



**Geology of Flagstaff and Geologic  
History of Rio de Flag, Northern Arizona  
with Trail Guides to Geology along Rio de Flag**

**Arizona Geological Survey**

**Richard F. Holm**



**UA Science**

# Arizona Geological Survey

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Cover: Rio de Flag spilling into Picture Canyon, Flagstaff, Arizona (Photo by Tom Bean)



UA SCIENCE

**Geology of Flagstaff and Geologic History of Rio de Flag,  
Northern Arizona,  
with Trail Guides to Geology Along Rio de Flag**

**Richard F. Holm**

**2019**

*Spring runoff in Fort Valley*

1973



1983



1993



2018



“...rivers are by far the most important agents in molding landscapes...”\*

\*ENCYCLOPÆDIA BRITANNICA

In Flagstaff, however, the landscape has shaped the Rio.

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## INTRODUCTION

This geology and trail guide is for anyone who likes to walk, be outdoors, and is interested in the geology in and around Flagstaff. The geologic story is focused on Rio de Flag because it flows through Flagstaff, touches or passes by all of the geologic elements in the city, and is accessed easily. The origin and history of the Rio, and how geologic structures and deposits have controlled and changed its **watercourse** through time, are presented with extended text, maps, photographs, and trail guides. Words in **bold** font, or **bold and underlined**, are defined in the Glossary. Trails along Rio de Flag include segments of the Flagstaff Urban Trails System (FUTS), local unofficial social trails used for convenience by people and animals, and the Flagstaff Open Space Program trails at Picture Canyon Natural and Cultural Preserve.

Rio de Flag is part of the regional drainage system in northern Arizona. In order to place the Rio in its geologic context, the next section of Regional Perspectives summarizes relevant geologic elements of the three **physiographic provinces** in Arizona: the southern Colorado Plateau, the Basin and Range, and the Arizona Transition Zone; this is followed by overviews of the San Francisco volcanic field and the local geology in Flagstaff. The geologic background concludes with description and interpretation of the origin of Rio de Flag, its history of changes and diversions, and its relation to Walnut Creek. Trail guides along Rio de Flag are in Part 2.

### PART 1.

## GEOLOGY OF FLAGSTAFF AND GEOLOGIC HISTORY OF RIO DE FLAG

### REGIONAL PERSPECTIVES

. Flagstaff's landscape is a microcosm of the broader geologic setting of the southern Colorado Plateau. Rio de Flag, an active component of the landscape in Flagstaff, is dry most of the time, but when water does flow it follows a downhill path of least resistance. Running water erodes rocks and deposits at Earth's surface, so the stream adjusts its watercourse to the most easily erodible pathways. These pathways, or **reaches**, develop according to the slope of the land, the character of the **bedrock**, structural breaks in the bedrock, the amount and particle size of the sediment transported, and new barriers such as **lava flows** and landslides.

#### Colorado Plateau

Positioned on the "four corners", the Colorado Plateau is a large physiographic province that includes most of northern Arizona, southeast Utah, western Colorado, and northwest New Mexico. The southern part of the plateau in Arizona has well-defined edges: the Mogollon Rim on the south side, and the Grand Wash Cliffs on the west side (Fig. 1, p. 6). Flagstaff is only about 20 miles from the Mogollon Rim at the mouth of Oak Creek Canyon.

The Colorado Plateau is characterized by high elevations (average is over 5,000 feet), flat-lying to gently tilted layers of rocks, and deep **canyons**. Broad **plateaus** and **mesas** capped by colorful rocks are typical. Large areas of the same color on the Arizona geologic map indicate flat-lying rocks at the surface (Fig. 1). Locally, steep **faults** break the rocks, and **uplifts** up to 2,000 feet high tilt them steeply, as at Gray Mountain north of Flagstaff. The principal drainage of the Colorado Plateau is the Colorado River and, in Arizona, its major tributary is the Little Colorado River.

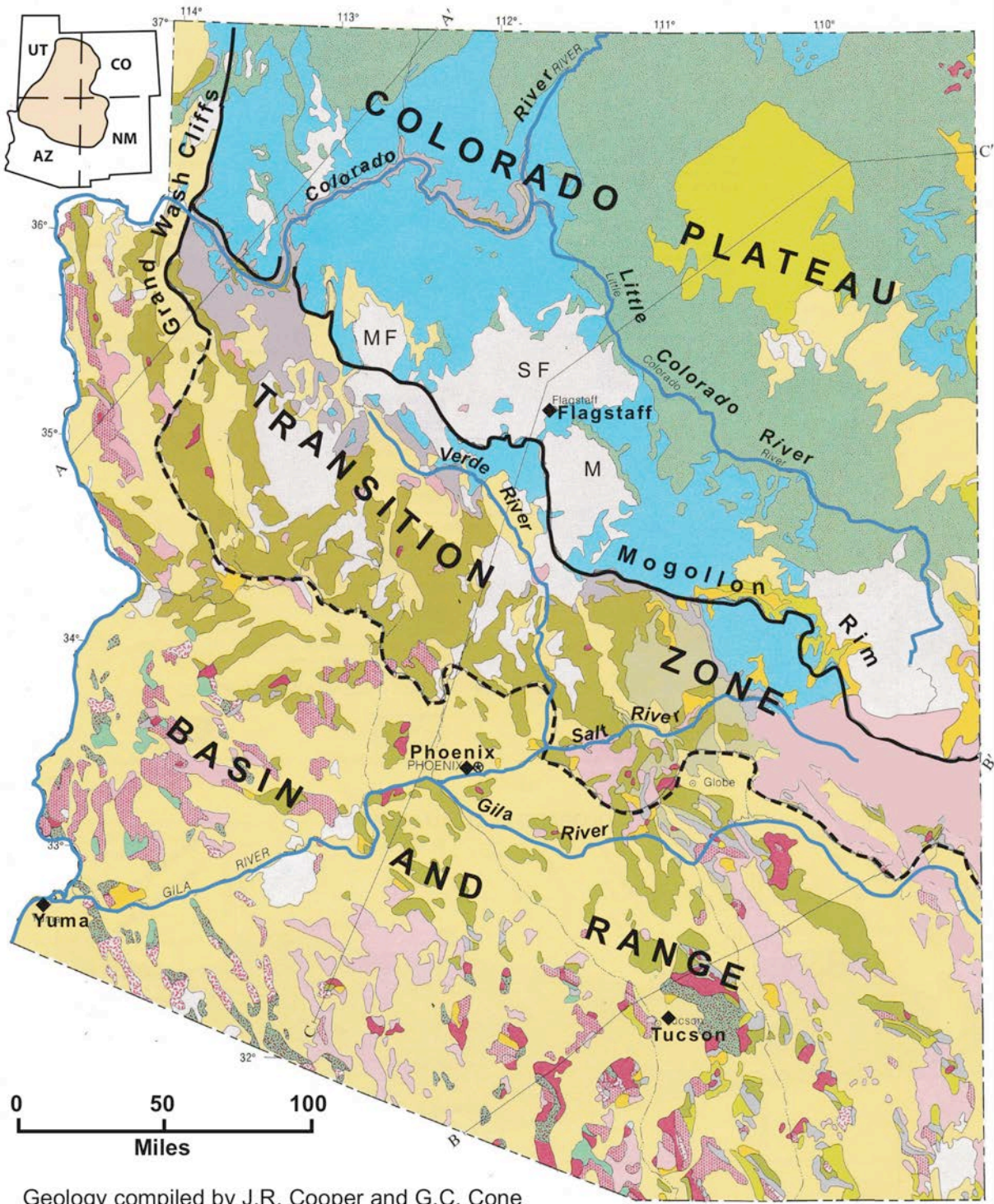


Figure 1. Geologic map of Arizona. Colors represent rocks of different ages and types. Light pink: volcanic rocks less than 16 million years old. Sedimentary rocks on the Colorado Plateau: blue and green are generally between 280 and 145 million years old; dark yellow are generally between 145 and 66 million years old. Yellow in all provinces: mostly young river deposits of sand and gravel. Other colors: a variety of sedimentary, igneous, and metamorphic rocks of different ages. M: Mormon volcanic field. MF: Mount Floyd volcanic field. SF: San Francisco volcanic field. Geology modified by R.F. Holm. Small map in upper left corner shows location of Colorado Plateau (orange).

## Basin and Range

The Basin and Range province extends from southern Oregon and Idaho through Nevada and western Utah to southern Arizona and northern Mexico. Throughout, the province is characterized by broad valley floors and narrow but high mountain ranges. Between about 15 and 8 million years ago, large **offsets** along steep faults broke southern and western Arizona into a **terrane** of alternating deep basins and high mountain ranges. Today, the valleys are underlain by very thick deposits of sand and **gravel** that fill the basins next to the deeply eroded ranges. In southern Arizona the valleys lie at low elevations, mostly less than 3,000 feet, but some ranges exceed 9,000 feet in elevation. The principal drainage is the Gila River, which enters the Colorado River at Yuma (Fig. 1).

## Transition Zone

Intermediate between the Colorado Plateau and Basin and Range in geographic position, geologic structure, **physiography**, and overall elevation is the Transition Zone (Fig 1). Deep narrow valleys between broad, high mountain ranges are characteristic of this central part of Arizona that extends from the southeast side of the state to the northwest corner. Streams that head in narrow canyons along the central and eastern parts of the Mogollon Rim carry water south, eventually to the Gila River.

About one mile south of Flagstaff's Pulliam Airport is a **stream divide** between Skunk Canyon and Pumphouse Wash (Fig. 6, p. 18). Skunk Canyon water flows northeast to join Walnut Creek, which joins Rio de Flag, and eventually enters the Little Colorado River. Pumphouse Wash water flows south into Oak Creek, which joins the Verde River, and then the Salt and Gila Rivers. Waters that start out only a few hundred feet apart near Flagstaff ultimately flow through Yuma, but they take very different routes to get there.

## Uplift and Erosion of the Colorado Plateau

About 90 million years ago northern Arizona was below sea level. Sedimentary deposits that contain fossils of marine organisms accumulated in shallow sea water. Today, these deposits are over 6,600 feet in elevation. Clearly, the Colorado Plateau has risen. Details of the timing of uplift and the mechanism that drove it are debated vigorously by geologists, but the general ideas are broadly accepted.

Initial uplift of the Plateau probably began about 75 million years ago when **compressive** mountain-building forces elevated southern Arizona. Upland streams in southern and central Arizona carried sand and gravel onto lower-level **flood plains** in northern Arizona, generally around 40 to 60 million years ago. About half, or more, of the plateau uplift had occurred by about 20 to 30 million years ago when **extensional forces** lowered southern and central Arizona. This change in elevations across the state produced the Mogollon Rim as a regional drainage divide. The Mogollon Rim is a steep **escarpment** capped by rocks resistant to erosion. Final uplift has been in the last five to six million years, coincident with erosion of Grand Canyon by the Colorado River. Dynamic flow of hot rocks below Earth's crust in response to **plate tectonic** and gravitational forces can explain the uplift.

Before uplift began, as much as 9,000 to 15,000 feet of sedimentary rocks covered the **limestone** bedrock that forms most of Flagstaff's surface today. The ancient gravels from

central and southern Arizona were deposited on flood plains only a few hundred feet above the limestone, so most of the overlying rocks must have been eroded during the early stages of plateau uplift. By 6 million years ago, much of the Flagstaff area had been eroded down to the limestone bedrock, and only thin layers of overlying red **sandstone** remained, mostly in east Flagstaff. An ancestral Rio de Flag might have been active far to the east at this time, but the Rio as we know it today was still several million years in the future.

## SAN FRANCISCO VOLCANIC FIELD

Flagstaff is near the center of a large **volcanic province** on the southwest edge of the Colorado Plateau (Fig. 1). The sector containing San Francisco Mountain, named the San Francisco **volcanic field** (Fig. 2, p. 9), covers more than 2,000 mi<sup>2</sup> with volcanoes, lava flows, and blankets of **cinders** (Tables 1, 2, p. 8, 9) Eruptions began around six million years ago at three locations: a few miles south of Flagstaff at Woody Ridge, north of San Francisco Mountain at Cedar Ranch, and south of Williams, Arizona. Over the years, the locus of eruptions gradually migrated northeast until the most recent eruption occurred at Sunset Crater about 950 years ago.

In the volcanic field are more than 800 small volcanoes, including **cinder cones**, **lava domes**, and less familiar volcanoes called **tuff cones**, **tuff rings**, and **maars**; cinder cones are the most numerous type of volcano in the volcanic field. Clusters of lava domes make up the nearby Dry Lake Hills, Elden Mountain, and O’Leary Peak, as well as Bill Williams Mountain, Sitgreaves Mountain, and Kendrick Peak in the western part of the volcanic field. Mormon Mountain, south of Flagstaff, is also a cluster of lava domes. **Shield volcanoes** erupted lava flows at Williams, Woody Ridge, Cedar Ranch, and Hart Prairie, and the largest volcano, San Francisco Mountain, is classified as a **composite volcano**. Over 120 mi<sup>3</sup> of lava were erupted.

**Table 1. Volcanoes In San Francisco Volcanic Field**

<b>volcano type</b>	<b>cinder cone</b>	<b>tuff cone</b>	<b>tuff ring</b>	<b>maar</b>	<b>lava dome</b>	<b>shield volcano</b>	<b>composite volcano</b>
<b>typical rocks</b>	basalt andesite	basalt	basalt	basalt	dacite rhyolite	basalt	andesite dacite rhyolite
<b>examples</b>	Sunset Crater SP Crater	Red Mountain	Dry Lake	Colton Crater (Crater 160)	Elden Mountain Sugarloaf	Woody Ridge Hart Prairie	San Francisco Mountain
<b>character</b>	loose to welded cinders*	cemented cinders**	broad crater with low rim of tuff***	broad, deep crater with low rim of tuff ***	high profile, steep slopes, thick lava flows	low profile, gentle slopes, thin lava flows	layers of lava flows and cinder <b>beds</b> plus lava domes
<p>*welding occurs by pressing together molten cinders before they cool.  **common cements are calcite, gypsum, and palagonite; palagonite is a red to yellow to tan substance formed by water alteration of basaltic <b>glass</b> in cinders.  ***<b>tuff</b> is a name applied to a rock made of compacted or cemented particles such as cinders, <b>pumice</b>, <b>crystals</b>, and <b>ash</b> that were produced by volcanic explosions.</p>							

Table 2. Common Rocks In San Francisco Volcanic Field*				
parameters	basalt	andesite	dacite	rhyolite (obsidian)**
silica (SiO <sub>2</sub> )	45 wt. %	increasing →→→→		75 wt. %
alkali (Na <sub>2</sub> O+K <sub>2</sub> O)	3 wt. %	increasing →→→→		9 wt. %
iron (FeO+Fe <sub>2</sub> O <sub>3</sub> )	12 wt. %	decreasing →→→→		2 wt. %
color***	black to dark gray	gray	light gray	white (black)
viscosity****	low	medium	high	very high
lava temperature	1150°C	decreasing →→→→		750°C
large crystals	<u>olivine</u> (green) <u>pyroxene</u> (black)	pyroxene (black) plagioclase (white)	<u>plagioclase</u> (white)	<u>quartz</u> (clear) <u>sanidine</u> (white)

\*rocks are listed left to right in order of decreasing abundance in the San Francisco volcanic field.  
 \*\*rhyolite is **crystalline** (stony), obsidian is glassy; even small amounts of iron make volcanic glass black.  
 \*\*\*color is generally related to iron content; high iron content makes a volcanic rock dark.  
 \*\*\*\*viscosity is a measure of the resistance to flow; controlled mainly by silica content and temperature.

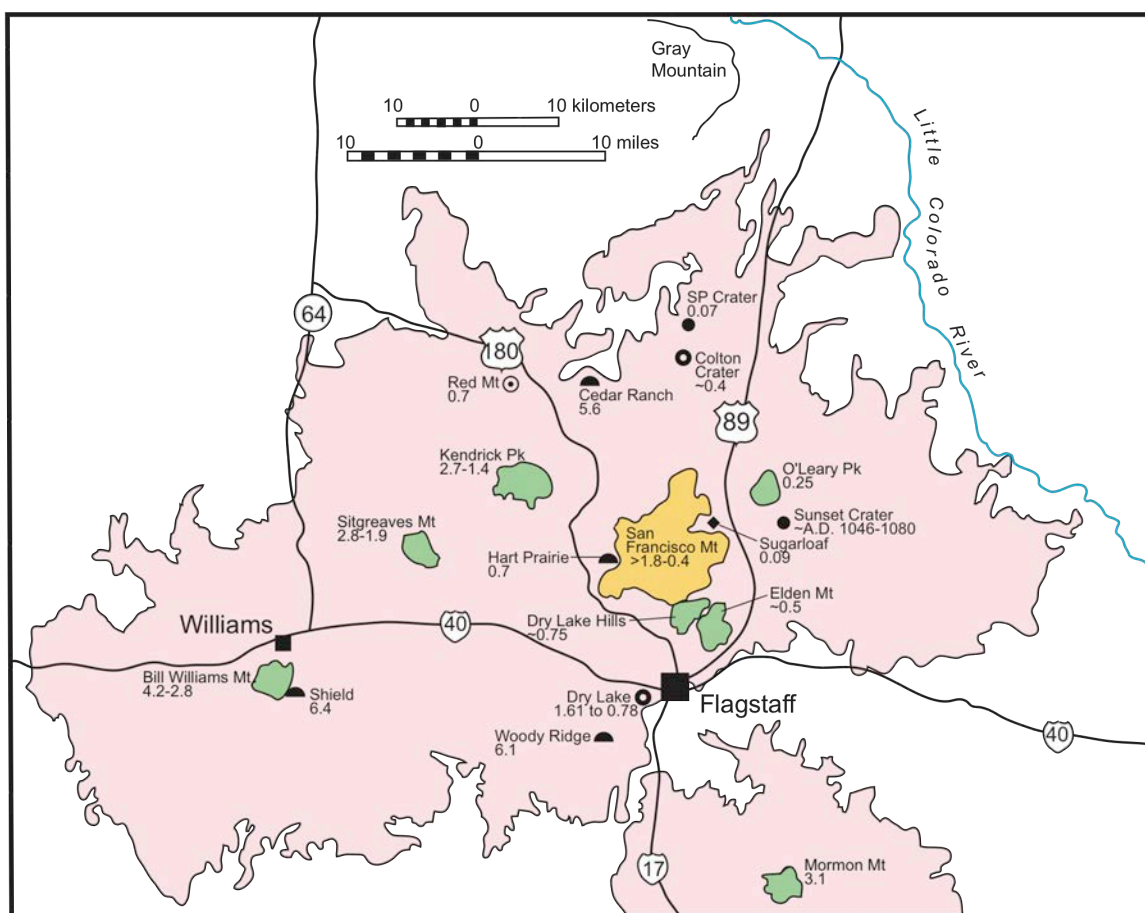


Figure 2. Map of the San Francisco volcanic field, northern part of the Mormon volcanic field, and selected volcanoes. Numbers by volcano names are ages of the volcanoes in millions of years, except for Sunset Crater. San Francisco Mountain is a composite volcano; clusters of lava domes are green; filled dots are cinder cones; open dots are maar (Colton Crater), tuff ring (Dry Lake) and tuff cone (Red Mountain); half dots are shield volcanoes; diamond is a lava dome (Sugarloaf). North is at the top.

## FLAGSTAFF GEOLOGY

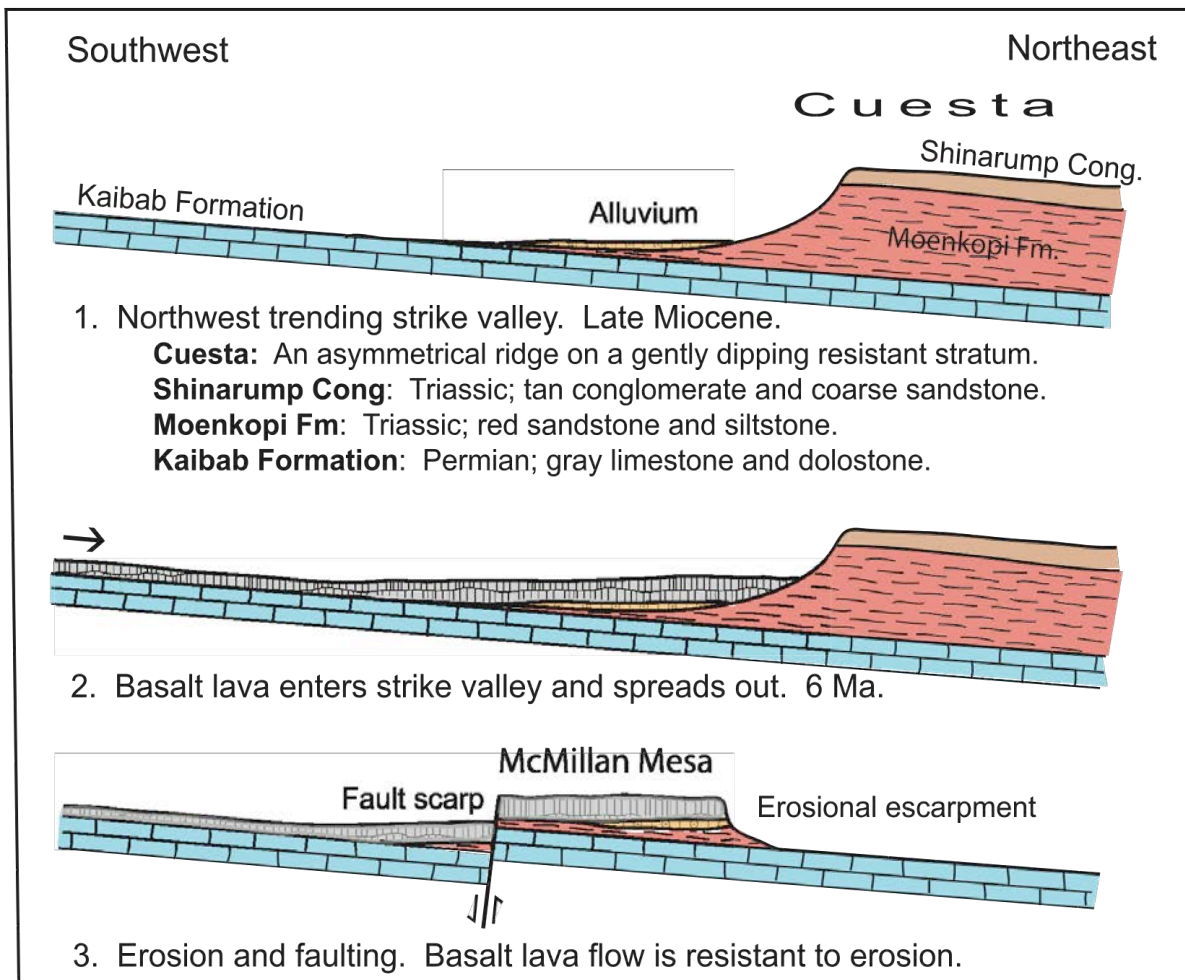
### The Effect of Tilt

The bedrock platform on which Flagstaff sits is tilted  $\frac{1}{2}^{\circ}$  to  $2^{\circ}$  down to the northeast. This direction of tilt, or **dip**, is typical for the southwest margin of the Colorado Plateau, and is approximately at a right angle to the Mogollon Rim. A tilt of  $1^{\circ}$  is very small, and changes the elevation of a layer of rock by only 92 feet in one mile. However, in 10 miles the change is 920 feet, and in 20 miles it is 1,840 feet. As an example, consider the rocks seen along Milton Road and Route 66. In downtown Flagstaff the boundary, or **contact**, between the gray Kaibab **Formation** and the red Moenkopi Formation is at an elevation of 6,840 feet. Near the visitor center at Wupatki National Monument, about 27 miles northeast of Flagstaff, the same contact is at an elevation of 4,740 feet, a difference of 2,100 feet. A trigonometry calculation indicates the tilt average is only  $0.83^{\circ}$ , an amount that is almost imperceptible to someone standing next to a rock exposure or **outcrop**.

Most sedimentary rocks on the southern Colorado Plateau are sandstone, **siltstone**, **shale**, and limestone of different resistances to erosion. Where the rocks are tilted, even by less than one degree, erosion bevels the edges of the layers. Strong, resistant rock layers form ridges, and weak, easily eroded layers form valleys. Hard-soft couplets form ridges and valleys that are parallel to the trend direction, or **strike**, of the tilted layers of rocks. The ridges, on which one side is steep, and the side in the direction of tilt is gentle, are called **cuestas**; the valleys are called **strike valleys**. As erosion lowers the landscape, the ridges and valleys shift their location and elevation in the direction of tilt. To illustrate, pick up a tablet of paper; hold it horizontal and then tilt it down with your right hand. To simulate erosion, imagine cutting the edge of the tablet with your left hand several times and envision the cut edge shifting down toward your right hand. The tablet doesn't move, but the cut edge shifts down and to the right.

This model can explain the origin of McMillan Mesa, formerly called Switzer Mesa, which is the high ground between west and east Flagstaff (Fig. 3, p. 11). About six million years ago, a strike valley and cuesta trended northwest through the present location of Flagstaff. The cuesta was on the resistant Shinarump **Conglomerate**, the lowest member of the Chinle Formation that forms the Painted Desert, and the valley was on the easily eroded red Moenkopi Formation. Low viscosity basalt lava that erupted from a shield volcano at Woody Ridge south of Flagstaff flowed into the valley and spread out. Subsequent erosion shifted the cuesta northeast and faults offset the layers of rocks. The basalt is resistant to erosion, and remains standing as a mesa. The evidence for the cuesta is recorded by pebbles typical of the Shinarump Conglomerate that can be found below the basalt on the east side of the mesa; careful searching on top of the mesa is rewarded by finding rare pebbles. Today, the Shinarump Conglomerate  **crops out** near the Little Colorado River, which flows in a northwest-trending strike valley. The northwest-trending Mogollon Rim is essentially a mega-cuesta capped for most of its length by the resistant Kaibab Formation and basalt lava flows.

Anderson Mesa southeast of Flagstaff is a twin of McMillan Mesa (Fig. 4, p. 12). Basalt lava that erupted from a shield volcano near Mormon Mountain (Fig. 2) flowed into the same strike valley about the same time as the Woody Ridge lava erupted. A low stream divide on the Moenkopi Formation in the valley kept the two lava flows from merging. As the cuesta shifted northeast, erosion removed the Moenkopi Formation and the stream divide, and Rio de Flag and Walnut Creek established their watercourses through the low ground between the mesas (Fig. 4).



*Figure 3. Schematic diagram that illustrates the formation of McMillan Mesa; angle of tilt is exaggerated. 6 Ma is six million years. The City of Flagstaff changed the name from Switzer Mesa to McMillan Mesa on September 20, 1983; the change was approved by U.S. Board on Geographic Names in 1984. Switzer Mesa appears on older U.S. Geological Survey maps: Flagstaff, Ariz., 1:125000, 1912; Flagstaff West, Ariz., 1:24000, 1962.*

## Rock Formations

**Geologic maps** show rock formations with specific colors and distinctive symbols consisting of letters. Sedimentary rocks are assigned colors according to their age; for example, **Permian** rocks are blue, **Triassic** rocks are green, and **Quaternary** deposits are yellow. Volcanic rocks are typically colored shades of red, orange, purple, and tan. The first letter of the symbol is a capital and indicates the age of the rock; the next lower-case letters can indicate the name, type of rock, composition, or position in a sequence of rocks. Common age symbols in the Flagstaff area are: P=Permian (252 to 299 million years old [**m.y.**]), Tr=Triassic (201 to 252 m.y.), T=**Tertiary** (2.6 to 66 m.y.), Q=Quaternary (< 2.6 m.y.). Most Tertiary rocks in the Flagstaff area are younger than 6.5 m.y. When the geologic map on the next page (Fig. 4) was published in 1984 the older age boundary of the Quaternary Period was 1.8 **Ma**; ages listed above are from the **Geologic Time Scale** published in 2012.

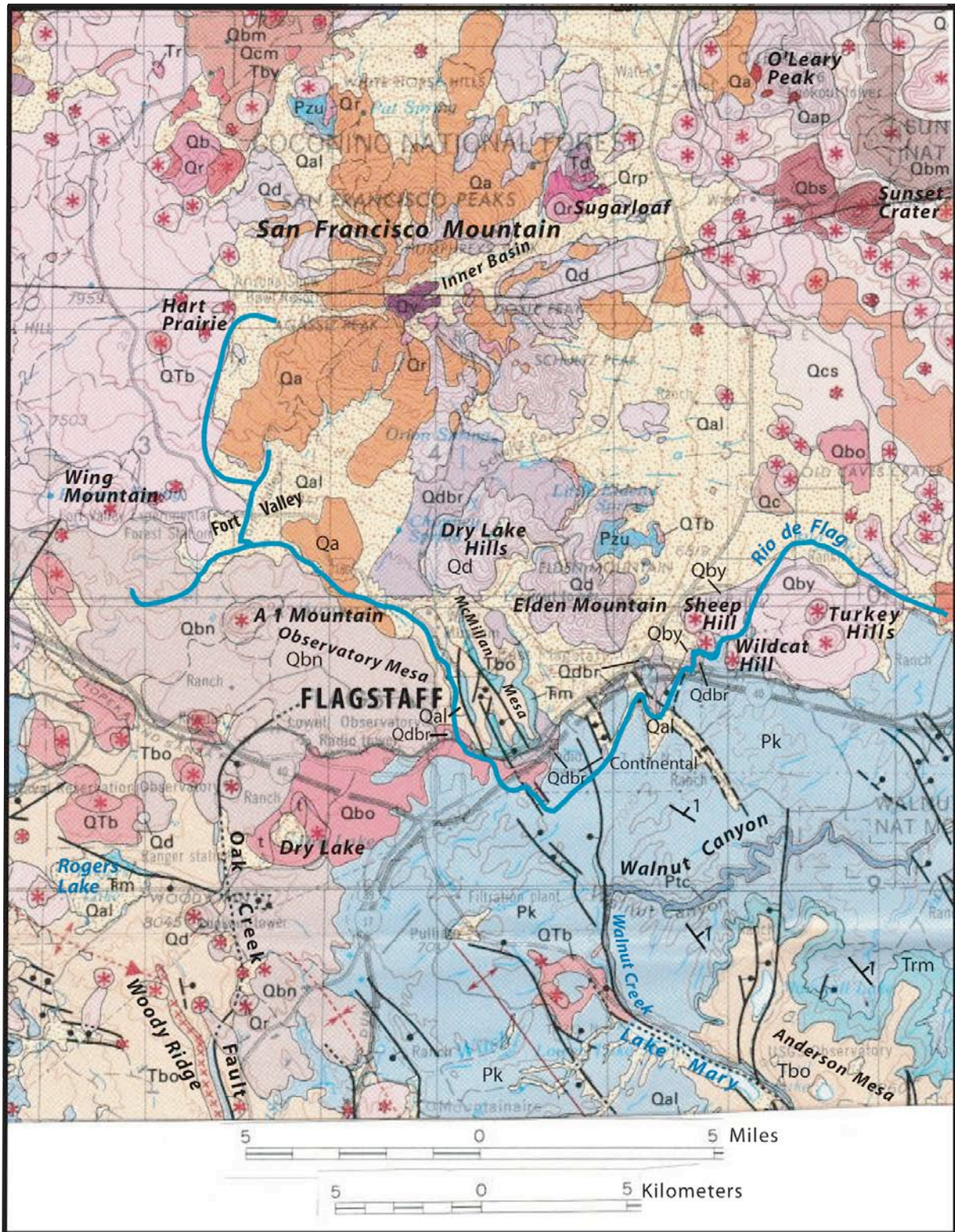


Figure 4. Geologic map of Flagstaff area (Ulrich and others, 1984). Symbols: Qal: alluvium; Qcm, Qcs, Qc: basalt cinders; Tbo, Tby, QTb, Qbo, Qby, Qbm, Qb, Qbs,: basalt; Qa, Qbn: andesite; Qap: andesite cinders; Td, Qd: dacite; Qdbr: dacite breccia; Tr, Qr: rhyolite; Qrp: rhyolite pyroclastics; Qv: San Francisco Mountain vent intrusions and deposits; Trm: Moenkopi Formation; Pk: Kaibab Formation; Ptc: Coconino Sandstone; Pzu: Paleozoic sedimentary rocks undivided. Red asterisks: cinder cones. |— 1: short bar and number show direction and degree of tilt. Black lines: faults, ball on down side.

Below are brief descriptions of rock formations and **map units** shown on the geologic map in Figure 4 that are related to the origin and history of Rio de Flag; the order is from oldest to youngest. For details about the rocks consult: Marie D. Jackson, 1999, and Wolfe, E.W., Ulrich, G.E., Holm, R.F., Moore, R.B., and Newhall, C.G., 1987.

**Paleozoic Rocks Undivided (Pzu): *blue.***

The oldest rock in the Flagstaff area is the Temple **Butte** Formation (Middle to Late **Devonian**, 372 to 388 m.y.). The **stratum** crops out on the northeast side of Elden Mountain where it was pushed up during the early stages of the Elden Mountain eruption. Other **strata** included in the Pzu symbol are: Redwall Limestone, Supai Group, Hermit Formation, Schnebly Hill Formation, Coconino Sandstone, Kaibab Formation.

**Coconino Sandstone (Ptc): *Lower Permian, ~279 to 299 m.y., dark blue.***

The Coconino Sandstone is exposed in three areas: on the northeast side of Elden Mountain, in Walnut Canyon, and in the **fault scarp** next to Lower Lake Mary and along Walnut Creek. The tan sandstone is characterized by large-scale **cross beds** of wind-blown origin.

**Kaibab Formation (Pk): *Lower Permian, ~272 to 279 m.y., blue.***

The Kaibab Formation underlies much of Flagstaff south of the railroad tracks; it covers the large blue area in the southeast corner of the geologic map (Pk). Although the Kaibab Formation is commonly referred to as limestone, most of the yellowish-gray to light-gray rocks are **dolostone**, dolomitic sandstone, and dolomitic limestone. The formation is strongly resistant to erosion because of its crystalline texture. Where overlying rocks have been eroded away, the Kaibab Formation covers large areas, such as the rim of Grand Canyon.

**Moenkopi Formation (Trm): *Middle? and Lower Triassic, ~241? to 252 m.y., bluish-green.***

The brick red to brownish red rocks are **mudstone**, siltstone, sandstone, and minor conglomerate. The formation occurs where it has been protected from erosion by overlying basalt lava flows at McMillan Mesa, Anderson Mesa, and Rogers Lake, and locally by the Dry Lake basalt lava flow.

**Oldest Basalts (Tbo): *Late Miocene, ~6 m.y., pale orange.***

The oldest lava flows in the Flagstaff area are basalts that cap McMillan Mesa and Anderson Mesa, crop out along Rio de Flag at the Museum of Northern Arizona, and cover the area around Woody Ridge and Rogers Lake southwest of Flagstaff. The lavas on McMillan Mesa erupted from a shield volcano at the north end of Woody Ridge, flowed north for several miles, then east into a northwest-trending strike valley; later they were covered by the lava flow of Observatory Mesa. The lavas on Anderson Mesa flowed north from a shield volcano at the southeast side of Mormon Lake; the volcano is about 10 miles south of the edge of the geologic map (Fig. 4, p. 12). These oldest basalt lava flows predate any vestige of Rio de Flag.

**Andesite Lava Flow Below Wing Mountain (Qbn): *Quaternary, 1.29 Ma, tan.***

Wing Mountain, a basalt cinder cone, appears to cover the vent of the andesite lava flow that extends southeast from the south side of the mountain (Qbn, tan). The distal end of the lava flow is covered by the younger Observatory Mesa lava flow (also tan); the two flows are

separated on the map by the dash line. The Wing Mountain lava flow is elongated down-slope toward the southeast, which indicates the direction of flowage. This flow direction is the oldest hint of an ancestral watercourse of Rio de Flag. The andesite is a sodium-rich variety called **benmoreite**, named after Ben More, a mountain on the Scottish island of Mull.

**Dry Lake Volcano (t) and Dry Lake Lava Flow (Qbo): *Quaternary, red.***

Dry Lake volcano (t) is a tuff and cinder ring over one mile in diameter; it is four miles southwest of downtown Flagstaff. The volcano erupted through an older basalt cinder cone (red asterisk). A basalt lava flow (Qbo, red) that erupted from the cinder cone flowed northeast for about three miles to where it entered the ancestral watercourse of Rio de Flag. After entering Rio de Flag, the lava followed a curving path eastward around the south end of McMillan Mesa for an additional 3.5 miles. The lava flow blocked the upstream drainage of Rio de Flag with a lava dam; clay, silt, and fine sand sediment that accumulated in a pond behind the dam is shown on the geologic map in pale yellow (Qal). Neither the tuff ring nor the lava flow have been dated with radiometric methods; **magnetic** and **stratigraphic** information suggest the lava flow is between 0.78 and 1.61 m.y.

**Dry Lake Hills (Qd): *Quaternary, ~0.75 Ma, light lavender.***

Dry Lake Hills are a cluster of eight coalesced lava domes of dacite five miles north of downtown Flagstaff. A thick lava flow poured down the west side of the cluster. The domes and lava flow were extruded on top of the old basalts that cap McMillan Mesa. The domes have **normal magnetic polarity** and one of the domes is overlain by a lava flow from Elden Mountain; these relations suggest the age of the domes is about 0.75 Ma. Dry Lake Hills are in the headwaters of Schultz Creek, a major tributary of Rio de Flag.

**Andesite Lava Flow on Agassiz Peak (Qa): *Quaternary, 0.60 Ma, orange.***

The andesite lava flow on the southwest side of Agassiz Peak on San Francisco Mountain extruded from a vent on the upper flank of the composite volcano and flowed down to the volcano's base on the north side of Fort Valley. The lava flow controls two of the headwater branches of modern Rio de Flag. Big Leroux Spring exits from a rubble and fracture zone at the bottom of the lava flow, and a drainage from Arizona Snow Bowl passes along the western edge of the flow. (**Note:** Several other lava flows of different ages are included in map unit Qa).

**Elden Mountain (Qd) and Elden Block and Ash Breccia (Qdbr): *Quaternary, ~0.53 Ma, light lavender.***

Elden Mountain is a composite lava dome with several summit vents from which bulbous lava flows extruded and flowed down the sides of the volcano. The initial vent opened like a trap door, pushing up more than 3,000 feet of Paleozoic strata (Pzu). A powerful **Peléan**-type eruption blew pumice, blocks, crystals, and ash several miles above the vent. These pyroclastic particles descended from the eruption column in a hot, gaseous mass that rapidly spread across the ground between Flagstaff Mall and west Flagstaff. The **pyroclastic-flow** deposit (Qdbr, light lavender; several patches are labeled on the geologic map) is also called a block and ash breccia (**breccia** is a rock or deposit composed of large, broken fragments). After the gas boiled out of the underground lava (**magma**), thick, viscous lava flows emerged and piled up to build Elden Mountain. The average of two age analyses is 0.53 Ma. (**Note:** The Qdbr map unit north of Dry Lake Hills is not related to Elden Mountain; it erupted from a dome on San Francisco Mountain).

**Sheep Hill (Qby): *Quaternary, < ~0.53 Ma, pink.***

Sheep Hill is a basalt cinder cone in east Flagstaff that erupted in an ancestral watercourse of Rio de Flag; quarry operations have degraded the symmetry of the volcano. Two basalt lava flows extruded from the base of the cone. The largest flow extruded on the north side of the cone, filled Rio de Flag, and advanced about two miles downstream; this lava flow forms the modern waterfalls at Picture Canyon. The smaller flow extruded on the south side of the cone and flowed about 1.5 miles upstream in the Rio de Flag channel as a narrow finger, which suggests that the gradient of this reach of the Rio was very low. Water impounded by the lava dam covered most of the low-lying parts of the Continental area; the clay, silt, and fine sand sediment (Qal) in the flood plain of modern Rio de Flag accumulated in this lake. Sheep Hill has not been dated; however, it must be younger than ~0.53 Ma because it erupted after deposition of the Elden block and ash breccia. “Little Sheep Hill” and Wildcat Hill, the two basalt cinder cones southeast of Sheep Hill (red asterisks), postdate the Sheep Hill eruption, but they did not produce lava flows.

**A 1 Mountain and Observatory Mesa (Qbn): *Quaternary, 0.33 Ma, tan.***

A 1 Mountain is a cinder cone composed of the sodium-rich variety of andesite called benmoreite. A thick, viscous lava flow that extruded from the east-southeast side of the cinder cone advanced southeast nearly five miles and now forms Observatory Mesa. Parts of the lava flow spread around the sides of the cone and covered the end of the andesite (benmoreite) lava flow from Wing Mountain (also Qbn, tan). The Observatory Mesa lava advanced in the same direction as the Wing Mountain lava. Both lava flows appear to have followed an ancestral watercourse of Rio de Flag.

**Alluvium (Qal): *Quaternary, pale yellow with red dots.***

Alluvium includes silt, sand, and gravel deposited by streams, debris-flow deposits around San Francisco Mountain, and fine clay and silt sediment deposited in lakes. Two deposits related to ancestral watercourses of Rio de Flag are in the flood plain of the modern river; both deposits accumulated in lakes where ancestral watercourses of Rio de Flag were blocked by lava flows. In the Coconino Estates-downtown area immediately east of Observatory Mesa, clay, silt, and fine sand sediment records a lake impounded by the Dry Lake lava flow (Qbo). Rio de Flag was flowing southeast in a valley now covered by Observatory Mesa lava flow, and the Dry Lake flow entered the valley from the southwest. Another thick deposit of similar sediment covers the low parts of the Continental area where several faults intersect. Here, Rio de Flag was flowing north-northeast and was blocked by Sheep Hill cinder cone and its associated lava flows (Qby).

**Faults**

Faults are shown on the geologic map with thick, black lines (Fig. 4, p. 12). Dotted lines indicate where the fault is covered by younger lava flows and deposits. The bar and ball attached to the fault line are on the down side of the fault.

**Oak Creek Canyon Fault**

The trace of the Oak Creek Canyon fault extends from Horse Mesa, about seven miles southeast of Sedona, Arizona, through Oak Creek Canyon, to the south side of Observatory Mesa

(Fig. 4); the distance is about 35 miles. The fault has a complex history of movement. When compressive forces elevated mountains in southern Arizona 75 to 45 million years ago the east side of the fault was pushed up at least 580 feet near the present mouth of Oak Creek Canyon; such movement on a fault in response to compression is called “**reverse**” (opposite of “normal” movement). The latest fault movement was in response to extensional forces that displaced the east side down about 990 feet; such movement is called “**normal**.” (In the early history of geology it was thought that all faults moved in response to extension, or gravity—hence, normal). Today, the east side of the fault is about 410 feet lower than the west side. On the geologic map (Fig. 4, p. 12), the fault is shown to cut the old basalts that extruded from Woody Ridge shield volcano (Tbo), and to be covered by the Observatory Mesa lava flow (Qbn); normal movement, therefore, is bracketed between about 6 Ma and 0.33 Ma.

When the east side of the Oak Creek Canyon fault was high, it would have had a west-facing fault scarp. This scarp likely directed the old basalt from Woody Ridge shield volcano (Tbo) several miles north before it flowed around the bend of the fault to the area of McMillan Mesa.

### **Normal Faults**

The other faults on the geologic map (Fig. 4) are normal faults—that is, they moved in response to extensional forces. None of the normal faults have been eroded deeply enough to determine if any of them had earlier reverse movement like the Oak Creek Canyon fault.

Most of the faults trend northwest-southeast. According to first-motion studies of recent earthquakes, and regional analysis of faults, the extensional-stress direction of the southern Colorado Plateau is northeast-southwest, which produces pull-apart forces at right angles to the northwest-trending faults. Some faults, particularly the long ones that have north-south and northwest-southeast segments, probably are connected to ancient, deep-seated faults that have had multiple episodes of movement. The few northeast-trending faults are also likely connected to ancient, deep faults, which are well-known in Grand Canyon.

Except for the north end of the Oak Creek Canyon fault and the fault on the west edge of the map by Wing Mountain, the faults cut only the Permian and Triassic sedimentary rocks and the old basalts. No other faults have been mapped in the area covered by the young volcanic rocks. Crustal fractures probably exist, however, even where no fault is known at the surface. For example, the southeast-trending row of six cinder cones immediately south of Sunset Crater probably erupted along a buried fracture (Fig. 4, p. 12, northeast corner).

A geologic structure where the land has been displaced down between two parallel or sub-parallel faults is called a **graben**, using the German word for ditch or trench. Such extensional structures are common in Flagstaff; for example, the west side of McMillan Mesa (Switzer Canyon), the Continental area, Lake Mary, and the northwest end of Anderson Mesa.

### **Lavas and Landscapes**

Typically, a river and its tributaries drive the development of the landscape. In Flagstaff, however, the landscape guides Rio de Flag. Volcanism has, on occasion, changed the landscape independently of the river, and the Rio has had to adjust its watercourse to new surface contours. Bedrock structures, such as long, straight faults and grabens in the Kaibab Formation, lock the Rio in confining reaches as the water follows the most adaptable downhill course (Fig. 4, p. 12).

## Lavas as Liquids

Lavas are liquid (molten) because they are hot. Temperatures are around 1150°C to 1200°C for basalt and 750°C to 800°C for rhyolite; these temperatures are 7.5 to 12 times hotter than boiling water.

The physical state of lava is liquid, not necessarily entirely liquid because most lava flows contain a few percent of solid crystals. Because lavas are liquid they respond to gravity as water does—they flow downhill, seeking the lowest level possible. This is why lavas tend to push out of the base or flank of a cinder cone on the downhill side of the land surface on which the cone erupted. In many cones, the unconsolidated cinders lack enough strength and mass to support a column of lava high enough to pour over the crater rim. When the dense liquid emerges from its underground conduit below the cone gravity pulls it downhill and the lava breaches the side of the cone.

Lava flows can spread out as they flow on broad gentle slopes, or form narrow rivers as they flow down valleys. Either way, the lava covers the pre-existing land surface and preserves it from erosion. Hence, a lava flow provides clues about the pre-eruption topography and landscape

Lavas can even flow uphill. This can happen where the uphill slope is very gentle, and the lava flow is thick enough so that the top of the flow is higher than the slope up which the lava is advancing. Two places in Flagstaff where this happened are in the graben occupied by Qbo south of McMillan Mesa, and in the graben occupied by Qby south of Sheep Hill (Fig. 4, p. 12).

## Inversion of Topography

Solidified lava flows are typically harder and more resistant to erosion than sedimentary rocks. A lava that flows down a valley eroded in sedimentary rocks forms a tough, protective layer above the sediments at the bottom of the valley. Erosion then tends to wear away the sedimentary rocks along the valley sides. Eventually, the former sides of the valley get worn down below the lava flow; thus, a valley bottom that used to be low is now high. This process is called inversion of topography. McMillan and Anderson mesas are examples of inversion of topography. The Citadel lava flow on Wupatki National Monument is an excellent example (Fig. 5). Looking south from Citadel Pueblo, a cross section of the lava flow (Tb) that filled a former valley eroded in the Moenkopi Formation (TRm) can be seen above the **sinkhole**. The lava flow now forms a dark ridge that extends over four miles northeast of the pueblo, and traces a former tributary of the Little Colorado River.



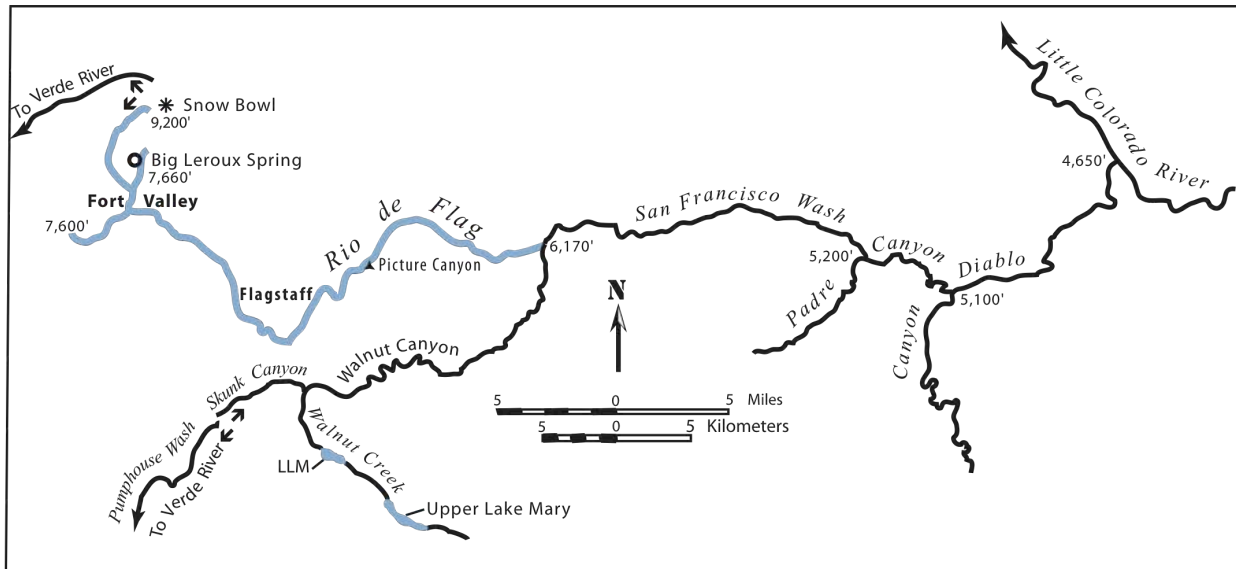
*Figure 5. Photograph of Citadel lava flow and sinkhole. View is south toward O'Leary Peak (left) and San Francisco Mtn. (right). Pk: Kaibab Formation. U: up, D: down on Citadel fault.*

## ORIGIN AND GEOLOGIC HISTORY OF RIO DE FLAG

No geologic record exists of the inception of Rio de Flag. Streams probably flowed into the strike valley now occupied by the old basalt lava flow (Tbo, ~6 Ma) on McMillan Mesa, but comments on the location and character of such streams are speculative. Integration of drainages that led to the development of Rio de Flag and Walnut Creek probably began after erosion had shifted the Shinarump Conglomerate cuesta northeast (Fig. 3, p. 11). The Moenkopi Formation between the emerging McMillan and Anderson mesas would have been removed by small streams advancing their headwaters southwest behind the cuesta. Eventually, the new streams would join with older streams west of the mesas to establish watercourses of the ancestral Rio de Flag and Walnut Creek.

### The Modern Rio

Rio de Flag collects **runoff** from several tributary branches in Fort Valley (Fig. 6). Rio de Flag joins with Walnut Creek east of Flagstaff, and downstream, San Francisco Wash enters Padre Canyon. Padre Canyon enters Canyon Diablo, which enters Little Colorado River.

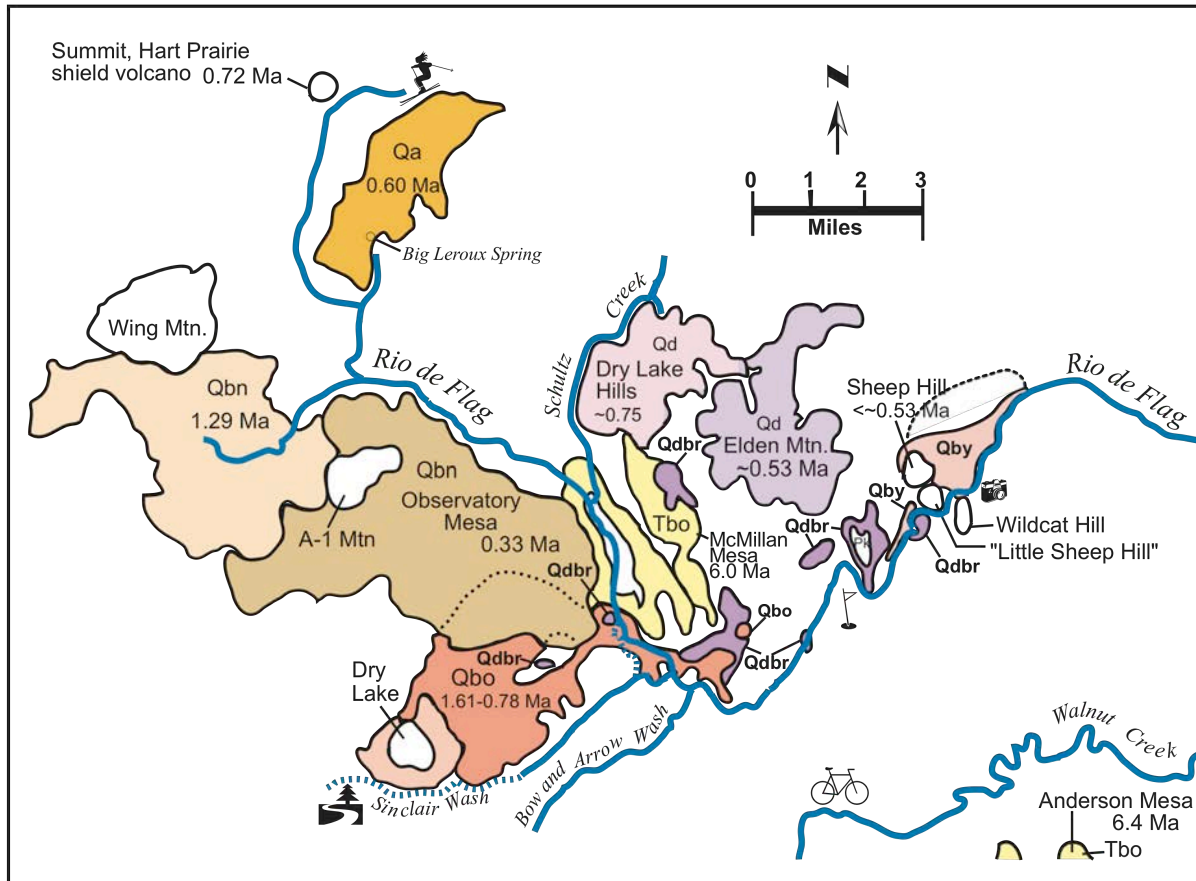


*Figure 6. Map showing Rio de Flag (blue) and related drainage systems (black). Map traced from U.S. Geological Survey Map NI 12-2, 1954, Flagstaff, Arizona, scale 1:250,000. Elevations in feet are shown at the headwaters and stream junctions. Bold arrows show stream divides LLM is Lower Lake Mary.*

Walnut Creek and Rio de Flag are only about two miles apart south of Flagstaff. Stream divides between Little Colorado River and Verde River are on the west side of San Francisco Mountain by Arizona Snow Bowl, and south of Flagstaff near Pulliam Airport.

Rio de Flag exits Fort Valley through a narrow **gully** in andesite lava flows from San Francisco Mountain and old basalt from Woody Ridge, and passes closely around the northeast side of Observatory Mesa lava flow (Fig. 7 p. 19). The river enters Flagstaff from the north along a fault-controlled valley between Observatory Mesa and McMillan Mesa. The pre-settlement channel crosses the lava flow from Dry Lake volcano (Qbo) in downtown Flagstaff. The river then enters the graben south of McMillan Mesa, bends northeast along a fracture in the

Kaibab Formation, and follows faults in a zigzag fashion in east Flagstaff. Rio de Flag exits the city through a steep **chasm** or **gorge** at Picture Canyon in the lava flow from Sheep Hill (Qby).



*Figure 7. Map showing the watercourse of Rio de Flag through Flagstaff, principal tributaries, Walnut Creek, and volcanic rock formations that caused diversions of the ancestral river to its modern channel; map-unit symbols defined on pp. 13, 14, 15. Black dotted lines show inferred part of Dry Lake lava flow (Qbo) covered by Observatory Mesa lava flow, and inferred part of Sheep Hill lava flow (Qby) covered by debris eroded off of Elden Mountain. Blue dotted lines show diverted reach of Rio de Flag in downtown Flagstaff, and post-Dry Lake reach of upper Sinclair Wash. Icons: skier, Arizona Snow Bowl; pine tree, The Arboretum at Flagstaff; golf hole with flag, Continental Country Club; camera, Picture Canyon; bicycle, Fisher Point.*

Rivers that display a long-term balance between discharge, velocity, erosion, sediment transported and deposited, and gradient are classified as **graded**, or **mature**. Through a succession of seasons erosion and sediment deposition occur, and these processes may change locations along the river through time. A graded river has a concave-up curve on a graph that plots channel elevation against distance along its length from headwaters to mouth; the curve is called a **longitudinal profile** (Fig. 8, p. 20).

A lava flow that enters a river's valley can cause flattening of the profile in an impounded lake on the upstream side of the flow, and steepening of the profile on the downstream side. Deposition of sediment will occur in the lake, and erosion, possibly under a waterfall, will occur on the downstream side of the flow. The steepened place on the profile at a

rock resistant to erosion is called a **knickpoint**. Over time, erosion lowers the knickpoint and shifts it upstream.

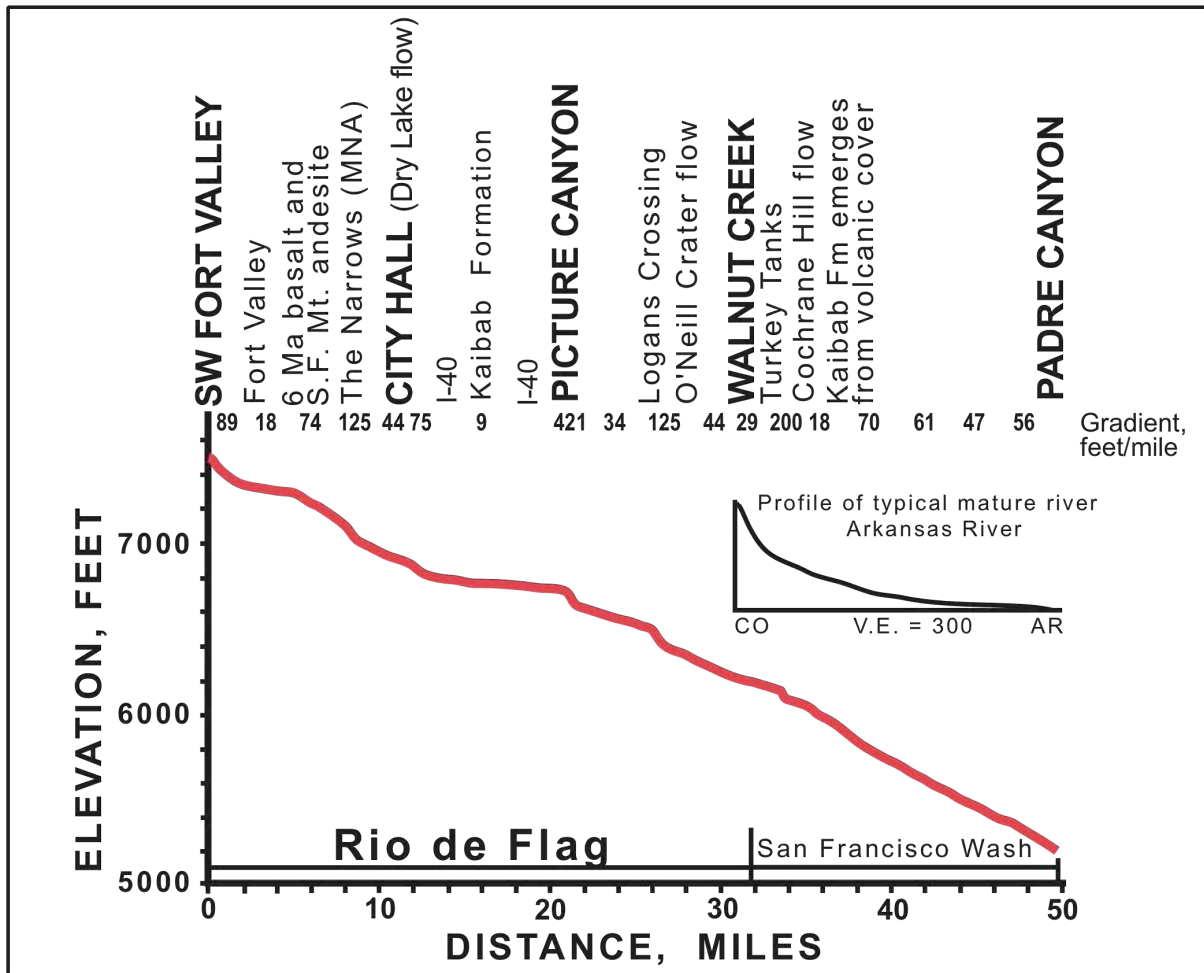


Figure 8. Longitudinal profile of Rio de Flag and San Francisco Wash, red line. Vertical exaggeration (V.E.) is 52.8. Inset shows an example of the profile of a graded, or mature, river between Colorado and Arkansas.

Modern Rio de Flag has numerous convexities on its profile, and several abrupt increases and decreases in its **gradient** (Fig. 8). The profile is irregular and broadly convex-up, so Rio de Flag is an **immature river**. All of the convexities on Rio de Flag’s profile are at resistant lava flows in its valley. Some of the flatter parts of the profile record former lakes, such as in Fort Valley, and the Continental area upstream from I-40. Modern Rio de Flag is an **intermittent**, or **ephemeral**, river, and only flows seasonally. It seems that local volcanism has occurred at a faster rate than Rio de Flag can remove convexities from its profile.

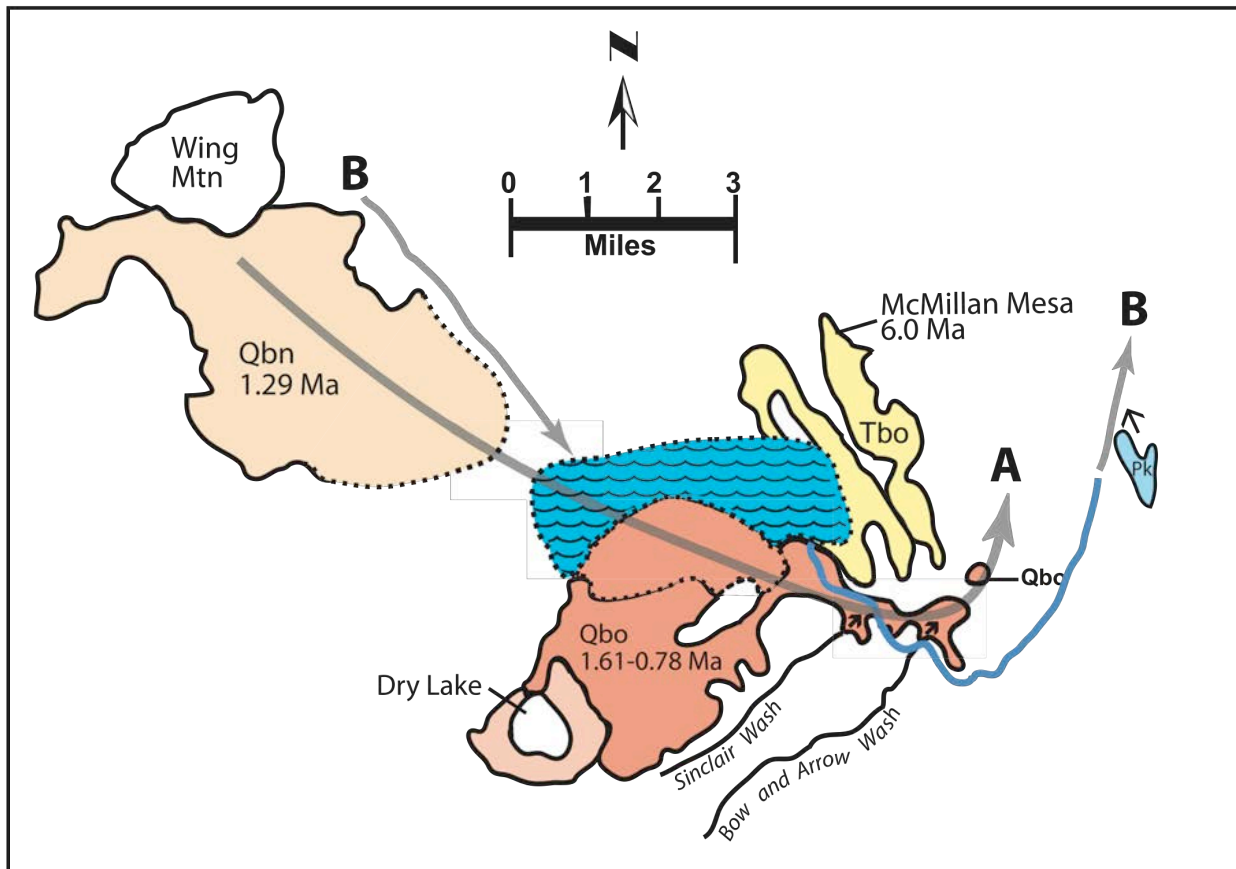
### The Ancestral Rio

No convincing record exists of the earliest course of Rio de Flag; its recorded history, however, starts over one million years ago. Since its origin, Rio de Flag changed its watercourse several times in response to changes in Flagstaff’s landscape. Episodic eruptions of volcanoes and lava flows in different places are the agents of change that occurred independently of the river. The modern watercourse is complicated because different reaches of the river have

different ages, largely a result of eruptions at different times. Ancestral watercourses of Rio de Flag are interpreted with known positions of volcanoes and shapes of lava flows, the principles of liquids and gravity as applied to lava flows and water, geologic structures as displayed on the geologic map (Fig. 4, p. 12), and field-based **stratigraphy** of lava flows, pyroclastic deposits, and lake sediments.

### Ancestral Watercourses A and B

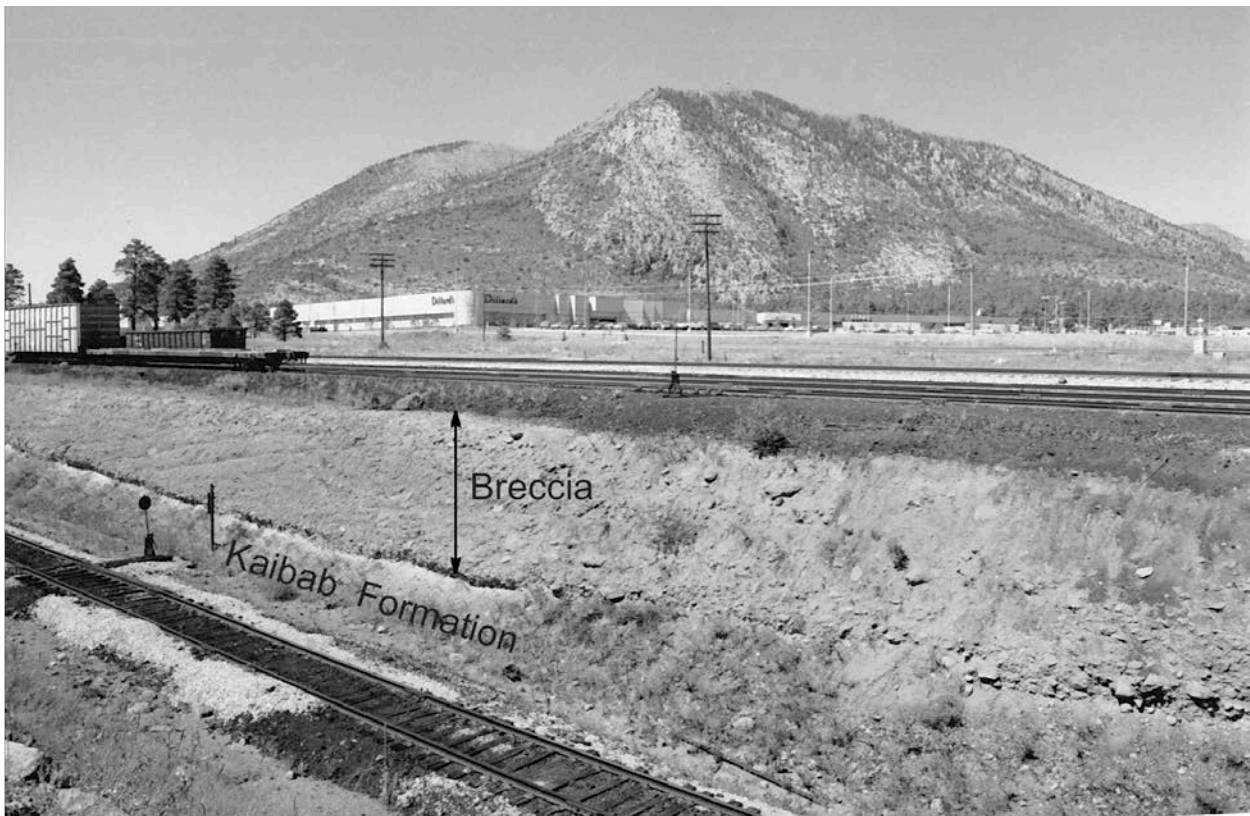
The oldest watercourse that can be demonstrated runs from Wing Mountain to downtown Flagstaff. This valley, ancestral watercourse A, existed when the Wing Mountain lava flow (Qbn) and the Dry Lake lava flow (Qbo) erupted, but their order of eruption is not known (Fig. 9); Wing Mountain is described first. The Wing Mountain lava flow extruded on the south side of Wing Mountain cinder cone and flowed southeast; this was the only direction it could flow. The volcano blocked flow to the west and north; early San Francisco Mountain also blocked flow to the north; south was up hill toward Woody Ridge; east was blocked by McMillan Mesa. After the Wing Mountain lava flow (Qbn) filled upstream watercourse A, ancestral Rio de Flag probably started eroding a new channel along the northeast side of the lava as watercourse B (Fig. 9). Age of the Wing Mountain lava flow is fairly tightly constrained to be about 1.29 Ma.



*Figure 9. Map showing ancestral watercourses A and B (gray lines), tributaries Sinclair Wash and “Bow and Arrow Wash”, relevant volcanoes and lava flows, and depiction of a lake (blue) behind the Dry Lake lava flow (Qbo). Black dotted lines show inferred extent of Qbn and Qbo now buried below the Observatory Mesa lava flow, and the inferred extent of the lake. Bold arrows show pre-lava connections of the tributaries to watercourse A. Thin arrow shows inferred connection of small tributary to watercourse B. Rio de Flag (blue line) was rearranged to watercourse B when a new channel was eroded across the dam made by the Dry Lake lava flow.*

The Dry Lake lava flow extruded on the northeast side of its cinder cone southwest of Flagstaff (Fig. 4, p. 12), and flowed northeast as a broad sheet and a narrow stream; the latter probably flowed in a tributary to watercourse A. This direction of flow is parallel to the watercourses of Sinclair Wash and “Bow and Arrow Wash” and is straight down the tilt direction of the Kaibab Formation (Figs. 4, 9). After entering watercourse A, the Dry Lake lava then flowed southeast and northeast as a narrow stream around the south end of McMillan Mesa. The Dry Lake lava also advanced into the mouths of Sinclair Wash and “Bow and Arrow Wash”, and flowed southeast up a gentle slope into the graben south of McMillan Mesa (Figs. 4, 9). The age of the Dry Lake flow is bracketed between 1.61 Ma and 0.78 Ma.

Dry Lake lava flow blocked watercourse A, and impounded a lake behind it (Fig. 9). Evidence for the lake is clay, silt, and fine sand sediment in the Coconino Estates area; outcrops can be seen along the Flagstaff Urban Trail shortly north of the neighborhood. The lake probably was intermittent (ephemeral). Eventually, the lake filled and water spilled over the lava dam. The renewed Rio de Flag carved a new channel across the lava flow, eroded the graben south of McMillan Mesa, and made a new channel along a northeast-trending fracture in the Kaibab Formation as watercourse B (Fig. 9). A small tributary from the southeast cut a valley in the Kaibab Formation (Fig. 9, 10).

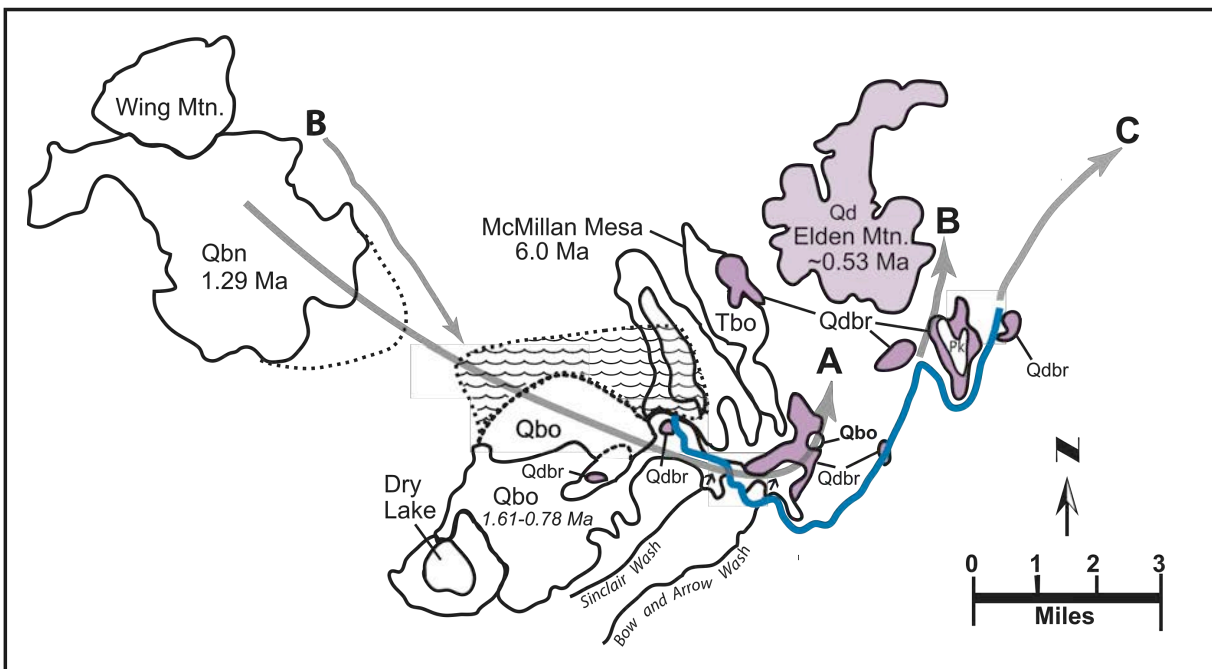


**Figure 10. Photograph of a paleovalley eroded in Kaibab Formation (below shadow in small recess) that was filled with the Elden block and ash breccia (above shadow); axis of valley trends north-northwest. View is looking northwest from the Nestle Purina plant railroad spur. Before the Elden Mountain eruption the paleovalley might have been a tributary to watercourse B. Flagstaff Mall is in middle distance. Elden Mountain is on the skyline; several overlapping lava flows form the southeast flank of the volcano.**

### Ancestral Watercourse C

The Elden Mountain eruption around 0.53 Ma. forced another rearrangement of the Rio de Flag watercourse. The hot **pyroclasts** (pumice, blocks, ash) and gas of the Elden block and ash breccia (Qdbr) exploded out of the vent during the early stage of the eruption. Pulled down from the eruption column by gravity, the hot mass acquired enough momentum to spread across a broad swath of Flagstaff, from east of the Flagstaff Mall to west Route 66. Part of the deposit covers the north end of McMillan Mesa, but most of it fills stream courses and other low-lying areas, such as grabens (Figs. 4, 11). Degassed lava then extruded from the vent (or vents), and multiple thick lava flows piled up on top of each other to build Elden Mountain (Fig. 10).

Elden Mountain and the block and ash breccia blocked ancestral watercourse B. Water probably backed up behind the new volcanic deposit until it could spill into the graben system in the Continental area. Because the block and ash breccia is not consolidated and is easily eroded, Rio de Flag likely carved ancestral watercourse C fairly quickly. The zigzag trace of watercourse C follows the intersecting northwest- and northeast-trending grabens in the Continental area (Figs. 4, 11).



*Figure 11. Map showing ancestral watercourse C, Elden Mountain (Qd, medium purple), and the distribution of the preserved and exposed remnants of the Elden block and ash breccia (Qdbr, dark purple). Rio de Flag is blue. Volcanic formations and the inferred lake on Figure 9 are shown in outline.*

### The Sheep Hill Eruption

Sheep Hill and A 1 Mountain, both cinder cones, erupted lava flows at about the same time, but their order of eruption is not known. Sheep Hill is described first. Sheep Hill and its two lava flows (Qby) are younger than Elden Mountain, therefore, younger than 0.53 Ma. The map in Figure 12 (p. 24) displays outcrops of the Elden block and ash breccia (Qdbr) on both the west and east sides of the narrow, finger-like lava flow (Qby) that extruded from the south side of Sheep Hill. Breccia is not shown on top of the lava flow. This field relation indicates the lava must be younger than the breccia because the pyroclastic flow that deposited the breccia covered the ground between the vent at Elden Mountain and the distal edges of the breccia.

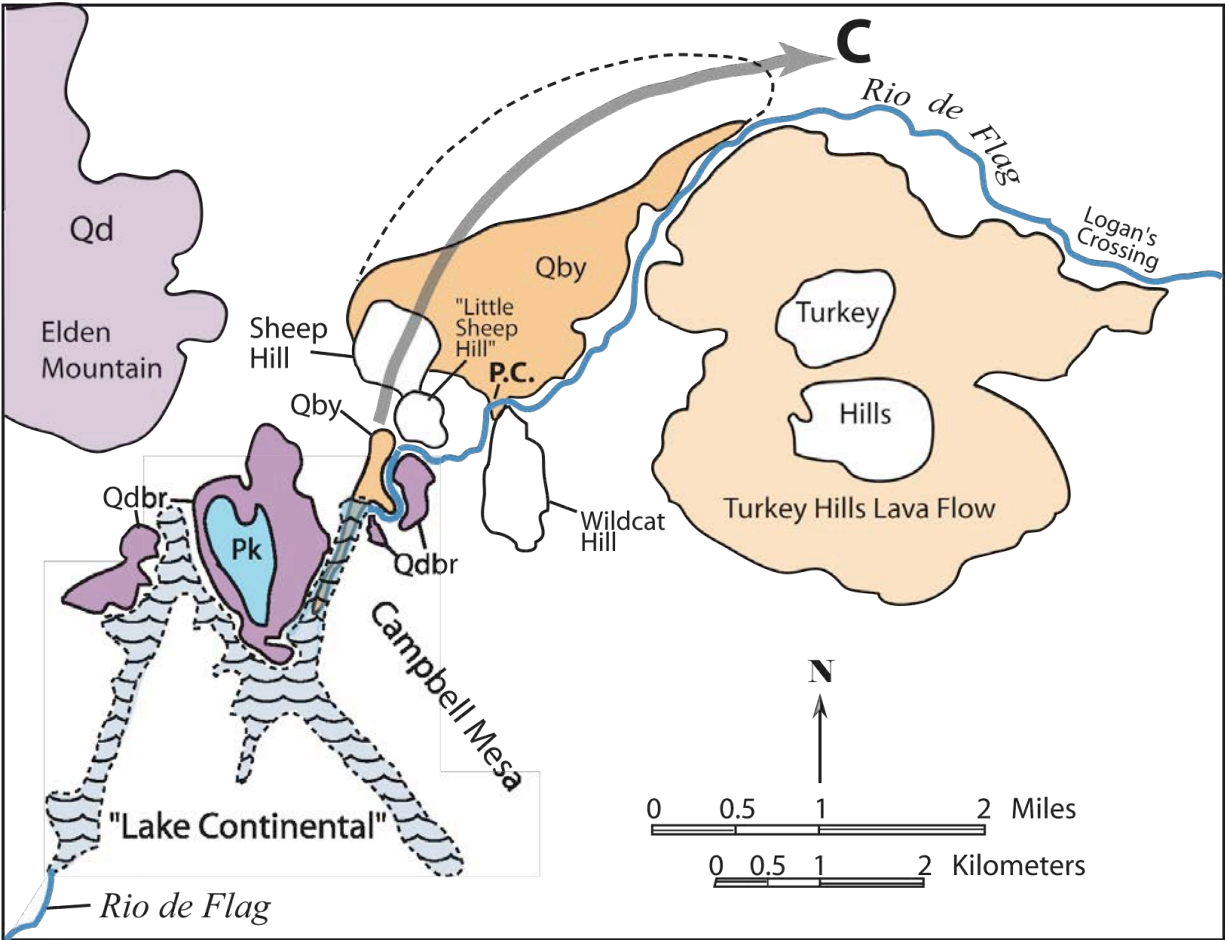


Figure 12. Map showing modern watercourse of Rio de Flag (blue) in the Sheep Hill-Picture Canyon area. Picture Canyon (P.C.) is where the modern Rio de Flag crosses the south point of the large Sheep Hill lava flow (Qby, orange) at the north end of Wildcat Hill. "Lake Continental" (light blue with waves) filled behind the dam at the small Sheep Hill lava flow (Qby) until the water could spill out at about 6,780 feet elevation (modern) to erode the new watercourse of Rio de Flag. The southwest end of the lake where Rio de Flag enters is drawn at about 6,770 feet elevation for drafting convenience. Dotted line next to ancestral watercourse C (gray arrow) shows inferred part of large Sheep Hill lava flow covered by debris eroded off of Elden Mountain.

In carving ancestral watercourse C, Rio de Flag eroded the block and ash breccia that filled the intersecting grabens in the Continental area and continued around the north side of the Turkey Hills lava flow (Figs. 11, 12). Sheep Hill erupted in watercourse C and produced two lava flows (Qby). The larger flow extruded on the northeast (downhill) side of the cinder cone and followed watercourse C for about 2.5 miles. The smaller flow extruded on the south (uphill) side of the cone and flowed southwest up a gentle gradient in the Rio de Flag channel for about 1.5 miles. The "hook" on the east side of the small lava flow is where the lava entered the mouth of a tributary at the north end of Campbell Mesa.

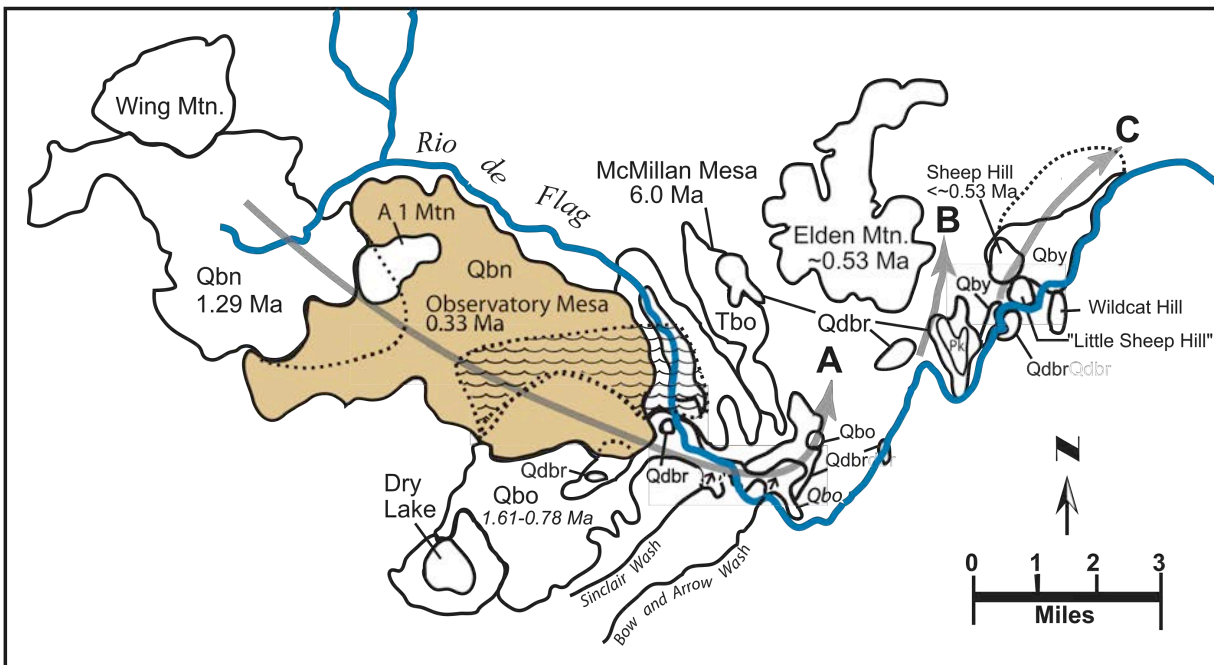
The small lava flow from Sheep Hill cinder cone blocked watercourse C and impounded water, probably intermittently, in the low-lying parts of the graben system in the Continental area; informally, the lake has been called "Lake Continental." Evidence for the lake is the thick deposit of clay, silt, and fine sand sediment in the grabens. The sediment was also deposited on top of the south half of the small lava flow from Sheep Hill (Qby, orange) (Fig. 12).

Small benches on the south side of “Little Sheep Hill” at 6,780 feet elevation, and benches at the same elevation on the north end of Campbell Mesa, suggest that “Lake Continental” filled to that elevation (modern) before overflowing. The new, modern, channel of Rio de Flag passes along the east side of the small lava flow, cuts between “Little Sheep Hill” and Campbell Mesa, crosses the large lava flow from Sheep Hill at Picture Canyon, and continues around the north side of the lava flow from Turkey Hills (Fig. 12).

### A 1 Mountain and Observatory Mesa

A 1 Mountain cinder cone erupted in the valley of ancestral watercourse A about 0.33 Ma (Fig. 13). Extruding lava pushed out the southeast side of the cone, which rotated around to the north like an opening door. Most of the lava that poured out of the vent supplied a thick flow that filled the ancestral valley and advanced southeast down-valley for 4.5 miles; this lava flow is Observatory Mesa (Fig. 13, Qbn, brown). The thick mass of extruded lava might have blocked the last surges of lava that spread around the north and south sides of the cinder cone. The Observatory Mesa lava flow covered the distal end of the Wing Mountain lava flow (Qbn, no color), part of the Dry Lake lava flow (Qbo, no color), and most of the lake behind Qbo (waves). The old basalt from Woody Ridge shield volcano (Tbo) that caps McMillan Mesa was also covered by the Observatory Mesa lava flow (Fig. 13, Fig. 4, p. 12).

Again, ancestral Rio de Flag was displaced by lava. The rearranged modern drainage passes closely around the north and east sides of the Observatory Mesa lava flow, follows the fault-controlled valley through Coconino Estates between McMillan and Observatory mesas, continues through west-side neighborhoods, and joins ancestral watercourse B in downtown Flagstaff at the spill-over point of the Dry Lake lava dam (where the blue line crosses the dotted black line at the south end of the lake; also see Fig. 9, p. 21).

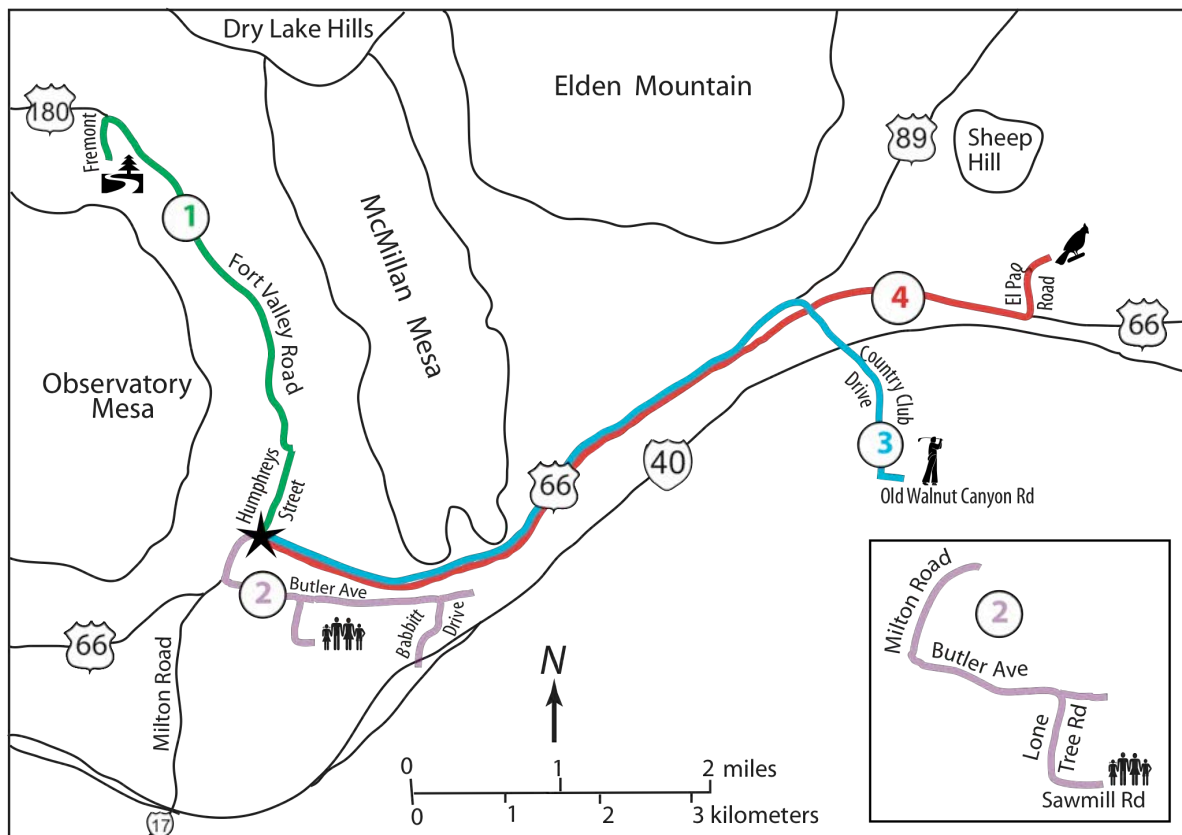


**Figure 13.** Map showing A 1 Mountain cinder cone and Observatory Mesa lava flow (Qbn, brown). Modern Rio de Flag is blue. Older volcanic formations are shown in outline form. Features buried by A 1 Mountain and Observatory Mesa lava flow are dotted; inferred lake behind Dry Lake lava flow shown with wavy lines. Ancestral watercourses A, B, and C are gray. Upstream reach of watercourse B and diverted course through downtown Flagstaff are omitted to avoid congestion on the map.

## PART 2. TRAIL GUIDES TO GEOLOGY ALONG RIO DE FLAG

### OVERVIEW

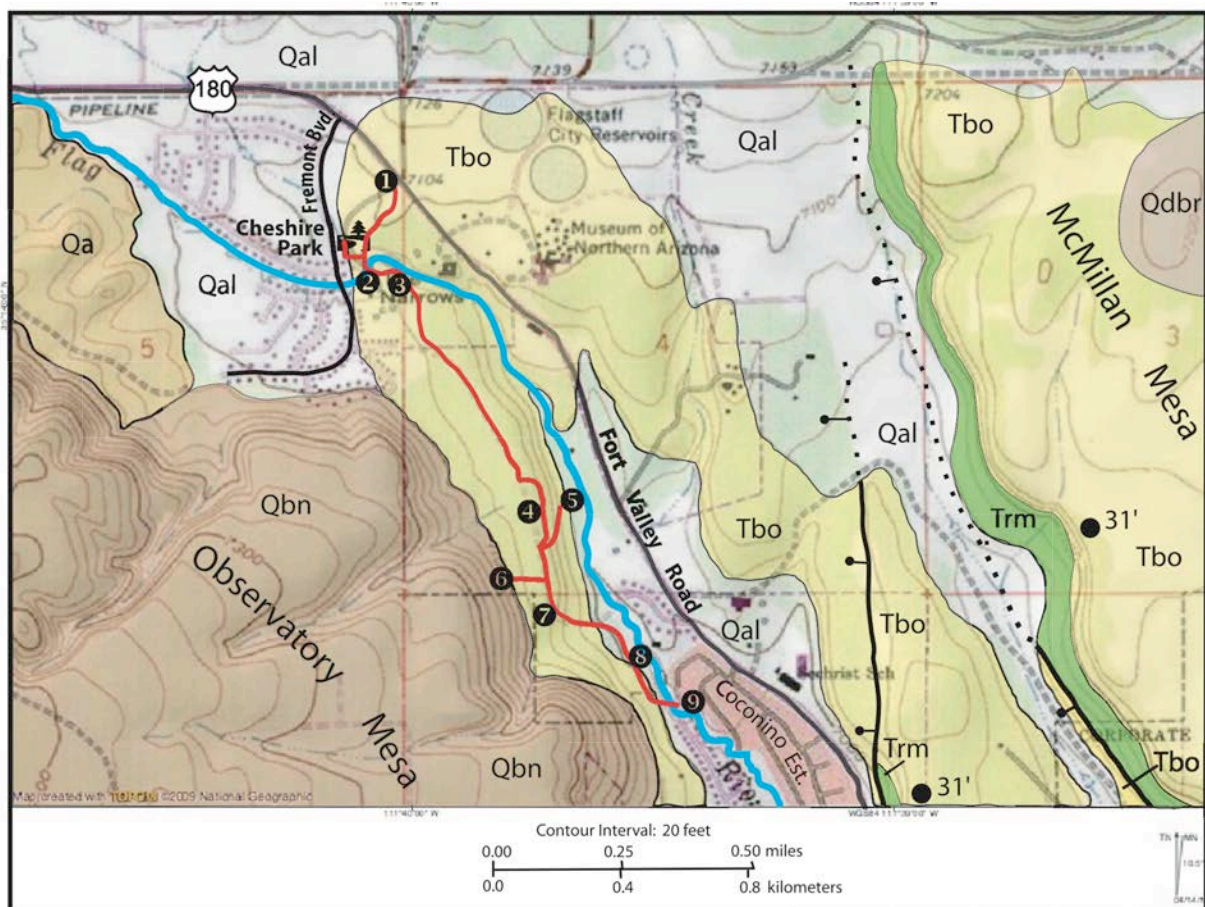
Rio de Flag is accessed in Flagstaff with City-maintained trails and well-used social trails. The trail guides apply field observations and analysis of maps as an out-door way for walkers to gain information about the general geology of Flagstaff and the geology along Rio de Flag. Four trails in downstream order are: 1. Cheshire Park to Crescent Drive; 2. Sawmill County Park to Little America; 3. Old Walnut Canyon Road to Big Fill Lake; 4. Picture Canyon loop trail (Fig. 14). Each guide has a topographic and geologic map that shows the trail, Rio de Flag, numbered locations on the trail keyed to numbered sections of the text, and names of prominent physiographic and geologic features. The trails are appropriate for most walkers. Public toilets are at or near all trailheads. Out and back lengths of the trails range from 2.6 to 4.8 miles, and elevation gains are 10 to 144 feet. All directions to the trailheads start at the downtown intersection of Historic Route 66 and Humphreys Street (star on Fig. 14).



*Figure 14. Map showing routes to trailheads that are marked by icons; star shows start location of driving directions at intersection of Historic Route 66 and Humphreys Street. Trailhead 1: Cheshire Park, tree next to trail; Trailhead 2: Sawmill County Park, hiking family; Trailhead 3: Old Walnut Canyon Road, golfer; Trailhead 4: Picture Canyon Natural and Cultural Preserve, bird. Inset map is enlarged to show streets to Trailhead 2. Trail 2 can be walked in two visits: Stops 1 to 6, and Stops 6 to 9. Stop 6 is accessed by South Babbitt Drive.*

## TRAIL 1: CHESHIRE PARK TO CRESCENT DRIVE (COCONINO ESTATES)

**Synopsis:** The trail is the Karen Cooper section of the Flagstaff Urban Trails System. The guide starts at a panoramic scene of volcanoes and lava flows that dominate Flagstaff's landscape, and which forced multiple rearrangements of the Rio de Flag watercourse. The location, shape, and gradient of Rio de Flag are examined, and interpreted with geologic principles. Rock outcrops along the trail provide close-up views of textures of lava flows that had different viscosities and, therefore, have different sizes and shapes that can be compared on the trail and on maps. Fault control of the watercourse where the Rio enters Flagstaff is demonstrated with the geologic map and a view of McMillan Mesa. Sediment composed of clay, silt, and fine sand seen near the end of the trail is evidence for a lake behind a lava dam in downtown Flagstaff. The trail guide ends at a new foot bridge that crosses Rio de Flag next to Crescent Drive in Coconino Estates.



**Figure 15.** Map showing Trail 1 (red line), Rio de Flag (blue line), faults (heavy black lines, bar and ball on down side, dotted where covered by younger deposits). Rock formations: Trm: Moenkopi Formation; Tbo: oldest basalt lava (~6 Ma); Qdbr: Elden block and ash breccia (~0.53 Ma); Qa: andesite lava from Fremont Peak on San Francisco Mountain (~0.43 Ma); Qbn: Observatory Mesa lava flow (benmoreite, 0.33 Ma); Qal: alluvium and lake sediments. Watercourse of Rio de Flag in the Cheshire neighborhood taken from Google Earth (2017). •31' is measured thickness of Tbo. Stop numbers on trail are keyed to text. Pine tree icon is at trailhead at Cheshire Park.

**Directions to trailhead:** Take Humphreys Street north about 0.6 miles to its end at Fort Valley Road and Columbus Street. Turn left and follow Fort Valley Road for about 2.6 miles to the signal at Fremont Boulevard and Schultz Pass Road. Turn left onto Fremont Boulevard and go about 0.25 miles; the parking lot on the left is at the north end of Cheshire Park.

**Character of trail:** Maintained trail of the Flagstaff Urban Trails System (FUTS).

**Length round trip:** About 4 miles.

**Elevations:** 7102 ft to 6977 ft. On return, one short uphill stretch rises 50 feet.

**Time:** Allow 2-3 hours.

**Difficulty:** Easy.

**Base map:** U.S. Geological Survey, Flagstaff West Quadrangle, Arizona, 7.5' Series, 1962.

**Road and trail distances and elevations:** Google Earth.

**Trail Guide:** *From parking lot at Cheshire Park walk south on sidewalk to path along south side of the park. Follow the path east to the Karen Cooper Trail and turn left. Walk north on the trail to a point about 200 feet (0.04 mi) past the third culvert with guard rails where you get a good view of the surrounding terrain.*

### Stop 1. North end of Karen Cooper FUTS Trail

A. Landscape features seen in clockwise panorama from south (Fig. 16):

**Observatory Mesa:** thick andesite (benmoreite) lava flow from A 1 Mountain, 0.33 Ma.

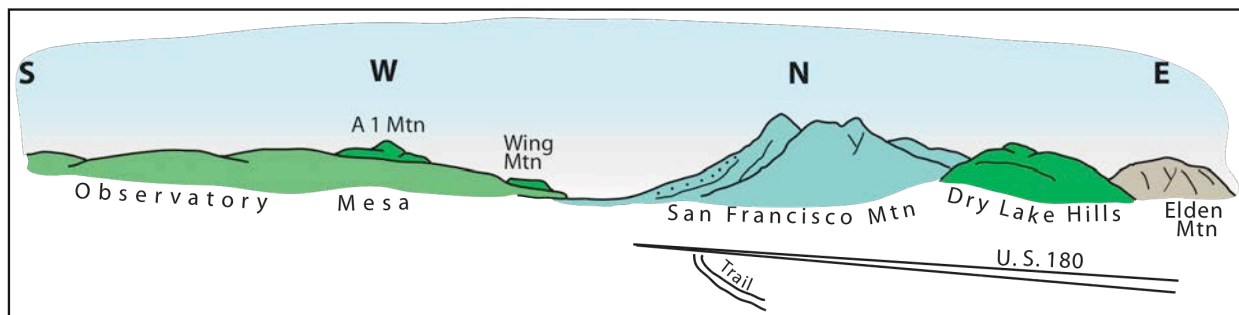
**A 1 Mountain:** andesite (benmoreite) cinder cone; source of Observatory Mesa lava flow.

**Wing Mountain:** basalt cinder cone on top of vent of andesite (benmoreite) lava flow in ancestral Rio de Flag valley; andesite (benmoreite) lava flow is 1.29 Ma. See Fig. 9, p. 21.

**San Francisco Mountain:** composite volcano, >1.82 Ma to 0.40 Ma.

**Dry Lake Hills:** cluster of eight dacite lava domes, ~0.75 Ma.

**Elden Mountain:** cluster of four dacite lava domes, ~0.53 Ma.



**Figure 16.** 270 degree panorama sketch of landscape features seen at Stop 1. Principal peaks on San Francisco Mountain are, from left: Agassiz Peak, Fremont Peak, Doyle Peak (lower, round). Andesite lava flow on southwest side of Agassiz Peak (dots on sketch) is 0.60 Ma; this lava is older than the Qa flow on Figure 15.

B. Modern headwater tributaries of Rio de Flag are 0.60 to 1.29 million years old. The andesite lava flow on the southwest side of Agassiz Peak (Fig. 16) directs surface drainage from Arizona Snow Bowl along its west side to Fort Valley, and ground water seeps from the bottom of the lava flow at Big Leroux Spring (Fig. 7, p. 19). Surface flow from the southwest side of Fort Valley starts on the Wing Mountain andesite lava flow (Fig. 7).

**C.** The reach of modern Rio de Flag in Cheshire is contemporary with the Observatory Mesa lava flow, about 0.33 Ma. The river follows a curving watercourse closely around the west, north, and east sides of Observatory Mesa (Fig. 7, p. 19). The river adjusted its watercourse to the lava flow; the lava flow, over 250 feet thick did not adjust its edge to the river's channel. Hence, Rio de Flag from Fort Valley to downtown Flagstaff is 0.33 m.y. old.

**D.** Between 0.60 Ma and 0.33 Ma what direction did the Rio's headwaters flow before the Observatory Mesa lava extruded? Not north, San Francisco Mountain was in the way. Not west, Wing Mountain was in the way. Not south, land was uphill to Dry Lake and Woody Ridge. Not east, McMillan Mesa was in the way. The only possible direction was southeast.

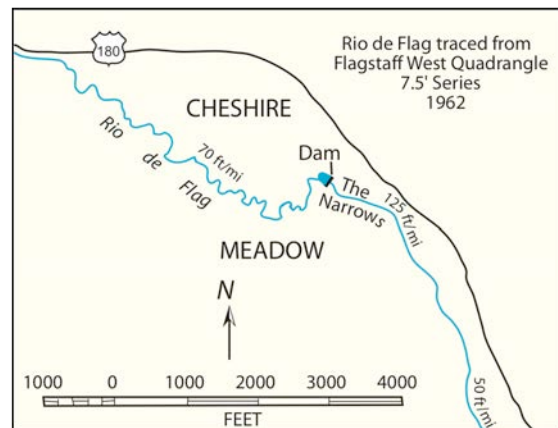
**E.** The Observatory Mesa lava flow was also constrained to flow southeast. The lava breached the southeast side of A 1 Mountain, which is the downhill side of the land surface on which the cinder cone erupted. The lava flow is elongated southeast (Fig. 7, p. 19), which indicates the flow direction from A 1 Mountain. The lava followed and filled ancestral watercourse A of Rio de Flag (Fig. 13, p. 25).

**F.** The bedrock in Cheshire is a basalt lava flow (Tbo, Fig. 15, p. 27) that extruded around 6 Ma from Woody Ridge shield volcano 10 miles to the south-southwest (Fig. 2, p. 9 and Fig. 4, p. 12). From Cheshire the lava advanced eastward into an ancient valley now preserved below the lava flow on McMillan Mesa (Fig. 3, p. 11). When plotted on a geologic map, the vent structure and its lava flow trace the flow direction of the lava and reveal the slope and configuration of the ancient landscape (Fig. 4, p. 12).

*Retrace steps to Cheshire Park and continue south on Karen Cooper Trail to Stop 2.*

## Stop 2. FUTS bridge over Rio de Flag

Today, Rio de Flag has a smooth, curving course through Cheshire (Fig. 15, p. 27). The watercourse was channelized by developers in the 1960s for an "efficient" layout of streets and houses. Predevelopment, the river followed a meandering course across the meadow (Fig. 17). The Rio's channel is in alluvium on top of the basalt lava flow Tbo (Fig. 15). The gradient in the meadow was fairly steep, 70 feet per mile; this gradient was adjusted to the eastward slope of the surface of the basalt lava flow on the west side of the paleovalley under McMillan Mesa (Fig. 3, p. 11). Most streams have the potential for flooding under the right conditions, and most of the Rio's discharge in Cheshire comes from Fort Valley. Currently (2018), Snow Bowl Road in Fort Valley acts as a check dam so the flood potential is greater in Fort Valley than in Cheshire.



*Figure 17. Map showing Rio de Flag before development of Cheshire neighborhood. Traced from U.S. Geological Survey, Flagstaff West Quadrangle, 7.5' Series, 1962, with photorevision in 1983. Gradient is feet per mile (ft/mi).*

*Continue along the Karen Cooper Trail to Stop 3 at The Narrows, about 175 feet past the dam.*

### **Stop 3. The Narrows**

**A.** The Narrows is a small canyon eroded in the oldest basalt lava flow (Tbo). The canyon is about 20 to 30 feet deep and 80 feet wide. The change in shape of Rio de Flag from predevelopment meandering in Cheshire meadow to straight in The Narrows suggests a knickpoint at the head of the canyon. Steep rapids and possibly a small waterfall are likely below the cattails, willows, and sediment fill in the pond. Here, the gradient steepens abruptly to 125 feet per mile in concert with the change to a straight channel (Fig. 17). The alluvium of angular boulders was derived from the canyon and indicates increased velocity of the Rio (when water is flowing). The knickpoint below the pond might be the site of “San Francisco spring” described by the Whipple expedition in 1853 (see Bill Wade, *Arizona Daily Sun*, June 8, 2017, page B1; also Bills and Enyedy, 2014-2015, endnote 3, p. 78).

**B.** The rate of erosion of Rio de Flag at The Narrows is about 30 feet in 330,000 years, or about 90 feet per million years. At Picture Canyon, the geology is more complex and the basalt has not been dated. The chasm at Picture Canyon is approximately 75 feet deep and about 300 feet wide; the estimated rate of erosion by Rio de Flag is about 165 feet per million years. Rio de Flag at Picture Canyon is more vigorous than it is upstream at The Narrows, which probably results from additional discharge supplied by tributaries such as Sinclair Wash and "Bow and Arrow Wash." In comparison, the rate of erosion of Walnut Creek in a basalt lava flow at Canyon Vista Campground southeast of Flagstaff is about 210 feet per million years.

**C.** It is uncertain when and why the dam was built. According to Merriam Pederson, a former resident in the area, the dam was built in the 1940s or 1950s by Mr. Cheshire, probably as an impoundment structure for his farm. (also see Bills and Enyedy, 2014-2015, p. 53).

*Continue along the trail to Stop 4. Cross Blue Willow Road. At the junction of Karen Cooper Trail and Observatory Mesa Trail bear left to stay on the Karen Cooper Trail and continue for about 550 feet (0.1 mi) to where you can see McMillan Mesa through the trees to the left (east).*

### **Stop 4. View of McMillan Mesa from Karen Cooper Trail**

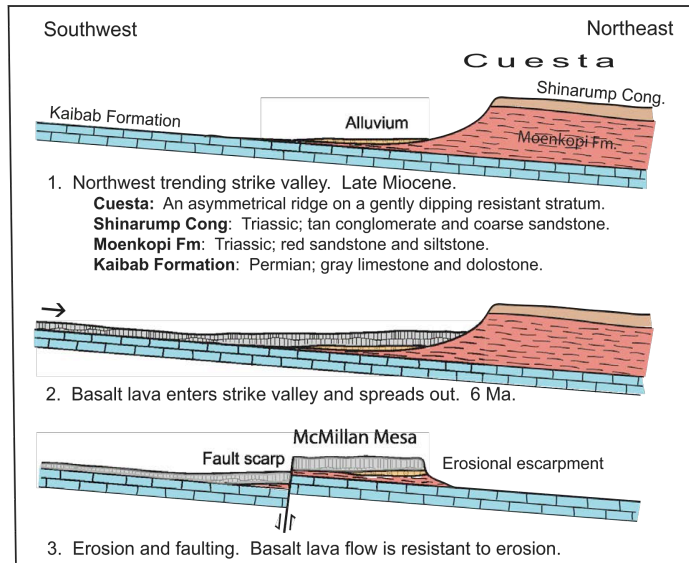
**A.** Seen to the east, McMillan Mesa is about one mile away and about 100 feet higher (Fig. 18). The mesa is capped by the same basalt lava flow seen at The Narrows and along the Karen Cooper Trail. The difference in elevation is due to faults that lowered the land west of the mesa (Figure 15, p. 27). The largest faults are along Fort Valley Road, Switzer Canyon, and the west side of McMillan Mesa.



*Figure 18 (right). View of McMillan Mesa from Stop 4 on Karen Cooper Trail.*

The diagram at right, reproduced from Figure 3 on p. 11, schematically illustrates the sequence of events of landscape development. Stop 4, at about 7078 feet elevation, is on the left (southwest) side of panel 3; the north end of McMillan Mesa ranges in elevation from about 7140 feet to 7200 feet.

**B.** The lava flow on McMillan Mesa thins southeastward from about 30 to 35 feet thick in the middle of the mesa (Fig. 15, p. 27) to 13 feet thick above Route 66 (Fig. 21, p. 35). Originally, the surface of the lava in the strike valley was approximately horizontal. The thinning of the lava is due to the bottom of the paleovalley rising in elevation southeastward toward an intravalley stream divide (see discussion p. 10).



**C.** At 6 Ma, when the basalt lava extruded from its vent at Woody Ridge, Rio de Flag did not exist. The modern Rio de Flag follows, in part, the fault-controlled valley between "Cherry Hill" (west of Switzer Canyon, Fig. 21, p. 35) and Observatory Mesa.

*Walk south on the Karen Cooper Trail to the intersection with North Creekside Drive. Turn left and walk down North Creekside Drive about 400 to 500 feet (0.095 mi) to get a good view of the road cut in the basalt lava flow at Stop 5.*

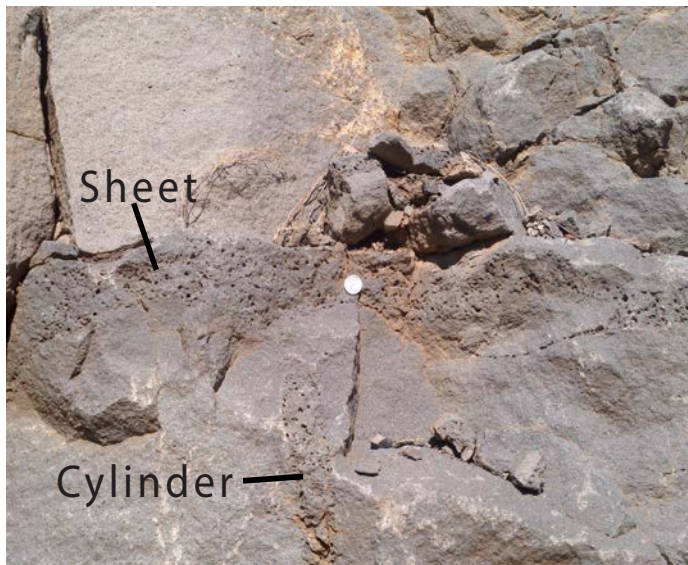
### Stop 5. Road cut in oldest basalt lava flow (Tbo) on North Creekside Drive

**A.** This road cut lets you see what the interior of a low-viscosity, highly fluid lava flow looks like. The lava flow is similar to those that erupt on Hawaii, which commonly get good video coverage on TV news channels. Features of low viscosity (a measure of resistance to flow) seen here include:

**a.** Very low aspect ratio (thickness divided by length). The top of the lava flow has been eroded, but not by very much. The bottom of the lava flow is not exposed in this area, but the lava's thickness here is judged to be about 45 feet, and the length is about 10 miles from the Woody Ridge shield volcano. Aspect ratio is 0.00085. Fed by large erupted volumes, sheet lava flows like this one can flow a long distance from the vent because they advance through a system of **lava tubes**, which help retain heat by insulating the lava from cool air and ground surfaces.

**b.** Interior of lava flow is crystalline, no glass. This texture indicates that even with rapid cooling the lava was fluid enough for atoms to move easily to nucleation sites to grow crystals. Glass would indicate that the lava was too stiff for atoms to collect together in an orderly manner to grow crystals.

c. **Prominent vesicles** (gas pockets), **vesicle cylinders**, and **vesicle sheets** (Fig. 19). Vesicles indicate that the lava is sufficiently fluid so that gas bubbles can easily escape from the hot liquid. Vesicle cylinders are vertical bubble trains that rise from a nucleation (or **exsolution**) spot in the interior of the lava flow. Vesicle sheets are horizontal layers full of bubbles trapped by partly solidified layers higher in the lava flow. Cylinders feed sheets.



*Figure 19 (right). Photograph of vesicle cylinder and vesicle sheet in road cut in Tbo basalt on North Creekside Drive at Stop 5. Coin gives scale.*

**B. Low viscosity results from:**

- a. Low silica content ( $\text{SiO}_2 = 49\text{-}50\%$ , range of several analyses).
- b. High temperature ( $\sim 1150^\circ\text{C}$ ,  $2100^\circ\text{F}$ ).
- c. Dissolved water and other gases (that escape as bubbles as the lava cools and solidifies).

**C.** Large green crystals partly altered to reddish substance ( $\sim 3$  mm) are olivine; small sparkly white crystals are plagioclase; small black crystals are pyroxene and magnetite.

*Return to the Karen Cooper Trail where it joins North Cobblestone Circle. Continue south (left) on North Cobblestone Circle and follow it around the bend to the west. Walk about 400 feet (0.075 mi) west to the steep rocky slope on the hillside next to the sidewalk.*

**Stop 6. On North Cobblestone Circle at the base of Observatory Mesa**

**A.** At this stop you can make observations about the Observatory Mesa lava flow (0.33 Ma) for comparison with the oldest basalt lava flow at Stop 5 (Tbo,  $\sim 6$  Ma). The dark gray, angular blocks of rock here are on a colluvial slope at the base of the Observatory Mesa lava flow, an alkali-rich andesite called benmoreite (Fig. 15, p. 27). The **colluvium** forms by weather induced disintegration of the lava flow and down-slope movement of the blocks by gravity. Because the Observatory Mesa lava flow is on top of the basalt lava flow it must be younger, as confirmed by their radiometric ages.

The benmoreite is dense, compact, and composed mostly of crystals too small to be seen without a lens. Sparse white crystals ( $< 2\text{mm}$ ) are plagioclase. Glass can be observed with a microscope.

The lava flow here is 160 feet thick (Fig. 15, p. 27); elsewhere it ranges between 100 feet and 300 feet in thickness. The average thickness is about 250 feet. The length of the lava flow is 4.5 miles. The aspect ratio is 0.011, 13 times larger than the basalt lava flow.

**B.** The lava flow was of medium viscosity (or fluidity). Controlling factors are:

- a. Medium silica content:  $\text{SiO}_2 = 58.45\%$  (average of 4 analyses).
- b. Medium temperature: probably around  $1000^\circ\text{C}$ ,  $1830^\circ\text{F}$ .
- c. Low water content: no gas pockets (or vesicles).

In comparison with the low viscosity basalt, the medium viscosity of the benmoreite resulted in: thicker lava flow, shorter length of flow, smaller crystals, glass in the matrix.

**C.** Elden Mountain, seen to the east through the trees, is a composite lava dome composed of dacite; the dome is an example of lava that had high viscosity because of these properties:

- a. Medium-high silica content:  $\text{SiO}_2 = 65.81\%$  (average of 3 analyses).
- b. Numerous large crystals of plagioclase; these grew underground before eruption. The large crystals stiffen the lava because they reduce the amount of liquid (the lava is not completely liquid because it is already partly crystallized).
- c. Medium-low temperature probably around  $950^\circ\text{C}$ ,  $1740^\circ\text{F}$ .

Elden Mountain is characterized by: high profile (about 2,000 feet high), steep sides, short lava flows. Aspect ratio of the lava flows is variable, but generally ranges 0.05 to 0.09, 59 to 106 times larger than the basalt lava flow.

*Return to the Karen Cooper Trail and turn right to Stop 7, about 400 feet.*

### **Stop 7. Karen Cooper Trail bends east and descends to valley floor**

The Karen Cooper Trail descends from the top of Tbo lava flow into the Rio de Flag valley. Here, the valley is wider than at The Narrows, the valley sides are more eroded and rounded, the gradient of Rio de Flag is much lower (about 50 feet/mile, Fig. 17, p. 29), and the alluvium is finer grained. Even though Rio de Flag is intermittent, the evidence is of a dynamic, changing landscape. Rio de Flag is advancing its valley upstream by **headward erosion** focused at the knickpoint just west of The Narrows.

*Continue south on Karen Cooper Trail to the floor of Rio de Flag valley at Stop 8.*

## Stop 8. Floor of Rio de Flag valley

**A.** The valley floor is underlain by a deposit of brown **sediment** more than 20 feet thick. Rio de Flag has cut, or incised, a narrow V-shaped channel about 10 to 15 feet down in the sediment. The flat surface of the grassy meadow on top of the sediment is a terrace formed when Rio de Flag eroded the gully. Incision likely occurred shortly after Rio de Flag established its watercourse around the north and east sides of Observatory Mesa (Fig. 13, p. 25).

**B.** The sediment exposed at the bicycle loops has been disturbed to make the mounds (Fig. 20); however, the character of the sediment can be examined. Here, the deposit consists mostly of poorly compacted clay, silt, and very fine sand. Elsewhere in the valley, gravel occurs locally in lenses or layers. Fine-grained sediment is characteristic of low-velocity or calm water. The deposit extends south in the Rio de Flag valley under Coconino Estates and west-side neighborhoods. The sediment is inferred to have been deposited in a lake behind a lava dam formed by the Dry Lake lava flow (Qbo) in downtown Flagstaff (Fig. 9, p. 21). The gravel implies that the lake probably was intermittent and occasionally dry when flash floods or spring snow melt carried coarser sediment across the lake beds.



*Figure 20. Photograph of sediment in Rio de Flag valley at Stop 8. The sediment has composition and fine-grained texture characteristic of deposition in low-energy water, such as in a lake.*

*Continue south on Karen Cooper Trail to foot bridge over Rio de Flag and on to Crescent Drive. The trail crosses the lower part of Tbo basalt lava flow before descending to the bridge.*

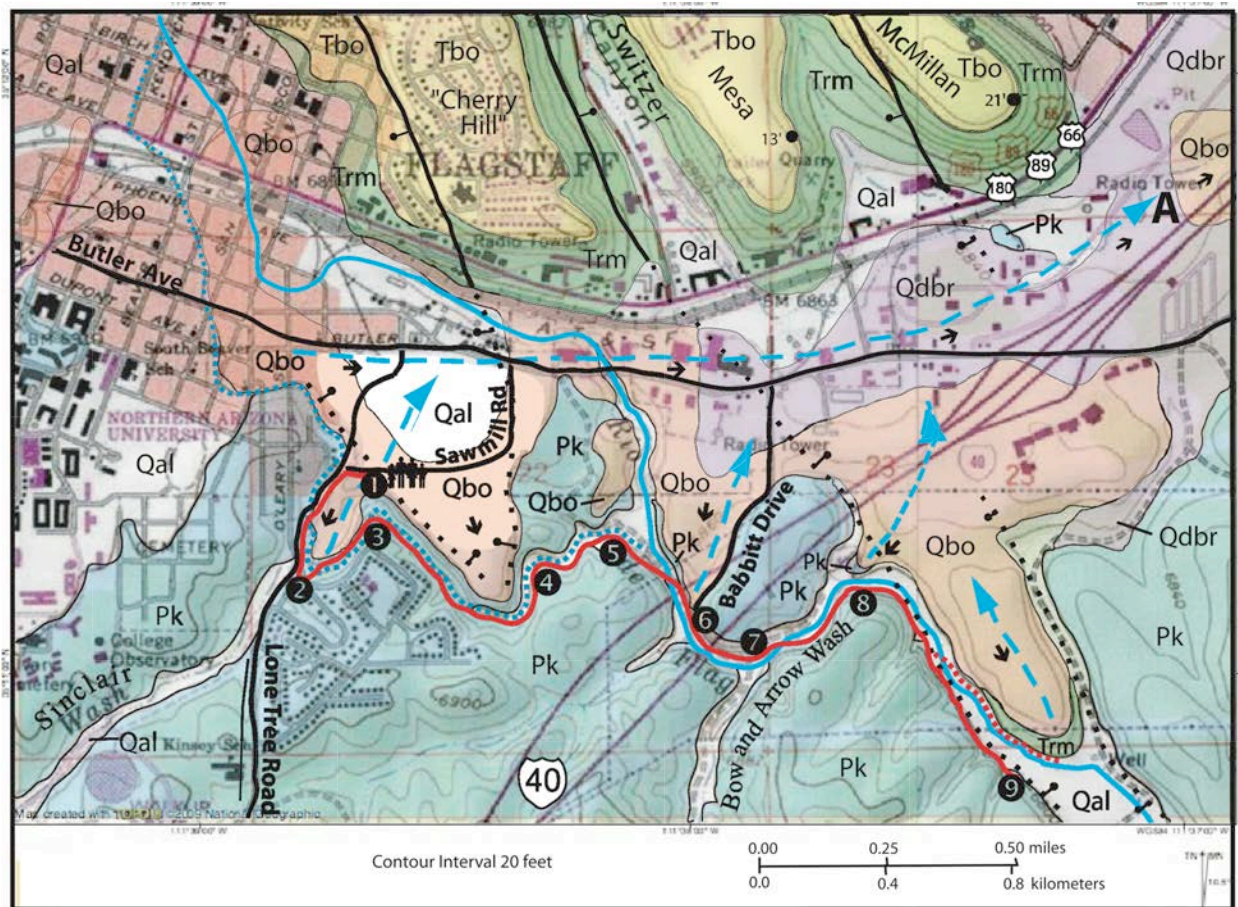
## Stop 9. Foot bridge over Rio de Flag at Crescent Drive: End of Trail 1 Guide

Rio de Flag enters Coconino Estates and displays a meandering pattern on the deposit of sediment (Fig. 15, p. 27). Farther south the Rio has been channelized, and the gradient flattens to 44 feet per mile. To put the gradients of Rio de Flag in perspective, the Colorado River through Grand Canyon has rapids, riffles, and pools, and the average gradient between Lee's Ferry and Lake Mead is 7 feet per mile. Some reaches of the lower Mississippi River have gradients as low as 2 inches per mile. The FUTS trail continues along Rio de Flag to downtown Flagstaff and reaches Historic Route 66 in about 1.7 miles.

*Return to Trailhead, or continue on FUTS to downtown Flagstaff.*

## TRAIL 2: SAWMILL COUNTY PARK TO LITTLE AMERICA

**Synopsis:** The Trail Guide starts at Sawmill County Park, continues along the Sinclair Wash section of the Flagstaff Urban Trails System, and ends along a social trail on private property owned by Little America. In this area southeast of downtown Flagstaff the Kaibab Formation limestone was broken by faults and eroded by Rio de Flag and its tributaries Sinclair Wash and "Bow and Arrow Wash." Basalt lava that extruded from Dry Lake volcano southwest of Flagstaff flowed into the low-lying areas and displaced the streams. Rio de Flag then eroded a new channel across the lava flow and together with the tributaries eroded new channels along the contact between the limestone and the basalt. The walk begins on top of the lava flow and continues around its edges along incised channels and fault structures in the limestone. At numbered points along the trail, descriptions, the geologic map, and photographs explain how the sequential stages of a changing landscape can be reconstructed by field observations.



**Figure 21.** Map showing Trail 2 (red line), Rio de Flag (solid blue line), diverted Rio de Flag and rearranged Sinclair Wash (dotted blue line), faults (heavy black lines, bar and ball on down side, dotted where covered by younger deposits). Rock formations: Pk: Kaibab Formation; Trm: Moenkopi Formation; Tbo: oldest basalt lava; Qbo: basalt lava from Dry Lake volcano; Qdbr: Elden block and ash breccia; Qal: alluvium. Other symbols: long blue dash lines with arrowheads: watercourse flow directions of ancestral Rio de Flag A, tributaries Sinclair Wash and "Bow and Arrow Wash", unnamed tributary at Stop 6, and unnamed tributary in graben at Stop 9; black arrows: flow directions of Qbo lava; •13': measured thickness of Tbo. Stop numbers on trail are keyed to text. Family hikers icon at trailhead.

**Directions to trailhead:** Drive west on Route 66 from Humphreys Street, bend left under the railroad, and continue south on Milton Road/Route 66, left lane. Turn left at first signal onto Butler Avenue and drive east for 0.65 miles to Lone Tree Road, right lane. Turn right onto Lone Tree Road and go about 0.25 miles to Sawmill Road--first road to left past signal at Franklin Avenue. Parking and toilets are at Willow Bend Environmental Education Center. Alternative parking is on neighborhood streets. To start the guide at trail Stop 2, continue south on Lone Tree Road past Sawmill Road to the next intersection and turn left onto Brannen Circle; parking is on the left. To access Trail 2 at Stop 6 continue east on Butler Avenue to the second signal past Lone Tree Road and turn right onto South Babbitt Drive; park on the left at Sams Club. Walk south on South Babbitt Drive to Trail 2 at Stop 6.

**Character of trail:** Maintained trail of the Flagstaff Urban Trails System (FUTS) and well-used social trail on Little America property.

**Length round trip:** About 4.8 miles from Stop 1, and 4.2 miles from Stop 2.

**Elevations:** 6882 ft to 6789 ft, mostly gradual.

**Time:** Allow 3-3.5 hours.

**Difficulty:** Easy.

**Base map:** U.S. Geological Survey, Flagstaff West Quadrangle, Arizona, 7.5 Minute Series, 1962, Photorevised 1983. Road updates by R. Holm, 2018.

**Road and trail distances and elevations:** Google Earth.

### **Stop 1. Sawmill County Park/Willow Bend Environmental Education Center**

**A.** The park is on top of a basalt lava flow that extruded from Dry Lake volcano about four miles southwest of downtown Flagstaff (Fig. 4, p. 12, Qbo). The age of the lava flow has not been determined, but is probably between 0.78 and 1.61 million years (based on paleomagnetic data and stratigraphy). Large blocks of the lava in the park display crystals of plagioclase (white), augite (black pyroxene), and olivine (green, fresh; red, weathered). Several blocks of the lava by the sidewalk have **pahoehoe cords** on their original flow surfaces, which indicate high fluidity (low viscosity) of the lava.

**B.** The lava flowed northeast from Dry Lake volcano and entered the drainage system of Rio de Flag ancestral watercourse A (blue dash lines with arrowheads on Figure 21). Ancestral Rio de Flag was incised in the Kaibab Formation on a curving course around the south end of McMillan Mesa (Fig. 9, p. 21). Tributaries Sinclair Wash and "Bow and Arrow Wash" entered watercourse A from the southwest and an unnamed tributary in a graben entered from the southeast (Fig. 21).

*Walk west on the sidewalk to Lone Tree Road and then south on cinder path to Brannen Circle.*

**Stop 1 to Stop 2.** The cinder path and Lone Tree Road follow a gully eroded along the side of the Dry Lake volcano lava flow; the gully is a tributary to Sinclair Wash. Intermittent channeling between 1890 and 1916 diverted modern Rio de Flag into the gully in order to reduce flooding in downtown Flagstaff, thereby shifting flooding to southside neighborhoods. About half way down to Brannen Circle the diverted Rio de Flag passes through a culvert under Lone Tree Road from the west side to the east side. The walk down from Sawmill Road to Brannen Circle descends from the top to the bottom of the lava flow, about 40 feet.

## Stop 2. Lone Tree Road at Brannen Circle. Trailhead of Sinclair Wash Trail

**A.** The road intersection is in Sinclair Wash. Compare the size, shape, and bounding rocks of Sinclair Wash upstream (southwest) with Sinclair Wash downstream (northeast). Upstream (on Sinclair Wash Trail across Lone Tree Road) the wash is broad and open, with limestone slopes on both sides (Fig. 22); this is the old, original Sinclair Wash. Downstream (along Trail Guide 2) the wash is narrow and the sides are steep; basalt is on the north (left) side of the wash and trail and limestone is on the south (right) side (Fig. 23). The downstream reach of the wash was eroded after the lava flow entered and filled ancestral Sinclair Wash.



**Figure 22.** Upstream view of Sinclair Wash about 1350 feet west of Lone Tree Road on Sinclair Wash Trail. Kaibab Formation limestone crops out on both sides of the wash.



**Figure 23.** Downstream view of Sinclair Wash on the Sinclair Wash Trail between Stops 2 and 3. Basalt (Qbo) outcrops are on the north (left) side of the trail and limestone outcrops (Pk) are on the south (right) side.

**B.** Take the Sinclair Wash Trail downstream (northeast). About 200 feet from the trailhead, diverted Rio de Flag flows through culverts under the trail to join modern Sinclair Wash (Fig. 21). From here to Stop 5 the drainage is referred to as Sinclair Wash. About 50 feet beyond the culverts, on the left, is the end of the Dry Lake volcano lava (Qbo) that flowed upstream in ancestral Sinclair Wash from Rio de Flag ancestral watercourse A (Fig. 21, black arrow). The lava filled ancestral Sinclair Wash that was incised in Kaibab Formation limestone (Fig. 21, blue arrow). The rearranged modern Sinclair Wash was eroded later along the contact of the basalt and the Kaibab Formation limestone (Pk). The narrow downstream reach of the wash along the edge of the lava flow (Fig. 23) is younger than the broad upstream reach of the wash west of Lone Tree Road (Fig. 22).

*Continue along Sinclair Wash Trail to Stop 3 where the trail crosses to the south side of Sinclair Wash.*

**Stop 2 to Stop 3.** Basalt outcrops near the end of the Qbo lava flow display planar fractures slanting down to the northeast (Fig. 24). These structures are **ramping shear fractures** that form at the front of a lava flow as it advances. The lava overrides, or "ramps up" over, the cooler and stiffer front as the flow moves forward, which in this location indicates the lava flowed from northeast to southwest, upstream in ancestral Sinclair Wash (Fig. 21, black arrow).



**Figure 24. Photograph showing ramping shear fractures in basalt lava flow Qbo between Stops 2 and 3. Arrow points in flow direction of lava. Knife on fracture for scale**

### **Stop 3. Trail 2 Crosses to South Side of Sinclair Wash**

Kaibab Formation limestone forms the cliffs on the south side of Sinclair Wash and crops out below the basalt lava flow on the north side. Modern Sinclair Wash is eroded about 5 feet to 10 feet below the bottom of the lava flow, which filled ancestral Sinclair Wash. Note that the basalt is at the same level as the limestone cliffs on the south side of the wash. If the basalt could be removed the original pre-lava Sinclair Wash that flowed northeast to join Rio de Flag ancestral watercourse A would be exposed (Fig. 21, blue arrow). The finger-like shape of the basalt west of Stop 3 on Figure 21 shows the original position and shape of ancestral Sinclair Wash, which was incised about 50 feet to 60 feet in the Kaibab Formation.

*About 160 feet past crossing over Sinclair Wash the trail turns abruptly southeast. Follow the trail for the next one-half mile southeast, then east, then north to Stop 4 where the trail bends east.*

**Stop 3 to Stop 4.** Sinclair Wash makes an abrupt bend to the southeast and flows along the side of basalt that filled a northwest-trending wedge-shaped graben (Fig. 21). The wash then bends to the north around the end of the lava flow.

#### **stop 4. Sinclair Wash and Trail 2 Bend East; Utility Lines West of Trail**

Look at the low cliffs below the utility lines. The contact between the basalt lava flow (Qbo, west side, left) and the Kaibab Formation limestone (Pk, east side, right) is the east-bounding fault of the wedge-shaped graben (Fig. 21; Fig. 25). This fault is the southeast-trending fault that forms a scarp along the east side of Fort Valley Road (Fig. 15, p. 27) and the west side of "Cherry Hill" (Fig 21, p. 35). After faulting and erosion of the Moenkopi Formation, the basalt lava from Dry Lake volcano entered and filled the graben and flowed against the fault scarps. The surface of the lava flow is not displaced by the fault, which indicates the basalt is younger than the fault (Fig. 21).



**Figure 25. View of low cliffs at Stop 4. Basalt lava flow (Qbo) abuts Kaibab Formation (Pk). The contact (white line) is a fault scarp buried by the lava; the scarp slopes west, away from the camera.**

*Continue east downstream along the Sinclair Wash Trail for about 1000 feet (0.19 mi) to where the wash widens out in an open meadow at Stop 5.*

#### **Stop 5. Junction of Modern Sinclair Wash With Presettlement Rio de Flag**

Modern Sinclair Wash joins the presettlement Rio de Flag that flows from the valley on the north (left) side of the trail (Fig. 21, p. 35). Note how wide the Rio de Flag valley is in comparison with Sinclair Wash; the larger valley was eroded by the greater discharge of Rio de Flag. This reach of Rio de Flag was eroded across the basalt lava flow from Dry Lake volcano (Qbo) after the lava blocked ancestral watercourse A, formed a lava dam, and forced the rearrangement of Rio de Flag (Fig. 9, p. 21; Fig. 21, p. 35).

*Follow the Sinclair Wash Trail southeast downstream for about one-quarter mile to Stop 6. The trail crosses over Rio de Flag, then passes under the west-bound lanes of I-40, and joins South Babbitt Drive paved access road to the Rio de Flag water treatment facility.*

## **Stop 6. Sinclair Wash Trail Between West- and East-Bound Lanes of I-40 at South Babbitt Drive Access Road to Rio de Flag Water Treatment Facility**

At this point, Rio de Flag and Trail 2 cross a northeast-trending contact (Fig. 21; Fig. 26); basalt lava (Qbo, north side) abuts Kaibab Formation limestone (Pk, south side). This contact continues northeast for about one-third of a mile (Fig. 21). The contact lines up with a gully on the west side of the trail that enters Rio de Flag from the southwest (Fig. 21). These relations suggest that the basalt lava flow entered an ancestral reach of the gully (Fig. 21, blue dash arrow) from the northeast and flowed upstream to about this point (Fig. 21, black arrow). The contact was eroded, and South Babbitt Drive was constructed along the gully.



**Figure 26.** View northeast at Stop 6 on South Babbitt Drive access road to Rio de Flag water treatment facility. Road is along a contact where basalt lava flow (Qbo) on north side of the road abuts Kaibab Formation limestone (Pk) on south side. Sinclair Wash Trail intersects at sign on left.

*Continue southeast downstream on the Sinclair Wash Trail for about 550 feet (0.11 mi) to where the trail bends to the northeast at Stop 7.*

## **Stop 7. Junction of "Bow and Arrow Wash" With Modern Rio de Flag at Rio de Flag Water Treatment Facility**

Rio de Flag bends from flowing southeast to flowing northeast. "Bow and Arrow Wash" enters Rio de Flag from the southwest (Fig. 21, p. 35). "Bow and Arrow Wash" is informally named after a neighborhood near its headwaters. The name is not officially recognized for a geographic feature and does not appear on U.S. Geological Survey maps, so its name is in quotation marks.

*Continue northeast downstream on the Sinclair Wash Trail for about 1500 feet (0.28 mi) to Stop 8 where Rio de Flag bends from northeast flow to southeast flow. In about 300 feet (0.06 mi) from Stop 7 the trail crosses over Rio de Flag to the south side.*

**Stop 7 to Stop 8.** Modern Rio de Flag is flowing northeast in the original gully of "Bow and Arrow Wash." The ancestral "Bow and Arrow Wash" continued northeast beyond Stop 8 to join ancestral watercourse A of Rio de Flag somewhere between Butler Avenue and Route 66 (Fig. 21, p. 35, blue dash arrow).

## Stop 8. Sinclair Wash Trail and Rio de Flag Bend From Northeast Flow to Southeast

Rio de Flag bends from flowing northeast to flowing southeast. From the trail look north across Rio de Flag to the near outcrops. Find an outcrop of dark gray basalt on top of light gray Kaibab Formation limestone (Fig. 21; Fig. 27). The basalt is a "tongue" of the Dry Lake volcano lava flow that projects southwest into the ancestral gully of "Bow and Arrow Wash" (Fig. 21, blue dash arrow). At this point the lava flowed southwest upstream into the mouth of ancestral "Bow and Arrow Wash" (Fig. 21, black arrow). The position of the basalt lava flow directly on top of the Kaibab Formation limestone indicates that the Moenkopi Formation red sandstone was eroded before the lava entered the wash.



**Figure 27. Photograph of basalt lava flow (Qbo) on top of Kaibab Formation limestone (Pk) in the bottom of "Bow and Arrow Wash" at Stop 8. Moenkopi Formation red sandstone was eroded before the lava covered the limestone. Rio de Flag is in the foreground.**

*Continue downstream on the Sinclair Wash Trail for about 400 feet (0.076 mi) to the boundary between the City of Flagstaff property and Little America property. Here, the FUTS Sinclair Wash Trail ends and the path is a social trail on private property. The property line is marked by a metal pole and sign on the south (right) side of the trail.*

*Continue southeast downstream on the social trail for about one-half mile to Stop 9. About 800 feet (0.15 mi) past the property boundary the trail has a fork to the left, shown on Figure 21, p. 35 as a dotted red line. The trail to the left crosses Rio de Flag. If the Rio is dry or very low water judge if you want to cross; the trail leads to an exposure of Moenkopi Formation. If the Rio is flowing, take the right fork to Stop 9.*

### Stop 8 to Stop 9.

**A.** Rio de Flag flows southeast along the bounding fault of a northwest-southeast-trending graben. To the north, the trace of the fault crosses Route 66 and continues northwest along Switzer Canyon (Fig. 21, p. 35). Two northwest-trending faults formed the graben in the Kaibab Formation prior to eruption of the basalt lava from Dry Lake volcano. The lava entered the graben from the north (Fig. 21, p.35, black arrow). At Stop 8 the bottom of the basalt lava flow is directly on top of Kaibab Formation limestone at elevation 6800 feet. The basalt is 40 feet thick. Moenkopi Formation had already been eroded before the lava covered the limestone.

**B.** Traced southeast, the bottom of the basalt lava flow gradually rises in elevation, the lava flow gets thinner, and the soil below the basalt is reddish. In the clearing below the power line, the bottom of the basalt lava flow is at elevation 6808 feet, and the basalt is 28 feet thick.

C. At the south end of the basalt lava flow next to the meadow the bottom of the basalt is at elevation 6811 feet, and the lava's thickness, after weathering and erosion, is 19 feet.

D. Between Stop 8 and Stop 9 the elevation of the flood plain next to Rio de Flag drops by only 5 feet from 6794 feet to 6789 feet.

### Stop 9. Rio de Flag and Trail 2 Enter a Grassy Meadow: End of Trail 2 Guide

A. The Trail Guide stops at the south end of the basalt lava flow (Fig. 21; Fig. 28). At this point, the bottom of the basalt (Qbo) has climbed 11 feet in elevation from Stop 8, and the basalt's thickness has decreased by 21 feet. Below the basalt are chips and blocks of red Moenkopi Formation sandstone in a reddish soil (Trm). A few scattered blocks of red conglomerate with pebbles of gray Kaibab Formation limestone come from the bottom layer of the Moenkopi Formation, which is only about 20 feet thick here. This remnant of the Moenkopi Formation has been protected from erosion by the basalt.



**Figure 28. View northeast from Stop 9. Dotted white line is approximate contact of basalt lava flow (Qbo) on top of Moenkopi Formation (Trm). Alluvium (Qal) covers the Rio de Flag flood plain. Black line is contact of Qal on Trm.**

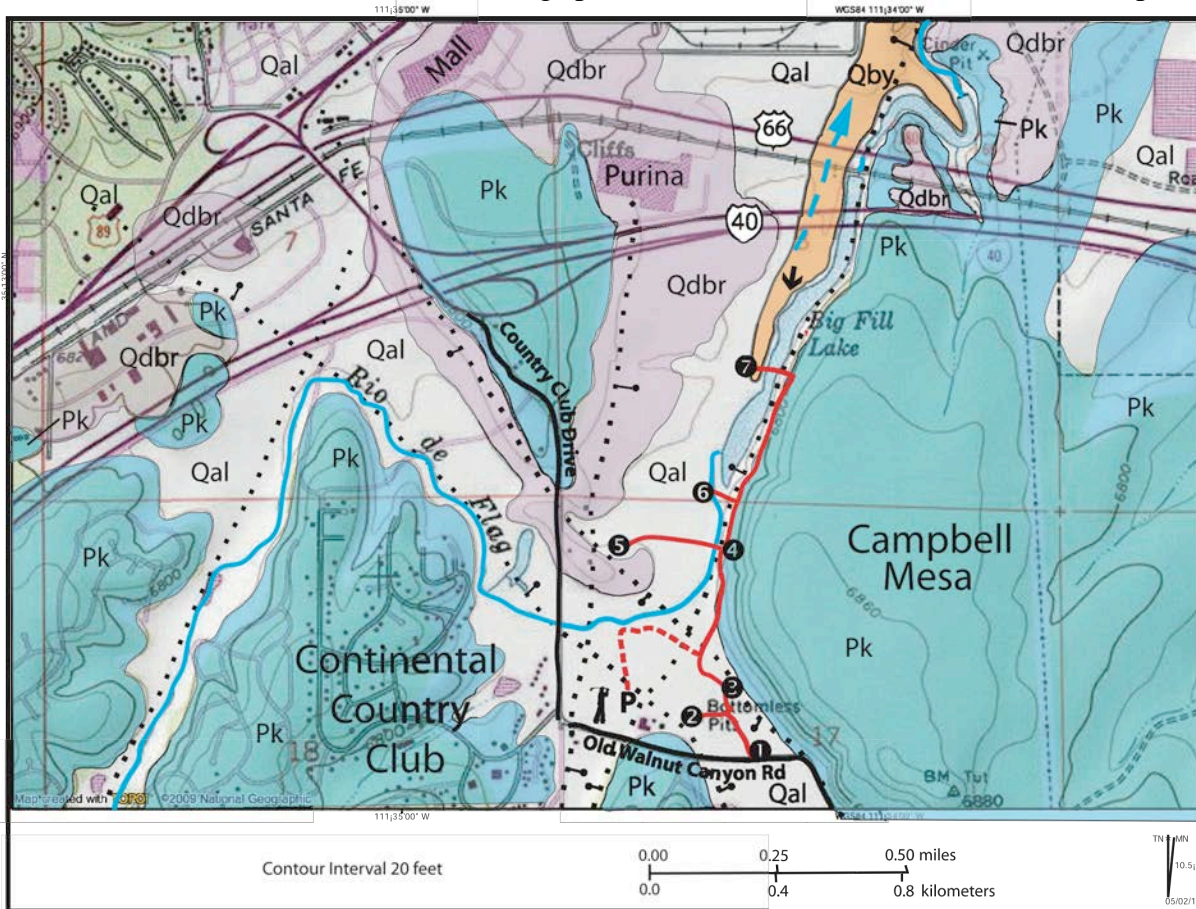
B. Recap: Where ancestral "Bow and Arrow Wash" entered the graben the basalt is directly on Kaibab limestone; red Moenkopi sandstone was eroded before the lava entered the graben. At the southeast end of the basalt the underlying red rocks are about 20 feet thick. A retrospective view of the landscape before the lava arrived reveals that the floor of the graben sloped north, and that "Bow and Arrow Wash" and a drainage in the graben flowed north to join Rio de Flag ancestral watercourse A. From north to south the original top of the lava was approximately horizontal. The bottom of the basalt rises in elevation from north to south, which accounts for much of the thinning of the lava flow. The lava must have flowed up hill in its advance southeastward in the graben. Up-hill flow of lava can happen where the lava is thick enough relative to the slope of the land for its top to stay above the surface it is flowing over.

C. The drainage in this area traversed by Trail 2 has been reversed. Prior to extrusion of the basalt lava flow, Sinclair Wash, "Bow and Arrow Wash", and unnamed drainages at Stop 6 and in the graben flowed north to join Rio de Flag ancestral watercourse A. Today, the modern Rio de Flag flows south before bending to northeast flow direction in east Flagstaff.

### TRAIL 3: OLD WALNUT CANYON ROAD TO BIG FILL LAKE

**Synopsis:** The walk is in an open, grass and weed-covered meadow in the flood plain of Rio de Flag. Social trails that cross the meadow in several places and directions provide access to points of geologic and cultural interest. Trail stop numbers are keyed to numbered sections of the text. Stops 4, 6, and 7, are on City of Flagstaff property; stops 1, 2, 3, and 5 are on private property. Respect private property. Do not enter if the area is fenced and posted.

The broad flood plain of Rio de Flag is contained in down-faulted valleys called grabens. Block and ash breccia deposited during the early explosive stage of the Elden Mountain eruption filled the grabens. Elden Mountain blocked watercourse B and diverted Rio de Flag to the Continental area where the river eroded a new channel in the block and ash breccia as watercourse C. Sheep Hill cinder cone erupted near the north end of the graben and, by coincidence, in Rio de Flag watercourse C. Lava flows from Sheep Hill filled watercourse C and impounded the water in ancestral "Lake Continental." The modern channel was eroded between the southern lava flow and the edge of the graben when the lake overflowed. Bottomless Pit, a sinkhole, serves as a drain when Rio de Flag spills out of its channel and covers the flood plain.



**Figure 29.** Map showing Trail 3 (red line), Rio de Flag (blue line), faults (bold black dots where covered by younger deposits, bar and ball on down side). Rock formations: Pk: Kaibab Formation; Qdbr: Elden block and ash breccia; Qby, basalt lava flow from Sheep Hill; Qal: alluvium, includes lake sediments. Other symbols: blue dash line with arrowhead: flow direction of Rio de Flag ancestral watercourse C; black arrow: flow direction of Qby lava. Stop numbers on Trail 3 are keyed to text. Dashed red line marks alternative trail to Trail 3 from Continental Sports Park parking lot (P). Golfer icon is on driving range. Big Fill Lake rarely contains water.

**Directions to Trailhead:** Drive about 4.25 miles east from Humphreys Street on Route 66/Santa Fe Avenue/U.S. 89/U.S. 180 to signs leading to I-40; stay on Santa Fe Avenue and go past right turn on Route 66. Right bend off Santa Fe Avenue leads to Country Club Drive on overpass above railroad tracks and I-40. Continue straight ahead about 0.90 mile through three traffic signals to fourth signal at Soliere Avenue. Continue south on Country Club Drive about 0.50 mile to E. Old Walnut Canyon Road. Turn left onto E. Old Walnut Canyon Road and drive 0.40 mile east to Trail 3. Parking is next to the road on the left. Alternative parking and toilets are at the Continental Sports Park (P on Fig. 29).

**Character of trail:** Well-used social trails and track road; one off-trail walk about 500 feet out and back. Walk is best done on dry days; the trail is muddy when wet.

**Length round trip:** About 2.6 miles.

**Elevations:** 6760 to 6770 ft.

**Time:** Allow 2-2.5 hours.

**Difficulty:** Easy.

**Base map:** U.S. Geological Survey, Flagstaff East Quadrangle, Arizona, 7.5' Series, 1962.

**Road and trail distances and elevations:** Google Earth.

### **Stop 1. Trailhead on E. Old Walnut Canyon Road**

The trailhead is at a track road that starts in a gap in the fence on the north side of E. Old Walnut Canyon Road. The track road is in the center of a broad, flat, northwest-trending valley that is bound by steep sides. The valley is in a geologic structure named graben, which is a down-faulted block of rock between parallel or subparallel faults; fault displacement is about 100 feet (U.S. Geological Survey). Alluvium and lake sediments underlie the valley floor.

*Walk north along the track road for about 550 feet (0.1 mi), and then head west (left) cross country for about 250 feet to a narrow gully that enters Bottomless Pit on its north side. The pit is surrounded by a fence and posted for No Trespassing—stay safe and do not cross the fence. You can see everything from outside the fence.*

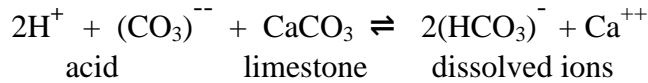
### **Stop 2. Bottomless Pit**

**A.** Bottomless Pit has been an attraction in Flagstaff for many years (Fig. 30). The depression is a sinkhole in Kaibab Formation limestone. The pit developed near the southwest-bounding fault of the northwest-trending graben (Fig. 29). The limestone is overlain by about 20 to 25 feet of fine, silty lake sediments and alluvium (Fig. 31).

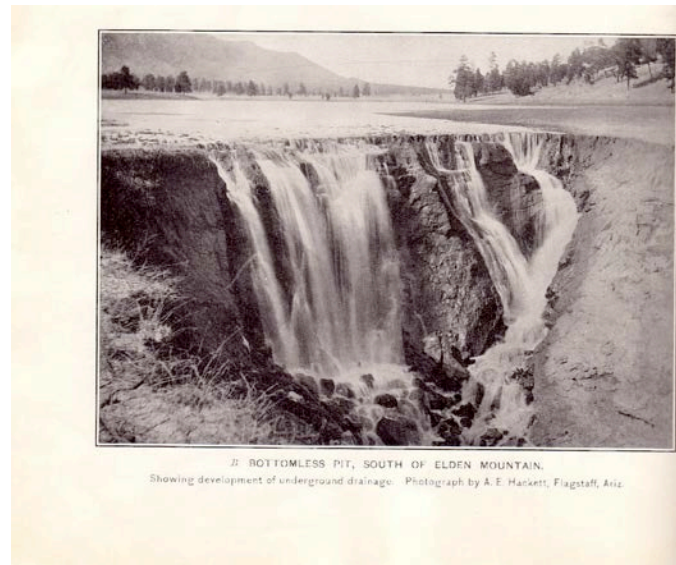
**B.** Geophysical research by the U.S. Geological Survey documented caverns down to at least 130 feet below the surface near Bottomless Pit. Elsewhere in the graben the U.S.G.S. found multiple large openings (“caves”) in boreholes down to 2000 feet below the surface. For safety concerns, the opening to the caverns in Bottomless Pit was covered in 1987 with rock and soil debris. The regional ground water table in this area is at a depth of about 1,300 feet.

**C.** Underground openings can develop where limestone is dissolved by weakly acidic meteoric water. Rainwater absorbs carbon dioxide from the atmosphere to form carbonic acid.

This weak acid dissolves limestone. Faults and fractures in the limestone give the water easy access to the rocks. The chemical process is shown in these equations:



**D.** Flood water pours into Bottomless Pit when Rio de Flag spills out of its channel. The Rio reached flood stage in February, 1993 during an exceptionally wet winter; Flagstaff had received 122 inches of snow by February 21. Over 9 inches of precipitation fell in the first three weeks of February, including 3.93 inches of rain on the 19th and 1.05 inches on the 20th. Inadequate culverts downstream under Route 66 and the railroad tracks forced water to back up and flood the Continental area on the 21st, creating modern "Lake Continental" with a shore line at about 6760 feet elevation. The lake was 4 to 6 feet deep on parts of the golf course. For three days the lake surface dropped about one foot per day. Then the sinkhole opened up and the lake drained in about 8 hours.



**Figure 30.** Photograph of Rio de Flag flowing into Bottomless Pit, looking north. Photograph by A. E. Hackett, date unknown. Published by H. H. Robinson, 1913.



**Figure 31.** Photograph of Bottomless Pit, about 20 feet deep; looking south in August, 2018. Ledges at the south end of the pit are Kaibab Formation limestone. Fine, silty lake deposits and alluvium overlie the limestone. The limestone ledge is truncated on the left side (east side) by a fault that displaced the east side down (Fig. 29).

Return to the track road and walk north (left) about 150 feet. Stop 3 is the depression on the east (right) side of the track road.

### Stop 3. Depression on east side of track road

This depression has been called a sinkhole. However, it usually contains a pond, which indicates that the bottom holds water and is not directly connected to fractures or openings in the underlying bedrock. The source of the water might be underground flow from the lake on the south side of Old Walnut Canyon Road. An alternative explanation for the origin of the depression is that it might be an excavation pit dug for material to construct the railroad bed about 100 feet east of the pit (see Stop 6).

*Continue walking north on the track road for about 1,700 feet (0.32 mi) to Stop 4 where a well-developed social trail to the left (west) intersects the track road. A shallow channel of Rio de Flag is next to the track road; culverts under the social trail usually are blocked by flotsam and jetsam.*

### Stop 3 to Stop 4.

The broad, flat ground west of the track road is at the intersection of two structural valleys classified as grabens (Fig. 29). Each graben is bound by two parallel to subparallel faults along which the land between them was displaced down. One graben trends northeast and the other trends northwest. The flood plain of Rio de Flag covers the flat ground, but the grabens account for its breadth and area, not erosion by the Rio. Exceptionally high discharge in wet seasons will spill out of the Rio's channel, flood the low, flat ground, and enter Bottomless Pit .

### Stop 4. Entry to northeast-trending graben

A. The low cliff on the right (east) side of the track road is a fault scarp in the Kaibab Formation limestone (Fig. 32). This scarp extends along the length of the west side of Campbell Mesa (Fig. 29, p. 43). From south to north the trend of the scarp changes from northwest to northeast where the two grabens intersect. Rocks on the west side of the faults moved down under extensional stress to form the grabens. The difference in elevation between the limestone on top of Campbell Mesa and limestone on the floor of the quarry in the graben at Stop 5 is about 140 feet, which might approximate the amount of displacement on the faults.



*Figure 32. Photograph of fault scarp in Kaibab Formation limestone at Stop 4. Higher parts of the scarp have been eroded to form the slope above the low cliff.*

The time of faulting is uncertain, but similar faults in the broader Flagstaff region are known to have moved between about 6 Ma and 0.25 Ma. Examples of faults include: 1. Faults and graben structures at Mormon Lake formed between about 6 Ma and 4 Ma. 2. In downtown Flagstaff, the 6 Ma basalt lava flow on McMillan Mesa is offset by faults that predate the basalt

lava flow from Dry Lake volcano, which is between 1.61 and 0.78 million years old. 3. The youngest known faults and grabens displace the surface of a debris fan on the northeast side of San Francisco Mountain. These grabens postdate the maximum age of the debris fan surface (0.46 Ma) and predate the minimum age of a lava flow that covers the fan (0.25 Ma).

Three prominent trend directions of faults in the Flagstaff area are northeast, northwest, and north-south. These young faults probably result from reactivation of old deep-seated faults, like those exposed in Grand Canyon, by later extensional stress. Rio de Flag flows in the grabens because the faults created low, flat valleys that could accommodate the Rio when upstream watercourse B was rearranged by the Elden Mountain eruption.

**B.** Earthquakes in and near Flagstaff document ongoing extensional stress and movements on faults, although surface ruptures have not been reported. First motion studies of recent seismicity indicate that extensional stress in northern Arizona is oriented northeast-southwest.

Selected earthquakes and **magnitudes** (M) in and near Flagstaff include:

1912, M = 6.2	1972, M = 3.7	1981, M = 2.0
1987, M = 2.6	1992, M = 1.9	2003, M = 1.3
2014, M = 4.7.	2018, M = 3.1	

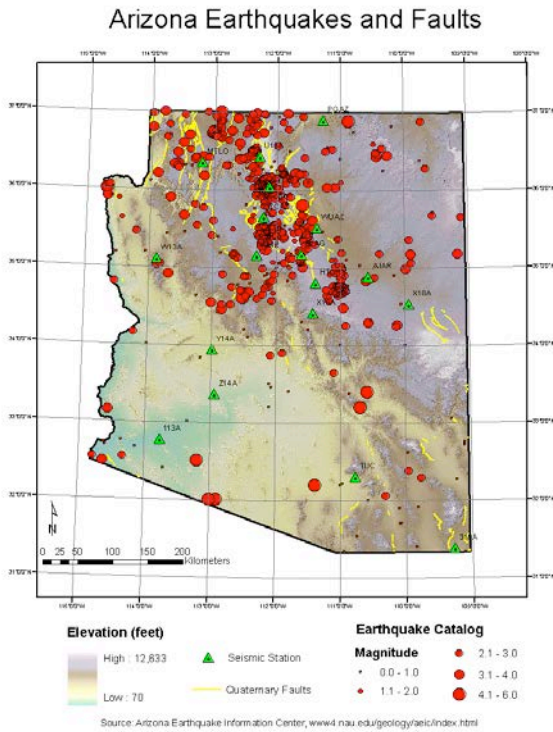
Magnitudes less than 3.4 are generally not felt, but are recorded by seismographs. Magnitudes of 5.5 to 6.9 can cause minor to considerable damage to structures.

Most earthquakes in Arizona are in the northern half of the state and most of these are in the northwest quadrant; in concurrence, most young faults are also in the northwest quadrant of the state (Fig. 33, p. 48).

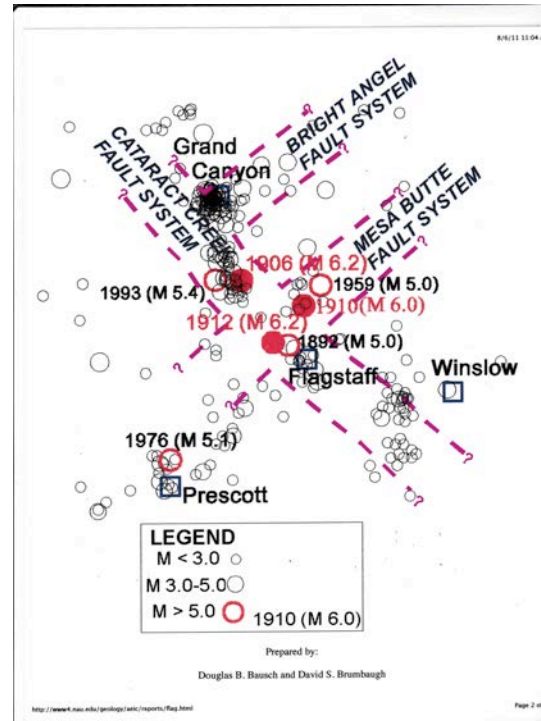
In the broader Flagstaff area earthquakes have a close spatial relation with parallel faults in long, wide lanes called fault systems. Field mapping and remote sensing with aerial photographs and satellite images have identified fault systems that trend northwest and northeast (Fig. 34, p. 48). Omitted from Figure 34 (for clarity of the map) are the boundary lines of the Oak Creek Canyon fault system that extends north from Verde Valley through Flagstaff to the Little Colorado River. The 2014 earthquake (M = 4.7) occurred south of Flagstaff near Oak Creek Canyon; shaking was felt in Kachina Village and Flagstaff.

On Figure 34, **epicenters** of earthquakes with magnitudes of 5 -5.9 are plotted with red circles; those with magnitudes of 6 or greater are plotted with red dots. The largest earthquakes are north of Flagstaff in or near the intersection of the Cataract Creek, Mesa Butte, and Oak Creek Canyon fault systems.

Faults in the Continental Country Club area have trends in the Cataract Creek and Mesa Butte fault systems (Fig. 29, p. 43). The fault that projects north under the Purina plant might be classified in the Oak Creek Canyon fault system. The northwest-trending graben on Figure 29 projects under Elden Mountain and the east side of Dry Lake Hills (Fig. 4, p. 12); the faults likely provided passageways for the lavas that built these volcanoes.



**Figure 33.** Map showing locations of earthquake epicenters (red dots) and young faults (yellow lines) in Arizona. Source of map: Arizona Earthquake Information Center at Northern Arizona University.



**Figure 34.** Map showing fault systems and earthquake epicenters in north-central Arizona. The Oak Creek Canyon fault system trends north-south through Flagstaff. Source of map: Arizona Earthquake Information Center at Northern Arizona University.

C. The prominent mountain northwest of Stop 4 is Elden Mountain, a volcano classified as a lava dome (Fig. 35). Vents that extruded lava flows are at the two prominent peaks on the main mass of the mountain, and at the distant peak on the right side. Several bulbous lava flows overlap on the southeast side of the highest peak. The youngest lava flow, mostly barren of vegetation, was so viscous that it stopped flowing on the steep slope before reaching the bottom of the volcano. The eruption of Elden Mountain progressed through several stages (Fig. 36, p. 49).



**Figure 35.** Elden Mountain, a lava dome composed of dacite, erupted about 530,000 years ago.

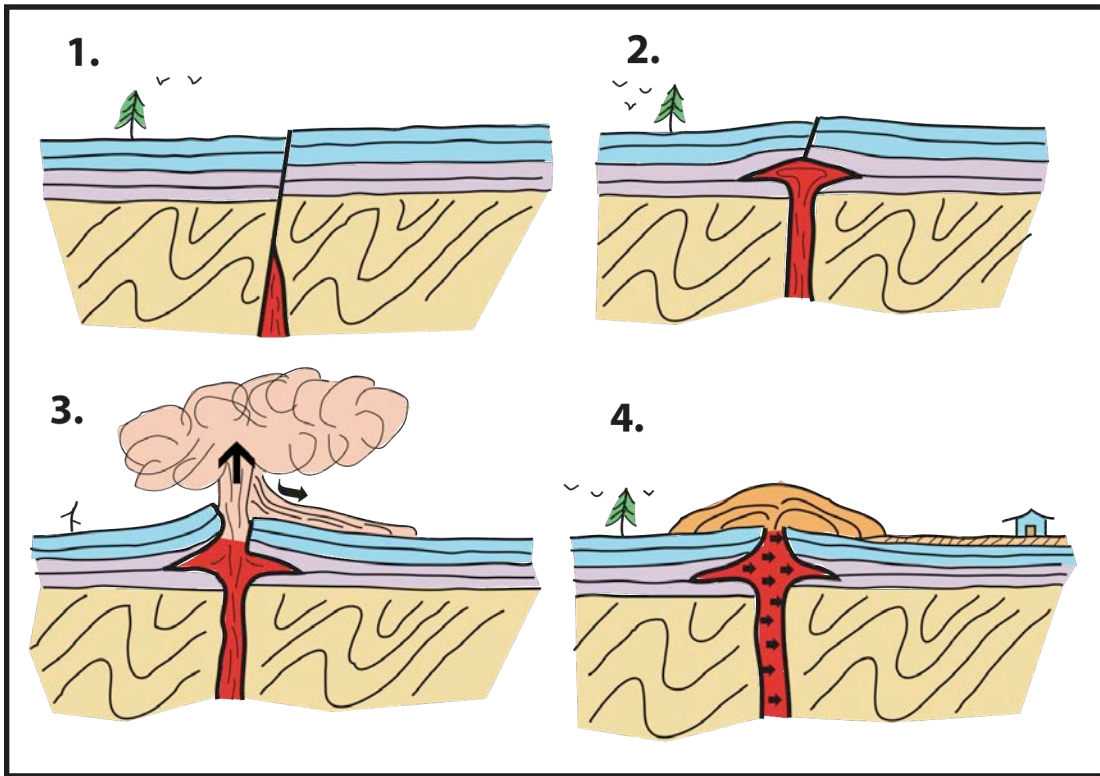


Figure 36. Schematic sketches that illustrate the eruption sequence at Elden Mountain. Not to scale.

1. About 0.53 Ma a dike of dacite magma intruded up along a fault.
2. The magma pushed into sedimentary rocks along bedding planes about 3,000 feet beneath the surface, and swelled up like a mushroom to make a dome-like structure called a laccolith.
3. Gas pressure in the magma built up until it exceeded the confining pressure of the overlying rocks. The roof of the laccolith broke open, and a powerful Peléan eruption blew out pumice, lava, rocks, crystals, and ash. Gravitational collapse of the eruption column produced pyroclastic flows that spread out over the land surface. As the pyroclastic flows lost momentum, a block and ash breccia was deposited. Preserved remnants of the breccia have been mapped between Campbell Mesa and west Route 66 (Fig. 11, p. 23, Qdbr); the most distant deposit is 7 miles (11 km) from the vent.
4. After the gas boiled out of the magma, lava extruded in thick flows and piled up around several vents to construct Elden Mountain, an exogenous lava dome. Parts of Flagstaff were built on the breccia.

From Stop 4 walk west across the meadow on the social trail; in about 570 feet (0.11 mi) take the left fork. In about 300 feet on the left fork of the social trail turn left and walk cross country about 100 feet to a quarry behind the clump of ponderosa trees at Stop 5.

### Stop 5. Quarry in Elden block and ash breccia

The Elden block and ash breccia is not consolidated, so it is easily excavated for use as construction fill material. The larger blocks of pumiceous dacite have been used as building stone in Flagstaff. The dacite blocks are relatively soft and can be shaped to flat surfaces and

square corners. In contrast, malpais (basalt) blocks are hard, and are installed by roughly fitting together their irregular shapes.

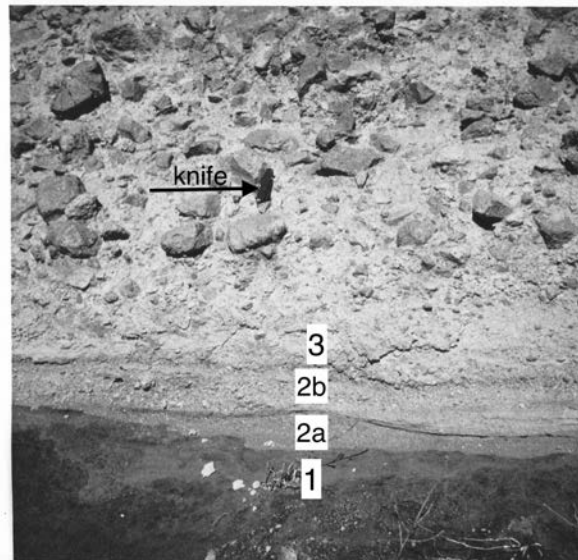
The quarry has been inactive for many years, and the side is weathered and eroded; nevertheless, the general massive, or structureless, character of the breccia is apparent (Fig. 37). In the quarry and Figure 38 the breccia displays: 1. very poor sorting (a wide range of particle sizes); 2. matrix supported texture (large blocks are isolated in fine particles); 3. inverse grading at the bottom (upward increase in particle size); 4. overall massive appearance (not layered internally). These features indicate that the breccia arrived at this location by lateral flow of a mass of particles from the vent (about four miles north of here), rather than fall of particles individually from the air. Fall deposits from an explosive eruption four miles away typically are well sorted, layered, and lack large blocks.

The transportation of the particles in the breccia from the vent was as a pyroclastic flow, which is a volcanic system that: 1. is generated by the gravitational collapse of an explosive eruption column; 2. is gravity-driven and ground-hugging; 3. is relatively dense due to a high concentration of pumice, ash, and blocks of lava; 4. has high mobility because hot gas lowers internal friction by buffering the solid particles; 5. moves with a straight, or uniform, internal flow mechanism (quasi-laminar; not turbulent due to particle concentration); 6. can travel long distances before deflation and loss of momentum.

**Paleomagnetic** poles measured in multiple blocks in the deposit near the Nestle Purina plant (Fig. 10, p. 22) all point in the same direction; that is, they are concordant. These data are interpreted to indicate that after deposition all of the blocks cooled together from a temperature above ~580°C, below which they acquired their magnetism.



*Figure 37. Photograph of weathered quarry face in Elden block and ash breccia at Stop 5. The breccia displays a structureless appearance and a wide range of particle sizes. Kaibab Formation limestone forms the floor of the quarry (white rock lower left corner).*



*Figure 38. Photograph of the bottom of the Elden block and ash breccia in the Nestle Purina railroad spur (Fig. 10, p. 22). 1. Cinders and ash in paleovalley above Kaibab Formation. 2a and 2b. Two layers deposited by high-velocity, dilute, and turbulent surges that preceded the pyroclastic flow. 3. Bottom of the block and ash breccia; particle size increases upward due to friction at the contact of the pyroclastic flow and ground surface.*

The ground-hugging pyroclastic flow filled low areas in Flagstaff, including Rio de Flag watercourse B, tributary gullies, and the grabens with the block and ash breccia. Rio de Flag watercourse B was blocked, and water probably backed up in a lake, but no geologic record of a possible lake has been found. Rio de Flag was diverted to the Continental area grabens where a new channel was eroded in the breccia as watercourse C (Fig. 11, p. 23).

*Return to the track road. Turn left and follow the track road about 440 feet to the first social trail to the left. Turn left and follow the social trail west for about 225 feet to the top of a mound, which is a railroad berm at Stop 6. The low place close to the track road is the Rio de Flag channel.*

### **Stop 6. Abandoned railroad berm**

Railroads for logging in the Flagstaff area ran from about 1887 through the 1920s and 1930s. The last line shut down in 1967. Most lines were south of Flagstaff, between Mormon Lake and Rogers Lake.

The Greenlaw Brothers main line ran from Walnut Canyon through the structural valleys to their mill about 1/4 mile north of the Flagstaff Mall. The line operated from 1907 to 1924. Because the railroad crossed the Rio de Flag flood plain the rails were laid on berms about 5 to 10 feet high. An old rail remains on the west side of the berm, just over the crest.

Material for the berm was excavated locally, from the Elden block and ash breccia, and from fine, silty lake deposits and alluvium that cover the flood plain. The excavation pits in the flood plain range from a few feet to about 15 feet deep and resemble sink holes, but they hold water in ponds (see Stop 3).

*Return to the track road. Turn left and walk northeast on the track road about 1,380 feet (0.26 mi) to Stop 7.*

### **Stop 6 to Stop 7.**

The track road is in the geographical feature on Figure 29 (p. 43) called Big Fill Lake (Fig. 39). The dam for the “lake” is about 0.8 mile north of here, on the north side of Route 66 (Fig. 29). The dam has been partly breached, and the lake contains water only during wet seasons and when melting snow feeds a large spring runoff. The outcrops of black rocks under the juniper trees on the left are at the south end of the basalt lava flow from Sheet Hill (Qby, Fig. 29, p.43).



*Figure 39. Photograph looking north along Big Fill Lake to Sheep Hill cinder cone. Fault scarp in Kaibab Formation limestone is in the trees on the right, and the basalt lava flow (Qby) from Sheep Hill is under the juniper trees on the left.*

*From the social trail at Stop 6 walk northeast on the track road for about 1,380 feet (0.26 mi) to the third social trail to the left. Turn left and walk west on the social trail about 300 feet to Stop 7 on top of the basalt lava flow.*

### **Stop 7. Basalt lava flow Qby from Sheep Hill cinder cone: End of Trail 3 Guide**

**A.** Sheep Hill cinder cone is about 1.5 miles north of Stop 7. The cinder cone erupted in the channel of Rio de Flag watercourse C near the north end of the northeast-trending graben (Fig. 12, p. 24; Fig. 29, p. 43; Fig. 42, p. 54). The basalt lava flow (Qby) extruded from the base of Sheep Hill and flowed south in Rio de Flag watercourse C, which was eroded in the Elden block and ash breccia next to the straight fault scarp.

The basalt (Qby, Fig. 29) is unusually straight and narrow. This shape is evidence that Rio de Flag watercourse C already existed and that the lava flow was confined to it. The “hook” of the basalt north of Route 66 (Fig. 29) is where the lava entered the mouth of a tributary that flowed down the north end of Campbell Mesa.

The basalt is younger than the Elden Mountain eruption (0.53 Ma). The eastern part of the Elden pyroclastic flow spread south and southeast from the vent across the northwest- and northeast-trending grabens and continued across the north end of Campbell Mesa. Preserved outcrops of the Elden block and ash breccia occur in both grabens and on the Kaibab Formation at the north end of Campbell Mesa, east of the basalt and Rio de Flag (Fig. 29, p. 43). Because the block and ash breccia is not on top of the basalt, the lava flow must be younger than the breccia.

**B.** Rio de Flag ancestral watercourse C and the modern channel slope north, but the surface of the basalt lava flow slopes south from Sheep Hill (elevations about 6,800 feet to 6,750 feet), and the basalt’s thickness decreases southward. The lava flowed upstream (south) in the ancient Rio de Flag channel. Lava can flow upstream if the lava is thick enough relative to a gentle slope of the land. Pahoehoe cords are preserved locally on the surface of the basalt, indicating the high fluidity (or low viscosity) of the lava and the relatively short time it has been weathered and eroded (Fig. 40).



*Figure 40. Photograph of ropy (or corded) structure on the surface of Sheep Hill pahoehoe basalt lava flow (Qby) about 150 feet north of the social trail at Stop 7. Coin for scale.*

C. Rio de Flag ancestral watercourse C was blocked by Sheep Hill and the lava flow. Water backed up in the grabens to form ancestral "Lake Continental" (Fig. 12, p. 24).

Fine sand, silt, and clay sediments deposited in the lake reach local thicknesses over 20 feet. Brown lake sediments on top of the basalt at Stop 7 indicate that the lake covered the south half of the lava flow (Fig. 12, Fig. 41).

The lake surface rose until the water spilled out at the lowest point on the shoreline, which was about 6,780 feet elevation (Fig. 12, p. 24); this elevation is about 10 feet above the surface of the lava flow at Stop 7. The new river flowed along the east side of the small Sheep Hill lava flow (Qby), exited ancestral watercourse C between "Little Sheep Hill" and Campbell Mesa, flowed along the west side of Wildcat Hill, and poured over the edge of the large Sheep Hill lava flow at Picture Canyon (Fig. 12, p. 24).

The west side and top of the lava flow at Stop 7 are covered by brown lake deposits of fine sand, silt, and clay. The east side of the lava flow was stripped of these deposits when the modern Rio de Flag eroded its channel in the lake sediments. Scattered pebbles on the surface of the lava flow are **chert** and limestone from the Kaibab Formation, andesite from San Francisco Mountain, and basalt, probably from the Dry Lake volcano lava flow (Qbo). The pebbles on top of the lava flow record the reestablishment of through-flowing modern Rio de Flag (Fig. 41).

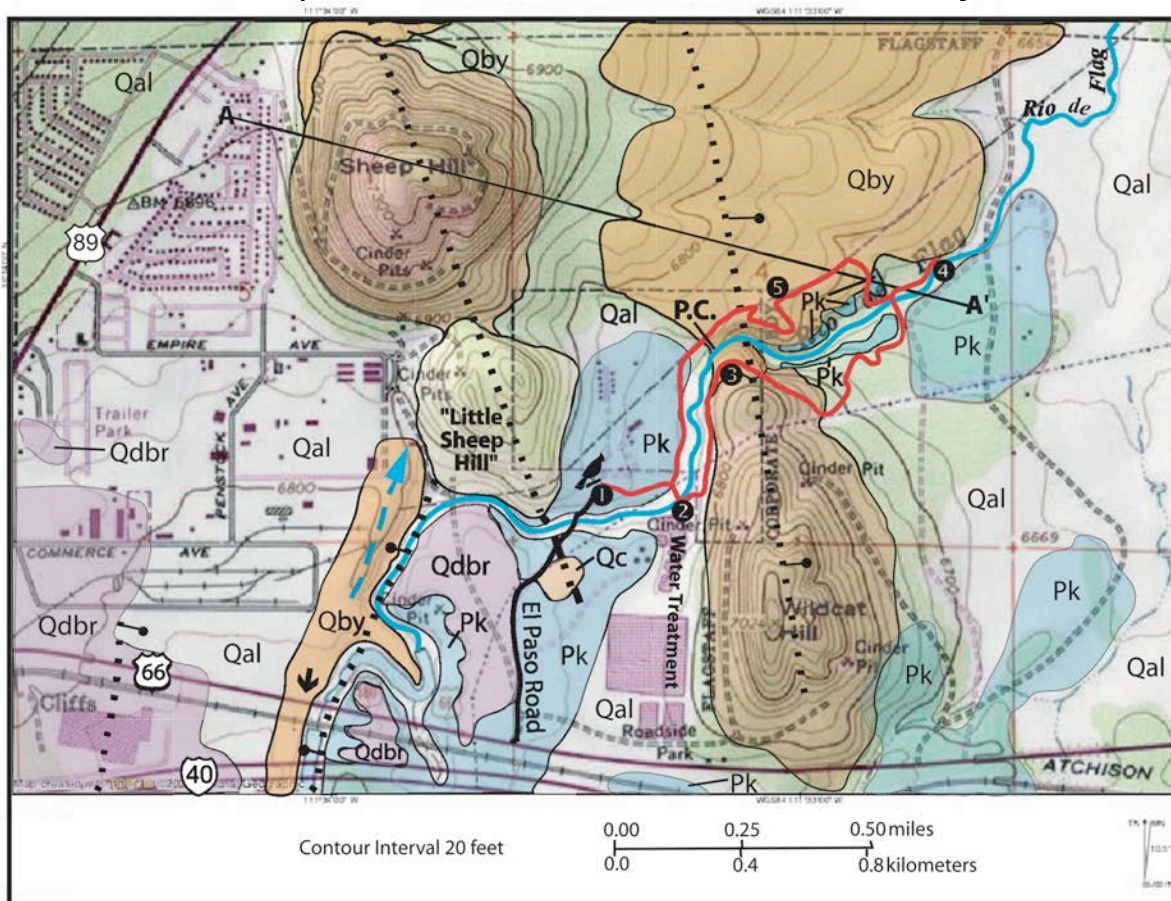


*Figure 41. Photograph of the top of the Qby basalt lava flow covered with fine brown lake sediments that were deposited in ancestral "Lake Continental." Pebbles derived from the Kaibab Formation, San Francisco Mountain, and Dry Lake volcano lava flow are concentrated as a lag deposit on the eroded east side of the lava flow. View is looking west.*

*.End of guide for Trail 3. Follow the track road south to Old Walnut Canyon Road, or alternatively, to Continental Sports Park.*

## TRAIL 4: PICTURE CANYON LOOP TRAIL

**Synopsis:** Trail 4 combines two trails on the Picture Canyon Natural and Cultural Preserve and part of the Arizona Trail to make a loop around Picture Canyon and a reach of modern Rio de Flag. An information sheet containing a map and description of the Preserve is usually available in a kiosk at the trailhead. Modern Rio de Flag started when water overflowed ancestral “Lake Continental” in watercourse C at about 6,780 feet elevation. The new river flows between the southern small lava flow from Sheep Hill (Qby) and the fault scarp along the west side of Campbell Mesa, exits watercourse C between “Little Sheep Hill” and the north end of Campbell Mesa, flows along the west side of Wildcat Hill, descends a series of small waterfalls at Picture Canyon, and continues northeast to rejoin ancestral watercourse C. A wetlands area was developed downstream from the Wildcat Hill water treatment plant in the low-gradient reach above the waterfalls. Trail 4 starts on Kaibab Formation limestone, crosses the flood plain to the base of Wildcat Hill cinder cone, traverses the side of Picture Canyon, continues downstream to an archaeological site, and returns to the trailhead on a path that climbs up a series of switchbacks on the edge of the large lava flow from Sheep Hill. On return, the trail accesses an ancient Native American pit house and views of the waterfalls in Picture Canyon.



**Figure 42. Map showing Trail 4 (red line), Rio de Flag (blue line), faults (bold black dots where covered by younger deposits, bar and ball on down side if known). Rock formations: Pk: Kaibab Formation; Qdbr: Elden block and ash breccia; Qby: basalt lava flows from Sheep Hill; Qc: red cinders; Qal: alluvium. Other symbols: blue dash line with arrowhead: flow direction of Rio de Flag ancestral watercourse C; black arrow: flow direction of Qby lava. A-A': line of cross section in Figure 50. Bird icon: trailhead of Trail 4. Stop numbers on trail are keyed to text. P.C.: Picture Canyon.**

**Directions to Trailhead:** Drive about 4.1 miles east from Humphreys Street on Historic Route 66/Santa Fe Avenue/U.S. 89/U.S. 180 to brown sign pointing right turn off Santa Fe Avenue to stay on Route 66. Continue east on Route 66 following brown signs to Picture Canyon for about 1.8 miles to N. El Paso Flagstaff Road. Turn left on N El Paso Flagstaff Road and drive north about 0.6 mile to trailhead; bear right at the first road fork and left at the second road fork. Two parking lots on the right.

**Character of trail:** Mostly well maintained. Narrow and rocky on short stretch of switchbacks, and at vista points at Stop 5.

**Length round trip:** About 3.2 miles.

**Elevations:** 6642 ft to 6786 ft

**Time:** Allow 2-3 hours.

**Difficulty:** Easy to moderate.

**Base map:** U.S. Geological Survey, Flagstaff East Quadrangle, Arizona, 7.5' Series, 1962, photorevised 1983. The cultural and geologic data at the Wildcat Hill water treatment plant have not been updated.

**Road and trail distances and elevations:** Google Earth.

**Approach to trailhead:** *North El Paso Flagstaff Road heads north from Route 66. Sheep Hill and “Little Sheep Hill”, the red hills in view straight ahead, are cinder cones, now greatly modified from original symmetry by quarry operations (Fig. 43). In about 0.4 mi. the road approaches a shallow valley; this is the Rio de Flag valley (Fig. 44). Two parking lots at Trail 4 trailhead are across the valley on the right. Toilets are at the northern lot.*



*Figure 43. Photograph of Sheep Hill (higher, left) and “Little Sheep Hill” (lower, right). The basalt cinder cones are quarried for aggregate, road material, and landscaping stones. The topography shown on the map in Figure 42 is based on aerial photographs taken in the 1950s.*



*Figure 44. View of Rio de Flag valley above Picture Canyon. Downstream is to the right (east). Parking lots are across the valley on the right.*

## **Stop 1. Trailhead on North El Paso Flagstaff Road**

The trailhead is on nearly flat-lying beds of the Kaibab Formation. Outcrops and loose blocks of the light gray limestone and dolostone poke through a thin overlying layer of cinders and soil. Elevation of the north parking lot is 6,774 feet.

Take the trail east from either parking lot for about 750 feet (0.14 mi) to the Outdoor Classroom where several display panels have information on the natural and cultural history of the Preserve. Continue down the trail for another 45 feet to a junction of trails. Turn right and take the trail to the Watchable Wildlife Site (about 200 feet). The trail to Stop 2 enters the flood plain of Rio de Flag.

## Stop 2. Developed wetland in flood plain of Rio de Flag

Many conservation groups and dedicated volunteers (too many to name individually; see brochure at trailhead and information panels on the trail) assisted the City of Flagstaff in developing the Preserve and changing the flood plain into a wetland. Treated outflow from the Wildcat Hill Wastewater Treatment Plant has changed this reach of Rio de Flag from an intermittent stream to a perennial stream. The pond was impounded by an earthen dam, and new meander bends were carved in the alluvium (Figs. 45, 46).



*Figure 45. Photograph of pond in Rio de Flag wetland. Wildcat Hill cinder cone is the tree covered hill in the background.*



*Figure 46. Photograph of Rio de Flag flood plain above Picture Canyon; view is downstream. The first meander bend passes between the tall trees in the middle of the flood plain.*

Follow the social trail on the earthen dam on the left (north) side of the pond to the history information panel by the Tom Moody Trail (about 200 feet). Turn right and follow the Tom Moody Trail to Stop 3 (about 1,550 feet; 0.29 mi). The trail heads north along the side of the flood plain at the base of Wildcat Hill cinder cone. Cinders and **volcanic bombs** mantle the slope of the volcano. The flood plain narrows abruptly where Rio de Flag meets the lava flow from Sheep Hill (Fig. 42, p. 54).

## Stop 3. Picture Canyon

**A.** The trail approaches Picture Canyon at the north end of Wildcat Hill cinder cone. Here, the cinder deposit overlies the basalt lava flow from Sheep Hill (Qby), which establishes the older age of the Sheep Hill eruption (Fig. 47). Rio de Flag flows in the low spot between the north end of Wildcat Hill and the higher elevations of the Sheep Hill lava flow (Fig. 42). Picture Canyon's convex curve to the north likely formed as Rio de Flag started flowing around the north end of Wildcat Hill. The low gradient of Rio de Flag in the flood plain gives way to a steep, narrow channel where Rio de Flag enters the west end of Picture Canyon (Fig. 48).



*Figure 47. Photograph on Tom Moody Trail where it approaches Stop 3. The north slope of Wildcat Hill (right) is covered by cinders and volcanic bombs. The lava flow from Sheep Hill (Qby) is exposed on the flat grassy area crossed by the trail. The cinders and bombs cover the lava flow.*



*Figure 48. Photograph of the upper west end of Picture Canyon. Rio de Flag is incised in a narrow, rocky channel where it enters the canyon.*

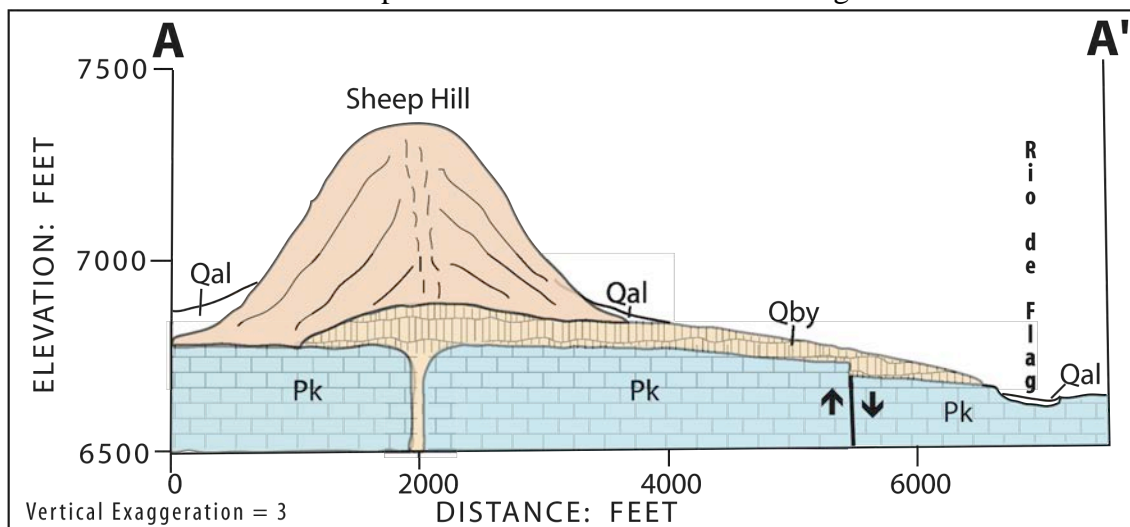
**B.** It is dangerous to try to see the bottom of Picture Canyon from Stop 3. Stay safe and do not go to the edge of the cliff. View the upper part of the canyon and the north side from a safe position. Better views of Picture Canyon from top to bottom can be found at Stop 5. A display panel at Stop 3 describes the history of logging in this area and the railroad constructed by the Greenlaw Lumber Co.

**C.** Exposed on the north side of Picture Canyon is a thick lower flow unit of the basalt lava flow from Sheep Hill (Qby) at and below the level of the trail; the vertical cracks are **columnar joints** that formed as contraction fractures perpendicular to the cooling surface (Fig. 49). Two to three thinner flow units of basalt cap the canyon wall. Erosion of **autoclastic breccia** between the upper flow units made recesses two to four feet deep; a ten-foot-deep recess with a shelter wall in front probably was excavated, at least in part.



*Figure 49a left, 49b right. Photographs of the north side of Picture Canyon taken from Stop 3. The lava flow from Sheep Hill consists of a thick lower flow unit with vertical columnar joints and several thin flow units on top.*

**D.** The Picture Canyon chasm was eroded by Rio de Flag into, but not through (yet), the basalt lava flow from Sheep Hill (Qby). The **cascades** drop about 75 feet as the water flows down the canyon. The elevation change is about the same as the offset of a fault buried by the lava flow. Above Picture Canyon the contact of the Qby lava flow on the Kaibab Formation (Pk) is at about 6,760 feet elevation. Below Picture Canyon the same contact is at about 6,680 feet elevation; the offset of the fault is about 80 feet down on the east side (Fig. 42, p. 54). Wildcat Hill reveals the position and orientation of the fault. Wildcat Hill has a strong **bilateral symmetry**, the plane of which projects slightly west of north through Picture Canyon and next to a decrease of the slope of the surface of the lava flow east of Sheep Hill (Fig. 42). Because the surfaces of the lava flow and Wildcat Hill do not display a comparable offset, the fault must predate the volcanoes. The lava conduit that supplied the Wildcat Hill eruption likely was a dike injected along the fault; the eruption produced a cinder cone elongated along the fault. The relations of the fault and Sheep Hill lava flow are illustrated in Figure 50.



*Figure 50. Cross section along line A-A' on the map in Figure 42, p. 54. Qby lava flow is draped over the fault. Sheep Hill possibly erupted on a fault that also localized the conduits of “Little Sheep Hill” and the mound of red cinders southeast of “Little Sheep Hill” (Fig. 42); offset on this presumed fault is unknown.*

**E.** Rio de Flag was diverted to the place where Picture Canyon was eroded when Sheep Hill and its small lava flow blocked ancestral watercourse C (Fig. 12, p. 24; Fig. 42, p. 54). The river postdates the lava at Picture Canyon, but the age of the river here is poorly known. The maximum age of the lava flow (and the river) is 0.53 Ma because it postdates the Elden block and ash breccia, which was deposited on both sides of the lava but not on its surface (Fig. 42). The minimum age of the lava is less certain, but might be estimated by comparison of Sheep Hill and A 1 Mountain. The slopes of both cinder cones are similarly dissected by gullies, which suggests similar stages of erosion and possibly similar ages. The age of A 1 Mountain lava flow is 0.33 Ma; Sheep Hill lava flow is undated, but might be about the same age. If this is true, Rio de Flag at Picture Canyon might be similar in age to Rio de Flag in Fort Valley and Cheshire.

Wildcat Hill is known to be younger than Sheep Hill, as documented by the field relations at Stop 3 (Fig. 47, p. 57). There is no surface evidence of a Rio de Flag watercourse that predates Wildcat Hill (Fig. 42, p. 54; Flagstaff East Quad., 1962), so it seems likely that the eruption of Wildcat Hill closely followed Sheep Hill and that the cinder cone was in place before ancestral “Lake Continental” overflowed.

*Follow the Tom Moody Trail (Trail 4) southeast for about 1,150 feet (0.22 mi) to its junction with the Arizona Trail. Turn left and follow the joint Tom Moody-Arizona Trail for about 1,965 feet (0.37 mi) to the trails junction just across Rio de Flag on the north side of the bridge. Turn right and follow the Tom Moody Trail for about 590 feet (0.11 mi) to Stop 4.*

### **Stop 3 to Stop 4**

The Tom Moody Trail from Stop 3 to the junction with the Arizona Trail crosses the northeast side of Wildcat Hill cinder cone (Fig. 42, p. 54). The red cinders are quarried in the middle and south parts of the volcano for building and decorative materials. The joint Tom Moody-Arizona Trail starts on cinder alluvium eroded off of Wildcat Hill and continues across flatter ground covered by a thin blanket of fine black cinders on top of the Kaibab Formation; the cinders probably erupted from Wildcat Hill. Shortly before reaching the bridge over Rio de Flag the trail passes an outcrop of Kaibab limestone. From the trails junction to Stop 4 the Tom Moody Trail follows Rio de Flag on the flood plain.

### **Stop 4. Waterbird Petroglyph Site**

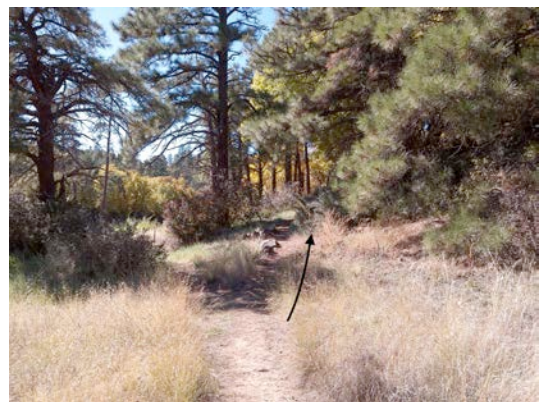
**A.** The eroded and weathered edge of the basalt lava flow from Sheep Hill displays petroglyphs that are easily accessed, examined, and photographed (Fig. 51). These are only a few out of the several hundred that have been discovered in the Preserve. Picture Canyon takes its name from the many well-preserved petroglyphs. Information panels at Stop 4 give details of the cultural history of the Preserve.



*Figure 51. Photograph of petroglyphs at Stop 4.*

**B.** Crystals in the solidified lava can be observed on clean fracture surfaces. The large black crystals (1-5 mm) are a variety of pyroxene named augite. The small white crystals are plagioclase; these are the most abundant. Sparse olivine crystals (<1mm) are green.

*Retrace steps to the trails junction by the bridge. Options: Either turn right (north) to take the Arizona Trail to the gas pipeline road, or continue straight ahead on the Don Weaver Trail to the gas pipeline road. No matter which trail is taken, turn left (west) onto the gas pipeline road on the top of the lava flow. The Don Weaver Trail leads west from the trails junction along the Rio de Flag flood plain. In about 310 feet the Don Weaver Trail reaches the west end of a small meadow where the trail branches (Fig. 52).*



*Figure 52. The Don Weaver Trail is the right fork that climbs 70 feet up the edge of the lava flow.*

Take the right fork of the Don Weaver Trail, which ascends the edge of the lava flow on three switchbacks. Turn left (west) on the gas pipeline road and follow it for about 970 feet (0.18 mi) to Stop 5, which is marked by a large block of basalt on the left (south) side of the road.

#### Stop 4 to Stop 5

The trail to Stop 5 traces the edge of the basalt lava flow from Sheep Hill back to the trails junction by the bridge. Rio de Flag flows next to the trail on a narrow flood plain. About 100 feet north of the trails junction are outcrops of Kaibab Formation limestone (Pk). Higher up the slope to the north are outcrops of the basalt lava flow (Qby). Here, the elevation of the contact of the lava flow on the limestone is at about 6,660 feet (Fig. 42, p. 54; Fig. 53).



*Figure 53. Photograph of basalt lava flow from Sheep Hill, Qby, on top of Kaibab Formation limestone, Pk, near the trails junction north of the bridge over Rio de Flag. The black line shows the approximate location of the contact. Line A-A' on Figures 42 (p.54) and 50 (p. 58) crosses these outcrops.*

The Arizona Trail passes the east side of these outcrops heading north (left to right in Fig. 53) and the Don Weaver Trail passes the west side of the limestone outcrop and then climbs the hillside to the top of the lava flow (Fig. 42). The Don Weaver Trail continues west (turn left) on top of the lava flow to Stop 5; keep your eye out for a large block of basalt on the left (south) side of the gas pipeline road.

## Stop 5. Loop trail on north side of Picture Canyon: End of Trail 4 Guide

Stop 5 is a loop of about 825 feet along the north side of Picture Canyon (Fig. 42, p. 54). On the south side of the large basalt block next to the Don Weaver Trail a narrow social trail leads down slope to the south toward Picture Canyon; in about 225 feet take the right fork. The trail passes a structure interpreted as a Native American pit house. Turn right at the pit house. Going west along the rim of Picture Canyon the trail becomes indefinite. Caution is advised in picking paths around large blocks of basalt on the top of the lava flow. If in doubt, pick a path that leads uphill away from the edge of the canyon.

Several vantage points along the edge of the canyon present photogenic views of Picture Canyon and the Rio de Flag cascades (Fig. 54). A few hundred feet farther along the edge of the canyon a narrow social trail leads uphill to the Don Weaver Trail on the gas pipeline road.



*Figure 54. Photograph of the upper part of Picture Canyon and the Rio de Flag cascades. View is southwest from the north side of the canyon.*

*From Stop 5 follow the Don Weaver Trail on the gas pipeline road west to the Tom Moody Trail, which leads south (left) along a well-traveled path to the Outdoor Classroom and back to the trailhead. The distance from Stop 5 to the trailhead is about 3,150 feet (0.60 mi).*

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## GLOSSARY

**Page numbers refer to where the term is first used in the text, a figure caption, or a table. No page number is given if the term is not used.**

**alluvium** unconsolidated sediment consisting of clay, silt, sand, gravel (pebbles and boulders) deposited by moving water such as a river. p. 12.

**andesite** a medium to dark gray volcanic rock; typically contains white crystals of plagioclase. Named after the Andes Mountains. p. 9.

**ash** particles smaller than 2 mm that are produced by volcanic explosions. p. 8.

**aspect ratio** thickness or height divided by length or area. p. 31.

**autoclastic breccia** angular fragments broken from solidified crust of flowing lava. Commonly the fragments tumble down the front of the lava and are overridden as the lava moves forward and covers the breccia. p. 57.

**basalt** a black to dark gray volcanic rock; typically contains green crystals of olivine. The most common lava type in the Flagstaff area. p. 9.

**bed** a layer of rock; typically sedimentary but includes pyroclastic (explosive volcanic). p. 8.

**bedrock** solid rock that forms the ground surface as an outcrop or is covered by unconsolidated deposits such as alluvium or soil. p. 5.

**bedding** plane to wavy layers in sedimentary and some pyroclastic volcanic rocks; represents the surface on which particles accumulated. p. 49.

**benmoreite** a medium gray variety of andesite that contains higher amounts of sodium; lavas in the Flagstaff area contain few visible crystals. Named after a mountain on the Scottish island of Mull. p. 14.

**bilateral symmetry** the property of an object that appears to be divided by a single plane into two halves that are mirror images of each other. p. 58.

**block and ash breccia** a volcanic deposit consisting of a structureless mixture of large (>64 mm) to small (<2mm) particles of irregular shapes; derived from explosive eruptions and propelled by gravity as a rapidly moving mass of hot particles and gas until loss of momentum causes deposition. p. 14.

**breccia** a general term for consolidated rocks (or partly consolidated deposits) consisting of large

angular particles embedded in a finer-grained matrix. Can originate by volcanic explosions, movement of faults, collapse of cliffs and sinkholes, and other mechanisms that break pre-existing rocks. p. 14

**butte** an isolated hill or small mountain with steep slopes or cliffs; composed of rocks resistant to erosion such as sandstone or basalt. Smaller than a mesa. p. 13.

**canyon** a long, deep, relatively narrow, steep-sided valley in a plateau or mountainous area; larger than a gorge. p. 5.

**cascades** a series of small, closely spaced waterfalls and very steep rapids. p. 58.

**chasm** a narrow and steep-sided gorge or canyon. p. 19.

**chert** cryptocrystalline to microcrystalline silica; multiple colors. Common in limestone. p. 53.

**cinder** a very **vesicular** glassy particle of variable sizes and shapes erupted as a clot of lava during a volcanic explosion; typically black to red and of basaltic to andesitic composition. p. 8.

**cinder cone** a small volcano composed of cinders. Cones are steep sided (25° to 32°), range from a few 10s of meters high and in basal diameter to 300 m high and 1.6 km in basal diameter. Young cones typically have a summit crater. Composition is basalt to andesite. Sunset Crater is an example. p. 8.

**cleft** an abrupt cut, breach, notch, or narrow recess.

**colluvium** unconsolidated soil and rock debris moved slowly down slopes by gravity. p. 32.

**columnar joints** contraction fractures in lava flows that form perpendicular to the cooling surface. Typically steep to vertical in lava flows and horizontal in vertical dikes. p. 57.

**composite volcano (syn. stratovolcano)** a large volcano bound by concave-up slopes that increase in steepness to over 30° at the summit. Heights range from 100s of meters to more than 4,000 m. Composed of lava flows, cinder beds, lava domes, and dikes of andesite, dacite, and rhyolite. San Francisco Mountain is an example. p. 8.

**compressive force** squeezing force in the Earth. p. 7.

**conglomerate** a sedimentary rock composed dominantly of rounded pebbles, cobbles, boulders (particles larger than 4 mm). Deposited by water moving with high energy, such as a river. p. 10.

**contact** the surface or boundary along which two different rocks touch. Shown on a geologic map as a line between two map units with different colors and symbols. p. 10.

**crop out** verb, applied to surface exposures of solid rock. p. 10.

**cross beds** layers in a sedimentary rock inclined to the (horizontal) bounding surfaces of the rock. Typically deposited at about the angle of repose of sand grains (~32°) on dunes, but also deposited by turbulent water currents in rivers and by ocean waves. p. 13.

**crystal** a naturally occurring solid substance composed of atoms of specific chemical elements arranged in a regular and repetitive three-dimensional geometric pattern. p. 8.

**crystalline** the property of a rock that contains only crystals (no glass). p. 9.

**cuesta** an asymmetrical ridge on a tilted layer of rock that is resistant to erosion; the gentler slope is in the direction of tilt. Typically paired with a weak, easily eroded layer. p. 10.

**dacite** a volcanic rock, medium to light gray to pinkish gray. Commonly displays white crystals of plagioclase. Named after a region in Romania. p. 9.

**Devonian** the Period in the Geologic Time Scale between 419 Ma and 359 Ma. p. 13.

**dike** a tabular body of igneous rock that was injected in a molten state into another rock. p. 49.

**dip** the angle of tilt of a planar geologic structure from a horizontal plane. Applied to joints, bedding, faults. p. 10.

**discharge** the rate of flow of a river measured in cubic feet per second (ft<sup>3</sup>/sec): the cross sectional area of a river at a specific place times the velocity of the river (ft<sup>2</sup> x ft/sec). p. 18.

**dolostone** a sedimentary rock composed of the mineral dolomite (calcium-magnesium carbonate). Typically medium to light gray. p. 13.

**epicenter** of an earthquake. The location on Earth's surface directly above the rupture site of a fault that generates an earthquake. p. 47.

**escarpment** a cliff or steep slope at the edge of an upland area like a plateau or mesa. Typically capped by a stratum resistant to erosion. p. 7.

**exogenous** said of a lava dome where the flows extrude from a summit vent and pour down the side of the volcano. Elden Mountain is an example. p. 49. (Opposite of **endogenous** where the lava inflates the dome on the inside; example is Sugarloaf Mountain).

**exsolution** the process of a substance (like a liquid) separating into two substances (like liquid + gas) with no change in bulk composition. p. 32.

**extensional force** pull-apart force in the Earth. p. 7.

**fault** a fracture in a rock along which a force caused one side to move relative to the other side; typically planar. p. 5.

**fault scarp** a cliff or steep slope formed by movement along a fault. p. 13.

**feldspar** a group of similar minerals; varieties are plagioclase (calcium and sodium), orthoclase (potassium), microcline (potassium), sanidine (potassium); all contain aluminum and silica. Typically white, but can be clear, pink or gray; uncommonly, green.

**flood plain** low, flat ground adjacent to the channel of a river. Covered with water when high discharge from a storm or during wet seasons fills the channel and spills over the banks. p. 7.

**formation** a distinctive igneous, metamorphic, or sedimentary rock or deposit that is large enough to show on a geologic map and which is given a formal name or map-unit name and map symbol. p. 10.

**geologic map** a map that displays the distribution of rocks, deposits, structures (faults) and other geologic features in a specific area. p. 11.

**Geologic Time Scale** a calendar of Earth history spanning the time from the present to the origin of the Earth about 4.6 billion years ago. The Scale is divided into sections and subsections called Eras, Periods, Epochs, and Ages. p. 11.

**glass (volcanic)** solidified lava that lacks crystals; the atoms are disordered. Results from rapid cooling that produces a "supercooled liquid." p. 8.

**gorge** a small, narrow, deep valley with nearly vertical rocky walls; smaller than a canyon. p. 19.

**graben** a block of rock that has moved down along faults on two sides under extensional force. The surface expression is a valley bound on both sides by fault scarps. p. 16.

**graded (mature) river** a river that displays a long-term balance between discharge and velocity, erosion, sediment transported and deposited, and gradient. Its longitudinal profile is a smooth concave-up curve. p. 19.

**gradient (of a river)** the downstream slope of a river's channel measured in feet/mile. p. 20.

**gravel** an unconsolidated sedimentary deposit composed dominantly of rounded pebbles, cobbles, boulders. p. 7.

**gully** a small, narrow channel worn by running water. p. 18.

**headward erosion** the lengthening of a river's valley or canyon upstream by erosion at the head of the valley or canyon. p. 33.

**igneous** rocks derived from molten material; also, processes that produce and solidify natural molten material. p. 6.

**immature river** a river that deviates from a smooth concave-up longitudinal profile because of abrupt increases in gradient. p. 20.

**intermittent (ephemeral) river** a river that flows after a storm and during wet seasons, and lacks water at other times. p. 20.

**joint** a planar fracture or crack in a rock that lacks evidence of relative movement of the rocks on each side. p. 57.

**knickpoint** an abrupt steepening of a river's gradient at a resistant rock, or a point of upstream migration of the steeper gradient of a younger longitudinal profile produced by accelerated downstream erosion. p. 20.

**laccolith** a dome-shaped igneous structure on a flat floor formed by magma intruded along bedding planes in sedimentary rocks. p. 49.

**lag deposit** concentration of large particles on the surface after smaller particles have been removed by a lower-energy erosional system. p. 53.

**lapilli** pyroclasts between 2 mm and 64 mm.

**lava** molten material that erupts or extrudes on Earth's surface. p. 5.

**lava dome** a small- to moderate-size volcano constructed by viscous lava that pushes up into the growing dome and inflates from inside (endogenous), or is built by thick overlapping lava flows that extrude from and pile up around the vent (exogenous). Slopes are steep, up to 30°-35°. Dacite and rhyolite are most common, but some lower-profile domes are andesite. Sugarloaf is an endogenous dome and Elden Mountain is an exogenous dome. p. 8.

**lava flow** molten material on the surface that is flowing away from the effusive vent; a body of rock formed by the solidification of lava. p. 5.

**lava tube** a tunnel in a lava flow that contains flowing lava; commonly forms when a crust solidifies as a roof on a stream of lava. A cave can result if the lava drains from the tube after the extrusion stops. p. 31.

**limestone** a sedimentary rock composed of the mineral calcite (calcium carbonate). Deposited by inorganic and organic chemical precipitation in oceans, lakes, springs. Typically medium to light gray. p. 7.

**longitudinal profile** a graph constructed by plotting the elevation of a river's channel (y axis or vertical axis) against distance along the length of the channel (x axis or horizontal axis). p. 19.

**Ma** mega-annum: million years; the place in geologic time of the age of a rock; a date. The Geologic Time Scale starts at the present (0.0 Ma) and increases back in time to the estimated age of Earth: 4,600 Ma. In comparison, the Christian Calendar starts at the birth of Christ (0.0 years) and increases forward in time to the present (ex. 2018). p. 11.

**maar** a small, low-profile volcano characterized by a broad, deep crater that is surrounded by a low rim of tuff. Craters range from ~10 m to ~500 m deep, and the bottom is below the pre-eruption ground surface; crater widths range from 10s of meters to over 1.6

km. Typically basalt. From German for sea. May contain a lake or pond if the bottom of the crater is below the level of the local water table. Colton Crater (Crater 160) is a maar. p. 8.

**magma** molten material underground. p. 14.

**magnetic** see **normal magnetic polarity**.

**magnitude (of an earthquake)** a logarithmic measure of the energy released by an earthquake. p. 47.

**map unit** a body of rock that is large enough and distinctive enough to show on a geologic map. p. 13.

**mesa** an isolated, generally flat-topped landform surrounded by steep sides or cliffs above the surrounding terrain; capped by a rock layer resistant to erosion. Larger than a butte, and smaller than a plateau. p. 5.

**metamorphic** rocks derived from pre-existing rocks by underground changes in temperature, pressure (which can include shearing stress), and chemical composition. Includes the solid-state processes of new crystal growth, recrystallization of old crystals, plastic deformation, addition and removal of chemical elements by intergranular fluids. p. 6.

**Miocene** the Epoch in the Geologic Time Scale between 23.0 Ma and 5.3 Ma. p. 13.

**monocline** a geologic structure in which flat-lying sedimentary rocks are flexed into two bends connected by strata that dip in one direction. Formed by compressive forces that push rocks up along a steeply dipping reverse fault. Gray Mountain is a monocline.

**mudstone** a sedimentary rock composed dominantly of clay and silt, particles smaller than 1/16 mm; typically massive. Deposited in low-energy water environments such as lakes, flood plains, tidal flats, oceans below wave action. Variable colors: red, brown, tan, gray, black. p. 13.

**m.y.** million years; an interval of geologic time. For example, if the age of a rock is 30 Ma, the rock formed 30 m.y. ago or the rock is 30 m.y. old. The Miocene Epoch spans 17.7 m.y. in the Geologic Time Scale. p. 11.

**normal fault** an inclined fault where the rocks above the fault moved down relative to the rocks below the fault; produced by extensional force. p. 16.

**normal magnetic polarity** the internal magnetic property of a rock corresponds with Earth's present directions of the north and south magnetic poles. p. 14. (Opposite is **reversed magnetic polarity** where the rock's internal magnetic property corresponds with reversed directions of Earth's north and south magnetic poles).

**obsidian** natural glass formed by rapid cooling of viscous lava; typically of rhyolitic composition (high silica content) and black. Texture is dense and smooth in contrast to pumice which is light and frothy. p. 9.

**offset** the amount of displacement of some identifiable geologic feature, such as a layer of rock cut by a fault. p. 7.

**olivine** a green mineral composed of magnesium, iron, and silica. Common in basalts. p. 9.

**outcrop** noun; an exposure of a solid rock, or bedrock, at the surface. p. 10.

**pahoehoe** Hawaiian name applied to lava flows characterized by surface structures that resemble cords or ropes; lava had low viscosity. p. 36.

**paleomagnetism** the magnetic property of a rock acquired when the rock originated. p. 50.

**paleovalley** a former valley that has been filled by a younger rock or deposit. p.22.

**Paleozoic** the Era in the Geologic Time Scale between 541 Ma and 252 Ma. p. 12.

**Pelêan** a type of eruption associated with lava domes and viscous lava when powerful explosions blow lava, rocks, crystals, pumice, and ash several kilometers above the vent. Gravity collapses the eruption column, which then spreads laterally across the ground surface as hot pyroclastic flows that deposit block and ash breccias. Named after a devastating eruption of Mt. Pelêe in 1902 on the Caribbean island of Martinique. p. 14.

**Permian** the Period in the Geologic Time Scale between 299 Ma and 252 Ma. p. 11.

**physiography** description of the broad, region-wide geographical and structural features of the Earth. p. 7.

**physiographic province** a large region characterized by particular features of geography and geologic structure, such as the Colorado Plateau and the Basin and Range provinces. p. 5.

**plagioclase** a variety of the feldspar group of minerals that contains calcium, sodium, aluminum, and silica; typically white. Common crystals in most volcanic rocks in the Flagstaff area. p. 9.

**plateau** a large upland region of fairly uniform elevation that is separated from surrounding lower terrain by escarpments or geologic structures such as large faults. Larger than a mesa. p. 5.

**plate tectonics** a theory that describes the outermost rigid layer of Earth as divided into segments called plates that move relative to each other in response to forces driven largely by gravity acting on internal plastic material. p. 7.

**pumice** frothy volcanic glass; typically occurs as pyroclasts. Most pumice is high in silica and white (rhyolitic composition), but basaltic pumice (black) occurs on Hawaii. Floatation on water is characteristic. p. 8.

**pyroclast** an individual fragment or particle produced by a volcanic explosion. A cinder is an example. p. 23.

**pyroclastic** said of a consolidated rock or unconsolidated deposit composed of fragments produced by volcanic explosions; fragments include pieces of pumice, crystals, ash, broken rocks, cinders. Includes the processes of volcanic explosions that fragment lava and pre-existing rocks. p. 12.

**pyroclastic flow** a rapidly moving mass of hot pyroclasts and gas that spreads out laterally on the surface from an eruption column collapsing under the force of gravity. Internal gas buffers the solid particles, which reduces internal friction and helps maintain momentum that allows long-distance run out. p. 14.

**pyroxene** a group of minerals composed most commonly of variable amounts of magnesium, iron, calcium, aluminum, and silica; typically black to dark green. Common crystals in basalt and andesite in the Flagstaff area. p. 9.

**quartz** a mineral composed only of silica; white to clear and transparent. Common in sedimentary rocks in the Flagstaff area. p. 9.

**Quaternary** the Period in the Geological Time Scale between 2.6 Ma and the present 0.0 Ma. p. 11.

**ramping shear fractures** planar fractures in a lava flow at its front end that result from forward motion of the lava pushing up over cooler, stalled lava at the front. p. 38.

**reach** a continuous part of a river between two specified points; a defined section of a river. p. 5.

**reverse fault** an inclined fault where the rocks above the fault moved up relative to the rocks below the fault; produced by compressive force. p. 16.

**rhyolite** a pale volcanic rock high in silica; typically white to light pink to light gray; found locally in the Flagstaff area. Bluish rhyolite occurs on San Francisco Mountain. page 9.

**runoff** the part of precipitation that enters surface streams. p. 1, 18.

**sandstone** a sedimentary rock composed dominantly of sand-size grains, 1/16 mm to 2.0 mm. Deposited by wind and moving water such as rivers and waves. Variable colors: red, brown, tan, white. p. 8.

**sanidine** a variety of the feldspar group of minerals; contains potassium, aluminum, silica. Commonly clear to white to light pink. Found in rhyolite and some dacite in the Flagstaff area. p. 9.

**scarp** a relatively straight cliff or steep slope formed by a fault or erosion of a resistant layer of rock. p. 13.

**sediment** unconsolidated or poorly compacted geologic material deposited or accumulated on Earth's surface. p. 33.

**sedimentary** rocks that originate on Earth's surface by mechanical deposition of solid particles by wind and water, and by inorganic or organic chemical precipitation from water. Applied to the processes of deposition. p. 6.

**shale** a sedimentary rock composed dominantly of clay and silt, particles smaller than 1/16 mm. Deposited in low-energy environments such as lakes, flood plains, tidal flats, oceans below wave action. Thinly layered with planes along which the rock breaks (bedding planes). Variable colors: red, brown, tan, gray, green, black. p. 10.

**shield volcano** a low-profile volcano with gentle slopes of about 5°. Sizes range from about 100 m

high and 1 to 2 km of basal diameter to 1,000s of meters high and 10s of kilometers of basal diameter. Constructed with many thin, very fluid (low viscosity) lava flows; typically basalt. Resembles an up-side-down saucer. Several small shields can be seen south of Mormon Lake. p. 8.

**silica** a chemical compound composed of silicon and oxygen; the formula is SiO<sub>2</sub>. p. 9.

**siltstone** a sedimentary rock composed dominantly of silt, particles 1/256 mm to 1/16 mm. Massive or layered (bedding planes). Deposited in low-energy environments such as lakes, flood plains, tidal flats. Variable colors: red, brown, tan, gray, black. p. 10.

**sink or sinkhole** a depression in Earth's surface caused by collapse of rocks into underground openings. Typically found in areas underlain by limestone. p. 17.

**strata (stratum)** layers (or layer) of rocks; typically applied to sedimentary rocks. p. 13.

**stratigraphic, stratigraphy** the sequence of rocks from oldest to youngest. Can be described on the scale of an outcrop, a canyon, a mountain, mesa, or plateau, or even a continent. p. 14, 21.

**stream or drainage divide** topographically high terrain that separates streams flowing in opposite directions. p. 7.

**strike** the compass direction of a horizontal line on an inclined planar geologic structure such as a joint, fault, bedding plane. p. 10.

**strike valley** a valley eroded by a river in the direction of the strike of tilted strata. The valley is commonly positioned on a soft layer between harder layers. The Little Colorado River flows in a strike valley. p. 10.

**tectonic** said of forces in the Earth that move rocks, provinces, continents, and oceans, and the geologic structures that result from the forces. p. 7.

**terrane** a term applied to an area or region dominated by a formation or group of formations. p. 7.

**terrain** a term applied to an area or region with regard to its geographic and topographic features. p. 28.

**Tertiary** the Period in the Geologic Time Scale between 66.0 Ma and 2.6 Ma. Some authors divide

the Tertiary into two Periods: Paleogene between 66.0 Ma and 23.0 Ma, and Neogene between 23.0 Ma and 2.6 Ma. p. 11.

**Triassic** the Period in the Geologic Time Scale between 252 Ma and 201 Ma. p. 11.

**tuff** a rock made of compacted particles such as cinders, pumice, crystals, ash, and rock fragments that were produced by volcanic explosions. p. 8.

**tuff cone** a small volcano composed of tuff. Cones have prominent profiles, are steep sided (up to  $\sim 25^\circ$ ), range from a few 10s of meters high and in basal diameter to 300 m high and 3.0 km in basal diameter. Typically basalt and andesite. Red Mountain is a tuff cone. p. 8.

**tuff ring** a small, low profile volcano characterized by a broad crater and low rim of tuff. The crater has a small depth to width ratio, and the floor is above the pre-eruption ground surface. The rim is typically  $< 50$  m high, but the diameter of the volcano can be more than 3.0 km. Typically basalt and andesite, but all lava compositions are known. Dry Lake volcano is a combination tuff and cinder ring. p. 8.

**uplift**, noun, a structurally high area produced by forces that push rocks up. p. 5.

**vertical exaggeration** the ratio of the horizontal to vertical scales of a graph or cross section: vertical exaggeration = horizontal scale  $\div$  vertical scale. For example, if the horizontal scale is 1 inch = 1 mile (5,280 feet) and the vertical scale is 1 inch = 2,000 ft, then V.E. = 2.64, so that the vertical scale is increased or “exaggerated” 2.64 times. p. 20.

**vesicular** description of a lava flow or pyroclast that contains vesicles. p. 65.

**vesicle** a gas bubble trapped in rapidly cooling lava. p. 32.

**viscosity** a measure of the resistance to flow of a liquid (or plastic) substance. The “stiffness” of a lava flow. A very “fluid” lava that flows readily has low viscosity. p. 9.

**volcanic bomb** a rounded pyroclast larger than 64 mm. Surface tension of molten clots of lava from a volcanic explosion shapes the rounded forms. Typically basalt, but also andesite and dacite. p. 56.

**volcanic field** a well-defined geographic region covered by lava flows, tuffs, and volcanoes.

Typically, the volcanic products are related by similar ranges of compositions and ages, and similar mechanisms of volcanism. p. 8.

**volcanic province** a moderate to large geographic region covered by lava flows, tuffs, and volcanoes; typically includes several volcanic fields. For example, three volcanic fields near Flagstaff on the southern Colorado Plateau are considered a volcanic province p. 8.

**watercourse** a natural well-defined channel through which water (as a river) flows continuously or intermittently. p. 5.