Late Cenozoic Volcanism in the San Francisco and Mormon Volcanic Fields, Southern Colorado Plateau, Arizona

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INTRODUCTION

The objective of this trip is to study the volcanic history, volcanology, petrology, and structural geology of two late Cenozoic volcanic fields in north-central Arizona. In the northern and eastern San Francisco field, latest Miocene to Holocene basaltic flows, cones, and maars are well displayed, and their relationships to tectonic structures and erosion surfaces are observable. Silicic and andesitic lavas and pyroclastic deposits of the San Francisco Mountain composite volcano and five peripheral silicic centers occur in the central part of the field. The Mormon field is composed of late Miocene to Pliocene(?) basaltic sheet lavas and shields, scoria cones and small associated flows, and scattered silicic and andesitic domes, in addition to the major silicic centers of Mormon Mountain and Hackberry Mountain. Older basalt lavas of the field accumulated against an ancestral Colorado Plateau marginal escarpment, but younger lavas cascaded over the escarpment and formed a westward-sloping ramp from the Plateau into the Transition Zone. Unless referenced otherwise, K-Ar ages are by P.E. Damon (written comm., 1977) and E.H. McKee (written comm., 1973).

LATE CENOZOIC VOLCANISM ON THE SOUTHERN COLORADO PLATEAU

Geologic provinces in Arizona include the Colorado Plateau in the north and the Basin and Range in the south (Figure 1). Between these provinces is a structurally intermediate region known as the Transition Zone; in most places its boundary with the Colorado Plateau is paralleled by the Mogollon Rim (Escarpment; Peirce, 1985).

Late Cenozoic volcanism (younger than 16 Ma) was widely distributed in Arizona, but the eruptive products are most voluminous in volcanic fields situated on the southern margin of the Colorado Plateau and in the adjacent Transition Zone. The major volcanic fields, which are dominated by basalt, form a zone that trends southeast across the State from its northwest corner (Luedke and Smith, 1978). The San Francisco and Mormon volcanic fields are in the middle of this zone; both fields are predominantly on the southern Colorado Plateau margin, but they extend across the Mogollon Rim into the Transition Zone.

SAN FRANCISCO VOLCANIC FIELD

Late Miocene to Holocene lava flows and pyroclastic deposits of the San Francisco volcanic field cover more than 5000 km^2 of the southern Colorado Plateau and Transition Zone (Figure 1). About 500 km^3 of volcanic rocks were deposited on erosion surfaces above nearly horizontal strata (Wolfe and others, 1983). In general, the oldest lavas were extruded on the highest erosion surfaces, which in many places were developed on the Triassic Moenkopi Formation, whereas younger lavas rest on the erosionally stripped Kaibab Formation of Permian age or on the older lavas (Cooley, 1962; Ulrich and others, 1984).

Major structural features in the San Francisco field are high-angle faults and monoclines (Figure 1). Faults of small displacements are dominantly on northwest trends, but north- and northeast-trending faults occur. Although normal faulting and volcanism in the field are broadly coeval, most of the faults displace the older lavas and only a few lavas and deposits of Brunhes age (<0.73 Ma) are faulted (Wolfe and others, 1983; Tanaka and others, 1986). The major silicic centers and many of the scoria cones are aligned or elongated on trends subparallel to the principal strike lines of the faults. In the San Francisco Mountain volcanic system, several of the major vents, the conduit system of the central volcano, and a large valley that breaches its northeast side are colinear on a northeast trend parallel with the three major silicic centers in the western part of the field (Figure 1).

Basaltic lava flows and tephra deposits dominate the eruptive products in the volcanic field and constitute most of the nearly 600 volcanoes that have been identified. The less abundant intermediate to silicic rocks occur in, or peripheral to, a few major volcanic centers (Robinson, 1913; Figure 1). The basaltic volcanism was broadly contemporaneous with the development of the intermediate to silicic centers, and K-Ar ages reveal a general progression of volcanism from the Transition Zone, beginning more than 14 Ma ago, to the central and eastern parts of the San Francisco field by latest Miocene to Holocene time (Luedke and Smith, 1978).

Mafic rocks of the San Francisco field are dominantly alkali basalts, but compositions range from strongly undersaturated basanitoids to olivine tholeiites, and hawaiitic to mugear-

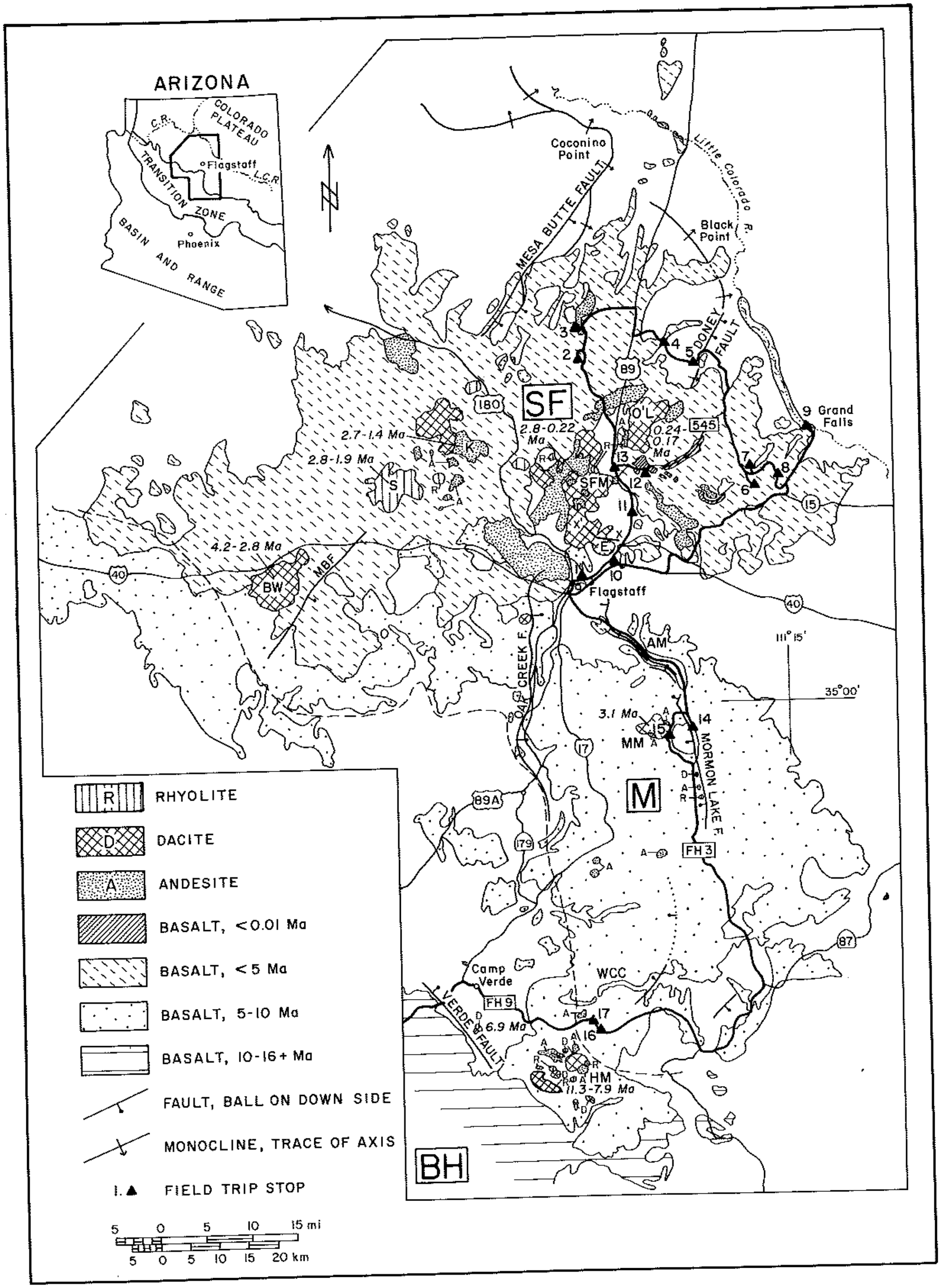

Figure 1. Map showing field-trip route and distribution of late Cenozoic volcanic rocks in the San Francisco (SF) and Mormon (M) volcanic fields; BH, Black Hills. Volcanic geology modified from Luedke and Smith (1978) and Lewis (1983); structure from Ulrich and others (1984). AM, Anderson Mesa; BW, Bill Williams Mountain; CR, Colorado River; LCR, Little Colorado River; E, Elden Mountain; HM, Hackberry Mountain; K, Kendrick Peak; MM, Mormon Mountain; O'L, O'Leary Peak; S, Sitgreaves Mountain; SFM, San Francisco Mountain; WCC, West Clear Creek. Dashed line shows approximate location of Mogollon Rim. Cross section X-X' across Elden Mountain is shown in Figure 8. K-Ar ages (Ma) from Wolfe and others (1983), Luedke and Smith (1978), and McKee and Elston (1980).

itic varieties occur. Volcanic rocks of the San Francisco Mountain composite volcano and five smaller silicic centers peripheral to it constitute a coherent and continuous suite of lithologies, from low-silica andesite to alkali rhyolite (comendite), that forms a compositional continuum with the mafic rocks of the field (Figure 2).

In the central and eastern parts of the San Francisco field the lavas and cones have been classified in five age groups primarily on the basis of stratigraphic and physiographic relationships, degree of weathering and erosion, and K-Ar ages (Moore, 1974). These age groups are: Cedar Ranch, 6-5 Ma; Woodhouse, 3.0-0.8 Ma; Tappan, 0.7-0.2 Ma; Merriam, <150,000 years; Sunset, 1064 A.D.

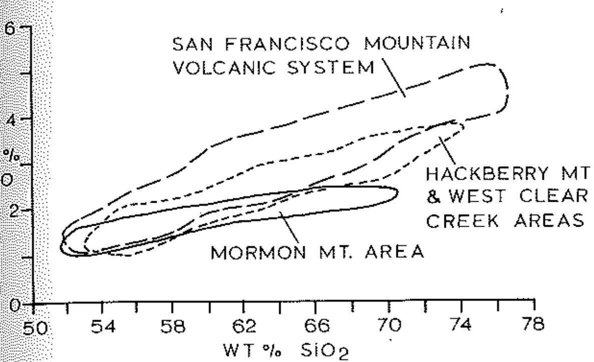

Figure 2. Variation diagram of SiO_2 and K_2O in weight percent showing fields of andesitic to rhyolitic rocks in the San Francisco Mountain volcanic system (169 analyses), Hackberry Mountain and West Clear Creek areas (56 analyses), and the Mormon Mountain area (33 analyses).

MORMON VOLCANIC FIELD

A distinct group of vent structures and lava flows between Anderson Mesa and Hackberry Mountain sets the Mormon volcanic field apart from the San Francisco field to the north and the Black Hills field to the southwest (Figure 1). A convenient boundary between the Mormon and San Francisco fields can be drawn in the Oak Creek area. In the southern Mormon field, basaltic to silicic rocks have been assigned to the Thirteenmile Rock Volcanics of Elston and others (1974), which overlie the Hickey Formation that is named for mid-Miocene basalt lavas and sedimentary deposits in the Black Hills field. Stratigraphic and K-Ar age data document essentially continuous basaltic volcanism from middle- to late-Miocene time near Hackberry Mountain (McKee and Elston, 1980). The volcanism that was well established in the southern Mormon field at this time migrated or shifted to the north end by latest Miocene to middle-Pliocene time (Luedke and Smith, 1978). Quaternary volcanism has not been recognized in the Mormon field.

Basaltic rocks in the Mormon field are broadly similar in composition to those in the San Francisco field, ranging generally from mildly alkaline basalts to olivine tholeiites. The silicic rocks, however, form two distinctive suites, a northern suite at and near Mormon Mountain, and a southern suite at the Hackberry Mountain center and West Clear Creek (Figures 1 and 2). The northern suite is markedly lower in K_2O than the San Francisco Mountain suite, and this is reflected in the sparse occurrence of biotite in the former. Silicic rocks of the southern suite are intermediate in K_2O content between the Mormon Mountain and San Francisco Mountain suites and commonly contain biotite.

DESCRIPTION OF FIELD TRIP

First Day: Stop 1.
Cherry Street, Flagstaff (30 minutes)

A small cut immediately north of the Coconino County Courthouse exposes a mesa-capping, late Miocene (5.82±0.34 Ma) basalt lava flow that rests unconformably on Lower Triassic redbed sandstone of the Moenkopi Formation. The basalt is in the oldest age group (Cedar Ranch) in the San Francisco volcanic field. The purpose of this stop is to observe the unconformity and the structural and petrographic features of the lava flow. A structureless regolith about 1 m thick separates the sandstone and the basalt; this weathered surface may be correlative with the regional Zuni erosion surface (Cooley, 1962). The top 20 cm of the regolith has been baked red by the lava, which displays a smooth, generally breccia-free bottom. Spherical, smooth-wall vesicles are concentrated in the lower part of the lava; above this zone, large vesicles are concentrated in vesicle cylinders. The olivine tholeiite basalt carries phenocrysts of olivine (Fo81) and sparse clinopyroxene (Moore, 1974).

The route to stop 2 is north on U.S. 89. At the bottom of the long downgrade north of San Francisco Mountain turn left on the good dirt road, which was originally a stagecoach road to Grand Canyon village. Continue to the north side of Crater 160 and pass through the gate in the barbed-wire fence.

Stop 2. Crater 160 (60 minutes).
Hike to the north rim.

The purpose of this stop is to examine the structure and xenoliths of Crater 160, a composite cinder, tuff, and spatter cone of Tappan age (Figure 3). Its growth began with the buildup of welded basalt spatter and rootless flows, which form the layers exposed in the crater's wall. A dikelike body of spatter fragments in the northeastern wall was the source of the lava flow to the north. A phreatic event late in the history deepened the crater, widened the rim, and deposited a mantle of palagonitic tuff that contains an abundance of xenoliths for which the locality is noted. The most abundant xenoliths display cumulus textures and include clinopyroxenite and wehrlite, but websterite, gabbro, anorthosite, granite, granulite, and Paleozoic sedimentary rocks are also present (Cummings, 1972; Stoeser, 1973). The last events in the cone's history included a series of fire-fountain eruptions, ending with the 35-m-high red cinder cone on the floor and scattered bomb fragments around the rim. The floor of the crater is about 80 m lower than the average surface outside.

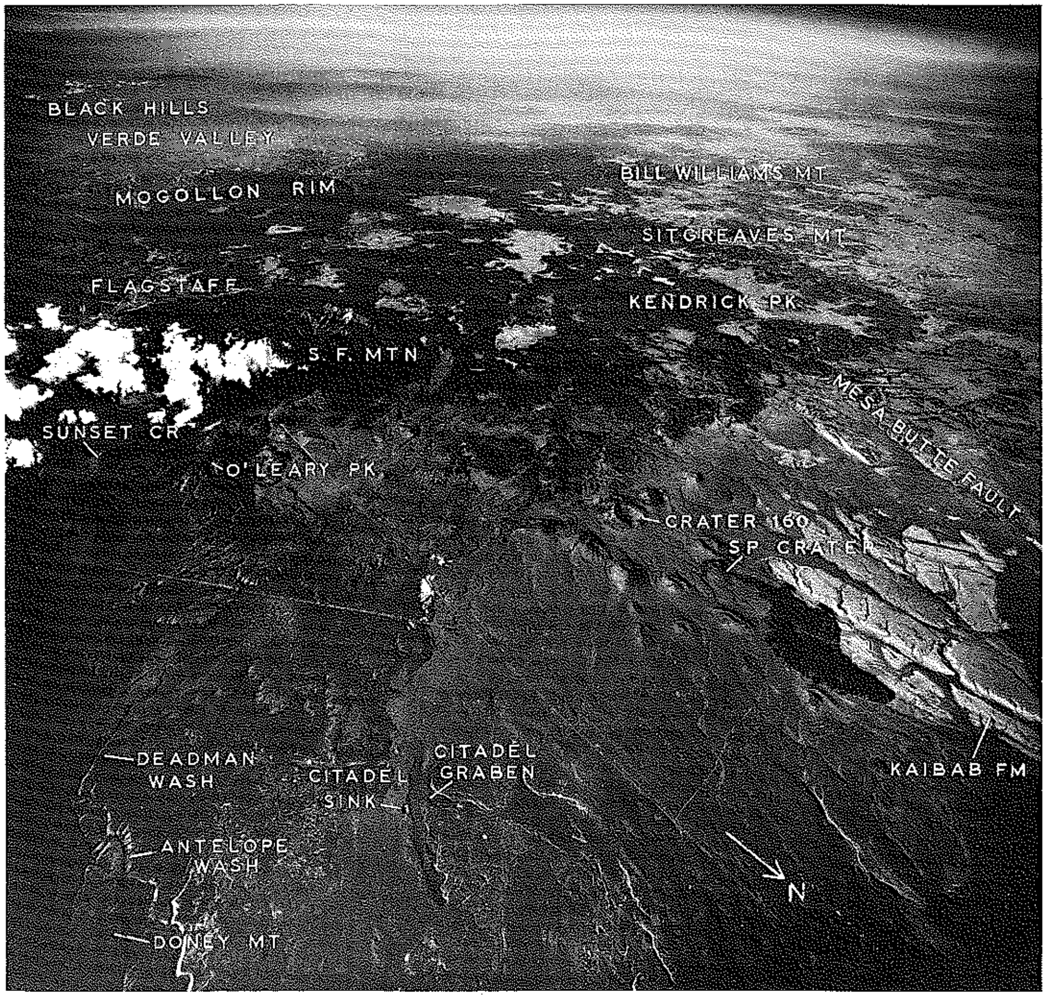

Figure 3. High-altitude (U-2) oblique aerial photograph by U.S. Air Force of the San Francisco volcanic field. View is to southwest.

Stop 3. SP Cone and Flow (20 minutes)

The purpose of this stop is to see the cone and lava flow of SP Mountain, which are examples of the basaltic andesites of the San Francisco volcanic field. The cone's sharp-rimmed profile, radial symmetry, and steep flanks mark it as the youngest volcano in the northern part of the field (Figure 3); its age was determined as 71,000±4,000 yrs (Baksi, 1974; revised for new constants) and it is typical of the Merriam age group. The cone is 250 m high and 1200 m in diameter at its base; its summit crater is 400 m across and about 120 m deep. The slopes of the cone are covered with lapilli and bombs; ash is minor. Welded spatter forms a ruff around the crater's rim. The blocky lava flow, 15 m thick in this location, extruded early in the vent's history and moved down a multiple graben for 7 km; it is 55 m thick near its terminus. Spatter from the cone contains phenocrysts of clinopyroxene, olivine, and embayed and sieved plagioclase in a hypocrystalline groundmass. The flow is similar but contains, in addition, sparse orthopyroxene and embayed quartz. The base of the cone overlies the lava flow and is interpreted to be younger because it is not deformed by the extrusion (Hodges, 1962).

Stop 4. Citadel Ruin (30 minutes)

Citadel Ruin is a Sinagua Indian structure next to the paved road that crosses Wupatki National Monument. No collecting is allowed within the National Monument. The ruin was built on a Woodhouse-age basalt lava that flowed down a tributary of the Little Colorado River. The tributary's channel was eroded in the Moenkopi Formation, and subsequent erosional stripping of the Kaibab Formation resulted in topographic inversion; the lava now forms a low ridge that extends over 7 km northeast of the ruin. The purpose of this stop is to examine the relationships of the lava flow with erosion surfaces and faulting.

Rocks that are exposed in Citadel Sink (Figure 4) include the Kaibab Formation, the Moenkopi Formation, which thickens to the left (east) away from the paleovalley, and the Citadel basalt lava flow, which thickens to the right (west) toward the paleovalley. The southeast-bounding fault of the Citadel graben displaces the Kaibab Formation by a down-to-the-northwest throw of about 16.5 m (54 ft), of which about 6.5 m (21 ft) postdates the lava flow. The sink originated by karst solution in the Kaibab Formation along the fault.

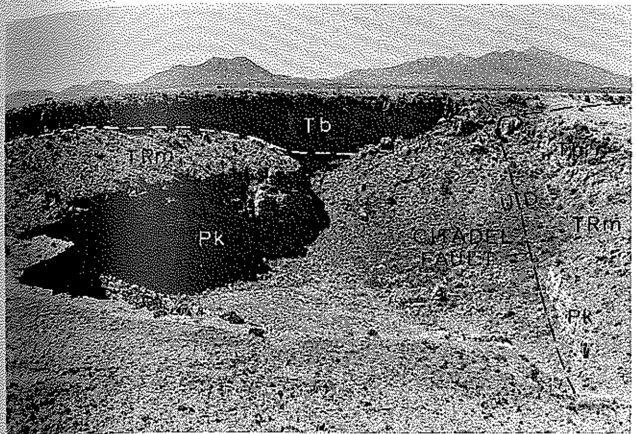

Figure 4. Photograph looking south across Citadel Sink toward O'Leary Peak (left) and San Francisco Mountain from stop 4. Citadel basalt flow (Tb) thickens in paleovalley eroded in Moenkopi Formation (TRm) above Kaibab Formation (Pk). Bounding fault of Citadel graben is downthrown on northwest (right) side.

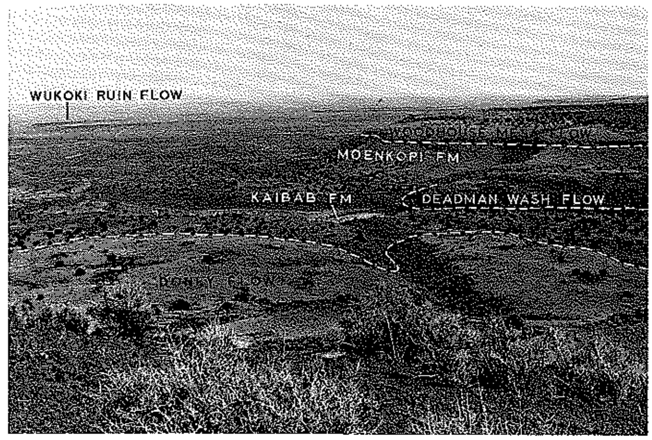

Figure 5. Photograph looking east from summit of scoria cone south of Doney Mountain at stop 5.

Stop 5. Doney Mountain (40 minutes)

Doney Mountain is the prominent cone northeast of the picnic area on the paved road that crosses Wupatki National Monument. The Doney scoria cone and an associated row of three small coalesced cones to the south erupted along the fracture system of the Black Point section of the East Kaibab monocline. The purpose of this stop is to examine the volcanic products of the Doney Mountain eruption, see their relationships with Colorado Plateau structures and erosion surfaces, and review the volcanic stratigraphy of the eastern San Francisco volcanic field.

Take the nature trail to the summit of the southern small scoria cone for a panoramic view (Figure 5). Many examples of a variety of bombs, some more than 1 m long, can be seen along the trail. To the east across Deadman Wash two basalt lavas are visible: Woodhouse Mesa, capped by 1.07±0.06-Ma-old basalt lava that flowed on the highest and oldest erosion surface on the Moenkopi Formation in this area; and a Tappan-age basalt lava that flowed down Deadman Wash after it had captured Antelope Wash, the abandoned drainage along the west side of the cones. Five small Merriam-age basalt flows were extruded from Doney Mountain and its associated cones; one of these lavas breached the east side of the southern cone and flowed toward Deadman Wash. East of Woodhouse Mesa on a lower erosion surface the mesa-capping Wukoki Ruin flow (0.89±0.14 Ma) is visible. The Black Point lava flow (2.43±0.32 Ma) on the highest erosion surface in the eastern volcanic field can be seen over the left shoulder of Doney Mountain.

The paved Wupatki road passes between a fault scarp of the Black Point structure and Doney Mountain, in which planar-bedded scoria and carbonate xenoliths can be seen. Turn left onto a good dirt road 5.5 miles south of Wupatki Visitor Center and continue south across the top of Tappan- (more weathered) and Merriam-age (less weathered) basalt lava flows to stop 6.

Stop 6. The Sproul (40 minutes, optional)

The stop is at the low cone situated on the west side of prominent Merriam Crater. Park on the west side of The Sproul and follow the foot trail to the crater rim. The Sproul is a large spatter cone of Merriam age. The purpose of this stop is to observe the structure of the volcano and the lithology of the lava.

Alkali basalt spatter, agglutinate, and rootless flows in outward-dipping layers compose the cone. These welded pyroclastic deposits form ramparts that enclose a broad, northwest-trending fracture-controlled, elliptical crater. Lava that extruded from the crater breached the northeast side of the cone and rafted large blocks of the wall material away. One of the lava flows extruded from The Sproul reached the Little Colorado River and formed the dam at Grand Falls (Wolfe, 1984).

Stop 7. Vent 235 Tuff Ring (20 minutes)

The purpose of this stop is to examine a wide-rimmed vent of Tappan age that is typical of maars in the volcanic field. The tuff contains fragments of basalt from the underlying flow of Woodhouse age, Moenkopi and Kaibab Formations, Coconino Sandstone, and oxidized basaltic cinders in a sandy palagonitic matrix. Depositional structures include cross-beds, low-angle dune forms, and inversely graded planar beds. Gravity data indicate a steep-walled crater in the subsurface floored at about 150-m depth; a magnetic high in the center may reflect an intrusive body beneath the crater floor (H.D. Ackerman, J. Hassemer, and J.D. Hendricks, unpub.). The focus of explosion is interpreted to have occurred in the Coconino Sandstone. A subsequent lava flow from the cone just to the north appears to have spilled into the maar.

Stop 8. Merriam Crater (20 minutes)

The stop is on top of a cinder-mantled lava flow that extruded from the northeast base of Merriam Crater, the largest cinder cone in this part of the volcanic field and the type cone of the Merriam age group. Southeast of Merriam Crater is a smaller cinder cone, and nestled between the two cones is the pushed-up, pluglike, layered mass of a third vent. Two flows that were extruded from the latter vent flowed northeast on a low surface beside a Woodhouse-age mesa. The flow from the north side of the vent moved directly northeast toward the Little Colorado River, but the flow from the southwest side first skirted the south side of the southeastern cone before heading down the regional slope; both flows moved in lava channels and formed prominent levees, which can be seen south of this stop. To the north are Woodhouse-age basalt lavas capping east-facing mesas over which lavas of Tappan age cascaded. Between this locality and Roden Crater to the north is the basalt lava that flowed about 13 km (8 mi) to dam the Little Colorado River at Grand Falls (next stop).

Stop 9. Grand Falls (30 minutes)

Grand Falls was formed 0.15±0.03 Ma ago when a basalt flow or series of flow lobes from the Merriam Crater vent group poured into the canyon of the Little Colorado River, overfilling it at the pourover and flowing 24 km downcanyon. The lake behind the new lava dam filled and eventually overflowed around the distal end of the flow (Figure 6), cascading approximately 43 m down the canyon wall. The river canyon is cut into the Kaibab Formation (sandy dolomite), which is overlain by the basal part of the Moenkopi Formation just northeast of Grand Falls. The uppermost cross-bedded dunes of the Coconino Sandstone are exposed beneath the Kaibab Formation below the falls. Alluvial deposits caused by the damming of the canyon extend at least 45 km up the broad river valley.

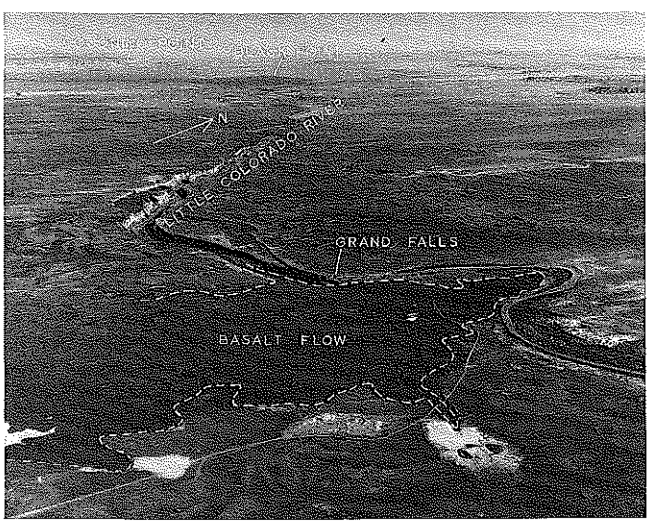

Figure 6. Oblique aerial photograph of the Grand Falls area on the Little Colorado River at stop 9. View is north. Photograph by J.F. McCauley.

Second Day: Stop 10.
Elden Mountain (40 minutes)

The stop is in a railroad spur between the Ralston Purina plant and the connecting ramp between U.S. 89 and I-40. The southern part of Mount Elden is a composite lava dome composed of bulbous, dacite lobes that flowed radially from at least two extrusion points onto the flat-lying Kaibab Formation 0.57±0.03 to 0.49±0.06 Ma ago. Prior to construction of the exogenous lava dome, Pelean-style eruptions about 4.8 km (3 mi) north of this locality generated pyroclastic flows that deposited a block and ash fan south of the vent. The purpose of this stop is to examine the structure of the lava dome and to study the block and ash deposit.

Six flow lobes, several of which overlap, are visible on the southeast dome of Elden Mountain. The lowest flow displays subhorizontal concentric benches that appear to be related to ramping shear fractures, whereas the highest flow is broken by longitudinal tension fractures (Kluth, 1974). The preserved thickness of the block and ash deposit at this locality is about 5 m where it thickens in a paleovalley in the Kaibab Formation. The deposit consists of two parts: 1) a lower layer (0 to 25 cm thick) composed of poorly sorted, structureless to crudely stratified ash and fine lapilli, and 2) an upper layer composed of very poorly sorted ash, lapilli, and blocks up to 1 m in diameter. The basal part of the upper layer (10-25 cm) ranges in character from fines-retained and matrix-supported to fines-depleted and clast-supported. The upper part of the upper layer, apparently structureless, contains matrix-supported essential blocks that range from dense dacite vitrophyre to poorly vesiculated pumice. Concordant paleomagnetic poles of the blocks indicate deposition above the Curie temperature (K. L. Tanaka, 1981, oral comm.).

Stop 11. Black Bill Park (20 minutes)

The stop is on the paved Timberline Estates road a few hundred feet west of U.S. 89. Black Bill Park is an intercone basin bounded by San Francisco Mountain, Elden Mountain, and Tappan-age scoria cones. The purpose of this stop is to examine the eastern part of the San Francisco Mountain volcanic system.

From south to north the following features can be seen on the west side of U.S. 89 (Figures 7 and 8): 1) southeastern dome of Elden Mountain; 2) broad recess in Elden Mountain underlain by east-dipping (30°-65°) Paleozoic strata in a continuous section down from the Kaibab Formation (Permian) to the Temple Butte Formation (Devonian) in contact with intrusive dacite at the base of the cliffs; 3) Little Elden Mountain composed of dacite flow lobes; 4) uplifted block of Paleozoic strata that dip northwest at 17°; strata are overlain by basalt lava flows and a block and ash deposit from a dome on Fremont Peak; 5) Schultz Peak (Brunhes geochron), a composite dacite dome partly buried on its north end by lavas from San Francisco Mountain; 6) Fremont, Doyle, and Reese Peaks on San Francisco Mountain, all capped by outward-dipping andesite lavas about 0.43 Ma old; 7) Sugarloaf Mountain, rhyolite dome extruded 0.22±0.02 Ma ago; and 8) block lava flow of dacite extruded 0.40±0.03 Ma ago from a vent on the upper east side of Doyle Peak.

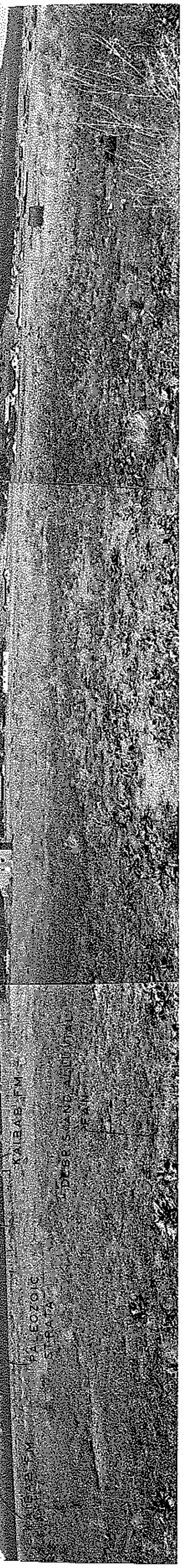

Figure 7. Panorama photograph, southwest on left to northwest on right at Black Bill Park, stop 11. Block and ash deposit, derived from a dacite dome at Fremont Peak, predates Elden Mountain. V is vent area of dacite lava flow. Scoria cone is of Tappan age.

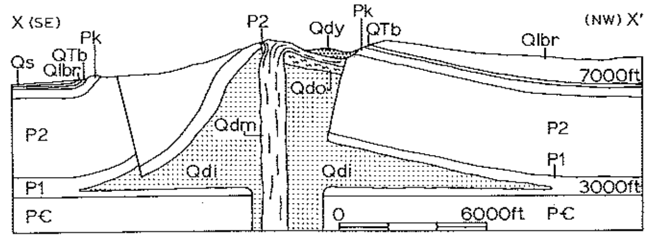

Figure 8. Cross section along X-X' on Figure 1; the view southwest from stop 11 is approximately normal to the line of section. Explanation: PЄ, Precambrian; P1, Tapeats Sandstone(?) (Cambrian), Temple Butte Formation (Devonian), and Redwall Limestone (Mississippian); P2, Supai Group (Permian and Pennsylvanian) and Coconino Sandstone (Permian); Pk, Kaibab Formation (Permian); QTb, basalt; Qlbr, lavas and breccias from San Francisco Mountain; Qdi, intrusive dacite; Qdo, older dacite dome; Qdm, middle dacite domes (major exogenous domes of Elden Mountain); Qdy, younger dacite flow; and Qs, alluvium and debris.

Stop 12. Bonito Lava Flow (80 minutes)

The Bonito lava flow extruded from the northwest base of Sunset Crater (Hodges, 1962), a scoria cone built during an eruption that began in 1064-1065 A.D. (Smiley, 1958) and continued episodically for about 120 years (D. Champion, written comm., 1985). The basalt lava was extruded in at least three stages and ponded in an intercone basin. North of the Bonito flow is the O'Leary Peak center, which is composed of several silicic lava domes and flows (0.25 to 0.17 Ma) and an andesitic lava flow. The purposes of this stop are to 1) examine the flow units and structures of the Bonito lava flow; 2) discuss the history of the Sunset Crater eruption; and 3) review the volcanic history of San Francisco Mountain.

Beginning at the parking lot on the Bonito flow, follow the route on Figure 9 counterclockwise to observe 1) stage 1 of the Bonito flow, covered with a thick mantle of tephra (Colton, 1967); 2) pahoehoe-type structures on stage 2B, lava that is at a similar level as stage 1 but has a thin and patchy mantle of tephra; 3) a squeeze-up that breaks through the crust of stage 2B; 4) stage 3 lava at a low topographic level; the flow is covered with aa clinkers and lacks a tephra blanket; 5) several hornitos above a lava tube; 6) large spheroidal bombs from the last summit eruption of Sunset cone on top of a small unit of stage 3 lava; 7) the stage 2A unit that was extruded onto the surface of the 1st stage; 8) a spatter rampart at the extrusion point of the stage 2A unit; 9) a pit crater that collapsed when stage 3 lava extruded; and 10) several large mounds of spatter, agglutinate, and rootless flows, some injected by shallow dikes, that were rafted by stage 1 lava when it breached an early cone of Sunset Crater. The high part of the stage 2A unit provides a vantage point from which San Francisco Mountain can be seen (Figure 10). The Inner Basin originated between 0.43 and 0.22 Ma ago as a result of collapse that displaced the top of

San Francisco Mountain outward in debris avalanches and debris flows. Truncated lava and pyroclastic units and buried silicic domes form the walls of the caldera, and the central conduit system of the composite volcano is exposed on the northeast-trending Core Ridge; Sugarloaf Mountain erupted through the largest debris fan.

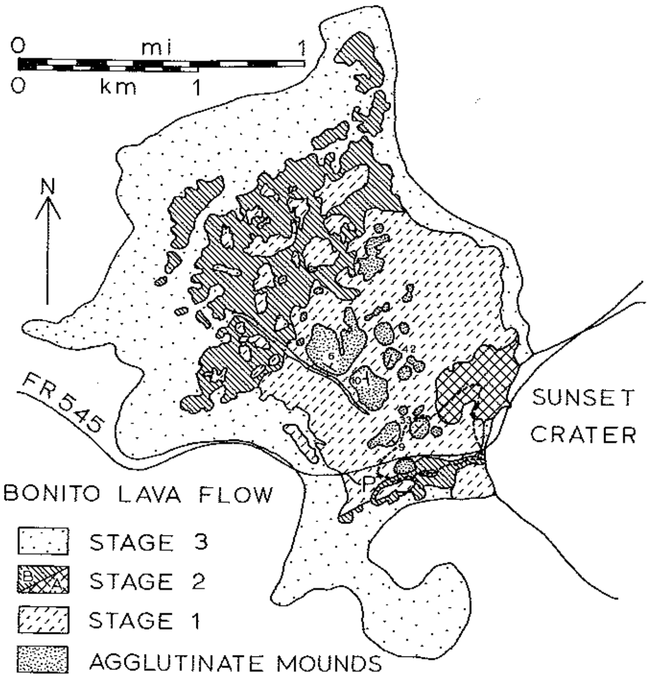

Figure 9. Geologic map of the Bonito lava flow. Dashed line shows traverse at stop 12. Strike and dip symbols indicate attitude of bedding in agglutinate mounds. FR, forest road; P, parking lot.

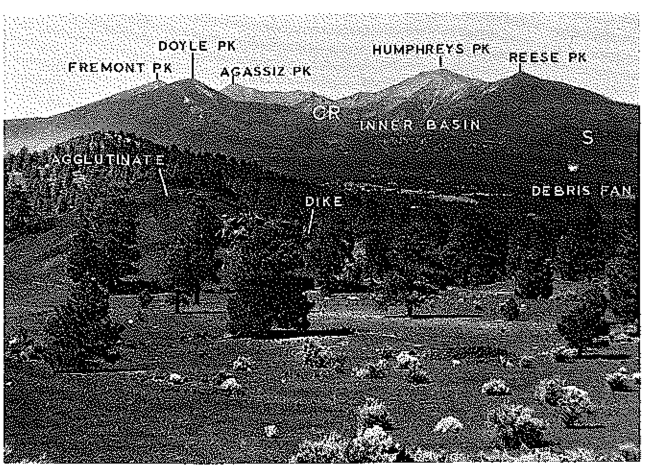

Figure 10. Telephoto picture of view toward San Francisco Mountain from the Bonito lava flow at stop 12. CR, Core Ridge; S, Sugarloaf Mountain. Dark lavas on top of Humphreys Peak are andesites approximately 0.43 Ma old. The dike injected the agglutinate before it was rafted from Sunset Crater.

Stop 13. Debris Fan (30 minutes)

The stop is at the information sign for Sunset Crater National Monument on Forest Road 545, the paved access road to the Monument. One of nine debris fans deposited around San Francisco Mountain as a result of its collapse forms the surface at this locality. The estimated volume of all the fans is 7.7 km^3, which compares favorably with the 8 km^3 calculated for the Inner Basin and restored cone.

The debris-fan slopes gently away from San Francisco Mountain, which gives rise to intermittent streams that have dissected the top of the fan. The deposit is coarse, polymictic, very poorly sorted, and poorly consolidated; it is part of the Sinagua Formation of Updike and Péwé (1970). Clasts of a wide variety of San Francisco Mountain lithologies can be seen in a partly excavated Sinagua Indian pit house and gullies south of the information sign.

Return to east Flagstaff on U.S. 89 and take I-40 west to exit 195B; follow the signs to Lake Mary Road, FH-3.

Stop 14. Mormon Lake (25 minutes)

The stop is at a scenic overlook next to FH-3 on the northeast side of Mormon Lake. The lake is bounded on its east side by a normal fault and on its other sides by the Mormon Mountain silicic center and basaltic cones and lavas. The purpose of this stop is to examine the volcanic stratigraphy and structure of the northern part of the Mormon volcanic field.

Basalt sheet lavas (Late Miocene?) form the low-relief surface east of the lake and are exposed in the cliffs along the fault (Figure 11), which has a throw of more than 200 ft. South of the lake a small shield volcano overlies the sheet lavas and both volcanic units are offset by the lake-bounding fault, as well as by a smaller southeast-trending fault that intersects the former to create a wedge-shaped graben in the meadow. Posttectonic dacite lava that was emplaced along the smaller fault forms the dome near the summit of the shield volcano. The shield volcano, dome, and fault scarps are overlain by small scoria cones and basalt lava flows. The Mormon Mountain silicic center on the west side of the lake is composed of several bulbous, block lava flows of dacite (3.1± 0.6 Ma), which were extruded radially on top of andesite lavas, and a rhyodacite dome that forms the rounded peak on the south side of the mountain (Gust, 1978).

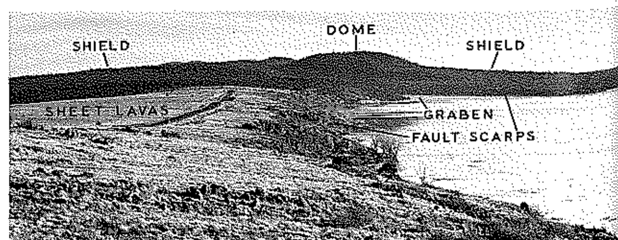

Figure 11. Photograph of view south along the east side of Mormon Lake at stop 14. Sheet lavas and shield volcano are basalt; both are cut by the faults. Dacite dome was emplaced along the fault that bounds the west side of the graben.

Stop 15. Mormon Mountain (25 minutes)

The stop is on the west side of Mormon Lake at a wide pullout between the lake and cliffs more than 100 ft high. The cliffs are at the toe of a thick (>55 m, 180 ft) block lava flow of pyroxene dacite that was extruded from the south side of the summit of Mormon Mountain, about two miles west of here. The purpose of this stop is to examine the lava-flow structures and petrography of the dacite.

The bottom part of the flow is a highly fractured zone consisting of randomly oriented open fractures bounding blocks of small or no displacement and autoclastic flow breccia of angular blocks. The middle part of the flow is a dense zone broken by moderately spaced (2-5 cm) ramping shear fractures that dip 60° to 70° west and northwest. Above the cliffs, the top of the flow is mantled by rounded (weathered) blocks of dacite, many of which appear to have little or no displacement. The dacite contains scattered phenocrysts of clinopyroxene and orthopyroxene, and sparse hornblende, in an aphanitic groundmass rich in plagioclase.

The route to stop 16 is south on FH-3 and AZ 87, and west on FH-9 toward Camp Verde; FH-9, the Zane Grey Highway, closely follows the General Crook Trail that connected Fort Verde and Fort Apache in the 1870's as an army supply route.

Stop 16. Mogollon Rim (25 minutes)

The stop is on a wide pullout on the right (north) side of the road 4.8 mi west of the Yavapai County line; at this point, the road begins to descend toward the Mogollon Rim, the southern Colorado Plateau marginal escarpment. Although the present Mogollon Rim is about 4.8 km (3 mi) west of here, sections of middle to late Miocene basalt lavas greater than 550 m (1,800 ft) thick in West Clear Creek to the north (Ulrich and Bielski, 1983) and in Fossil Creek to the south (Twenter, 1962; Weir and Beard, 1984) indicate that a buried ancestral escarpment, developed by pre-middle Miocene erosion into the Supai Group (Peirce and others, 1979), is several miles to the east, where the lavas thin abruptly on the Kaibab Formation. The youngest basalt lavas in this part of the volcanic field flowed westward down a constructional ramp from the Colorado Plateau into the Transition Zone (Elston and others, 1974). The purpose of this stop is to review the general geology, volcanism, and tectonism of the southern Colorado Plateau-Transition Zone boundary.

In a general sequence toward the west are 1) Thirteenmile Rock volcanics of Elston and others (1974); 2) Mogollon Rim, which trends north here, but swings around to the west along the north side of the Verde Valley where red and tan Permian strata form cliffs; 3) Verde Valley, an erosional and tectonic basin; 4) light-colored fluvial and lacustrine sediments of the late Miocene-Pliocene Verde Formation that were deposited in the valley when it was blocked at the south end by faulting and volcanism at the Hackberry Mountain center; 5) scarp of the Verde fault, which accommodated down-to-the-northeast throw of as much as 1,800 m (6,000 ft) since 8 Ma ago; 6) Black Hills, a horst capped by subhorizontal, mid-Miocene basalt lavas of the Hickey Formation (14-10 Ma; Elston and others, 1974) that were extruded onto an erosion surface cutting across gently northeast-dipping Paleozoic strata.

Stop 17.
Thirteenmile Rock Volcanics (60 minutes)

Stop 17 is 2 miles west of stop 16; park on the shoulder of the road in a gap between the guard rails. The upper part of the Thirteenmile Rock volcanics of Elston and others (1974) are well exposed in road cuts for the next 3 miles. The section consists of valleyward-dipping basalt lava flows, scoria beds, felsic air-fall tuffs and lapilli tuffs, felsic ignimbrite, a rhyolite lava flow or dome, and volcaniclastic sediments and debris. The basalt lavas were extruded on or near the plateau margin and flowed west toward the Verde Valley, locally filling channels. The felsic pyroclastic deposits presumably originated at the Hackberry Mountain silicic center about 11 km (7 mi) south-southwest of here. Small-displacement normal faults are generally downthrown on the west. The purpose of this stop is to review the stratigraphic relationships of the basaltic and silicic units in the southern Mormon volcanic field and to examine the lithologies and structures of the volcanic deposits.

Walk down the road for about a half mile to reboard the bus. Features of interest include 1) basalt lava flows and air-fall scoria deposits; 2) planar-bedded air-fall tuffs and lapilli tuffs, generally of dacite composition; 3) feeder dike (1 m thick) of columnar-jointed basalt lava flow and associated agglomerate; 4) air-fall pumice bed overlying a flow-banded rhyolite vitrophyre; 5) basalt lava flow containing plagioclase megacrysts up to 2 cm; 6) small-scale horsts and grabens; and 7) normal faults.

The road down to the Verde Valley passes cuts that expose debris-filled channels, nonwelded ignimbrite, felsic tuffs, basalt lava flows, and volcaniclastic sediments. The Hackberry Mountain silicic center can be seen on the left (south) shortly after passing the historical marker at Thirteenmile Rock; several dome-shaped mountains compose the center.

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