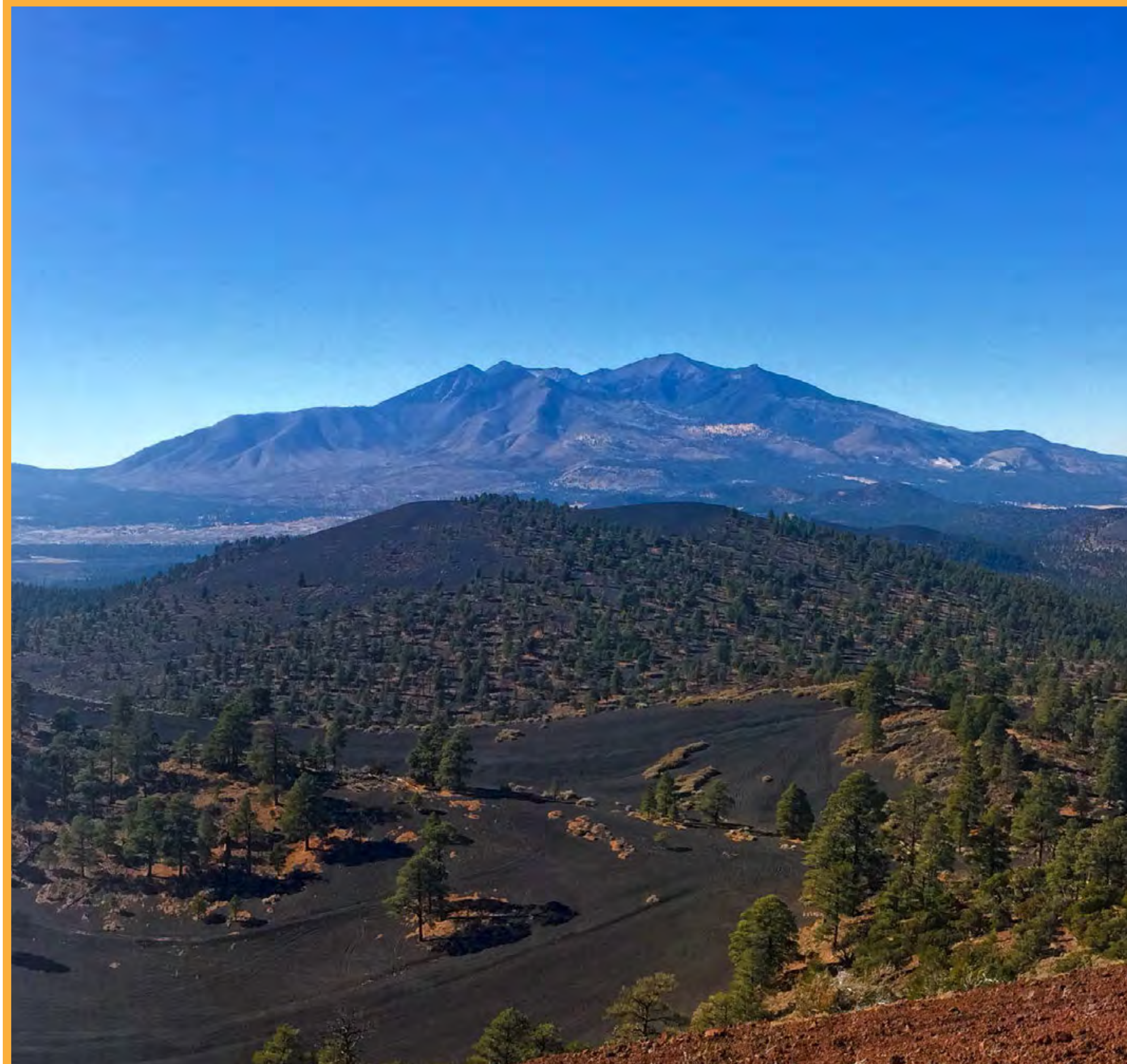
Field Trip: San Francisco Volcanic Field, Sunset Crater Volcano National Monument & Wupatki National Monument

Sunday, June 14, 2015



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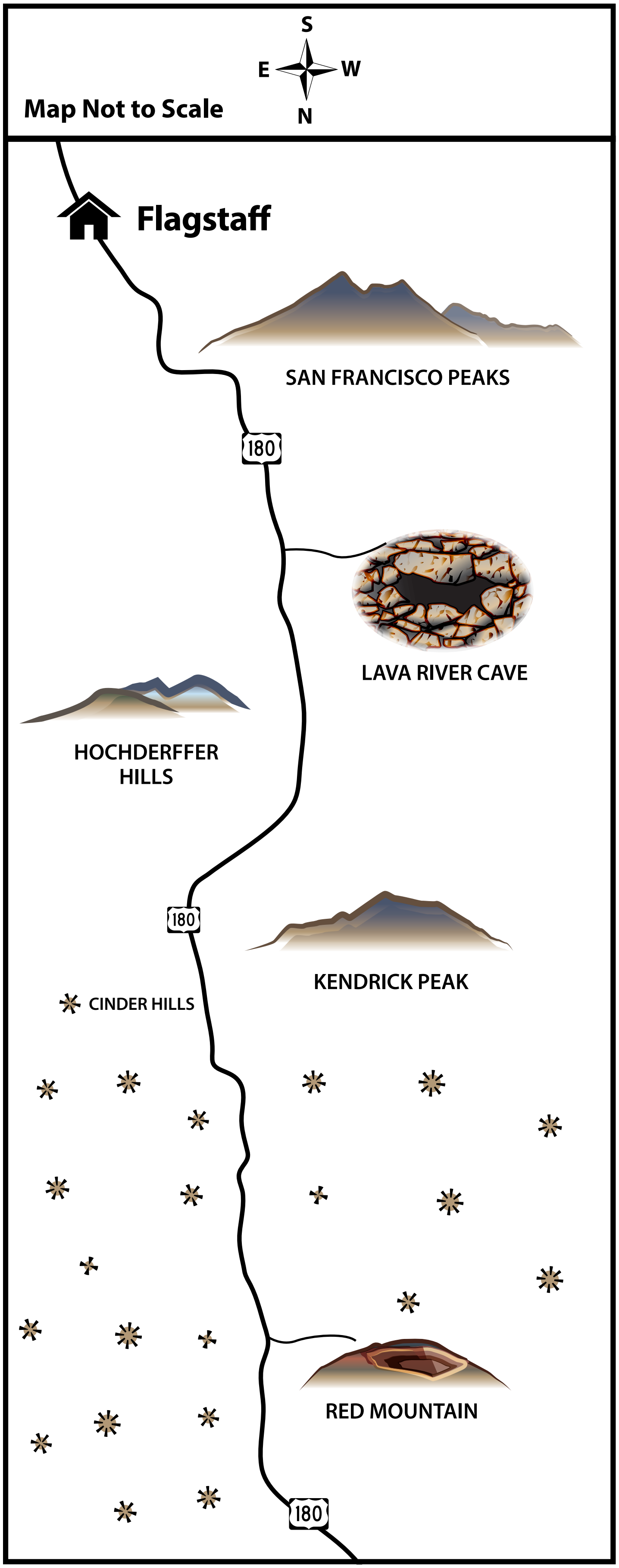
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Flagstaff
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KENDRICK PEAK
CINDER HILLS
RED MOUNTAIN
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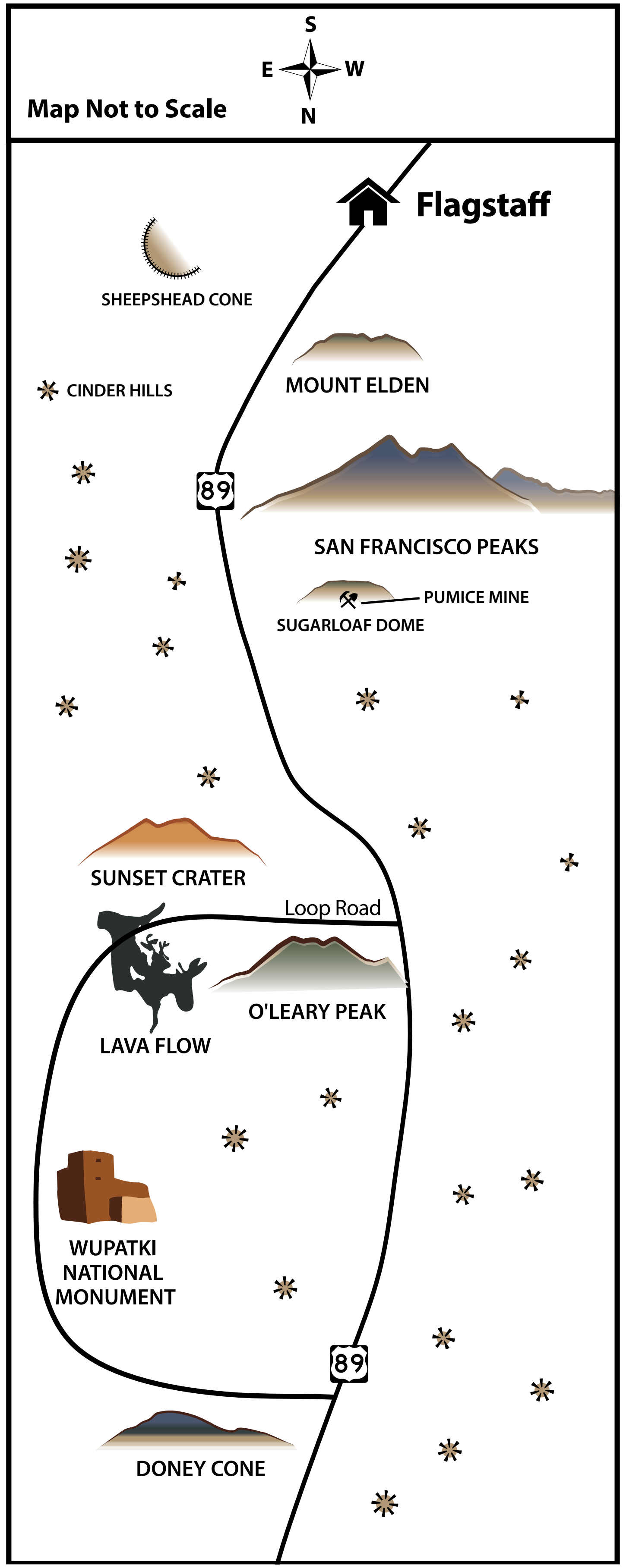
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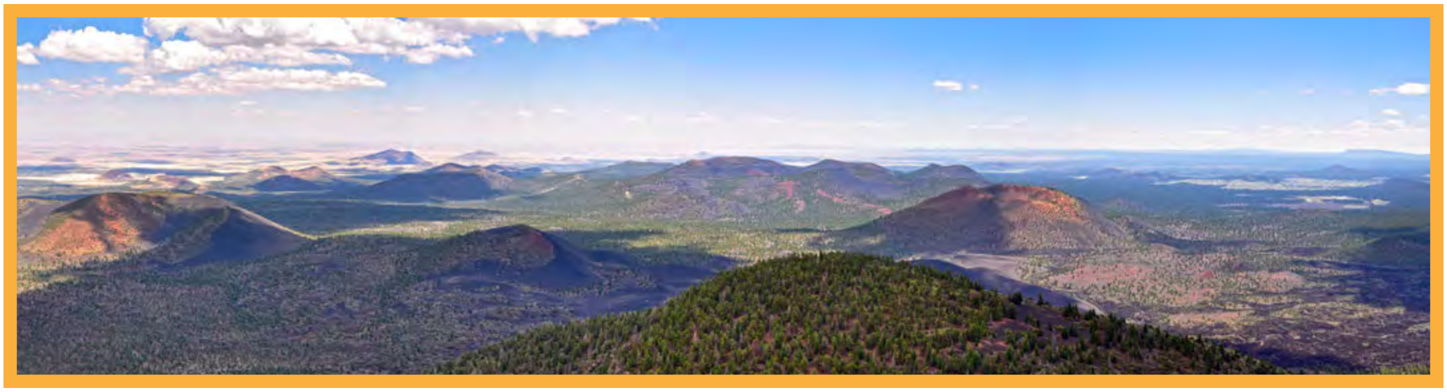

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San Francisco Volcanic Field

Kendrick Peak is situated about 20 miles northwest of Flagstaff and immediately west of US 180. The Peak is a complex of dacite to rhyolite domes that formed about 2 Ma.

Red Mountain is a breached, 300 meter high cinder cone that erupted about 740,000 years ago. (Rafted pieces of cone occur on breakout lavas on the west side of the cone.) A large natural amphitheater (250 meters high) crops out on the northeast flank, exposing the scoria cone stratigraphy.

The origin of the amphitheater remains a puzzle. One hypothesis involves late stage hydrothermal circulation, coeval weak cementation of scoria, and a pressure cooker scenario that culminated in phreatomagmatic blasts to expose the cone interior. Erosional forces—water, ice and wind—have left their mark, too; hoodoos are a common feature here.

The **San Francisco volcanic field** (SFVF) comprises more than 600 cinder cones and ten larger, silicic volcanic centers. The onset of volcanism began about 6 Ma in the far western part of the field; the locus of volcanism has migrated west to east. Lavas and vents cover about 5,000 km^2 of the southwestern Colorado Plateau. Lava composition ranges from basalt to rhyolite. The large San Francisco Mountain composite volcano (Peaks) (~ 80 km^3), was active from about 1 Ma to 0.1 Ma. Sometime before Sugarloaf Dome was emplaced (~ 0.09 Ma), the Peak's east flank underwent sector collapse, accounting for the prominent horseshoe-shaped collapse caldera referred to as the Inner Basin.

The SFVF remains an active volcanic field whose latest eruption occurred with the emplacement of Sunset Crater about 1075 CE.

Sunset Crater is a 300-meter high cinder cone that erupted about 1075 +/- 25 CE; it produced a lava flow field of about 8 km^2 and a ~2300-km^2 tephra blanket in an area inhabited for at least 1,000 years. The eruption began east of the present-day crater as a fissure eruption, but quickly transformed into a central vent eruption that lasted a few months to a few years. Thick ashfall from the Strombolian eruption had a deleterious impact on local American Indian populations, forcing them to abandon their homesteads and gardens.

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O'Leary Peak, a young dacitic to rhyolitic volcanic center that erupted about 0.17 to 0.23 Ma, is located immediately NW of Sunset.

A suite of cinder cones older than Sunset is mantled by black Sunset Crater scoria and ash fall. The hills are a popular recreation area for OHVs—off-highway vehicles.

Wupatki National Monument was established by President Coolidge on 9 Dec. 1924 to preserve Citadel and Wupatki pueblos. The monument encompasses 35,422 acres. Eight-hundred years ago, the Wupatki pueblos were among the tallest, largest, and perhaps the richest and most influential pueblos in what is now Arizona. Immediately following the eruption of Sunset Craters several thousand people lived within a day's walk of Wupatki. By 1250 CE, the pueblos here were largely abandoned and the American Indian population had moved on.

The **Doney Mountain** cinder cone formed about 68,000 to 70,000 years ago along the NNE-SSW trending Black Point – Doney Mountain fault.

Red Mountain Volcano—a Spectacular and Unusual Cinder Cone in Northern Arizona

Red Mountain, located in the Coconino National Forest of northern Arizona, 25 miles northwest of Flagstaff, is a volcanic cinder cone that rises 1,000 feet above the surrounding landscape. It is unusual in having the shape of a "U," open to the west, and in lacking the symmetrical shape of most cinder cones. In addition, a large natural amphitheater cuts into the cone's northeast flank. Erosional pillars called "hoodoos" decorate the amphitheater, and many dark mineral crystals erode out of its walls. Studies by U.S. Geological Survey (USGS) and Northern Arizona University scientists suggest that Red Mountain formed in eruptions about 740,000 years ago.

This aerial view of Red Mountain cinder cone in northern Arizona shows the deeply sculpted northeast flank of the volcano. The deep depression in the center of the image is a natural amphitheater, whose origin has been something of a geologic mystery. The back wall of the amphitheater is a nearly vertical 800-foot cliff, which tapers off to the right and left. The dipping layers of volcanic cinders that make up the cone can be seen in the walls of the amphitheater. The center of the volcano, the site of the vent where molten rock (magma) was erupted, is on the far side of the ridge. (Copyrighted photo courtesy of Michael Collier.)

Red Mountain is one of several hundred cinder cones within a swath of volcanic landscape that extends 50 miles eastward from Williams, Arizona, through Flagstaff to the canyon of the Little Colorado River. Geologists call this belt of volcanoes the San Francisco Volcanic Field, named for San Francisco Mountain, whose tallest peak is 12,633 feet above sea level, the highest elevation in Arizona. Red Mountain rises about 1,000 feet above the surrounding landscape, and its crest is at 7,965 feet elevation. The San Francisco Volcanic Field has been active for about 6 million years, and Red Mountain is roughly 740,000 years old.

Red Mountain is unusual in that its internal structure is exposed. This is not the case at most cinder cones in the San Francisco Volcanic Field, because erosion has not had enough time to expose their internal features. Although human quarrying creates frequently changing glimpses into a few of the cones in the volcanic field, quarries generally are unsafe for tourists and public access commonly is denied.

Near Red Mountain a large Forest Service sign along Highway 180 invites the motorist to exit and visit this cinder cone. A parking lot is located about a quarter mile off the highway. A gentle, uphill, 30-minute walk from the parking lot brings the visitor into a natural amphitheater carved into the northeast flank of Red Mountain. The back wall of the amphitheater is a nearly vertical 800-foot cliff, which tapers off to the right and left. Truncated layers of volcanic cinders form ledges and color bands across the amphitheater walls.

A visitor standing in the center of the amphitheater, nearly surrounded by towering cliffs of cinders, might think that this is the center of the volcano, the location of the vent where molten rock (magma) was erupted. However, the actual center of eruption was over the back wall of the amphitheater, out of sight. The amphitheater is a geologic feature that formed after the eruption ended and continues to be enlarged by erosion today.

An "Ideal" Cinder Cone

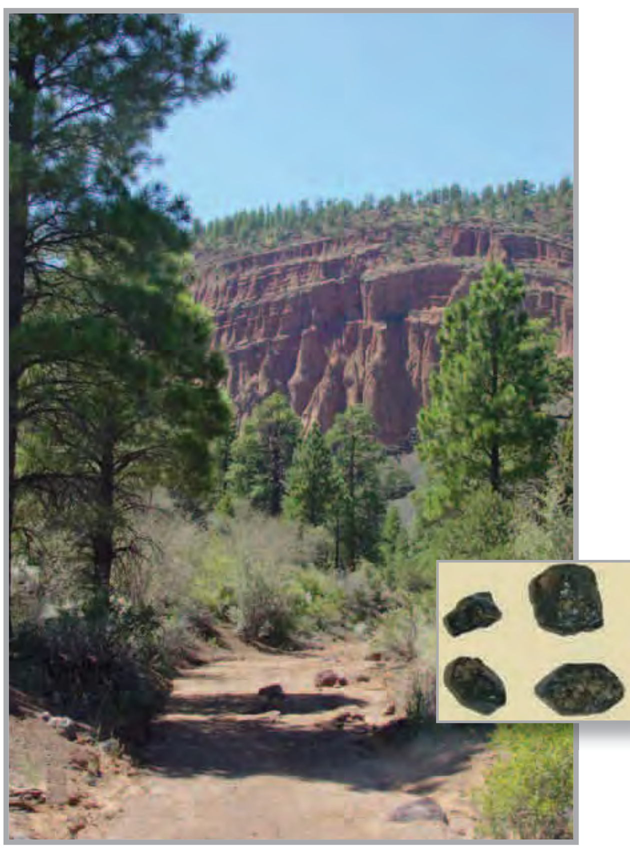
An "ideal" cinder cone forms when eruption occurs on flat ground. From deep within the Earth, magma charged with gas (like a carbonated drink) rises through a vertical pipe-shaped conduit and erupts as

The amphitheater of Red Mountain has many "hoodoos" (left, center foreground), rather bizarre landforms that are especially common in the western part of the amphitheater. These 10- to 20-foot-tall, upward-tapering earth pinnacles of cinders are capped by 1- to 3-foot-wide boulders of dense lava. The boulder "sombrero" capping each pinnacle (see above) protects the underlying cinders from erosion. These hoodoos and other odd-looking spires, ridges, and ribs found in the amphitheater were almost certainly sculpted by water and wind erosion.

a fountain of frothy lava that may spray as high as 2,000 feet into the air.

As an individual blob of this frothy molten rock flies through the air, it cools quickly enough to solidify before falling back to Earth. Many gas bubbles remain trapped in the fragments. If small, these fragments of rock are called "cinders," and if larger, "bombs." As eruption continues, cinders accumulate to form a conical hill. Periodically, the flanks of the growing hill may become so steep that lobes and sheets of cinders slide downward. When lava fountaining ends, a symmetrical cone-shaped hill, commonly indented by a summit crater, has been added to the landscape. Internally, the cone is a pile of loose cinders in layers that dip away from the volcano's vent in all directions.

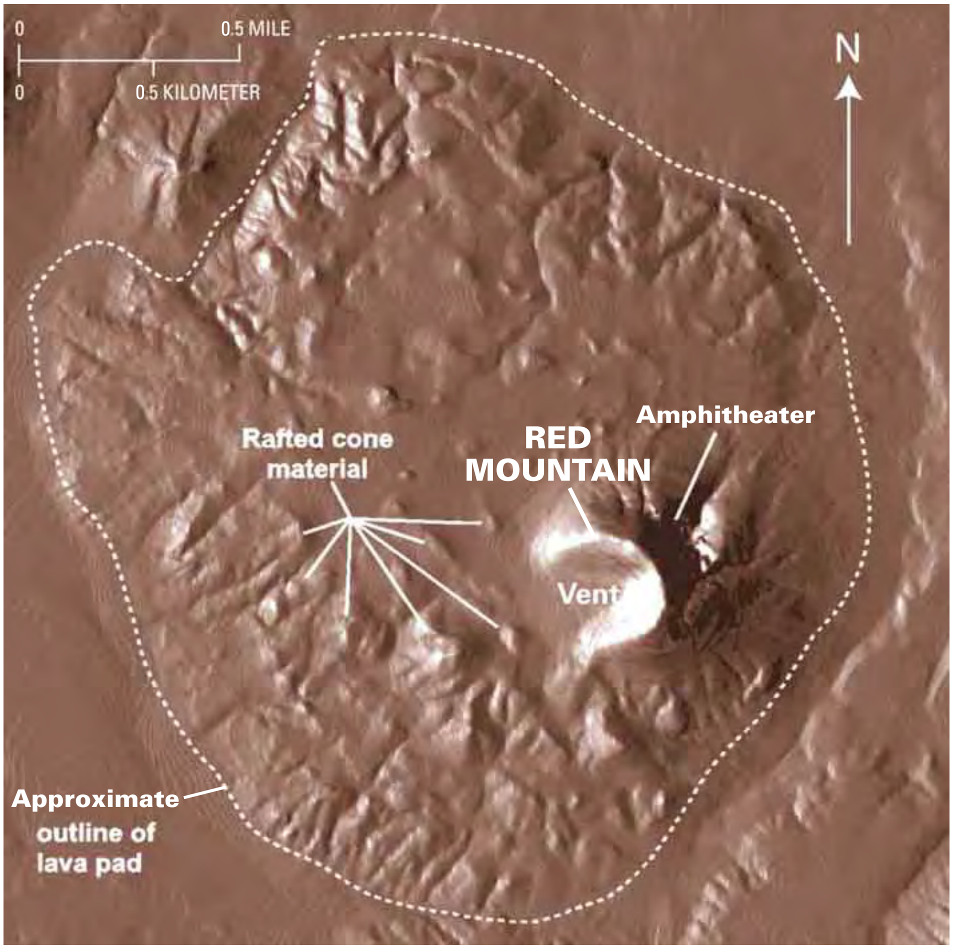
During the waning stage of an ideal cinder-cone eruption, the magma has lost most of its gas content. This gas-depleted magma does not fountain but oozes quietly into the crater or beneath the base of the cone as lava. Because it contains so few gas bubbles, the molten lava is denser than the bubble-rich cinders. Thus, it burrows out along the bottom of the cinder cone, lifting the less-dense cinders like a cork on water, and advances outward, creating a lava flow around the cone's base. When the eruption ends, a symmetrical cone of cinders sits at the center of a surrounding pad of lava.



This alluring view shows the foot trail leading to the amphitheater of Red Mountain. Roughly the last half of the foot trail follows a normally dry stream bed. The stream sand includes countless black shiny grains, a few as large as walnuts (see inset). These grains are sometimes mistaken for "Apache tears," which are composed of obsidian, the volcanic glass highly valued by ancient cultures for crafting arrowheads, knives, scrapers and other tools. However, the abundant black grains at Red Mountain are crystals of minerals (pyroxene and amphibole) eroded from the volcano. A close look at the walls of the amphitheater will reveal crystals of these minerals still embedded in cinders, waiting to be plucked out by water and wind erosion.

Red Mountain Cinder Cone

Field studies conducted by U.S. Geological Survey (USGS) and Northern Arizona University scientists suggest that Red Mountain grew on a nearly flat surface that may have sloped gently to the north. However, little else about this volcano mimics the features of an ideal cinder



This digital elevation model (DEM) of the Red Mountain area shows the features of the cinder cone. During the eruption that formed it, Red Mountain grew on a nearly flat surface, which was eventually covered by a lava flow that extruded from the base of the cone during the eruption's waning phase. This lava flow rafted away some of the volcanic cinders that formed the western side of the cone. When viewed from above, Red Mountain today is a U-shaped landform open to the west, rather than a symmetrical "ideal" cinder cone, with a large natural amphitheater carved into its northeast flank. U.S. Geological Survey and Northern Arizona University scientists think that the amphitheater may have been blasted out by one or more steam explosions shortly after eruption ceased at the volcano's vent 740,000 years ago.

cone. When viewed from above, Red Mountain is a U-shaped landform open to the west, rather than a symmetrical cone. The base of the U is a curving ridge that forms the highest part of the mountain. The nearly half-mile-long arms of the U slope down to the west and merge with the gently rolling surface of the Red Mountain lava flow.

By carefully measuring the orientation of cinder layers over all parts of Red Mountain, geologists have mapped a radial pattern of layers, dipping away from the middle of the U in all directions. At the amphitheater, all the exposed layers dip uniformly to the northeast. This pattern indicates that the vent is somewhere in the middle of the U and not at the amphitheater.

The shape of Red Mountain and its overall pattern of cinder layers raises the question of why a symmetrical cone was not created around the vent at the center of the U. Three possible explanations are:

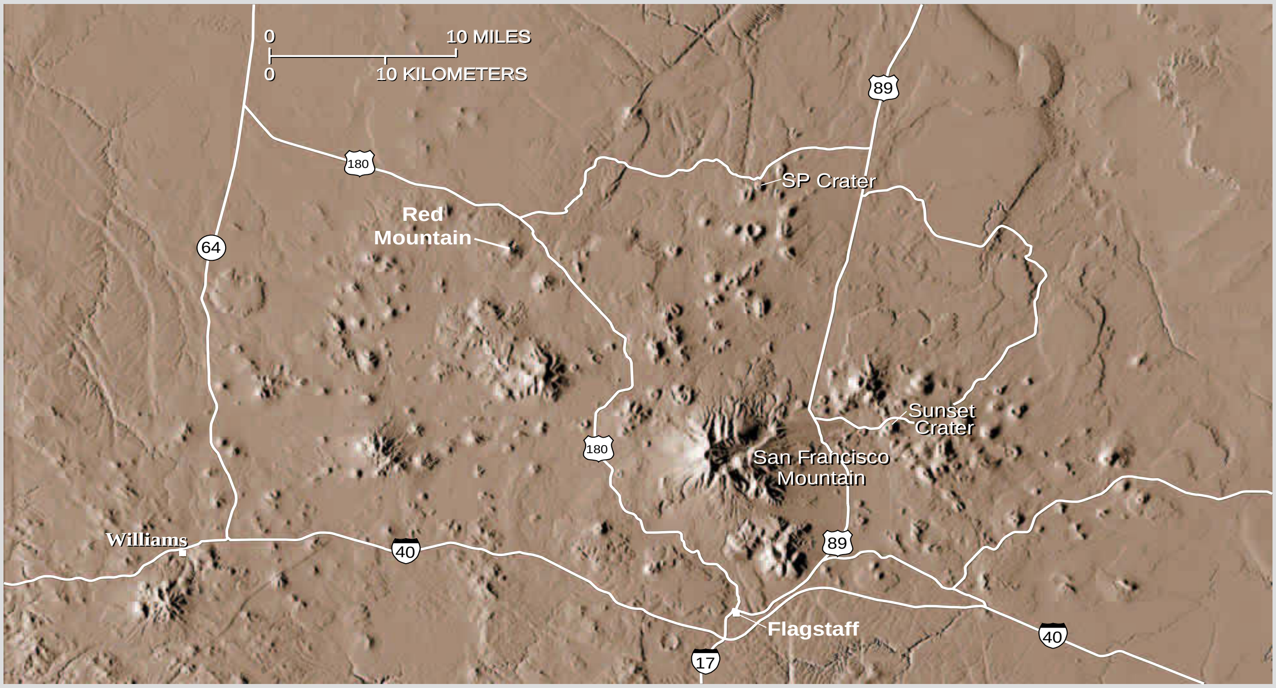
- If the lava-fountaining phase of eruption occurred during a time of sustained wind blowing from west to east, most cinders could have been blown eastward creating the asymmetrical shape of Red Mountain. However, eruptions of the type that built Red Mountain usually last several years to a decade or longer, and it seems unlikely that a westerly wind could have persisted for such a period of time.
- Perhaps the conduit through which magma rose to the surface was inclined eastward enough to give the same effect as a westerly wind, but this seems unlikely because the driving force for rising magma is the buoyancy of very hot volcanic gases. Like a cork released in water, such gases tend to rise vertically rather than follow an inclined path.
- The most likely possibility is that the waning-stage lava flow of the Red Mountain eruption rafted the western section of the cinder cone away, like wood on flowing water. When gas-poor molten lava burrows its way outward beneath a cinder cone, it may either leave the cone undisturbed or carry pieces piggyback, literally floating pieces on the surface of the denser lava. Many examples of both situations are known worldwide; a spectacular example of rafting is found at Sunset Crater National Monument, northeast of Flagstaff. At Red Mountain, geologists have discovered several outcrops of layered cinder deposits, some of which are hundreds of feet wide and tens of feet thick, at the top of the lava flow. Typically, these "floaters" form hills on the surface of an otherwise fairly flat flow. Apparently, molten lava oozed out beneath the west base of Red Mountain and rafted away much of that side of the cinder cone, creating its U shape.

Origin of the Amphitheater

The origin of the Red Mountain amphitheater is something of a geologic mystery. The truncated cinder layers exposed in the amphitheater walls are clear evidence that material has been removed. However, how this removal was accomplished is not entirely clear.

It seems unlikely that the entire amphitheater was created by water erosion, because there is so little surface area to catch rainwater and snowmelt and funnel it down channels to erode the side of the volcano. An intriguing, though speculative, possibility is that one or more steam explosions created an amphitheater-shaped hole in the side of Red Mountain shortly after eruption ceased. Newly erupted cinders probably cooled to about 600°F as they fell back to earth, but then remained well above the boiling temperature of water for some time. Rainwater seeping into the

GETTING TO RED MOUNTAIN



To reach Red Mountain from Flagstaff, head northwest on Highway 180. This highway snakes through the central part of the San Francisco Volcanic Field on its way toward the Grand Canyon. About 25 miles from Flagstaff (at milepost 247 along the shoulder of the highway), turn left at a large Forest Service sign that announces the Red Mountain Geologic Area. Drive about a quarter mile on the dirt road to a parking space at the trailhead. The walk from there to the base of Red Mountain takes about 30 minutes. Carry plenty of drinking water on a hot day (at least 1 liter of water per person). Trees in the natural amphitheater provide some shade.

cone and circulating through the still hot cinders may have quickly deposited a strong mineral cement that bound cinders together, creating the equivalent of a sealed "pressure cooker." Eventually, the pressure of the trapped superheated water may have exceeded the strength of that cooker, resulting in one or more steam explosions.

Two characteristics of the cinder layers seen in the amphitheater support this scenario. Although most cinder-cone volcanoes are piles of loose cinders, the cinders exposed in the walls of the amphitheater are partly cemented into hard outcrops by a mineral cement. Also, the cinders range in color from nearly black to reddish and brownish tints, indicating contact and chemical interactions with hot water and steam.

Even if a steam-blast scenario is correct, the initial amphitheater opening has been enlarged by normal surface-water and wind erosion during the approximately 740,000 years since it formed. For example, here and there, especially in the western part of the amphitheater, 10- to 20-foot-tall, upward-tapering pinnacles of cinders are capped by 1- to 3-foot-wide boulders of dense lava. The boulder "sombrero" capping each pinnacle protects the underlying cinders from erosion. Geologists call this rather bizarre type of landform an earth pinnacle or "hoodoo." Much of the amphitheater is decorated with hoodoos and other odd-looking spires, ridges, and ribs, all of which were almost certainly sculpted by water and wind erosion.

The work of USGS and Northern Arizona University scientists, in cooperation with the U.S. Forest Service, has led to a better understanding of the geologic history of Red Mountain and the San Francisco Volcanic Field. This work is only part of the USGS Volcano Hazards Program's ongoing efforts to protect people's lives and property in all of the volcanic regions of the United States, including Wyoming, eastern California, the Pacific Northwest, Hawaii, and Alaska.

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See also *The San Francisco Volcanic Field*, Arizona (USGS Fact Sheet 017–01), *What are Volcano Hazards?* (USGS Fact Sheet 002–97), *Volcanoes* (USGS General Interest Publication 94–0195), and *Volcanoes of Northern Arizona* by Wendell Duffield (Grand Canyon Association, 1997).

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U.S. GEOLOGICAL SURVEY and the U.S. FOREST SERVICE—OUR VOLCANIC PUBLIC LANDS

The San Francisco Volcanic Field, Arizona

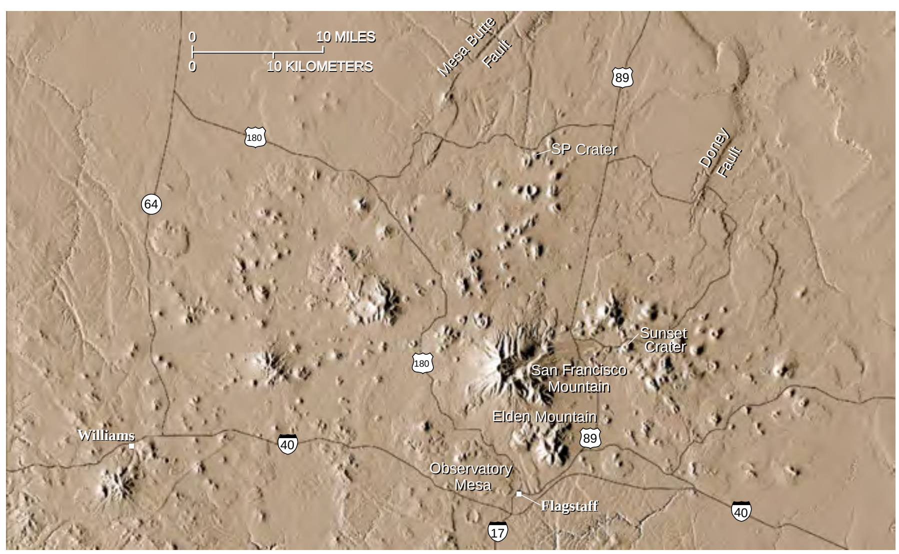
Northern Arizona's San Francisco Volcanic Field, much of which lies within Coconino and Kaibab National Forests, is an area of young volcanoes along the southern margin of the Colorado Plateau. During its 6-million-year history, this field has produced more than 600 volcanoes. Their activity has created a topographically varied landscape with forests that extend from the Piñon-Juniper up to the Bristlecone Pine life zones. The most prominent landmark is San Francisco Mountain, a stratovolcano that rises to 12,633 feet and serves as a scenic backdrop to the city of Flagstaff.

The peaks of San Francisco Mountain, an eroded stratovolcano—which includes Arizona's highest point, Humphreys Peak at 12,633 feet—tower over the ruins of an ancient Native American pueblo in Wupatki National Monument. The ancient inhabitants of this area must have witnessed the eruption of nearby Sunset Crater, the State's youngest volcano, which erupted in about A.D. 1064. San Francisco Mountain and Sunset Crater are only two of the hundreds of volcanoes in the San Francisco Volcanic Field, which covers about 1,800 square miles of northern Arizona. (Copyrighted photo courtesy of Michael Collier.)

The San Francisco Volcanic Field, which covers about 1,800 square miles, is part of northern Arizona's spectacular landscape. Much of the field lies within Coconino and Kaibab National Forests. Forest life zones in the region range from Piñon-Juniper at lower elevations through Ponderosa Pine to Fir and Bristlecone Pine at the highest elevations. The varied forests and geologic features of the San Francisco Volcanic Field offer diverse recreational opportunities, including camping, hiking, mountain biking, wildlife viewing, and winter sports.

Almost all hills and mountains between Flagstaff and the Grand Canyon are geologically young but extinct volcanoes of the San Francisco Volcanic Field. Without the volcanoes, this region would be a flat, arid plateau. Instead, the area includes both Arizona's highest mountain—San Francisco Mountain, with peaks rising to 12,633 feet—and the State's youngest volcano—Sunset Crater, which erupted less than 1,000 years ago and has been a National Monument since 1930.

Why does Northern Arizona have so many geologically young volcanoes? Most volcanoes are located near boundaries of the Earth's tectonic plates, but Arizona is well within the



This digital elevation model (DEM) of the San Francisco Volcanic Field shows many of the more than 600 vents which have erupted in the area during the past 6 million years. Some lava flows (flat lobate features) are easily recognized by their proximity to vents. Larger tectonic structures such as the northeast-trending Mesa Butte Fault and Doney Fault are also seen. Flagstaff lies at the south-central edge of the volcanic field nestled between the base of Elden Mountain and the Observatory Mesa flow emitted from A-1 Mountain.

U.S. Department of the Interior
U.S. Geological Survey

USGS Fact Sheet 017-01
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interior of the North American Plate. Some geologists suggest that there is a site of localized melting, or "hot spot," fixed deep within the Earth's mantle beneath northern Arizona. As the North American Plate moves slowly westward over this stationary source of molten rock (magma), eruptions produce volcanoes that are strung out progressively eastward.

The first volcanoes in the San Francisco Volcanic Field began to erupt about 6 million years ago, in an area where the town of Williams is now. Subsequently, a several-mile-wide belt of successively younger eruptions migrated eastward, to the area of modern Flagstaff, and even a bit beyond, toward the valley of the Little Colorado River. Today, this belt of volcanoes extends about 50 miles from west to east.

Although there has been no eruption for nearly 1,000 years, it is likely that eruptions will occur again in the San Francisco Volcanic Field. With an average interval of several thousand years between past periods of volcanic activity, it is impossible to forecast when the next eruption will occur. U.S. Geological Survey (USGS) scientists believe that the most probable sites of future eruptions are in the eastern part of the field and that the eruptions are likely to be small. These future eruptions may provide spectacular volcanic displays but should pose little hazard because of their small size and the relative remoteness of the area.

Volcanoes and Types of Magma

A volcano is an opening where magma erupts onto the surface as lava after rising from deep within the Earth. Not all magma is the same. Some magma contains as much as 75% silica (SiO_2), whereas other magma contains as little as about 50%. The more silica in a magma, the higher its viscosity, or resistance to flow. Viscosity controls the type of volcano that forms. Eruptions of high-viscosity magma build very steep-sided lava domes. Low-viscosity magma produces cinder cones and thin sheet-like lava flows, and intermediate-viscosity magma creates moderately steep mountains called stratovolcanoes.

SP Crater, in the San Francisco Volcanic Field, is an excellent example of a cinder cone and associated lava flow. This flow extends 4 miles from the cone and is only about 100 feet thick.

Most of the more than 600 volcanoes in the San Francisco Volcanic Field are basalt cinder cones. Basalt has the lowest viscosity of all common magmas. Cinder cones are relatively small, usually less than 1,000 feet tall, and form within months to years. They are built when gas-charged frothy blobs of basalt magma are erupted as an upward spray, or lava fountain. During flight, these lava blobs cool and fall back to the ground as dark volcanic rock containing cavities created by trapped gas bubbles. If small, these fragments of rock are called "cinders" and, if larger, "bombs." As the fragments accumulate, they build a cone-shaped hill. Once sufficient gas pressure has been released from the supply of magma, lava oozes quietly out to form a lava flow. This lava typically squeezes out from the base of the cone and tends to flow away for a substantial distance because of its low viscosity. SP Crater, 25 miles north of Flagstaff, is an excellent example of a cinder cone and its associated lava flow.

Stratovolcanoes

Stratovolcanoes have moderately steep slopes and form by the accumulation of layer upon layer of intermediate-viscosity (andesite) lava flows, cinders, and ash, interspersed with deposits from volcanic mudflows (lahars) at lower elevations. These tall, cone-shaped volcanoes, such as Mount Rainier, Washington, and Mount Fuji, Japan, normally rise to a central peak and are built up by countless eruptions over hundreds of thousands of years.

San Francisco Mountain is the only stratovolcano in the San Francisco Volcanic Field and was built by eruptions between about 1 and 0.4 million years ago. Since then, much of the mountain has been removed to create the "Inner Basin." The missing material may have been removed quickly and explosively by an eruption similar to the 1980 eruption of Mount St. Helens, Washington, or it may have been removed slowly and incrementally by a combination of large landslides, water erosion, and glacial scouring.

Lava Domes

The San Francisco Volcanic Field also includes several lava domes. Lava domes are formed by dacite and rhyolite magmas, which have high silica contents. Dacite and rhyolite are so viscous that they tend to pile up and form very steep-sided bulbous masses (domes) at the site of eruption. Domes can be active for decades or sometimes centuries. If a lava dome grows entirely by internal inflation, similar to a balloon, it is called an endogenous dome. If, however, magma breaks out through a dome's flank during inflation and adds new lava layers to the outer surface, the final dome is called exogenous.

Elden Mountain, at the eastern outskirts of Flagstaff, is an excellent example of an exogenous dacite dome and consists of several overlapping lobes of lava. Sugarloaf Mountain, at the entrance to San Francisco Mountain's Inner Basin, is a rhyolite lava dome. This dome is thought to be endogenous, but its forest cover hides direct evidence of its internal structure.

Elden Mountain is a steep-sided lava dome in the San Francisco Volcanic Field. Lava domes are formed by dacite and rhyolite magmas, which have high silica contents. Dacite and rhyolite are so viscous that they tend to pile up and form very steep-sided bulbous masses (domes) at the site of eruption.

The work of USGS scientists, in cooperation with the U.S. Forest Service, has led to a better understanding of the history of volcanism in the San Francisco Volcanic Field. This work is only part of the USGS Volcano Hazards Program's ongoing efforts to protect people's lives and property in all of the volcanic regions of the United States, including the Pacific Northwest, eastern California, Wyoming, Alaska, and Hawaii.

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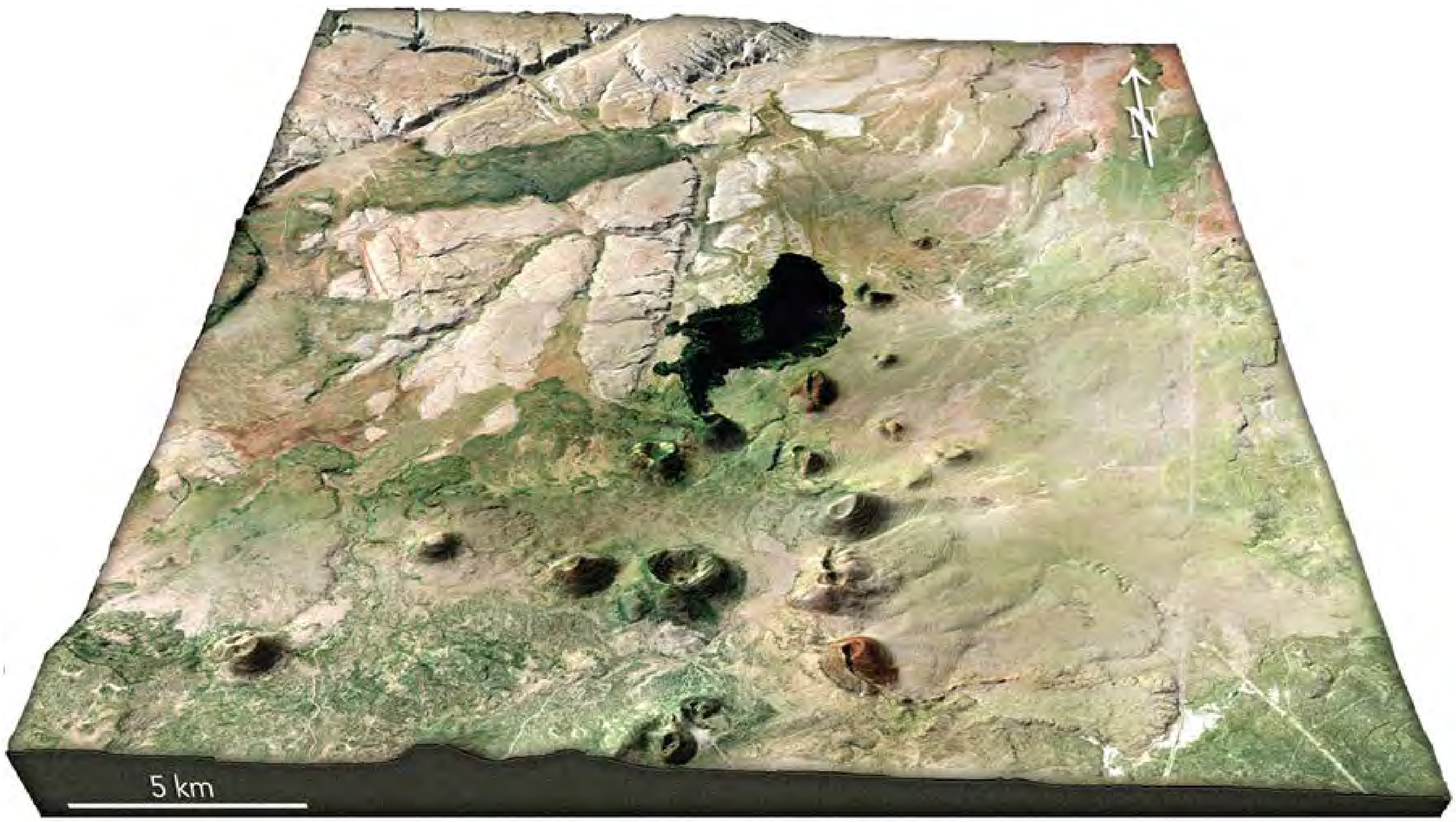

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