3.2  | Geologic map of San Francisco Mountain. . . . .   | 19 |
| Figure 3.3  | East-west cross section of San Francisco Mountain. . . . .  | 20 |
| Figure 4.1  | Oblique aerial view of the Inner Basin of San Francisco Mountain as it may have looked when occupied by Ice Age Glaciers. . . . . | 22 |
| Figure 4.2  | Cirques, moraines and the u-shaped Inner Basin of San Francisco Mountain. . . . .   | 22 |
| Figure 5.1  | Satellite image of Sunset Crater and the Bonito lava flow area. . . . .   | 23 |
| Figure 5.2  | Satellite image of SP Crater and associated lava flow. . . . .  | 24 |
| Figure 5.3  | Sunset Crater. . . . .  | 25 |
| Figure 5.4  | Bonito lava flow. . . . .   | 25 |
| Figure 5.5  | Aerial photograph of SP Crater and lava flow. . . . .   | 26 |
| Figure 5.6  | SP lava flow. . . . .   | 26 |
| Figure 6.1  | Squeeze-up on the Bonito lava flow. . . . .   | 27 |
| Figure 7.1  | Satellite image of windblown cinders and dunes, Wupatki National Monument area . . . . .  | 28 |
| Figure 7.2  | Wind-cut rock outcrop near Wupatki National Monument. . . . .   | 29 |
| Figure 8.1  | Sandstone with ripple marks, Wupatki National Monument. . . . .   | 30 |
| Figure 9.1  | Cross sectional diagram of the blowhole system, Wupatki Wupatki National Monument. . . . .  | 31 |
| Figure 10.1 | Doney Crater with a volcanic bomb in the foreground . . . . .   | 32 |
| Figure 10.2 | Block diagram of the Doney Fault and Doney Crater area. . . . .   | 33 |
| Figure 11.1 | Citadel sinkhole. . . . .   | 34 |
| Figure 11.2 | Block diagrams illustrating the formation of the Citadel sinkhole. . . . .  | 35 |
| Figure 12.1 | Block diagram illustrating the formation of the Citadel graben, Wupatki National Monument. . . . .                                | 36 |

|             |  |    |
|-------------|--|----|
| Figure 13.1 | Satellite image of the Black Point monocline. ....                                     | 37 |
| Figure 13.2 | Oblique aerial view of the Black Point monocline. ....                                 | 38 |
| Figure 13.3 | Block diagram illustrating the formation of the<br>Black Point monocline. ....         | 38 |
| Figure 14.1 | Aerial photograph of Walnut Canyon. ....   | 39 |
| Figure 14.2 | Block diagrams illustrating the development<br>of entrenched meanders. ....            | 40 |
| Figure 14.3 | Walnut Canyon. ....  | 40 |
| Figure 15.1 | The Kaibab Formation at Walnut Canyon. ....  | 41 |
| Figure 15.2 | Solution pits on a limestone rock surface,<br>Wupatki National Monument. ....          | 42 |
| Figure 16.1 | Cross bedding in Coconino Sandstone in Walnut Canyon ...                               | 43 |
| Figure 17.1 | Grand Falls. ....  | 44 |
| Figure 17.2 | Satellite image of the Merriam Crater<br>and Grand Falls area. ....                    | 45 |
| Figure 18.1 | Meteor Crater, Northern Arizona, USA. ....   | 46 |
| Figure 19.1 | Laccolithic mountain groups on the<br>southern Colorado Plateau. ....                  | 48 |
| Figure 19.2 | Block diagram illustrating the development<br>of the White Horse Hills laccolith. .... | 49 |
| Figure 20.1 | Red Mountain. ....   | 50 |
| Figure 21.1 | Tafoni at Red Mountain. ....   | 51 |
| Figure 22.1 | Hoodoos on Red Mountain. ....  | 52 |
| Figure 23.1 | Block diagrams illustrating the formation<br>of a lava tube. ....                      | 53 |



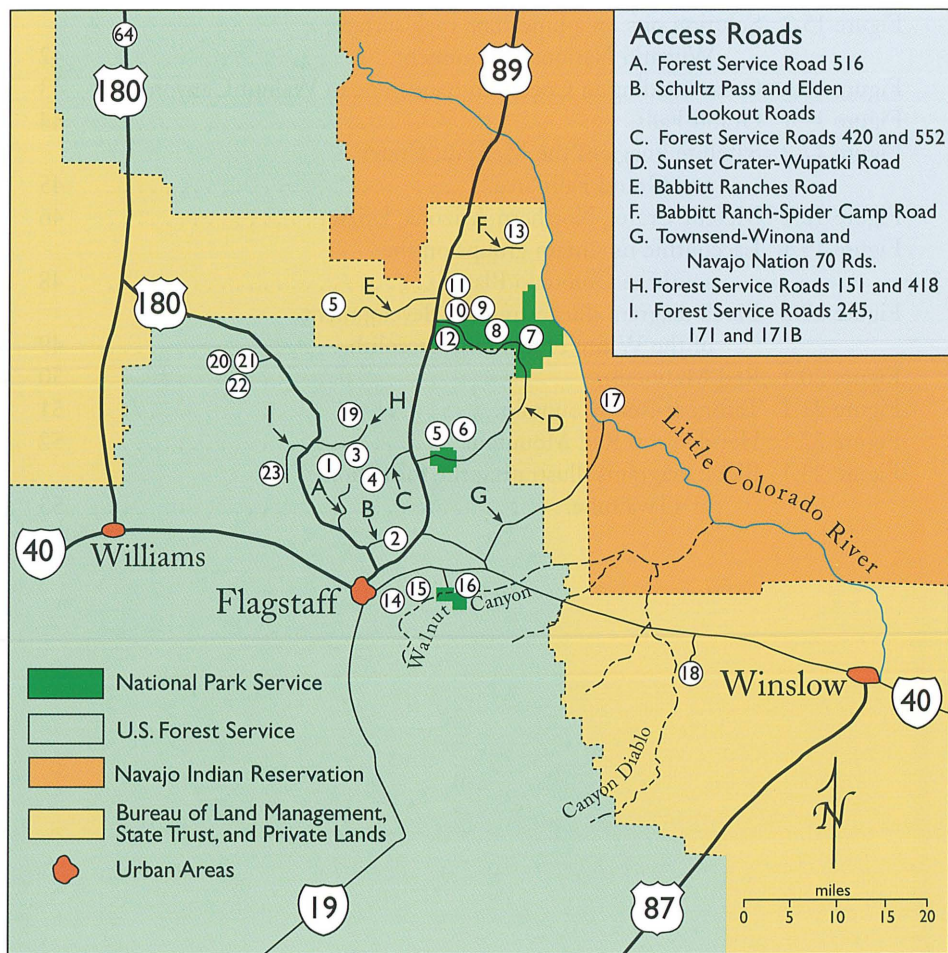


Figure A. Index map and location of geologic features and access roads in the Flagstaff area.

# Introduction

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**T**he Flagstaff area, on the southern margin of the Colorado Plateau, offers an exceptional variety of geologic wonders. The landscape of this plateau is composed of remarkable geologic features: the towering, glaciated peaks of San Francisco Mountain, underground lava tubes and blowholes; meteor-blasted Barringer Crater, and cinder cones and lava flows of the San Francisco volcanic field.

This booklet is your guide to the geologic features of the fascinating landscape of the Flagstaff area. It is a hiker's guide; walks to the geologic features described in the text are encouraged. This book was written for the visitor who has an interest in geology, but may not have had formal training in the subject. It may also help ensure that the visiting geologist does not overlook some of the features described.

To set the stage, I have briefly described the area's geologic setting and history. In the following pages, I have discussed geologic features that are common in the landscape and have given precise directions to each feature.

General locations of the geologic features are shown on Figure A. More detailed locations are provided in the text as needed. All of the roads that are recommended for use can be driven with any vehicle of moderate clearance. U.S. Forest Service roads are gravel or dirt; the road to Grand Falls may be impassable in wet weather. All dirt roads are slick when wet and should be driven with care. Drainages are subject to flash flooding during periods of heavy rainfall and should be crossed with caution. Restaurants, gasoline, information on road conditions, and emergency services are available in Flagstaff.

The purpose of this guide is to provide the reader with an understanding of the dynamic processes that have shaped this magnificent part of Arizona. You will encounter many of the features discussed in the text again and again as you continue to explore the Southwest. We hope that your experience in the Flagstaff area will enhance the pleasure of those explorations.







# General Geology

**T**he Flagstaff area is on the southern margin of the Colorado Plateau, a 130,000-square-mile geologic province of vast plains, high mesas and buttes, deep canyons, volcanic fields and isolated mountain clusters (Figure B). The landscape of this southern Plateau margin is dominated by the young San Francisco volcanic field and the underlying limestone-capped plateau. Elevations of the Colorado Plateau and the Flagstaff sub-province range from 5000 to 7000 ft (1500-2135 m).

The oldest known rocks underlying this part of the Plateau are 1.7-1.8 billion-year-old (Precambrian) granite and schist (Figure C). These rocks, which make up the original crust of North America, were beveled by erosion and offset by faults that moved again during younger geologic periods.

Horizontal layers of sandstones, limestones, shales, and siltstones of the Paleozoic Era (544 million to 248 million years ago) were deposited on the ancient Precambrian rocks. These younger units, named in ascending order, the Tapeats Sandstone, Bright Angel Shale and Muav Limestone, Martin Formation, Redwall Limestone, Supai Group, Coconino Sandstone, and the Toroweap and Kaibab Formations, were deposited when this part of the continent was a shallow sea floor, a

muddy tidal zone, a coastal plain crossed by silt-laden rivers, or a vast desert covered by sand dunes. The Coconino Sandstone and the Toroweap and Kaibab Formations are the only Paleozoic rocks exposed in the area covered by this guidebook.

More rock layers were laid down during the Mesozoic Era (248 to 65 million years ago). The Moenkopi Formation is the only Mesozoic rock that covers large parts of the Flagstaff area. Younger layers of sediment accumulated, but were later eroded away. The total thickness of sedimentary rock deposited during the Paleozoic and Mesozoic Eras may have reached 10,000 ft (3050 m), but much of this was stripped off by erosion.

Beginning about 65 to 75 million years ago, western North America was subjected to intense horizontal compression during an episode of mountain building called the Laramide Orogeny. The Rocky Mountains, for example, were formed during this period. This stress reactivated old faults and created new faults and folds. Vertical movement along these faults elevated the Precambrian basement rocks and the thick sequence of younger sedimentary layers thousands of feet, eventually forming the Colorado Plateau. The exact timing and causes of the uplift are still debated by geologists.

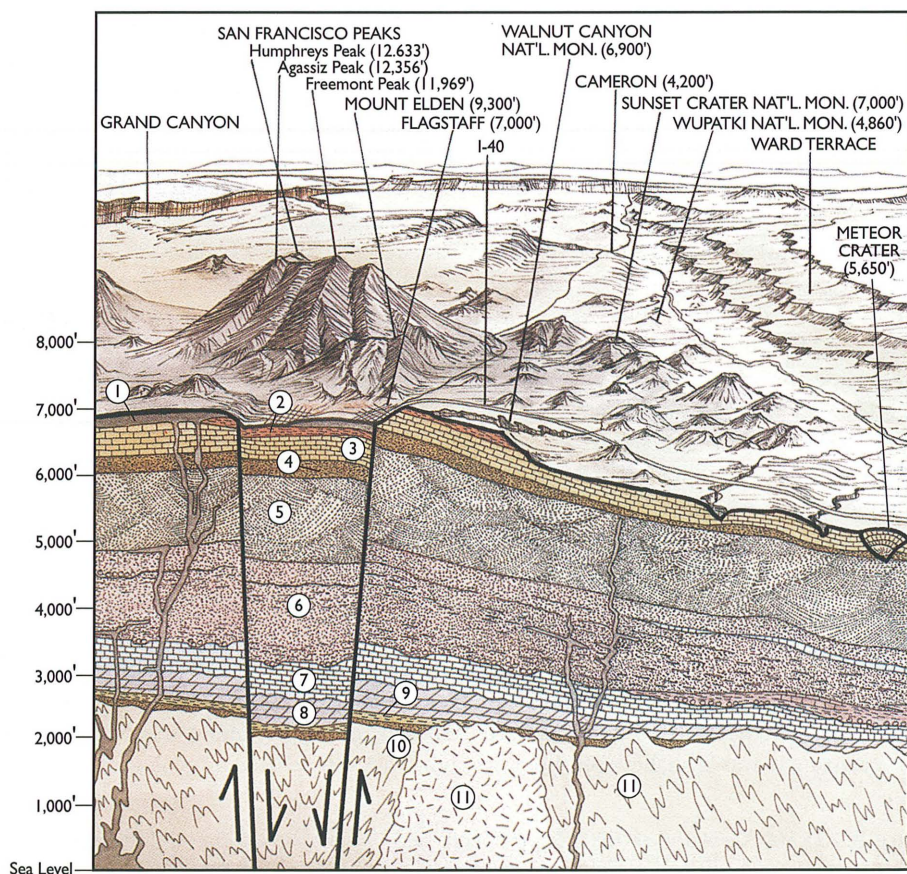
**Figure B. (Left)** Geology of the Flagstaff area with inset map of the Colorado Plateau. Qs=Quaternary sand, silt and gravel; Qb=Quaternary basalt; QTv=Quaternary and Tertiary rhyolitic to andesitic flows, plugs, and dikes; Qtb=Quaternary and Tertiary basalt; Ts=Tertiary sandstone, shale, and conglomerate; Trc=Triassic Chinle Formation; Trs=Triassic Shinarump Conglomerate; Trm=Moenkopi Formation; Pk=Kaibab Formation; Pc=Coconino Sandstone; Pu=undivided Paleozoic rocks (Moore and others, 1960).

In the Flagstaff area movement along faults deformed once-horizontal layers into long folds, such as the Black Point monocline north of Wupatki National Monument. The uplift also caused formerly sluggish rivers to cut deep canyons into the younger sedimentary layers.

Beginning about 25 million years ago, the crustal rocks of western North America were stretched, thinned, and broken along steep faults. Movement occurred again along the old faults of the Flagstaff area. About 6 million years ago, molten rock (called magma inside the earth and lava when it erupts) migrated upward along

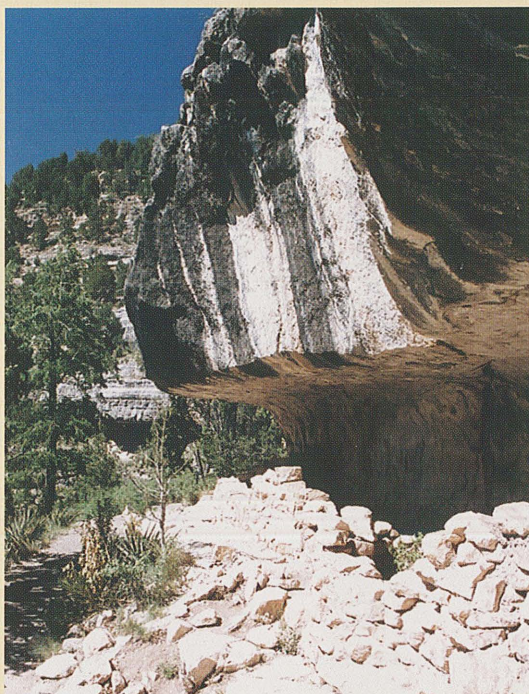
some of these fractures and flowed onto the land surface as lava flows. As eruptions continued during the period 3 million to 1000 years ago lava of the San Francisco volcanic field poured onto, exploded through, or was injected into Paleozoic and Mesozoic sedimentary layers of the plateau.

Finally, San Francisco Mountain, the high stratovolcano that towers over the volcanic field, was scoured by glacial ice several times during the last 1.8 million years. Today, running water is cutting into and wearing down this southern flank of the Colorado Plateau.



**Figure C.** Geologic cross-section of the Flagstaff area. 1. Quaternary and Tertiary volcanic rocks; 2. Moenkopi Formation; 3. Kaibab Formation; 4. Toroweap Formation; 5. Coconino Sandstone; 6. Supai Group; 7. Redwall Limestone; 8. Martin Formation; 9. Mauv Limestone and Bright Angel Shale; 10. Tapeats Sandstone; 11. Precambrian granite and schist (after Billingsley and others 1980).





## **Geologic Features**



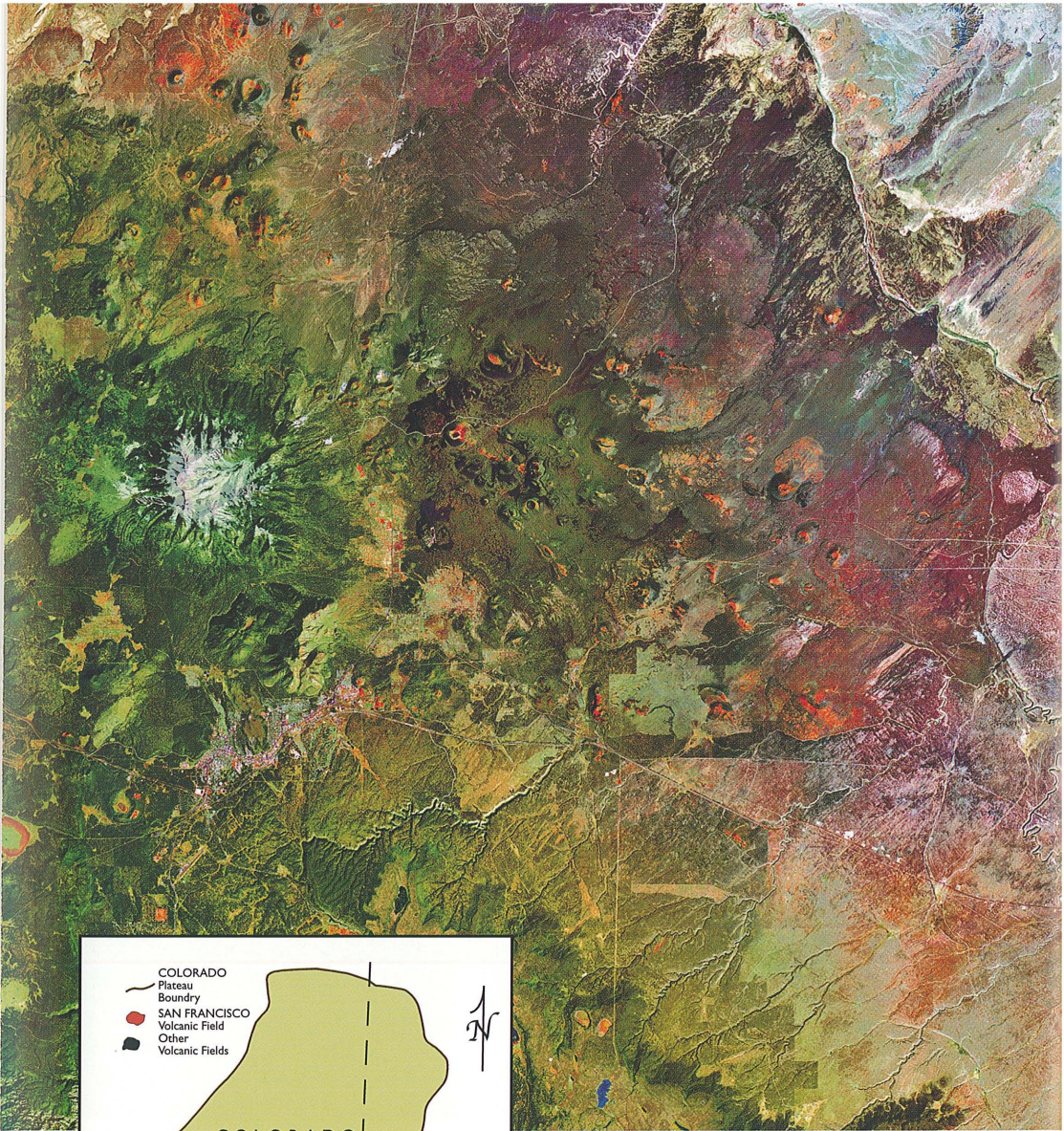


Figure 1.1. (Above) Satellite image of the eastern San Francisco volcanic field.

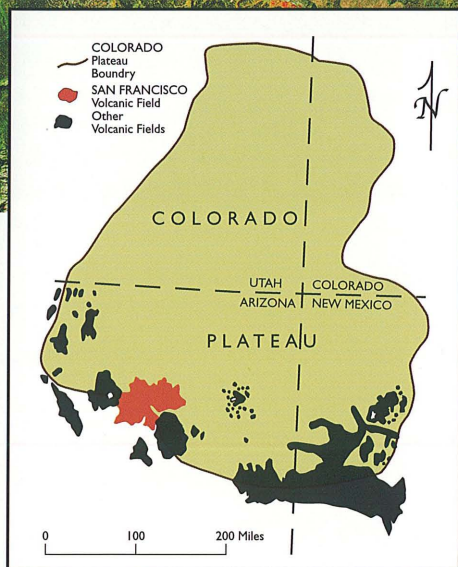


Figure 1.2. (Left) Volcanic fields of the southern Colorado Plateau (after Hunt, 1967).



# Feature [I]

## San Francisco Volcanic Field

**Location:** The volcanic field is best viewed from the top of San Francisco Mountain. Follow Highway 180 northwest from Flagstaff to milepost 223 and turn right (east) on Forest Service road 516. Follow this road to the Arizona Snow Bowl and take the ski lift to the high slopes of the mountain. The western part of the volcanic field can be seen from Forest Service road 516.

San Francisco Mountain, 600 nearby cinder cones and lava domes, numerous lava flows, and the extensive cinder and ash deposits in the Flagstaff area are collectively called the San Francisco volcanic field. Eruptions began in the western part of the volcanic field about 6 million years ago, and migrated to the northeast and east. Volcanic activity increased during the past 3 million years. The most recent event was the eruption at Sunset Crater less than 1000 years ago. The more recent cinder cones and lava flows in the eastern part of the volcanic field have the best definition on satellite images (Figure 1.1) because they have not yet developed soil and dense vegetation.

Molten rock that flowed, oozed, or exploded onto the land surface as lava varied in mineral content over time and distance and cooled to produce a variety of volcanic rocks and landforms. Generally, the greater the amount of silica in the lava, the greater its viscosity. Basaltic lavas are low in silica and relatively fluid. They can flow great distances from vents and fissures forming long sheets and tongues of lava. These basaltic lava flows are dark in color because they contain dark iron- and magnesium-bearing minerals. Andesite lava, with intermediate silica content and viscosity, forms cinder cones, domes of sticky lava, and thicker lava flows. Andesite is also the dominant rock in the towering San

Francisco Mountain volcano. Dacite and rhyolite lavas are rich in silica and very viscous. They extrude from vents as semi-plastic lava domes or short, thick flows.

The extrusive igneous rocks (basalts, andesites, dacites and rhyolites) that make up the 1800-square-mile (4700-square-kilometer) volcanic field rest on or are injected into the older, horizontal sedimentary rock layers that make up this part of the Colorado Plateau (Figure C). Locally, the magma appears to have broken through to the surface at vents aligned along preexisting cracks (fissures), such as the Mesa Butte fault northwest of Flagstaff. In a few areas thick masses of rising magma folded back or domed up the older sedimentary layers. The outpourings of volcanic material altered the river system in this part of northern Arizona. New streams flowed in a radial pattern from volcanic highlands; other drainages, such as the Little Colorado River, were displaced from their channels. The Sunset Crater eruption contributed cinders and ash to the dunes of the region and influenced the settlement patterns of early Native American residents.

The San Francisco volcanic field is one of several volcanic centers (Figure 1.2) along the southern margin of the Colorado Plateau. These massive outpourings of lava resulted when the Earth's crust here was stretched and fractured during the past 25 million years.



Figure 2.1. Aerial photograph of Mount Elden.



## Feature [2]

### Lava Dome: Mount Elden

**Location:** Follow Highway 180 northwest from Flagstaff to mile 217.2. Turn right (east) on Schultz Pass Road and follow it for 0.5 mi (about 800 m). Continue east to the Elden Look-out Road and follow it to the top of Mount Elden.

**M**ount Elden (Figure 2.1), the steep-sided mountain north of Flagstaff, is a 2300 ft-high (700-m) dome of dacite—a volcanic rock intermediate in composition between rhyolite and basalt. It formed about 500,000 to 600,000 years ago as especially viscous, silica-rich lava squeezed up through and upturned older volcanic and sedimentary rocks (Figure 2.2). The lava, too sticky to flow any distance, bulged out as an expanding bubble-like mass of molten rock. The surface of the mass solidified but shattered as more lava was injected into the growing dome from below. Continued cooling and fracturing of the brittle surface mantled the expanding

dome with boulders. In several places the dome broke open, allowing short lobes of lava to ooze out. Overlapping lobes give the south flank of Mount Elden its distinctive shape. Occasionally, when the steep lava flows collapsed, fast-moving avalanches of gas and dacite blocks formed an apron around the base of Mount Elden.

Lava domes form where semi-solid, molten rock that is too viscous to spread out extrudes onto the land surface. The lava that formed Mount Elden cooled to form dacite, but rhyolite and high-silica andesite lavas can also congeal as domes. O'Leary Peak, North Sugarloaf and the Sugarloaf are nearby rhyolite domes.

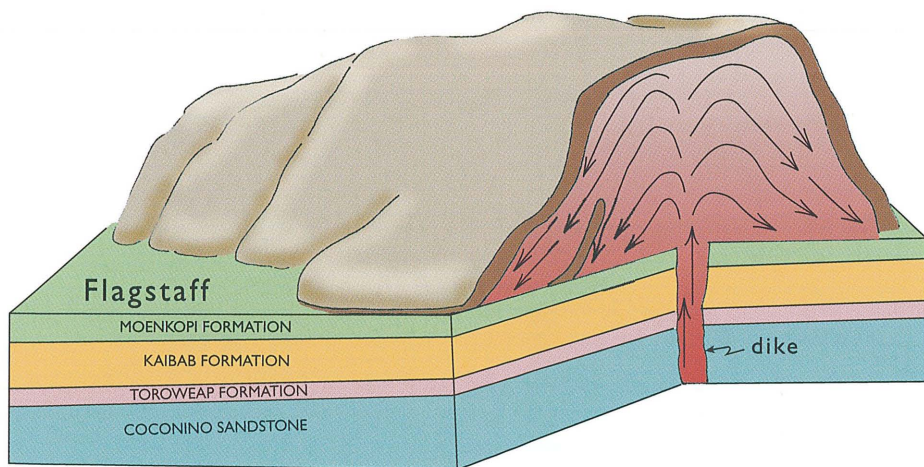


Figure 2.2. The Mount Elden dome formed by the injection of dacitic lava.

# Feature [3]

## Stratovolcano: San Francisco Mountain

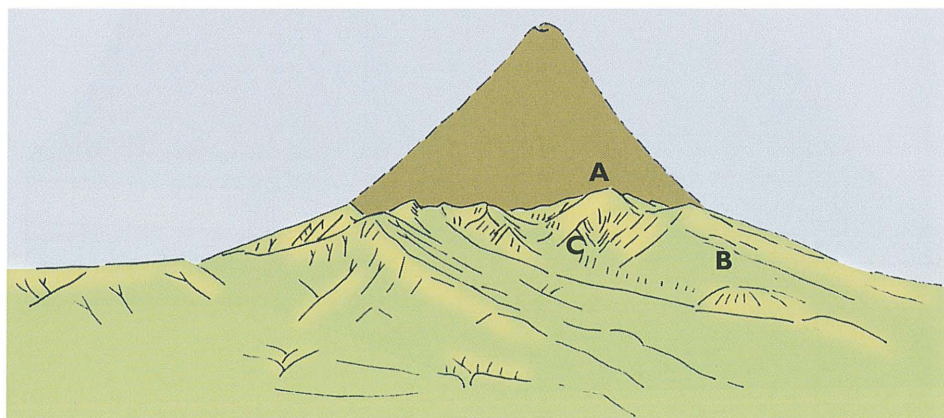
**Location:** Follow Highway 89 north from Flagstaff. At mile 430.4 turn left (west) on Forest Service Access Road. Follow Forest Service Road 420 for 0.5 mi (800 meters) to Forest Service Road 552. Turn right (north) and follow this road for 4.5 mi (7.2 km) to Lockett Meadow Campground (Day Use Area). If you wish to hike to the top of San Francisco Mountain, follow the trail to the high slopes of Fremont Peak (11,969 ft; 3648 m) and Agassiz Peak (12,358 ft; 3767 m).

**S**an Francisco Mountain (Figure 3.1) is a stratovolcano. It is the geological centerpiece of the San Francisco volcanic field. Humphreys Peak, at 12,643 ft (3854 m), is the highest point in Arizona. Unlike most of the other volcanoes of the area, this cone is a combination of cinder and ash layers, lava flows, domes of highly viscous lava, and the rock-filled conduits that once fed molten rock (magma) to the erupting volcano. The erosion-resistant flows and domes gave strength and form to the ash and cinder deposits, and enabled eruptions to build a volcano that may have attained an elevation of 15,500 to 16,000 ft (4725–4877 m). Because the erupting lavas were of different chemical composition, andesite, dacite, and rhyolite rocks

make up San Francisco Mountain (Figures 3.2 and 3.3).

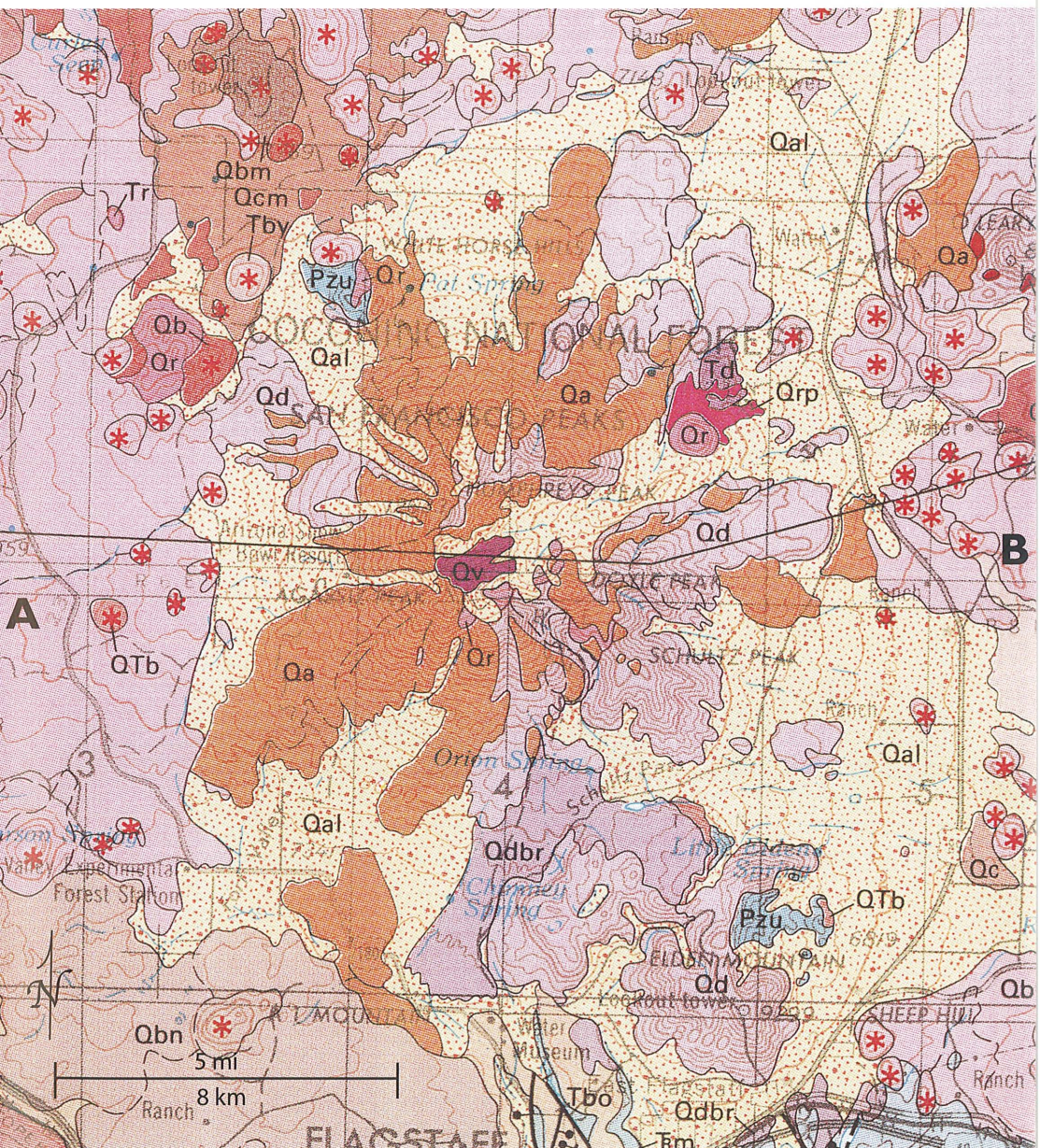
The building of the volcano began about 2.8 million years ago with outpourings of highly viscous lava that cooled to form the dacite rock of the North Sugarloaf and the rhyolite exposed in the Inner Basin. A cone of andesitic cinders and ash grew as the eruptions became more explosive. Continued outpourings of volcanic material eventually produced the towering San Francisco stratovolcano.

The development of the Inner Basin of San Francisco Mountain is poorly understood. This eastern slope of the volcano may have collapsed releasing ash in a Mt. St. Helens-type lateral gas explosion; or it could have been cut by stream erosion. Whatever the cause, the gaping opening in the moun-



**Figure 3.1.** San Francisco Mountain, with dashed lines showing the possible profile of the strato-volcano that may have attained an elevation of 15,500 to 16,000 ft (4725–4877 m). Humphreys Peak [12,643 ft, (3854 m)] A; Sugarloaf B; Inner Basin C.





**Figure 3.2.** Geologic map of San Francisco Mountain. Qal=mainly debris flows; Qv=volcanic vent flows; Qa, Qap, and Qbn=andesite; Qr and Qrp=rhyolite; Qd, Qdbr, and Td=dacite; Qbs, Qbo, Qby, Qc, Qcs, QTb, Tby, and Tbo=basalt; Pzu=Paleozoic sedimentary rocks. Red asterisks are cinder cones (rock units simplified from Ulrich and others, 1984).



tain's flank was later widened and deepened by running water and glacial ice (see Feature 4), producing the beautiful Inner Basin. Eruption ended some 220,000 years ago after the extrusion of the rhyolite lava that built the Sugarloaf at the mouth of the Inner Basin. Nine fan-shaped lobes of rock debris extend out in a radial pattern around the base of the volcano. These debris fans may have accumulated as cinder and ash were shaken loose from the steep slopes of the mountain by eruptions and earthquakes.

Another explanation is that heavy rain and snowmelt could have liquefied this unstable slope material and caused it to fail and flow to the base of the mountain.

San Francisco Mountain is one of the few stratovolcanoes in the Southwest. This type of volcano is most commonly associated with the very explosive eruptions that occur around the rim of the Pacific Ocean in the Andes, Cascades and other magnificent mountain ranges.

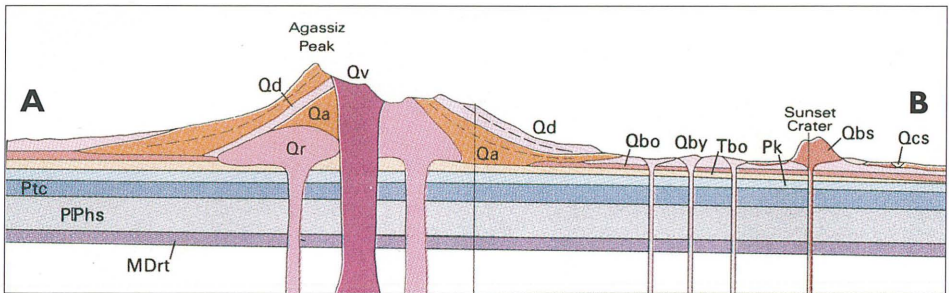


Figure 3.3 East-west cross section of San Francisco Mountain (after Ulrich and others, 1984).

## Feature [4]

### Glacial Features: Cirques, Moraines, and U-shaped Valley

**Location:** Follow the same directions given for Feature 3.

The San Francisco Peaks and Inner Basin derive much of their rugged alpine beauty from glacial erosion during the last 1.8 million years (the Ice Age). The sharp peaks, connecting ridges, high semicircular basins, and the trough-shaped Inner Basin are characteristic landforms produced by moving ice and the freezing and thawing of water in rock cracks.

The high, amphitheater-shaped basins at locations A in Figures 4.1 and 4.2 are *cirques*. Cirques were the birthplaces of mountain glaciers during the cooler, wetter periods of the Ice Age, when the elevation of permanent snow in the San Francisco Peaks was as low as 11,132 ft (3393 m). Cirques originated as high altitude, shallow depressions where thick snow accumulated and compacted to granular ice and then glacial ice. These depressions gradually enlarged as freezing and expansion of meltwater shattered bedrock beneath the ice. Eventually, the ice became thick enough to flow out of the cirques and down preexisting stream valleys.

The San Francisco Peaks experienced three major glaciations. The first (the Lockett Meadow Glaciation) and most extensive occurred sometime between 212,000 and 125,000 years ago. Ice from seven cirques joined to form a glacier more than 650 ft (200 m) thick that flowed down the Inner Basin for 3.9 mi (6.3 km). During the second glacial advance (the Core Ridge Glaciation), which took place about 100,000 years ago, the glacier was about 490 ft (150 m) thick and extended down the Inner Basin only 2.6 mi (4.2 km). Glaciers of the third glaciation (the Snowslide Spring

Glaciation) formed perhaps as recently as 25,000 to 30,000 years ago, reached a thickness of about 210 to 250 ft (about 65 to 75 m), and were mainly limited to the cirques. The longest glacier was only 1.4 mi (2.2 km).

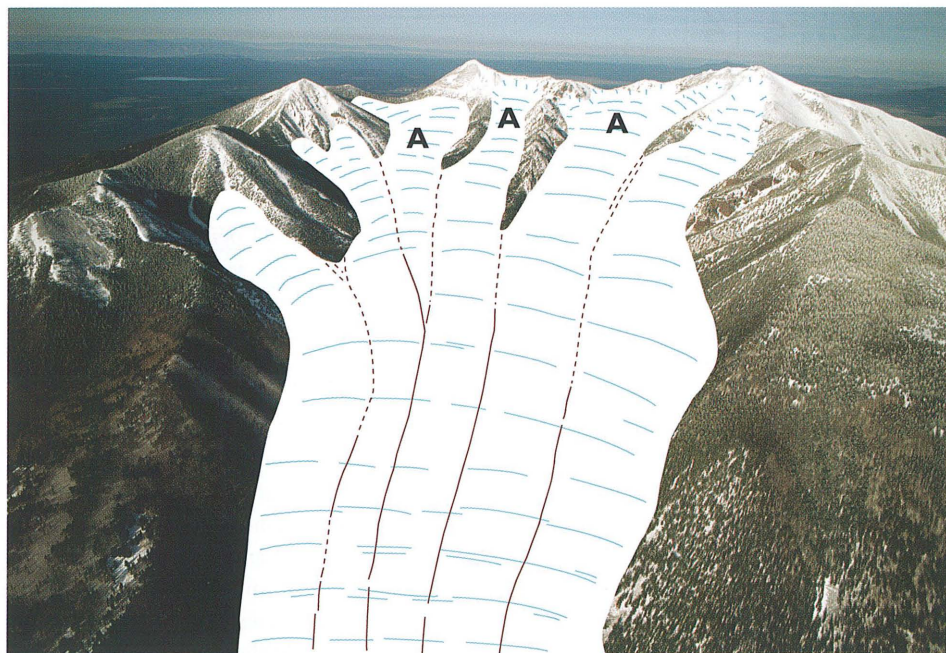
The farthest advance of each of these glaciers is marked by a curved ridge of rock debris called a *moraine* (B, Figure 4.2). Moraines consist of unsorted sediment (boulders, sand, silt, clay) that was pushed ahead of and deposited along the front of the glaciers. The Core Ridge moraines, the highest and most prominent, are accentuated by thick stands of aspen; the Snowslide Spring moraines, subjected to erosion for the shortest period of time, are the best preserved.

These rivers of ice were mighty agents of erosion that modified the landscape. Rock fragments frozen into the bottoms and sides of the glaciers scraped and scoured the narrow, pre-existing stream valley into today's broad Inner Basin. Rock shattering by ice in bedrock cracks and erosion by several smaller glaciers near the mountain's summit sharpened high peaks and ridges, giving the San Francisco Peaks their angular alpine form. The thick, porous and permeable glacial deposits of the Inner Basin are important sources of water for the city of Flagstaff.

Glaciers formed at only one other place in Arizona: on Mount Baldy in the White Mountains of eastern Arizona.

Ice Age glaciers modified much of Earth's landscape. Glaciations are the product of global climatic changes that dramatically impacted landscapes and plant and animal populations.





**Figure 4.1.** Oblique aerial view of the Inner Basin of San Francisco Mountain as it may have looked when occupied by Ice Age glaciers (photograph by Michael Collier).



**Figure 4.2.** Cirques (A), moraines (B), and the u-shaped Inner Basin (C) of San Francisco Mountain (photograph by Michael Collier).



## Feature [5]

### Young Cinder Cones and Lava Flows: Sunset and SP Craters

**Locations:** To visit Sunset Crater National Monument follow Highway 89 north from Flagstaff. At mile 430.4 turn right (east) on the Sunset Crater-Wupatki loop road and follow it for 3.3 mi (5.3 km). Park in the parking lot and follow the trail to the edge of the lava flow on the left (north) side of the road. For an elevated view of Sunset Crater, the Bonito lava flow, and the surrounding landscape follow the crosswalk across the road and take the 0.50 mi (0.8 km) hike to Lenox Crater. (There is a fee to enter Sunset Crater Volcano National Monument.)

To visit SP Crater drive north from Flagstaff on Highway 89 to mile 445.9 (about 100 yards before Hanks Trading Post). Turn left (west) on Babbitt Ranches Road and continue for 0.6 mi (1.0 km) to a fork in the road. Take the left fork and drive for 2.8 mi (4.5 km) to a second fork. Take the right fork and drive for 1.4 mi (2.4 km) to a third fork. Take the right fork, continue past a water tank for 1.1 mi (1.8 km) to a fourth fork. Take the right fork, drive for 0.1 mi (160 m), and park. Hike the road around the west side of SP Crater for a view of the lava flow (Figures 5.2, 5.5, and 5.6).

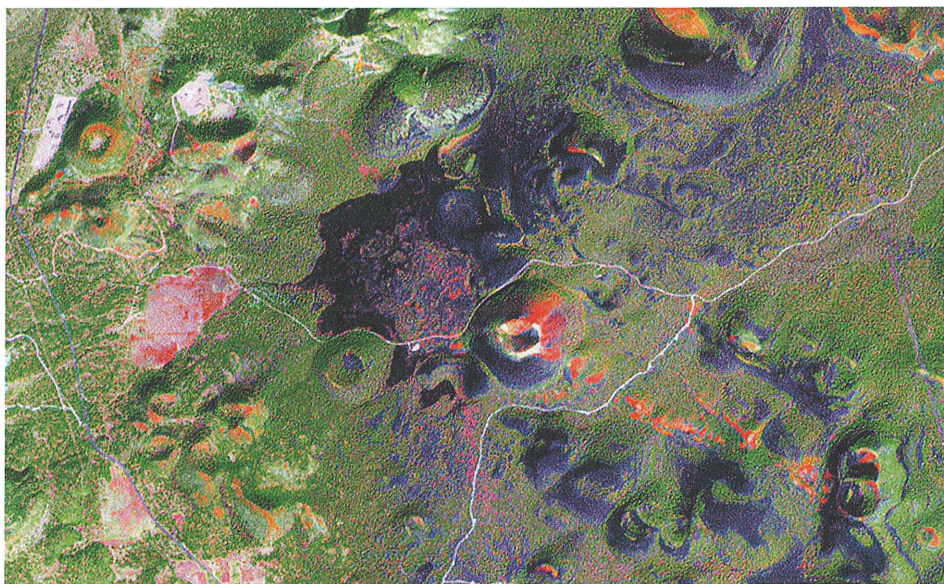


Figure 5.1. Satellite image of Sunset Crater and the Bonito lava flow area.

Volcanic activity in this part of the San Francisco volcanic field is geologically very recent. Sunset and SP Craters and their associated lava flows (Figures 5.1 and 5.2), for example, have not been significantly altered by weather-

ing and erosion and appear as if they formed yesterday. Examination of these cinder cones and their flows reveals that even volcanic features that are similar in appearance can have different eruptive histories.



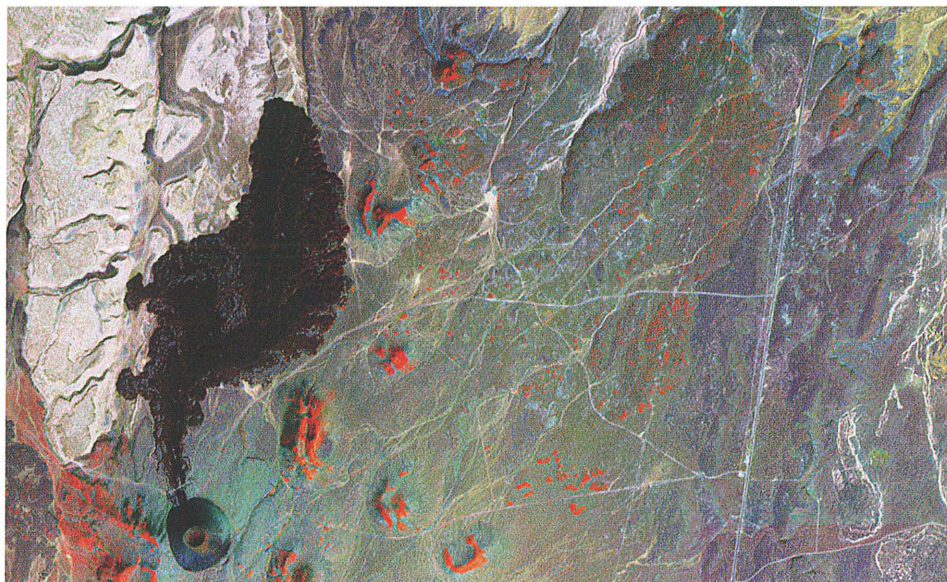


Figure 5.2. Satellite image of SP Crater and associated lava flow.

Sunset Crater (Figure 5.3), the youngest of the cinder cones in the volcanic field, was born of a violent eruption that began about 1000 years ago. Molten rock, called magma, surged from great depth and under intense pressure toward the surface along a 6.2-mi-long (10-km-long) fracture in the Earth's crust. The basaltic magma was very rich in explosive gases. As the fluid rose toward the surface, pressure decreased and dissolved gases came out of solution, producing a froth of suspended magma droplets. This mixture exploded from vents along the fracture as clouds of ash and cinder. Eruptions blanketed an area of 800 square mi (2100 square km) with this material and built cone-shaped Sunset Crater around one of these vents.

This mountain of cinders and ash rises about 1000 ft (300 m) above the surrounding country and is 1 mi (1.6 km) wide at the base. The central crater is 400 ft (120 m) deep and holds a smaller crater that is 160 ft (50 m) deep. The iron oxides from mineral-rich steam and gas vents give the dis-

tinctive orange-red tint to the crater rim and the name to the mountain.

The Bonito flow (Figure 5.4) formed from lava that emerged from the western margin of Sunset Crater as that cone was being built. This type of lava, called pahoehoe, has a smooth, ropy surface that can be crossed easily on foot. As the lava advanced from its vent it quickly lost gas and became more sticky. Along the margins of the cooling flows the lava was transformed to the rough, jagged, clinker type of lava known as *aa*.

The surface of the Bonito flow is broken by long, gaping cracks. These fissures may have opened due to the frictional drag of the fluid lava below. Cracks can also form when lava drains away and the weak overlying crust collapses. Curved wedges of plastic lava extruded through these fissures to form squeeze-ups (see Feature 6). Sprays of lava propelled by escaping gases built cones of spattered molten rock, called hornitos, along the surface of the flow. Cinders and ash from the continuing eruption of Sunset





Figure 5.3. Sunset Crater. Cinder dunes (A) in lower right.



Figure 5.4. Bonito lava flow

Crater mantle much of the flow. The Bonito flow may be more than 100 ft (30 m) thick in its center, where it filled a small basin between cinder cones. The flow thins to less than 6 ft (2 m) along its margins. The flow is less extensive than most flows in the San Francisco volcanic field, covering only 1.79 square mi (4.64 square km).

SP Crater (Figures 5.5 and 5.6) is the product of andesitic magma that erupted about 70,000 to 75,000 years ago. The cone is built mainly of pea-sized fragments of

ejected volcanic rock, called lapilli, and large volcanic bombs. The bombs were blobs of molten rock blown from a lava lake that ponded in the crater during the later stages of the cone's formation. Football-shaped bombs were molded by rotation during flight through the air prior to cooling and impact. Ribbon bombs formed from strings of lava. SP Crater contains little volcanic ash, because ash is most commonly associated with explosive eruptions—such as those that built Sunset Crater.

The cone is approximately 700 ft (213 m) high and 1400 ft (428 m) in diameter at its base. The crater is 150–200 ft (46–61 m) deep and its rim is well preserved by an erosion-resistant ring of fused volcanic material.

The 4.5-mi-long (7.2-km-long) lava flow in Figure 5.2 emerged from a vent at the base of the cone. Unlike the pahoehoe and aa lavas of the Bonito flow, this flow is composed of curved ridges of polyhedral andesite blocks (Figure 5.6). The lava lost





Figure 5.5. Aerial photo of SP Crater and lava flow.



Figure 5.6. SP flow. Photo by John V. Bezy.

gases and became increasingly thicker and viscous with distance from the vent, reaching a maximum thickness of 200 ft (61 m) at the northern end of the flow. Two tongues of lava poured into a faulted depression (called a graben; see Feature 12) to the west of the main flow.

The lava flows at Sunset and SP Craters formed during the later stages of cinder cone development. As the magma lost volatile gases, the lava oozed through

the cinder piles and flowed from the base of the cones. The flowing lava tore loose and rafted away huge chunks of the cinder cones.

The differences in the chemical composition of magmas are even more dramatic on a world scale. Magmas having lower proportions of silica are fluid and contain less explosive gases. The relatively quiet eruptions of these magmas have produced the basalts of the ocean floors and the shield-shaped volcanoes of Iceland and the Hawaiian Islands. Explosive eruptions of silica-rich, viscous magmas have constructed stratovolcanoes, such as Mount St. Helens, Mayon, and Fuji, that ring the Pacific Ocean.

Caution! Hiking on the lava flow can be hazardous. Rock surfaces are unstable and sharp. Falling into a fissure can result in severe injury or death. Hike with caution and only in areas that are open to visitors. Sunset Crater Volcano is closed to hiking.



# Feature [6]

## Squeeze-up: Bonito Flow

**Location:** Follow the directions given for Sunset Crater in Feature 5 to visit the Bonito lava flow.



Figure 6.1. Squeeze-up on the Bonito lava flow.

**T**he knife-like ridge (Figure 6.1) protruding above the surface of the Bonito lava flow is called a squeeze-up. As the surface of the lava flow cooled it crusted over very rapidly. This crust was cracked and buckled into pressure ridges by the frictional drag of the moving lava below. Wedges of partially cooled, plastic lava extruded through several of these cracks and solidified forming squeeze-ups. The faces of the still molten

squeeze-ups were striated and grooved as they squeezed through the cracks in the lava crust.

Squeeze-ups are most common where lava flows have been slowed or partially dammed, forcing pressurized lava to break through cracks in the surface crust.

To learn more about small scale volcanic features of the Bonito lava flow, drive to the next parking lot and walk the Lava Flow Trail.

## Feature [7]

### Cinder Dunes and Ventifacts

**Location:** Follow Highway 89 north from Flagstaff to mile 430.4. Turn right (east) on the Sunset Crater-Wupatki loop road and drive for 12.2 mi (19.6 km). Turn right (south) on an unnumbered dirt road with a cattle guard; drive about 300 yd (about 300 m). Park and walk east for 200 yd (about 200 m) across a wash to the top of a low, rocky ridge.

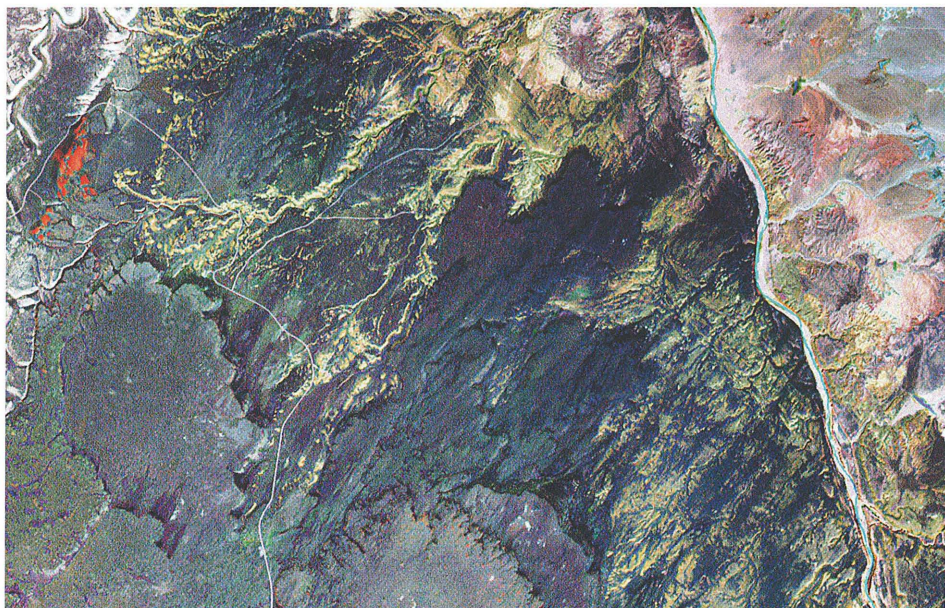


Figure 7.1. Satellite image of windblown cinders and dunes, Wupatki National Monument area.

Wind erosion and deposition have played roles in shaping this landscape. The black, northeast-trending pattern in Figure 7.1 consists of windblown cinder and ash dunes. Sporadic eruptions of Sunset Crater about 1000 years ago were the sources of the cinder and ash. Carried by the wind, this fine material once blanketed an area of 800 square mi (2100 square km) to the north, east, and south of Sunset Crater. Rains and strong southwesterly winds have reduced the ash and cinder cover to an area of 122 square mi (315 square km).

The slopes of the ridge that you are walking across are covered with fine ash

and cinder fragments drifted by the prevailing winds from the drainage and dunes to the southwest. Examine the basalt rock outcrops that project above the wind-drifted material. They are polished, fluted, and have sharp edges cut by natural sandblasting (Figure 7.2). Many of the round gas holes (vesicles) common in basalts have been enlarged in the downwind direction to form elongated grooves. These ventifacts, as wind abraded rocks are called, appear to have been cut in the past (some perhaps before the eruption of Sunset Crater) because rock varnish (a clayey, iron-manganese rind that takes hundreds of years to form) has developed on their surfaces.





Figure 7.2. Wind-cut rock outcrop near Wupatki National Monument.

Ventifacts illustrate the cutting power of wind-driven sand in semi-arid lands. Ventifacts, together with dune fields, wind-grooved cliffs, fluted bedrock, sand sheets, and expanses of desert pavement,

make up a wind-modified landscape that encompasses most of northeastern Arizona and the adjacent parts of southeastern Utah, southwestern Colorado, and northwestern New Mexico.



## Feature [8]

### Moenkopi Formation: Wupatki National Monument

**Location:** Drive north on Highway 89 from Flagstaff to mile 430.4. Turn right (east) on the Sunset Crater-Wupatki loop road and drive for 21.1 mi (34 km) to the Wupatki National Monument visitor center. Walk the trail to Wupatki Pueblo. An entrance fee is charged in the visitor center.



Figure 8.1. Sandstone with ripple marks, Wupatki National Monument.

The reddish layers of sandstone, siltstone and shale in this area (Figure 8.1) comprise the Moenkopi Formation. These soft layers erode easily, producing a landscape of rounded slopes and low ledges. Much of the formation has been stripped away by erosion and is best preserved where protected by lava flows.

The Moenkopi Formation was deposited more than 240 million years ago, during the Triassic Period, when this part of the continent was a broad, flat coastal plain. The climate was probably arid. Rivers flowing across the coastal plain deposited sand, silt, clay, and during floods, pebbles. Scant fossils found include those of

amphibians and reptiles. At times a shallow sea advanced over the plain and added deposits of mud and fine sand similar to those found in today's tidal environments. Over time, minerals from groundwater cemented the sediment particles together to form layers of sandstone, siltstone, and claystone. Small quantities of iron in the sediment oxidized ("rusted"), giving the formation its reddish hue.

Sandstone layers of the Moenkopi break along bedding planes to form the flat slabs that were preferred by the early Indians for building the structures preserved at Wupatki National Monument.

# Feature [9]

## Blowhole: Wupatki National Monument

**Location:** Use the directions for Feature 8 to find the Wupatki National Monument visitor center. Walk the interpretive trail past Wupatki Pueblo to visit the blowhole.

This small opening in the bedrock (screened for safety) is one of several dozen blowholes in the Flagstaff-Wupatki area. They have been explored to a depth of 500 ft (152 m) and are part of an extensive, interconnected system of cracks, small caves, and crevices in the Kaibab Limestone and Coconino Sandstone (Figure 9.1). This underground system may extend for several hundred miles and has an estimated volume of 7.2 billion cubic ft (5.50 billion cubic m).

The openings are called blowholes because they take in and discharge large quantities of air in response to temperature and atmospheric pressure changes at the surface. When surface air temperature is cool and atmospheric pressure is high, air flows into the blowhole system; on warm days with low pressure, air blows out in a cool, refreshing breeze. Place a dollar bill on the blowhole screen to test the airflow.

The origin of the blowhole system is complex. Some of the openings are in zones of bedrock shattered by fault movement.

Other blowholes occur where the roof of a small cave in the Kaibab Limestone has collapsed (see Feature 10). Blowholes and the labyrinth of natural crevices are probably due to widening of natural cracks (joints) in the Kaibab Limestone and Coconino Sandstone by groundwater dissolving calcium carbonate in the rock. This occurred at a time when the groundwater level was higher than its present depth of 1300 ft (396 m).

Blowholes and the underlying system of natural crevices that extend for hundreds of feet below the surface are testimony to the effectiveness of percolating groundwater in dissolving openings along cracks in carbonate rocks, such as limestone and dolomite. Some of Earth's great cavern systems have been developed in this way.

Bones of extinct species of Ice Age camels, horses, and hyenas were found in one blowhole. Today, blowholes are occupied by woodrats and porcupines and are important roosts for bats.

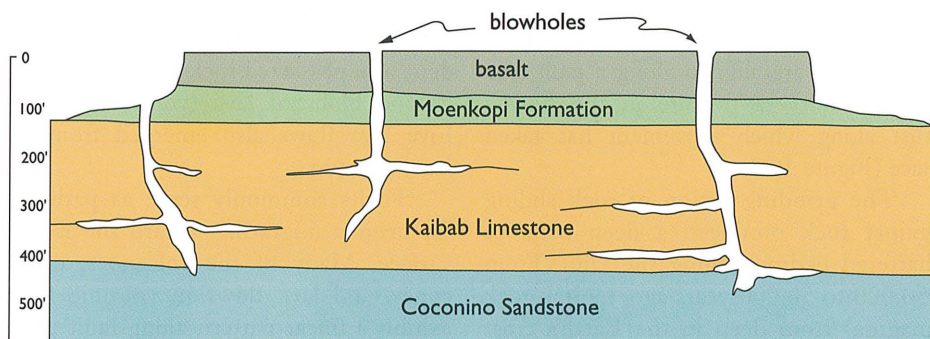


Figure 9.1. Cross sectional diagram of blowhole system.



## Feature [10]

### Fault-aligned Cinder Cones: Wupatki National Monument

**Location:** Follow Highway 89 north from Flagstaff to mile 430.4. Turn right (east) on the Sunset Crater-Wupatki loop road and drive for 25.5 mi (41 km) to the Doney Picnic Area. Walk the trail to the top of the cinder cone (0.1 mi; about 175 m).



Figure 10.1. Doney Crater with a volcanic bomb in foreground.

**D**oney Mountain (Figure 10.1) and the three other dark brown hills to the southwest are volcanic cinder cones. They are aligned along a fault (the Doney Fault)—a fracture in the Earth's crust along which movement has taken place (Figure 10.2).

The grinding action of rock sliding against rock produced a deep zone of shattered bedrock along the fault. From 150,000 to 50,000 years ago, molten rock (magma) from deep in the Earth's crust migrated upward along this zone of bro-

ken rock and exploded onto the surface. Successive eruptions along this part of the fault built a line of elongated cones of cinders, ash, pea-sized rock fragments (lapilli) and blobs of lava (volcanic bombs). Five lava flows also emerged from the fracture zone.

Faults commonly serve as pathways for magma migrating toward the Earth's surface. Many of the volcanoes, cinder cones, and lava flows in volcanic fields exhibit a linear pattern along fault zones that extend for dozens of miles.

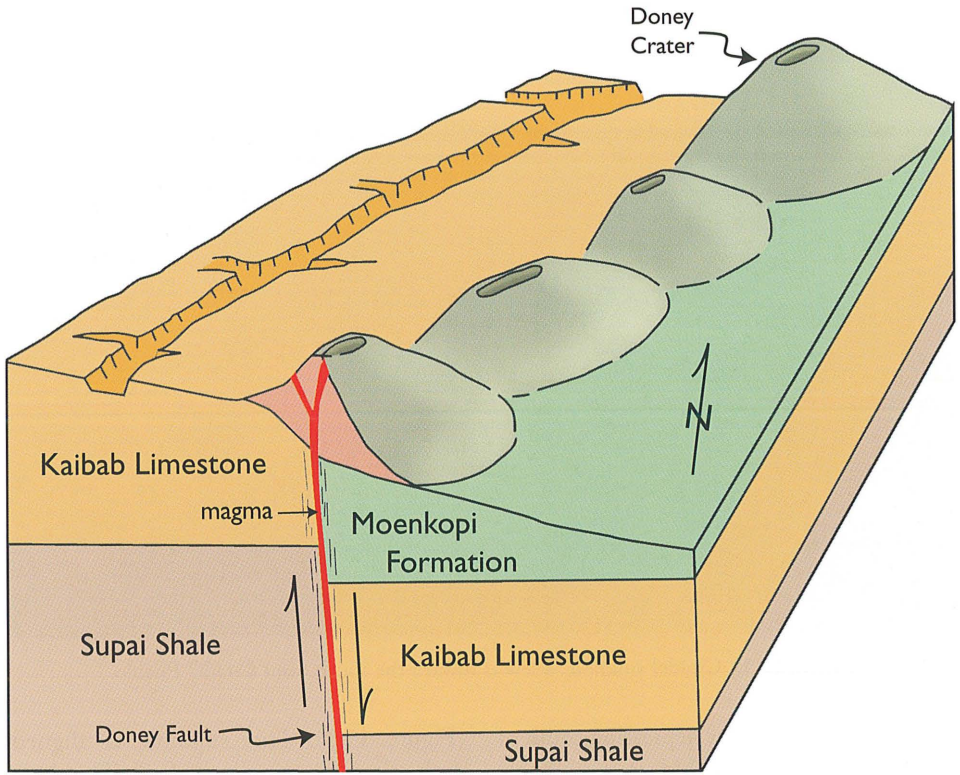


Figure 10.2. Block diagram of Doney Fault and Doney Crater.



# Feature [ I I ]

## Sinkhole: Wupatki National Monument

**Location:** Follow Highway 89 north from Flagstaff to mile 430.4. Turn right (east) on the Sunset Crater-Wupatki loop road and drive for 31.2 mi (50 km) to the Citadel Pueblo parking lot. Park and walk the trail to the Citadel Pueblo to view the sinkhole. Please stay on the trail.

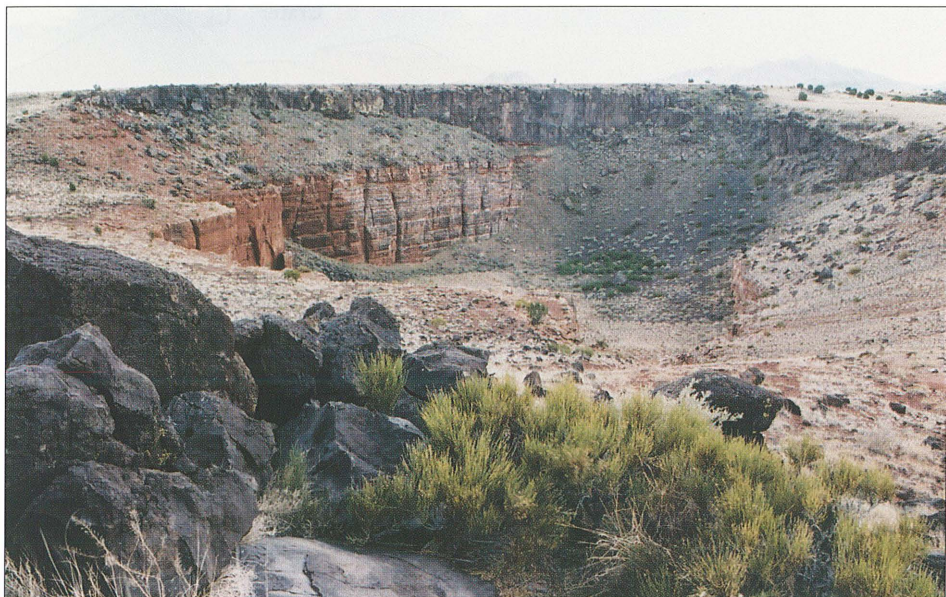


Figure 11.1. Citadel sinkhole. View is toward the south from Citadel Pueblo.

The large, circular depression south of the Citadel Pueblo is a sinkhole (Figure 11.1). It is about 800 ft (244 m) across and 173 ft (53m) deep. The sinkhole is developed in the Kaibab Limestone, which underlies the dark-colored basalt.

After lava flows cooled to form the basalt surface rock, downward-moving groundwater dissolved a cave in the underlying Kaibab Limestone. The thin-bedded limestone is not strong enough to support a cave roof of great width. When the cave grew beyond the supportive strength of the limestone its roof collapsed, forming a sinkhole that is partially filled with limestone and basalt boulders

(Figure 11.2). This sinkhole is aligned with others along a nearby fault. The shattered rock of the fault zone may have increased the flow of groundwater that dissolved the caves in the limestone.

Sinkholes are common features in landscapes produced by the dissolving action of groundwater on limestone, dolomite, or marble. Where sinkholes extend below the water table they hold small lakes or bogs. The sinkholes of the Flagstaff area are far above the current water table and are vestiges of a time when precipitation was greater and groundwater more plentiful.



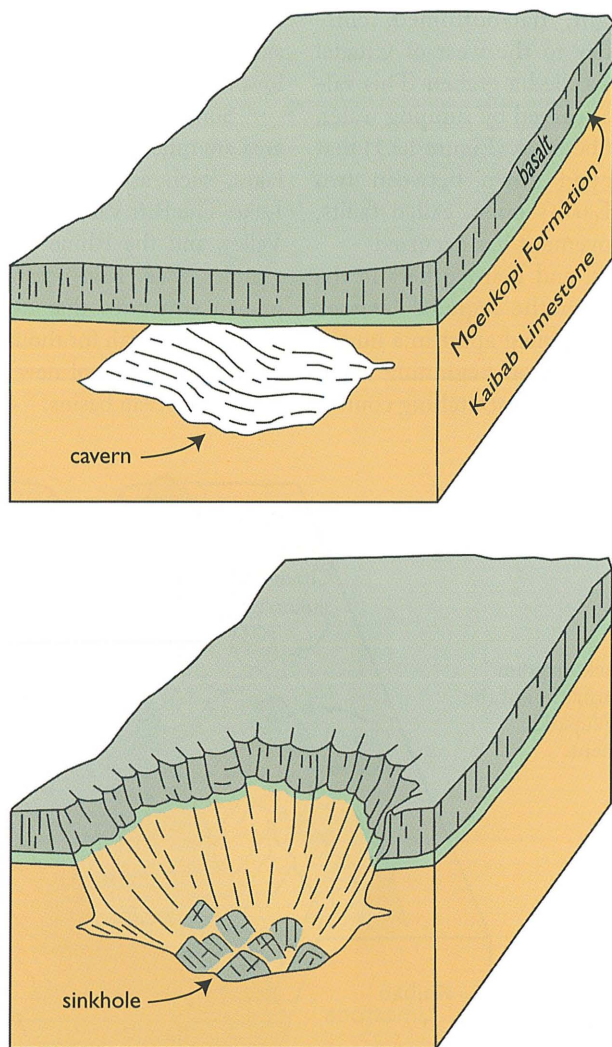


Figure 11.2. Block diagrams illustrating the formation of the Citadel sinkhole.

# Feature [12]

## Graben: Wupatki National Monument

**Location:** Follow Highway 89 north from Flagstaff to mile 430.4. Turn right (east) on the Sunset Crater-Wupatki loop road and drive for 31.2 mi (50 km) to the Citadel Pueblo parking lot. Park and hike to the Citadel Pueblo for the best view of the graben. Please stay on the trail.

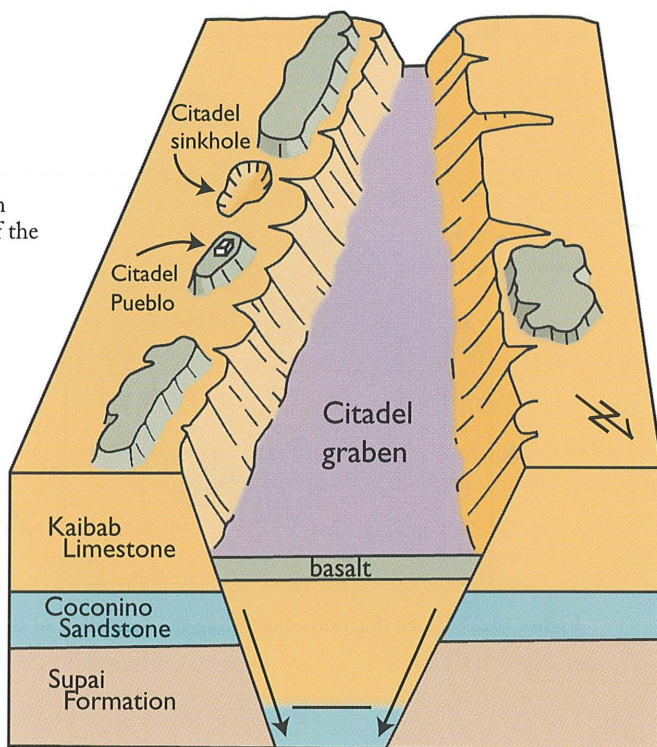
The straight, flat-bottomed, cliff-lined valley to the west of Citadel Pueblo is called a graben. This valley floor was not carved by running water, but is a block of bedrock (Figure 12.1) that has been dropped down between two breaks in the Earth's crust, called faults, along which movement has occurred.

These faults, and many others in the area, opened when the regional bedrock was stretched and pulled apart in a north-east-southwest direction beginning about 25 million years ago. As stretching contin-

ued the blocks of rock between the faults subsided due to gravity, forming the shallow, trench-like grabens.

Some grabens south of the Flagstaff area are miles in length and contain shallow lakes, such as Lake Mary and Mormon Lake. The Rift Valleys of East Africa, Death Valley, and the Rhine Graben are of even grander scale. Mid-oceanic rift valleys are graben structures that extend like a seam around the Earth for thousands of miles and are the birthplace of new igneous rock that floors the ocean basins.

Figure 12.1. Block diagram illustrating the formation of the Citadel graben, Wupatki National Monument.





## Feature [13]

### Folding: Black Point Monocline

**Location:** Drive north on Highway 89 from Flagstaff to mile 450.7. Turn right (east) on Babbitt Ranch Road, drive through two pipe gates at Spider Camp, and continue for about 9 mi (14.5 km) to the edge of the mesa to view the Black Point Monocline.



Figure 13.1. Satellite image of the Black Point monocline.

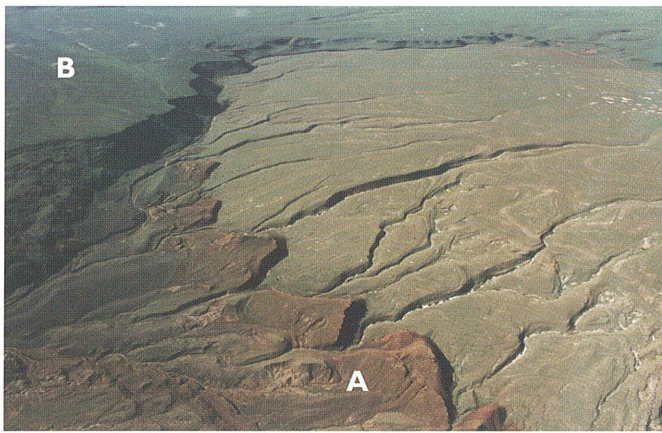
The steeply tilted rock layers at point A in Figures 13.1 and 13.2 are part of a huge fold in the Earth's crust, called a monocline. The buff-colored Kaibab Limestone and the overlying, burgundy-hued Moenkopi Formation were deposited as horizontal strata, but were arched up as the monocline formed. The Moenkopi beds that are the surface rocks in the lowland to the northeast (lower left part of Figure 13.2 once continued up and over the Kaibab Limestone on the plateau to the southwest (upper right part of Figure 13.2).

Below the Kaibab Limestone and the Moenkopi Formation, the Precambrian

rocks of the original continent are broken by a steep fracture or fault that is more than 200 million years old (Figure 13.3). Between 90 and 50 million years ago horizontal compressive forces within the crust of western North America caused vertical movement along this fault. The Precambrian rock southwest of the fault was uplifted relative to the rock northeast of the fault, folding the overlying sedimentary layers into the Black Point monocline. The monocline is broken by younger faults and to the south joins the Doney Hill fault (see Feature 11).

When the Black Point monocline formed, the Kaibab Limestone and the



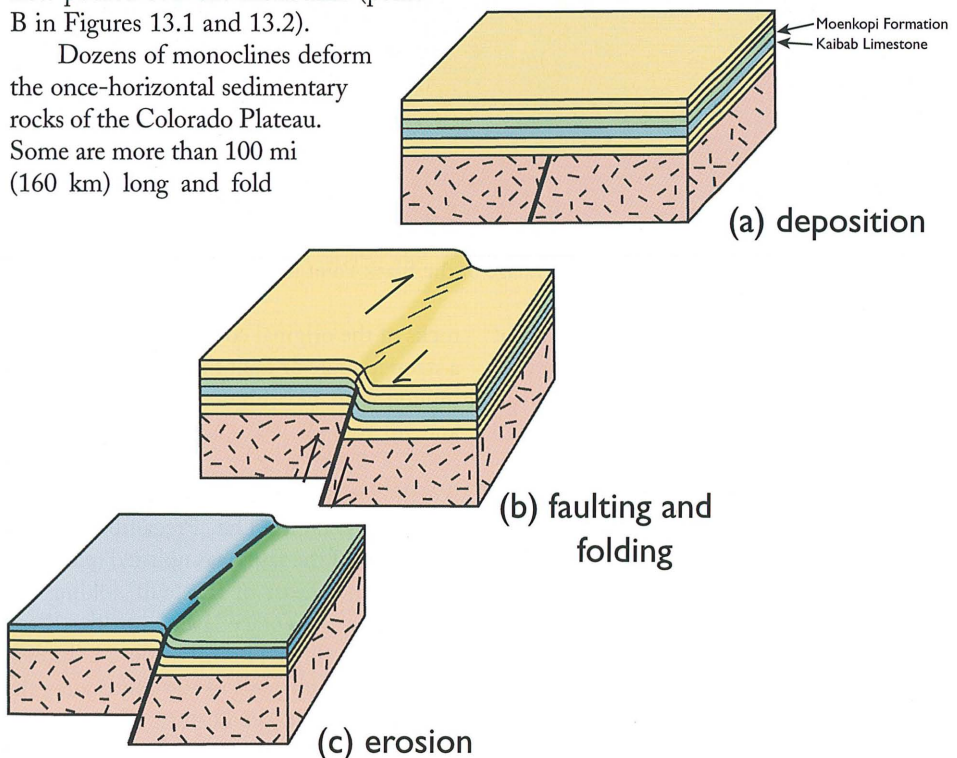


**Figure 13.2.** Oblique aerial view of the Black Point monocline (looking south-southeast).

Moenkopi Formation were buried beneath hundreds of feet of younger sedimentary rocks. These layers and most of the Moenkopi Formation have been stripped from the monocline by erosion. About 2 million years ago the Black Point lava flow poured over the monocline (point B in Figures 13.1 and 13.2).

Dozens of monoclines deform the once-horizontal sedimentary rocks of the Colorado Plateau. Some are more than 100 mi (160 km) long and fold

layers of rock that are thousands of ft (m) thick. Monoclines in northern Arizona, such as the East Kaibab monocline northwest of Wupatki National Monument, bound broad plateaus.



**Figure 13.3.** Block diagram illustrating the formation of the Black Point monocline.

## Feature [14]

### Entrenched Meanders: Walnut Canyon National Monument

**Location:** Drive east from Flagstaff on Interstate Highway 40 to exit 204 and follow the access road to the Walnut Canyon National Monument visitor center. Walk the Rim Trail to the overlook into the canyon. There is an admission fee at Walnut Canyon National Monument.



Figure 14.1. Aerial photograph of Walnut Canyon.

The deep, sinuous bends in the course of Walnut Canyon (Figure 14.1) are entrenched meanders. Diablo, Clear Creek and Chevelon Canyons to the south-east have a similar form. These entrenched meanders preserve the flow pattern of ancient rivers that rose in high mountains in what is now central and southern Arizona and flowed across a gently sloping plain in this area. Before cutting their canyons, these rivers swung in broad loops, called meanders (Figure 14.2, A), across their floodplains—as does the present lower Mississippi River.

At some point, probably during the later part of the Tertiary period (2 to 25 million years ago), these rivers were no longer able to maintain their floodplains and started eroding their beds, due to complex changes in stream bed slope and the quantity of sediment and flowing water. The rivers maintained their original meandering courses as they cut deeper and deeper into the Kaibab Limestone, eventually carving canyons containing deeply entrenched meanders. Walnut Creek continued to erode through the



Kaibab Limestone and Toroweap Formation and into the underlying Coconino Sandstone (Figure 14.2, B), reaching its current depth of 400 ft (123 m) below the Walnut Canyon visitor center (Figure 14.3). The canyons that are tributaries to Walnut Canyon are straight because they were cut along natural cracks (joints and faults) in the Kaibab Limestone that caps the plateau. Given enough time, Walnut Creek and its

neighboring streams will reduce the landscape to a gently sloping plain and will again meander along broad floodplains.

Entrenched meanders are common on the Colorado Plateau, where meandering streams have downcut their channels into underlying sediments and, eventually, bedrock. Entrenched meanders can also be seen at Goosenecks State Park and Natural Bridges National Monument in Utah, and in the Grand Canyon.

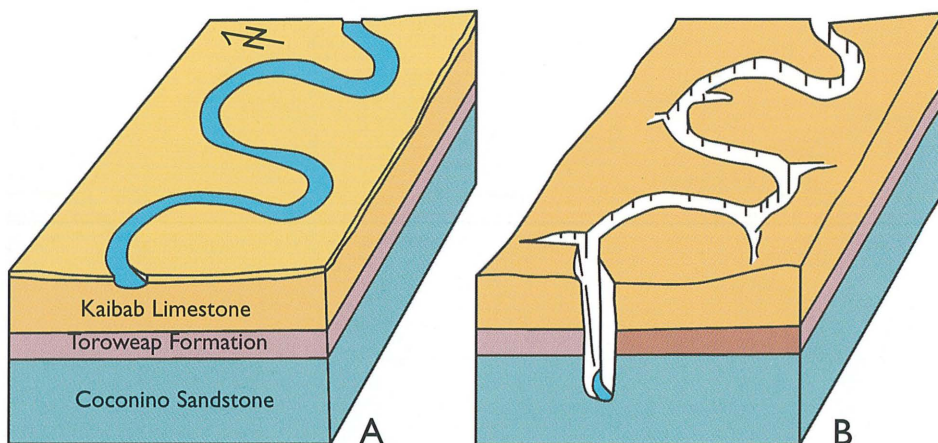


Figure 14.2. Block diagrams illustrating the development of entrenched meanders.

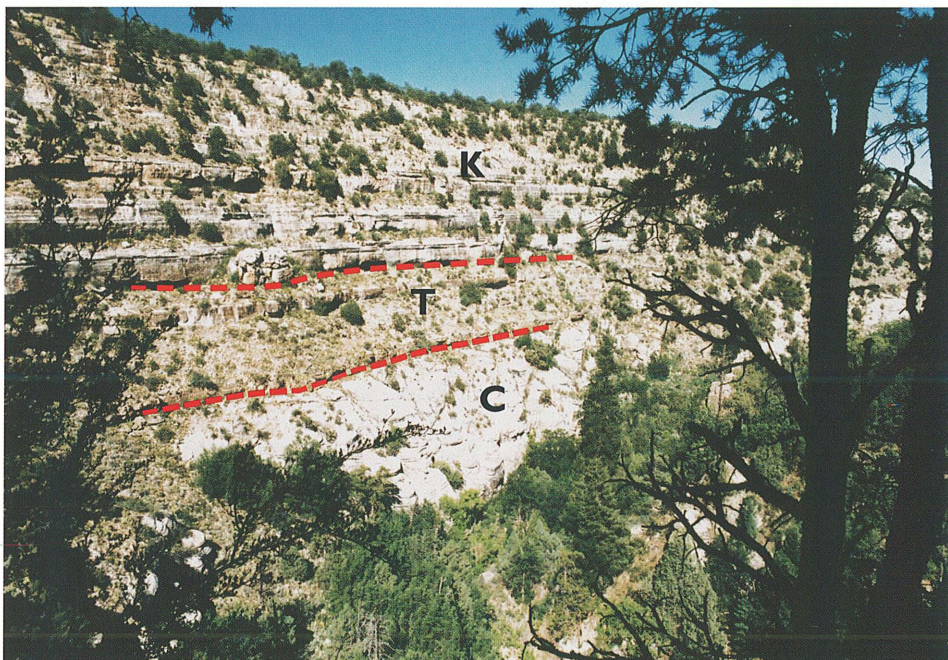


Figure 14.3. Walnut Canyon.

## Feature [15]

### Kaibab Formation: Walnut Canyon National Monument

**Location:** Drive Interstate Highway 40 east from Flagstaff to exit 204 and follow the access road to the Walnut Canyon National Monument visitor center. Walk the Island Trail 150 yd (about 150 m) to see this feature. There is an admission fee to Walnut Canyon National Monument.



**Figure 15.** The Kaibab Formation (K) at Walnut Canyon. The Toroweap Formation (T) and the Coconino Sandstone (C) are beneath the Kaibab Formation.

**T**he buff-colored rock that forms the plateau surface at Walnut Canyon and underlies most of the San Francisco volcanic field is the Kaibab Formation (Figure 15.1 K). This rock unit consists of silty limestone and dolomite, and siltstone and sandstone cemented by calcium carbonate. Limestone and dolomite are carbonate rocks that are composed of calcium carbonate and calcium-magnesium carbonate, respectively. The erosion-resistant limestone and dolomite form massive cliffs; the less resistant siltstone and sandstone weather and erode back into recesses that shelter

the cliff dwellings of early Indian residents of Walnut Canyon. Red and white chert nodules (a form of silica consisting of minute crystals) are common throughout the formation. Fossils of brachiopods, cephalopods, and sponges are abundant in the limestone and dolomite.

The Kaibab Formation, and the underlying, reddish-colored Toroweap Formation (T) were deposited in shallow seas and on arid coastal plains about 250 million years ago. The sea advanced and retreated across the plain a number of times. The limestone in the Kaibab formed in shallow seawater;





Figure 15.2. Solution pits on a limestone rock surface, Wupatki National Monument. Pencil for scale.

the dolomite precipitated from calm, shallow seawater; silty and sandy dolomites originated along the shore and in mud flats; sandstone and siltstone were deposited on the coastal plains by streams. Some of the sandstone in the Kaibab Formation may also have been beach sand and dune sand.

The Kaibab and Toroweap formations form sheer canyon walls and the resistant

caprock on high plateaus in this part of Arizona. Mildly acidic ground water has dissolved small caves and an extensive system of crevasses (see Feature 9) in the carbonate rocks of the Kaibab Formation near Flagstaff. Note the deep pits dissolved in Kaibab limestone by rainwater and snowmelt (Figure 15.2).



## Feature [16]

### Coconino Sandstone: Walnut Canyon National Monument

**Location:** Drive Interstate Highway 40 east from Flagstaff to exit 204 and follow the access road to the Walnut Canyon National Monument visitor center. Walk the entire Island Trail to properly view this feature. There is an admission fee at Walnut Canyon National Monument.

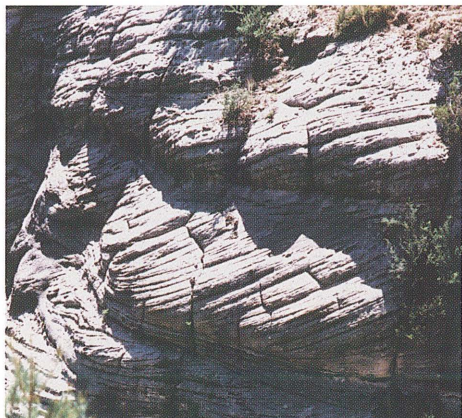


Figure 16.1. Cross bedding in Coconino Sandstone in Walnut Canyon.

The thick, cream-colored rock layer below the tan Kaibab Formation and the reddish Toroweap Formation in these canyon walls is the Coconino Sandstone (Figure 16.1). This sandstone is composed of curving beds that lie at a great variety of angles. Many beds curve in long, parallel arcs that are cut off by sets of similar layers lying at different angles. This complex layering, called cross-bedding, is the interior structure of ancient sand dunes.

Extreme aridity and abundant sand during Permian time (about 265 million years ago) permitted strong winds to accumulate massive sand dunes, similar perhaps to those in the great sand seas of the Sahara Desert and Saudi Arabia. As dunes migrate, sand is removed from the windward side, blown over the crest, to slide down the leeward slope—forming inclined layers. When dunes merge and shift, their

interior structures are superposed, producing a patchwork of cross strata oriented in a variety of directions.

The individual grains of quartz sand that make up the Coconino Sandstone are well rounded, of uniform size, and have surfaces that are pitted by innumerable collisions with other sand grains. These are typical characteristics of sand particles that have been transported by the wind. Over time, the grains were cemented together by calcium carbonate and silica carried by percolating groundwater, and the dunes were hardened into sandstone.

Evidence of life in these Permian dunes is limited to fossil footprints of insects, scorpions and reptiles. Fossil plants have not been found.

The Coconino Sandstone extends for about 32,000 square miles (about 8290 square kilometers) in northern Arizona and southern Utah. It forms vertical cliffs where it is exposed in the walls of the Grand Canyon, Oak Creek Canyon and many smaller gorges. The open spaces between the individual sand grains of the Coconino Sandstone make it a major source of groundwater.

The Navajo Sandstone of Zion National Park, the Entrada Sandstone of Arches National Park, the DeChelly Sandstone (an equivalent of the Coconino Sandstone) of Canyon de Chelly, and the Wingate Sandstone of Canyonlands National Park are other eolian or wind-deposited sandstones that add grandeur to the Colorado Plateau.



## Feature [17]

### Stream Displaced by a Lava Flow: Grand Falls

**Location:** Drive north from Flagstaff on Highway 89 and turn east on the Townsend-Winona Road. Follow that road 8 mi (13 km) to Navajo Nation Road 70 (at the sign for the Grand Falls Bible Church). Drive Navajo Nation Road 70 for 9 mi (14.5 km) to Black Falls. The road to Grand Falls may be impassable in wet weather; inquire in Flagstaff about road conditions.



Figure 17.1. Grand Falls on the Little Colorado River.

**G**rand Falls (Figure 17.1) is the result of a lava flow that dammed the Little Colorado River about 19,000 years ago. The flow, the second longest in the San Francisco volcanic field, emerged from a fissure in the vicinity of Merriam Crater (Figure 17.2, A) and traveled for nearly 10 mi (15 km) to the Little Colorado River Canyon (Figure 17.2, B). The main lava flow (there were at least five separate flows) filled the canyon to a depth of more than 200 ft (61 m) and overflowed to the northeast for about 0.6 mile (about 1 kilometer). A small branch of the flow followed the Little Colorado River Canyon downstream for another 15.5 mi (25 km).

In time, the ponded water of the Little Colorado River rose, flowed around the northeast end of the lava dam, and poured over the rim of the canyon, creating Grand Falls. The river has eroded back the individual layers of the Kaibab Formation, giving the falls a stair-stepped character. Grand Falls can be spectacular in wet years when the river has a strong flow.

Natural dams, whether they are lava flows, landslides, glacial moraines, or fault escarpments, are short-lived features in terms of geologic time. Eventually, the impounded water will over-top or flow around the dam, restoring the river to its former channel.



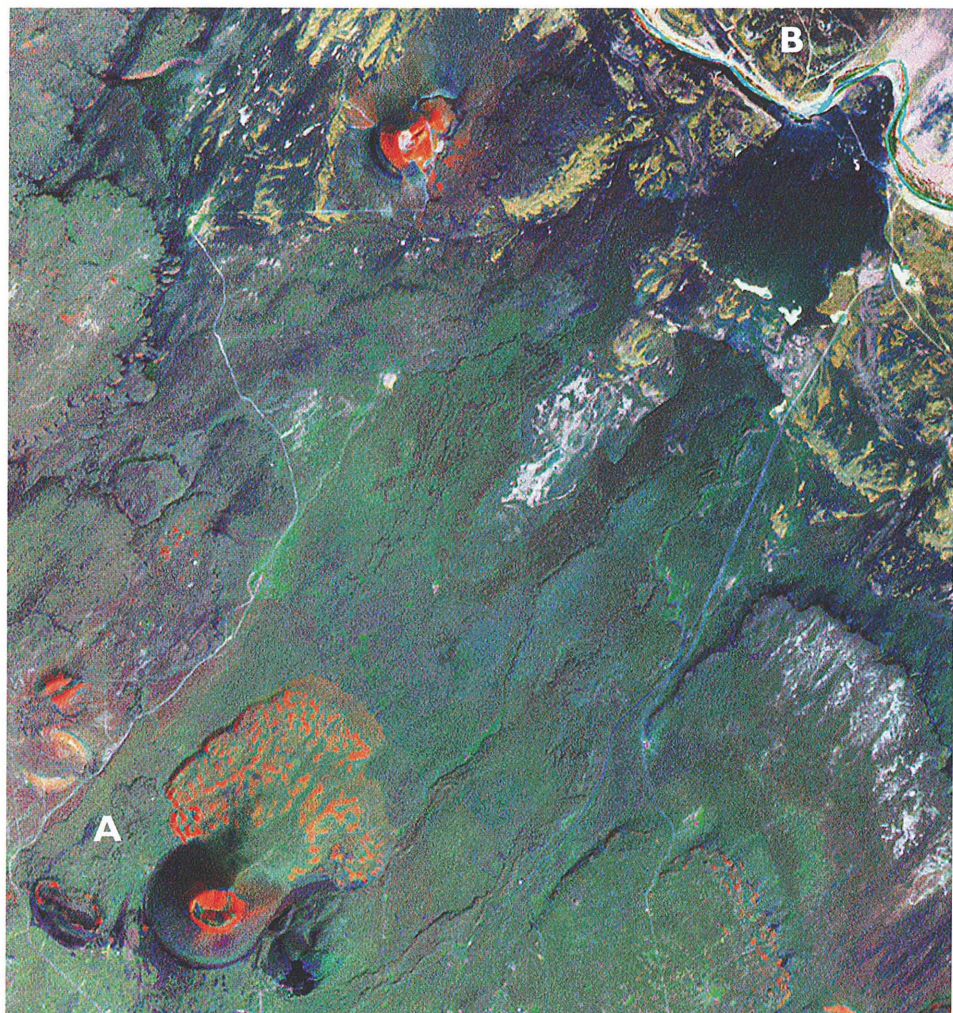


Figure 17.2. Satellite image of the Merriam Crater (A) and Grand Falls (B) area.



## Feature [18]

### Meteorite Impact Crater: Barringer Meteor Crater

**Location:** Drive east from Flagstaff on Interstate Highway 40 to exit 233. Follow the access road to the Barringer Meteor Crater visitor center. There is an admission fee at this site.



**Figure 18.1.** Oblique aerial view of Barringer Meteor Crater (Photograph Courtesy of Meteor Crater, Northern Arizona, USA).

**B**arringer Meteor Crater (Figure 18.1), 550 ft (185 m) deep, about 4000 ft (1300 m) across, and 2.4 mi (3.8 km) around the rim, was the first large feature on Earth to be recognized as a meteorite impact crater. About 50,000 years ago the Canyon Diablo meteorite, a 150-ft-(50-m)-wide mass of iron and nickel, blazed out of the northern sky at 36,000 mi (22,320 km) per hour and blasted the crater in the horizontal rock layers of the surrounding plateau. The encircling rim, rising 100 to 200 ft (30 to 60 m) above the surrounding plain, consists of upturned bedrock and rock debris ejected from the crater at the time of impact. The crater's somewhat square shape is due to bounding joints, a system of natural cracks in the

bedrock of this part of the plateau.

This huge crater was shaped by both the compressive force of impact and the upward explosive force of the vaporizing meteorite. The return shock wave from the crater floor peeled back surface layers of the Moenkopi Formation, arched up the Kaibab Formation, and fused the underlying Coconino Sandstone to a depth of 300 ft (90 m) below the crater floor. Extreme heat and compression accompanying the impact melted sand into natural glass, and created two new forms of silica—coesite and stishovite, both previously unknown on Earth in the natural state.

Although much of the original meteorite body was vaporized, about 12,000 tons of nickel-iron fragments litter the land

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and are mixed with rock debris blown out of the crater. Fine particles of the meteorite are dispersed in natural glass and pulverized sandstone 300 to 650 ft (90 to 200 m) below the crater floor.

Ejected debris surrounding the crater accumulated in the inverse order of rock layers exposed in the crater cliff. That is, the surface rocks of the Moenkopi Formation were blown out first, followed by blocks of Kaibab Formation, and then fragments of Coconino Sandstone. The crater rim and surrounding debris are light in color (Figure 18.1) due to a coating of pulverized sand from the Coconino Sandstone.

Meteorites tell us much about the development of Earth and our solar system. Some are fragments of comets; others are asteroids, most of which orbit the sun in a belt between Mars and Jupiter. A few are rocks from the Moon and Mars, blown into space by meteorite impacts. Most meteorites have been dated at 4.6 billion years,

which has been interpreted to be the age of the solar system.

When our planet was young its surface was pock-marked by meteorite-blasted depressions similar to Barringer Meteor Crater. After the development of Earth's atmosphere, most meteors burned up before reaching the ground. Gradually, the majority of these early impact craters were erased by erosion, covered by sediment, or submerged under the accumulating oceans. Fewer than 200 impact craters have been identified on Earth. Melted bedrock from an impact crater near Sudbury, Ontario contains nickel, platinum, and copper ores valued at \$100 billion.

Over the last 600 million years at least 60 large meteorites have struck Earth. Some of these may have filled the lower atmosphere with dust, triggering drastic climatic changes that resulted in mass extinctions of species. Because of concern about future impacts, asteroids that cross Earth's orbit are being charted.



# Feature [19]

## Laccolith: White Horse Hills (Marble Mountain)

**Location:** Drive northwest from Flagstaff on Highway 180 to mile 235.1. Turn right (east) on Forest Service road 151 and drive for 1.6 mi (2.6 km) to Forest Service road 418; follow this road for 2.8 mi (4.5 km) to a trailhead on the left (north) side of the road. Hike the trail for 1 mi (1.6 km) to a high ridge with mine workings to view the laccolith.

Sometimes viscous magma is injected into preexisting, horizontal layers and causes them to arch upward without spilling onto the land surface. The White Horse Hills (Figures 19.1 and 19.2) are an example of a dome (laccolith) produced in this manner.

Laccolithic intrusions have formed a number of large, isolated mountain ranges in the southern Colorado Plateau, including the Carrizo, Abajo, LaSal, Rico, San Miguel Mountains and Sleeping Ute Mountain (Figure 19.2).

In the case of the White Horse Hills laccolith, rhyolite accumulated as a flat-bottomed intrusion of molten rock beneath layers of older sedimentary and volcanic rock about 850,000 years ago. As the intrusion expanded, the overlying rocks arched up and eventually broke along numerous faults. Erosion later wore away the broken rocks from the crest of the laccolith, exposing the rhyolite core (Figure 19.2). The Redwall Limestone (Mr) that was in contact with the rhyolite magma was converted to marble by heat and chemical change.

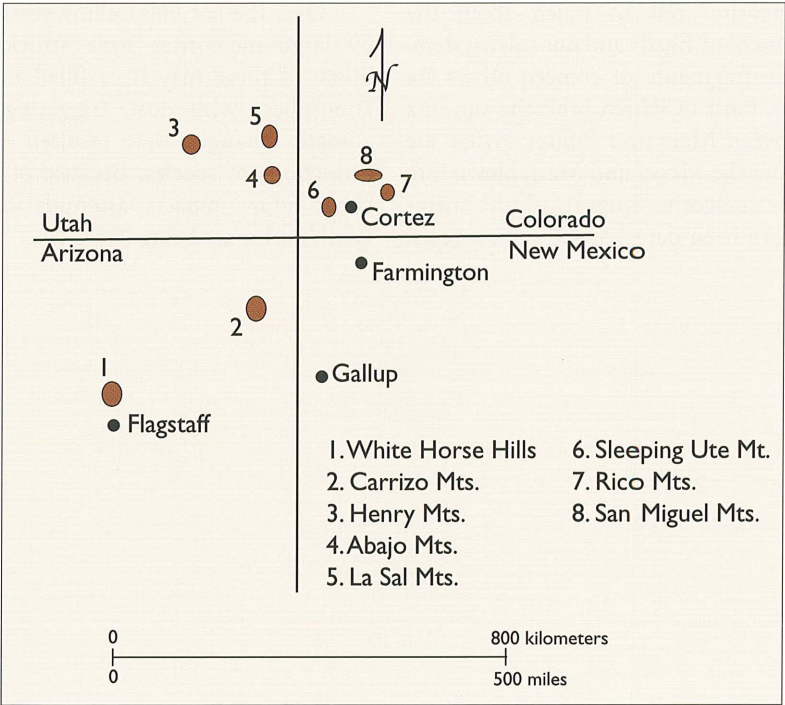


Figure 19.1. Laccolith mountain groups on the southern Colorado Plateau.

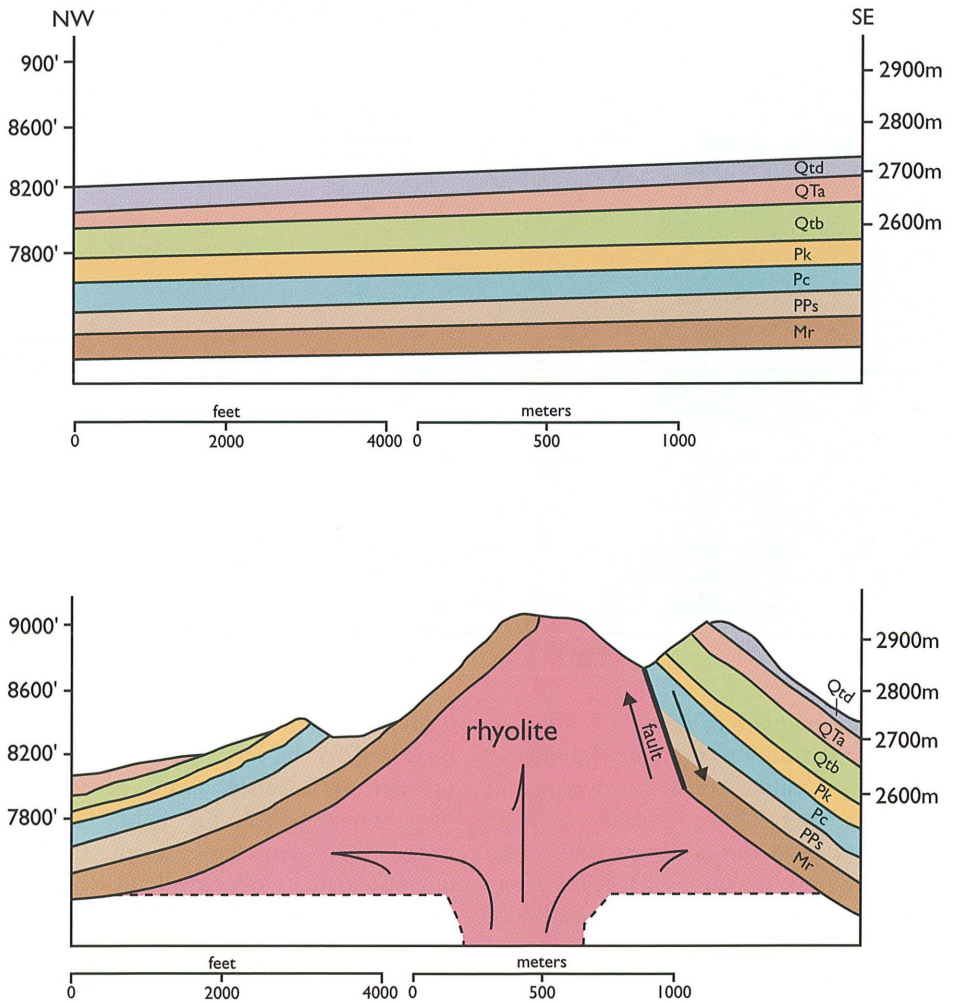


Figure 19.2. Block diagram illustrating the development of the White Horse Hills laccolith (after Updike, 1977).



## Feature [20]

### Anatomy of a Cinder Cone: Red Mountain

**Location:** Drive northwest from Flagstaff on Highway 180 to mile 247; turn left (west) on the Red Mountain access road and follow it for 0.25 mi (400 m) to the parking lot. Walk the trail for about 30 minutes to Red Mountain.



Figure 20.1. Red Mountain.

**R**ed Mountain (Figure 20.1) offers an opportunity to examine the interior of a cinder cone. Weathering and running water have carved a huge amphitheater in the northeast side of the cone, exposing numerous hardened layers of cinder fragments and ash called tuff. These layers are inclined to the north and northeast and dip away from a central vent located to the southwest of the amphitheater. Red Mountain does not have a typical cone shape because its western side was rafted away by a lava flow.

Steam and percolating groundwater consolidated and cemented these layers of volcanic rock fragments with mineral

oxides, forming tuff. Tuff is much less permeable than the loose cinders that make up many of the other volcanic cones in the San Francisco volcanic field. Running water that percolates down through unconsolidated cinders will cut deep gullies into tuff layers. At Red Mountain such erosion has incised a spectacular amphitheater filled with intricately carved pinnacles and honeycombed rock surfaces (see Features 21 and 22).

Volcanic cones are complex features. Their shape is commonly determined by the type of volcanic debris that has been ejected from their vent, as well as processes that were active after eruption ended.



# Feature [21]

## Tafoni: Red Mountain

**Location:** Drive northwest from Flagstaff on Highway 180 to mile 247; turn left (west) on the Red Mountain access road and follow it for 0.25 mi (400 meters) to the parking lot. Hike the trail for about 30 minutes to Red Mountain to view these features.



Figure 21.1. Tafoni (A) at Red Mountain.

The cavities weathered in the rock walls on the slopes of Red Mountain are called tafoni (Figure 21.1A). They occur in many different types of rock and in a great variety of climates, but they are particularly visible in arid and semi-arid climates where their shapes are not obscured by soil and vegetation.

These cavernous openings, which range up to several yards in diameter, are commonly aligned along joints, bedding planes, or other zones of weakness in bedrock. Tafoni, the product of several processes acting in concert, are particularly common where rock faces have developed a hardened crust of mineral salts that were drawn from the interior of the rock. This "case-hardened" outer surface is resistant to weathering and erosion. Small breaks in this resistant surface, however, enlarge relatively rapidly and, in time,

penetrate the softer interior of the rock. Within these shaded cavities, higher humidity and lower temperatures cause rock to disintegrate more rapidly than outside surfaces. Cavity walls are usually crumbling and flaking due to the expansion of clay minerals that swell when wet, the growth of ice crystals, and the dissolving of mineral cement that binds rock grains together.

Some cliffs contain fossil tafoni. Interiors of fossil tafoni are either case-hardened or covered with lichens or rock varnish (a clayey, iron-manganese rind). Shaped by processes that have slowed or ceased, these openings are relics from an earlier period when the climate was more humid. Tafoni weathering, common throughout the Southwest, is but one of the numerous processes that reduce solid rock to fragments that are then swept away by erosion.



## Feature [22]

### Hoodoos (Demoiselles): Red Mountain

**Location:** Drive northwest from Flagstaff on Highway 180 to mile 247; turn left on the Red Mountain access road and follow it for 0.25 mi (400 meters) to the parking lot. Walk the trail for 20 minutes, then hike cross-country to the high southeastern slope of Red Mountain for the best view of hoodoos.



Figure 22.1. Hoodoos on Red Mountain. Photograph by John V. Bezy.

The numerous distinctively shaped rock pillars that grace this slope of Red Mountain are called hoodoos or demoiselles (Figure 22.1). Each slender pillar of soft ash and cinders is protected by a hard caprock—remnants of once-continuous but thin, highly-cemented layers of ash and cinders. The natural cement is silica and calcium carbonate deposited by water or by steam when eruptions were building the cinder cone. A multitude of small streams has cut through both the thin, hard layers and the thick soft layers, leaving ranks of hoodoos temporarily shielded from ero-

sion by resistant blocks of the highly cemented rock. Although not as delicate as the name demoiselle (young lady) suggests, these pillars will topple when they become too thin and weak to support the weight of the caprock.

Hoodoos illustrate on a small scale the important geologic concept of differential erosion—that soft rocks wear away more rapidly than hard rocks. As a result, hard rocks such as basalt, limestone, and sandstone remain on the landscape for long periods of time as erosion-resistant layers capping the plateaus, mesas, and buttes of the Colorado Plateau.

## Feature [23]

### Lava Tube: Lava River Cave

**Location:** Drive northwest from Flagstaff on Highway 180 to mile 230.1. Turn left (west) on Forest Service road 245 and drive 3 mi (4.8 km) to F.S. road 171. Turn left (south) and drive for 1.1 mi (1.8 km) to F.S. road 171B. Turn left (east) and drive for 0.3 mi (480 m) to Lava River Cave (also called Government Cave).

The rock opening before you is a collapsed ceiling section of a lava tube.

This underground chamber, the path of a river of lava 675,000 years ago, is more than 0.75 mi (1.25 km) long and has a maximum ceiling height of 30 ft (about 10 m). The lava tube has a sinuous course, low ceilings, and a boulder-strewn floor that drops abruptly in places. If you plan to enter the tube, bring shoes with good tread, hard hat, flashlights with extra batteries, water, food, and gloves to protect your hands from rough rock surfaces. Annual temperature range in the chamber is 32-40 degrees F (0 to 4.4 degrees C), so a jacket is recommended. In the spring, ice can make the tube entrance particularly dangerous. Please do not damage or deface the cave or disturb wildlife.

The basalt you are standing on was once a lava flow. The sides of the flow, in contact with the ground, cooled and solidified quickly. The thicker and hotter center of the flow crust-

ed over due to contact with the cooler atmosphere. Below the crust, a current of molten rock continued to run as long as more lava was added upstream (Figure 23.1, A). Heat from the flowing lava partially melted the tube's ceiling, producing lavacicles. Rocks falling from the ceiling of the tube into the molten rock produced splashes that are preserved in the basalt. As the flow of lava slowed and then ceased the tube drained, leaving the underground passageway you are exploring (Figure 23.1, B).

By maintaining a forward moving current of molten rock, tubes serve to extend the length of lava flows. After cooling, tubes commonly provide shelter for animals, particularly bats.

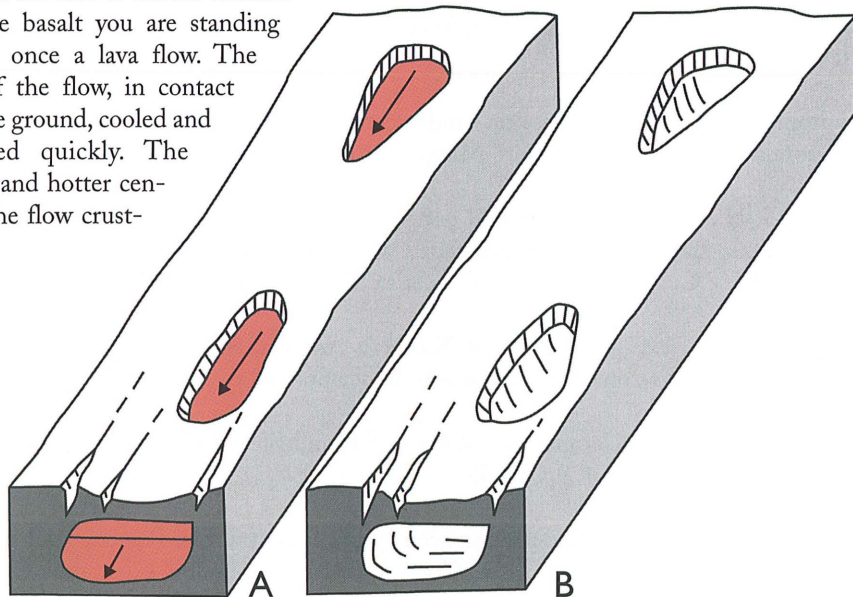


Figure 23.1. Block diagrams illustrating the formation of a lava tube.



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