GEOMORPHOLOGY AND THE AGE OF VOLCANIC ROCKS IN NORTHEASTERN ARIZONA

By

Maurice E. Cooley

ABSTRACT

The feasibility of using regional erosion surfaces to determine age relationships where few or no diagnostic fossil or radioactive datings exist is demonstrated in four volcanic areas in the Little Colorado River drainage basin. The erosion surfaces underlying flows in the San Francisco volcanic field, Sunset Buttes flows, the flows in the Mesa Redondo area of the White Mountains, and a solitary flow along the Zuni River are traced to or correlated with erosion surfaces near the Colorado River. The sequence of regional erosion surfaces is re-examined, and on the basis of recent fossil information the surfaces are dated as follows: Hopi Buttes surface, late Miocene to early Pliocene; Zuni surface, middle Pliocene; Black Point surfaces, late Pliocene to early Pleistocene; Wupatki surfaces, middle and late Pleistocene; and post-Wupatki erosion, Recent.

The relationships of the volcanic flows to erosional surfaces and alluvial deposits in the San Francisco field area show a sequence of events that can be correlated to the regional geomorphic history of the Little Colorado River. The White Mountain volcanic field shows similar associations and the geomorphic history of the two areas, and the areas between them, probably correlate.

Reconstruction of the erosion surface at the time of eruption of the Sunset Buttes flows shows association of the flows with the Black Point, but not the older Zuni, or younger Wupatki, surfaces. The volcanic flow along the Zuni River was deposited neither on Black Point or Wupatki surfaces, but occurred sometime between those two periods of planation.

GEOMORPHOLOGY AND THE AGE OF VOLCANIC ROCKS IN NORTHEASTERN ARIZONA

By

Maurice E. Cooley[1/]

INTRODUCTION

Geomorphology can be used in the Little Colorado River drainage area in the correlation and dating of late Cenozoic volcanic rocks and associated depositional units that contain few or no known diagnostic fossil occurrences. The area lies between the Little Colorado River and the Mogollon Rim from the San Francisco Plateau to the Zuni Plateau (figs. 1.1 and 8.1). The altitude ranges from about 4,000 feet in the valley of the Little Colorado River near Cameron to more than 10,000 feet on the summits of the San Francisco and White Mountains; the altitude of most of the land surface is between 5,000 and 7,000 feet. Volcanic rocks are distributed throughout the region either in isolated mountain groups or as single cones with associated flows.

The volcanic flows discussed in this report that illustrate the relationships of the lavas to their underlying erosion surfaces are the flows of the San Francisco volcanic field, Sunset Buttes flows, and the flows in the Mesa Redondo area of the White Mountains volcanic field. These underlying surfaces can be correlated with the regional erosion surfaces near the Little Colorado River. The flow along the Zuni River was selected in order to show relationships of an isolated flow which was deposited during an interval of general downcutting and is not associated with any regional erosion surface. Many of the flows of these volcanic areas have direct relationships to and are in close association with sediments preserved on the erosion surfaces. The associations are most apparent in the San Francisco volcanic field.

Study was made of the following events in order to obtain an age assignment of a volcanic flow: the general erosional conditions pertaining to that specific area; the description of the underlying sedimentary bedrock; the structural relationships; the physiographic shape and gradient of the underlying erosion surface and its relationship to the regional erosion surfaces; the distribution, composition, and depositional environment of any deposits preserved beneath the lava flow or on the associated erosion surface; the nature, distribution and altitudes of the volcanic rocks; and the extent of post-volcanic erosion.

The author acknowledges his indebtedness to other workers in the area for many of the ideas and principles applied in this report. In particular, the author thanks the consideration of Dr. J. F. Lance of the University of Arizona who suggested the possibilities of correlating lava flows with the regional erosion surfaces of the Little Colorado River valley. Many fruitful discussions,

1/ Museum of Northern Arizona, Flagstaff.

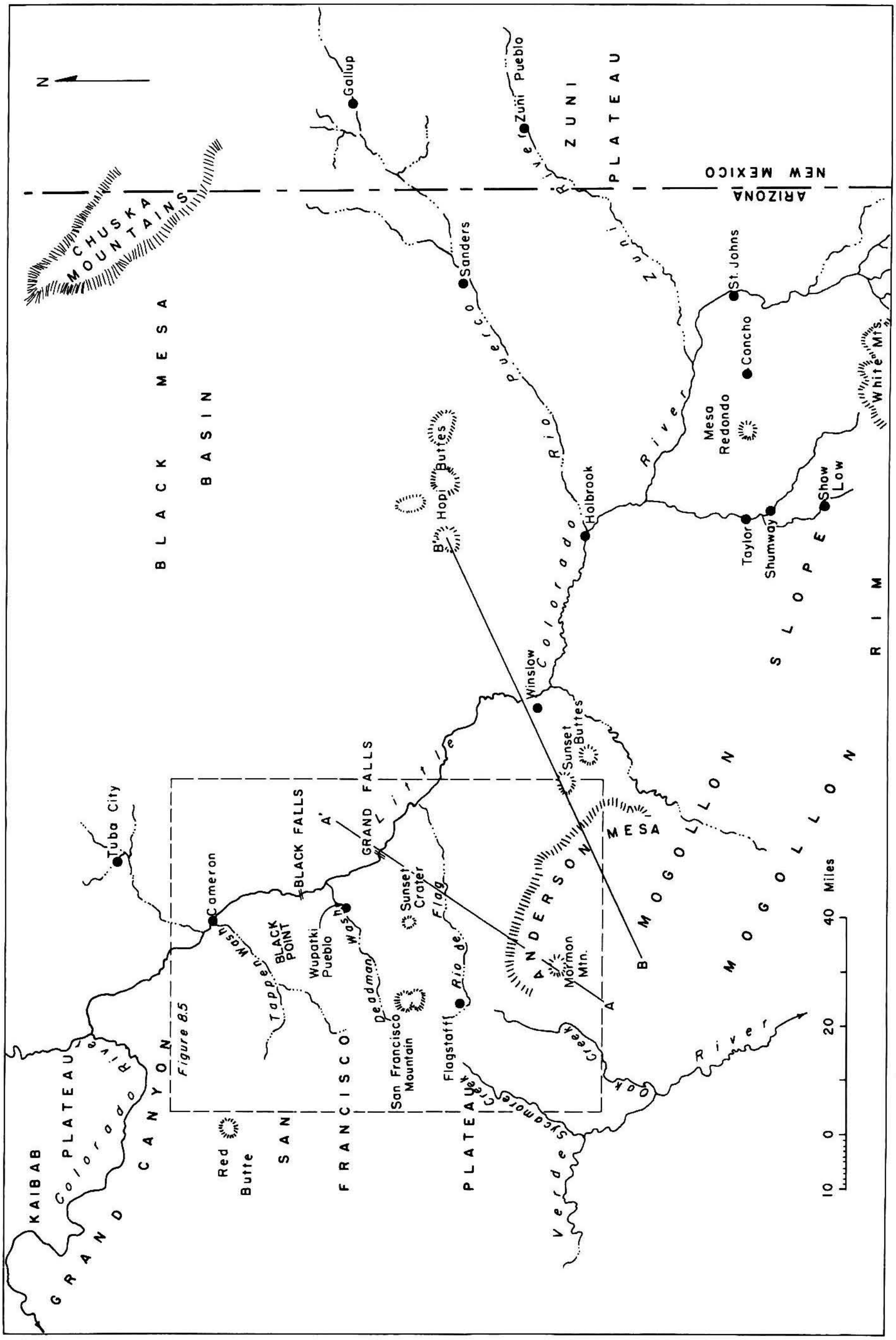


Figure 8.1. —Map of northeastern Arizona and adjacent part of New Mexico showing major physiographic features and locations of figure 8.5 and generalized geologic sections shown in figure 8.6.

chiefly over booze, were held with Messrs. J. P. Akers, Floyd Twenter, and O. J. Cosner of the U. S. Geological Survey Ground Water Branch, who have mapped portions of the San Francisco volcanic field. Many aspects of the stages of the San Francisco field were discussed with Dr. H. S. Colton of the Museum of Northern Arizona.

The investigation was made with the assistance of the Geochronology Laboratories, University of Arizona, Mr. Terah L. Smiley, Director.

REGIONAL GEOLOGY

In the Little Colorado River area, the exposed sedimentary rocks older than the Tertiary range in age from Permian to Upper Cretaceous with most of the area covered by Triassic sediments. The shaly Chinle and Moenkopi Formations of Triassic age and the resistant Permian Kaibab Limestone cover most of the region or lie buried beneath the volcanic rocks, but locally the Coconino Sandstone of Permian age and the Dakota Sandstone and other undifferentiated Upper Cretaceous units crop out at the surface. In the eastern part, the late Tertiary Bidahochi Formation makes up the summit of the Zuni Plateau and a large tablelike region along the Arizona-New Mexico boundary.

The dominating geologic structure is the Mogollon slope (Kelley, 1955) which gently dips to the northeast. The slope is bordered to the northwest by the Kaibab uplift, to the north by Black Mesa basin, and to the east by a shallow basin near St. Johns (fig. 8. 1). To the south and west the slope has been broken by complex structures that are common to central Arizona. Imposed on the Mogollon slope are many northwest-trending folds, including several monoclines. Several long north- and northwest-trending vertical faults form low escarpments, which locally have deflected drainages and have offset some of the late Tertiary flows.

The Little Colorado River has cut a large subsequent valley in the lower part of the Mogollon slope area. Within this valley are the multicolored "Painted Desert" badlands, which have been carved from the Chinle Formation. The region south of the river consists of gentle plains that have truncated the Moenkopi Formation or stripped surfaces eroded on the Kaibab Limestone. The plains extend headward along the tributaries and terminate below Anderson Mesa and other mesas on the summit adjacent to the Mogollon Rim. The landforms have a general accordance of heights that only apparently subdues the ruggedness of the shallow canyons and low mesas. The whole region appears to have been composed once of gentle plains whose general land surface has been slightly lowered by subsequent cycles of erosion and upon which the several volcanic mountains have been built up to break its ancient even skyline.

REGIONAL GEOMORPHOLOGY

Description of Surfaces and Terminology

The geomorphologic names used in this paper refer to four erosion surfaces or groups of surfaces, which can be traced throughout the Little Colorado River area. These surfaces are the Hopi Buttes surface (Gregory, 1917;

redefined by Hack, 1942; redefined by Cooley, 1958), the Zuni surface (McCann, 1938), the Black Point surfaces (Gregory, 1917; Childs, 1948), and the Wupatki surfaces (Childs, 1948). The ages and correlations of these surfaces are given in figure 8.2, and their physical relationships are shown diagrammatically in figure 8.3.

The Hopi Buttes surface is preserved only beneath the lower member of the Bidahochi Formation. Fossils occurring in the lower member have been dated as late Miocene(?) and early Pliocene (Lance, 1954). The reconstruction of the Hopi Buttes surface in the Hopi Buttes-Sanders area indicated that the axis of the ancestral Little Colorado valley occupied a position 30 to 50 miles to the northeast and subparallel to the trend of the present valley (Cooley, 1958). In areas of the southern plateau region where no protective cover of the lower member of the Bidahochi is present, this surface either has been destroyed by later erosion or is difficult to distinguish from the younger Zuni surface.

The Zuni erosion surface underlies the upper member of the Bidahochi Formation and is easily recognized on the Zuni Plateau and the adjacent valley of the Little Colorado. In addition, the erosion surfaces at the base of the Hopi Buttes lava flows, the volcanic member of the Bidahochi Formation (Repenning, Lance, and Irwin, 1958), and the upper surface on the summit of the Chuska Mountains are considered to be parts of the Zuni surface (Cooley, 1958). The Zuni erosion surface can be extended over much of the southern border region of the Colorado Plateau in places where it has been preserved below volcanic flows and the upper member of the Bidahochi Formation. The age of the Zuni surface is middle Pliocene because the surface bevels the lower member of the Bidahochi of early Pliocene age and underlies the upper member of middle Pliocene age (Lance, 1954).

The planation of the Zuni surface was terminated shortly after mid-Pliocene time when the entrenchment of the present valley began by the lowering of the base level of the ancestral Little Colorado River in the Grand Canyon area. The succeeding cycles of erosion, divided into periods of planation alternating with periods of downcutting, caused the formation of the terraces within the present Little Colorado valley. The upper levels of these terraces, formed during the early stage of the valley development, are the Black Point surfaces, and the lower terraces, cut in an inner valley below the youngest Black Point terrace, are called the Wupatki surfaces (figs. 8.2 and 8.3). The Black Point surfaces extend upstream along the Little Colorado River and tributaries eastward into the western part of New Mexico, southward to the Mogollon Rim, and northward into the Black Mesa basin. The Wupatki surfaces can be traced upstream along the Little Colorado River to St. Johns, along the Zuni River for about 50 miles above its mouth, and along the Rio Puerco to Sanders. Above these points the Wupatki surfaces lie buried by thick alluvial deposits.

Fossils from deposits associated with the Charlie Day Spring at Tuba City, Arizona, have been reported by Colton (1931), and these are believed by J. F. Lance (oral communication, 1957) to be Blancan types of early Pleistocene or late Pliocene age. The spring deposit lies only a few feet below a late Black Point surface in the area. Similar fossils have been reported by J. F. Lance (oral communication, 1957) from gravelly deposits lying on a late Black Point surface near Taylor, Arizona. These faunal relationships and the fact that the Black Point surface truncates the upper member of the Bidahochi Formation suggest that the age of the Black Point surfaces ranges from late Pliocene to early Pleistocene, and that most of the erosion probably occurred in the late Pliocene.

Dutton (1882)	Davis (1901)	Robinson (1907, 1910, 1913)	Gregory (1917, 1947)	Terminology in This Report	Age
Canyon Cycle	Canyon Cycle			Post-Wupatki Erosion	Recent
		Post-Tertiary Peneplain	Box Springs Peneplain	Wupatki Surfaces	Middle and Late Pleistocene
			Black Point Peneplain	Black Point Surfaces	Late Pliocene to Early Pleistocene
Great Denudation	Plateau Cycle	Tertiary Peneplain	Hopi Buttes Peneplain	Zuni Surface	Middle Pliocene
				Hopi Buttes Surface	Late Miocene to Early Pliocene
			Miocene Surface		Early and Middle Tertiary

Figure 8. 2—Chart showing age and correlation of the erosion surfaces and geomorphic cycles in the Little Colorado River area.

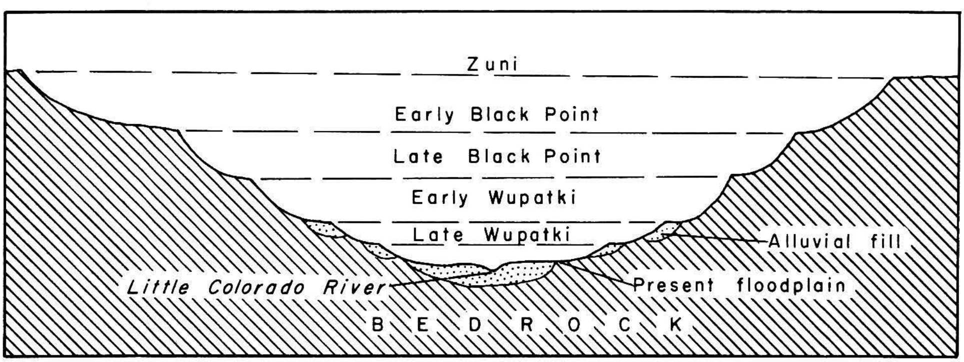


Figure 8. 3—Diagram showing relationships between the several erosion surfaces preserved in the valley of the Little Colorado River, Ariz.

The Wupatki surfaces have been dated as being of probable middle to late Pleistocene age on the basis of elephant remains and other mammalian fossils identified in sediments deposited on these surfaces near Holbrook and at several other localities near the Little Colorado River (J. F. Lance, oral communication, 1957).

Correlation of Earlier Terminologies

Past physiographic studies of the Colorado Plateau made by Dutton (1882), Davis (1901), Robinson (1907; 1910), and Gregory (1947) indicated a general entrenchment and development of the Colorado River system from a widespread erosion surface whose formation occupied most of mid-Tertiary time. Gregory (1947, p. 704) summarized the general conclusions by stating: "It is thought that some gaps in the physiographic history of the (Colorado) Plateau country may be filled by the recognition of a regional Miocene surface of erosion on which after uplift the Colorado River began its life as the master stream in an integrated, through-flowing, generally superposed drainage system." Dutton (1882) subdivided the Cenozoic history of the Colorado Plateau area into two erosional cycles, the older "Great Denudation" and the younger "Canyon Cycle." Davis (1901) called at least the later part of the "Great Denudation" the "Plateau Cycle" and believed it had been formed during the early stages of the outlining of the Colorado Plateau; he considered the "Canyon Cycle" represented the later stage of the formation of the Colorado Plateau and the Colorado River system. Robinson (1907) applied the name "Tertiary peneplain" in the southern part of the Colorado Plateau, and it is generally equivalent to the "Plateau Cycle" of Davis. Later he recognized a younger erosion surface, which he called the "post-Tertiary peneplain" (Robinson, 1910). Within the Navajo country near the Little Colorado River, Gregory (1917) described the "Hopi Buttes peneplain," "Black Point peneplain," and "Box Springs peneplain." These early terminologies and their relationships to the terminology used in this report are shown in figure 8.2.

The long period of mid-Tertiary erosion described by Dutton (1882) as the "Great Denudation" and by Davis (1901) as the "Plateau Cycle" has been correlated by McCann (1938, p. 277-278) and Reiche (1941, p. 63-64) with the Zuni surface which they described in the Gallup-Zuni area. Cooley and Akers (1961) considered the Zuni and the older Hopi Buttes erosion surfaces to be the equivalent of only the later part of the "Plateau Cycle" of Davis. The peneplain cycle of erosion described by Robinson (1907) is also believed to be equivalent of the Zuni and Hopi Buttes surfaces, whereas the post-peneplain cycle of erosion (Robinson, 1910) correlates with the Black Point surfaces. The formation of the Black Point and Wupatki surfaces in the Little Colorado River valley above Cameron is equivalent to the Canyon Cycle of erosion of Dutton (1882) and Davis (1901). The "Box Springs peneplain" of Gregory (1917) has been mapped as part of the Wupatki surfaces. The extension of the Zuni and Black Point surfaces from the Little Colorado River valley to the San Francisco Plateau substantiates the hypotheses postulated by the early investigators concerning the development of the present Colorado River system in this part of the Colorado Plateau.

SAN FRANCISCO VOLCANIC FIELD

The San Francisco volcanic field was built up by at least seven major eruptive stages that deposited lavas on the summit of the San Francisco Plateau and the adjoining Verde and Little Colorado River valleys. The volcanic field was divided by Robinson (1913) into three general periods of eruption—the first and third periods consisting of basalts with the intervening second period composed of intermediate igneous rock types. Later, Colton (1937, 1950) subdivided the basalts into five groups, using the degree of weathering and erosion of the lava flows and cinder cones as age criteria. This paper proposes a classification based primarily on the relationships between the volcanic rocks and the processes of erosion—i. e., relationships to the Zuni, Black Point, and Wupatki erosion surfaces—and the associated alluvial deposits (fig. 8.4). On the basis of these relationships, the basalts of the first period of Robinson (1913) and the stage I of Colton (1937; 1950) have been divided into a period of older basalts and a redefined stage I. Figure 8.4 shows the correlation and relationships of the volcanic flows with the erosion surfaces and alluvial units.

The volcanic rocks of the San Francisco field can be combined on the basis of geomorphic relationships into three broad groups. These are the older basalts; the igneous rocks of intermediate composition; and the younger basalts, which are divided into five stages. The older basalts lie on the Zuni and possibly the Hopi Buttes erosion surfaces and were deposited before the present entrenchment of the Little Colorado River. The younger basalts lie on the Black Point and Wupatki surfaces or in post-Wupatki valleys.

The older basalts occur on low mesas and buttes which protrude above the general level of the San Francisco Plateau. The plateau is a structural shelf that connects the Mogollon slope with the Kaibab uplift. The regularity of the shelf is broken by two structural troughs that trend to the northeast, from Oak Creek Canyon to Wupatki Pueblo and from Sycamore Canyon almost to Cameron. The troughs are bounded partly by the Coconino and Black Point segments of the East Kaibab monocline and a monocline along the northeast side of Anderson Mesa (fig. 8.5). The general positions of these valleys were entrenched in the structural troughs before the formation of the San Francisco Mountain. The Oak Creek fault and other large, generally north-, northwest-, and northeast-trending faults have accentuated to profile of the troughs and locally have offset the older basalts and some of the younger basalts. The troughs are occupied by Tappen Wash and parts of Deadman and Rio de Flag drainages. The present valleys of these drainages were cut below the older basalts, but the younger basalts, preserving the Black Point and Wupatki surfaces, and the intermediate flows show in successive steps the development of the present drainage systems.

Older Basaltic Flows and Associated Deposits

The older basalts lie at altitudes greater than 7,000 feet and border the Mogollon Rim from Sycamore Canyon to the southern part of Anderson Mesa. Outliers of these basalts have been preserved as far north as Red Butte, 10 miles south of the Grand Canyon. This unit is composed of several basalt flows with interbedded sandy sediments. The total thickness of the flows and sediments ranges from 30 to about 800 feet. The older basalts locally have been offset more than 300 feet by faulting and form prominent cliffs.

The older basaltic flows and sediments consist of four units which can be recognized on the San Francisco Plateau. In descending order, these deposits include the following units: (1) basaltic unit that generally consists of a single flow 30 to 50 feet thick; (2) "pink" sandy deposit 100 feet thick; (3) several

SAN FRANCISCO VOLCANIC FIELD								
Robinson (1913)		Colton (1950) (Basaltic stages only)	Cooley (This paper)					
			Basaltic stage and typical flow	Flows of intermediate types	Viscosity of basalt and physiographic location	Erosion cycle	Relationship with depositional unit	Age
Third Period (Basalt)	3B	Stage V	**V.** Sunset Crater	None	Fairly fluid; in broad canyon.	Post Late Wupatki	None	Recent
	3A	Stage IV	**IV.** Black-Grand Falls flow; Doney Crater		Chiefly highly fluid, some viscous; in narrow canyons.		Underlies alluvial Tsegi formation; overlies intermediate alluvium.	Late Pleistocene(?) to early Recent
		Stage III (III a, b, c)	**III.** Flow along Deadman Wash west side of Woodhouse Mesa; flows in Doney Park area	Flows flanking O'Leary Peak	Viscous, formed broad lobes; did not flow down narrow canyons.	Late Wupatki	Deposited contemporaneously with intermediate alluvium; overlies **older** alluvium.	Late Pleistocene
				Robinson's fourth and fifth eruptive stages of San Francisco Mountain				
		Stage II	**II.** Tappen Spring		Highly fluid; in narrow canyons and broad valleys.	Middle and Early Wupatki	Contemporaneously with and underlies older alluvium.	Middle to Late Pleistocene
			II. Flows east of Wupatki pueblo				Underlies older alluvium	
Second Period (Intermediate types)			**IA or II.** Flows of upper Tappen Wash	Robinson's second and third eruptive stages of San Francisco Mountain; Elden Mountain.		Period of chiefly downcutting	Underlies and was source for **older** alluvium.	Early to Middle Pleistocene
First Period (Basalt)		Stage I	Stage 1: **IA.** Woodhouse Mesa; Citadel flow	Robinson's first eruptive stage of San Francisco Mountain; Observatory Mesa.	Fluid; broad and narrow valleys.	Late Black Point	Thin gravelly deposits	Early(?) Pleistocene — Blancan(?)
			Stage 1: **IB.** Black Point	None	Fluid; broad valleys.	Early Black Point		Late(?) Pliocene — Blancan(?)
			Older basalts Anderson Mesa; Oak Creek Canyon area; Red Butte; flow south of Cedar Ranch.		Fluid; gently sloping plains.	Zuni	Interbedded with silty sand, overlies gravel and sand.	Middle Pliocene

Figure 8. 4—Chart showing correlation and relationships of the volcanic flows in the San Francisco volcanic field, Arizona.

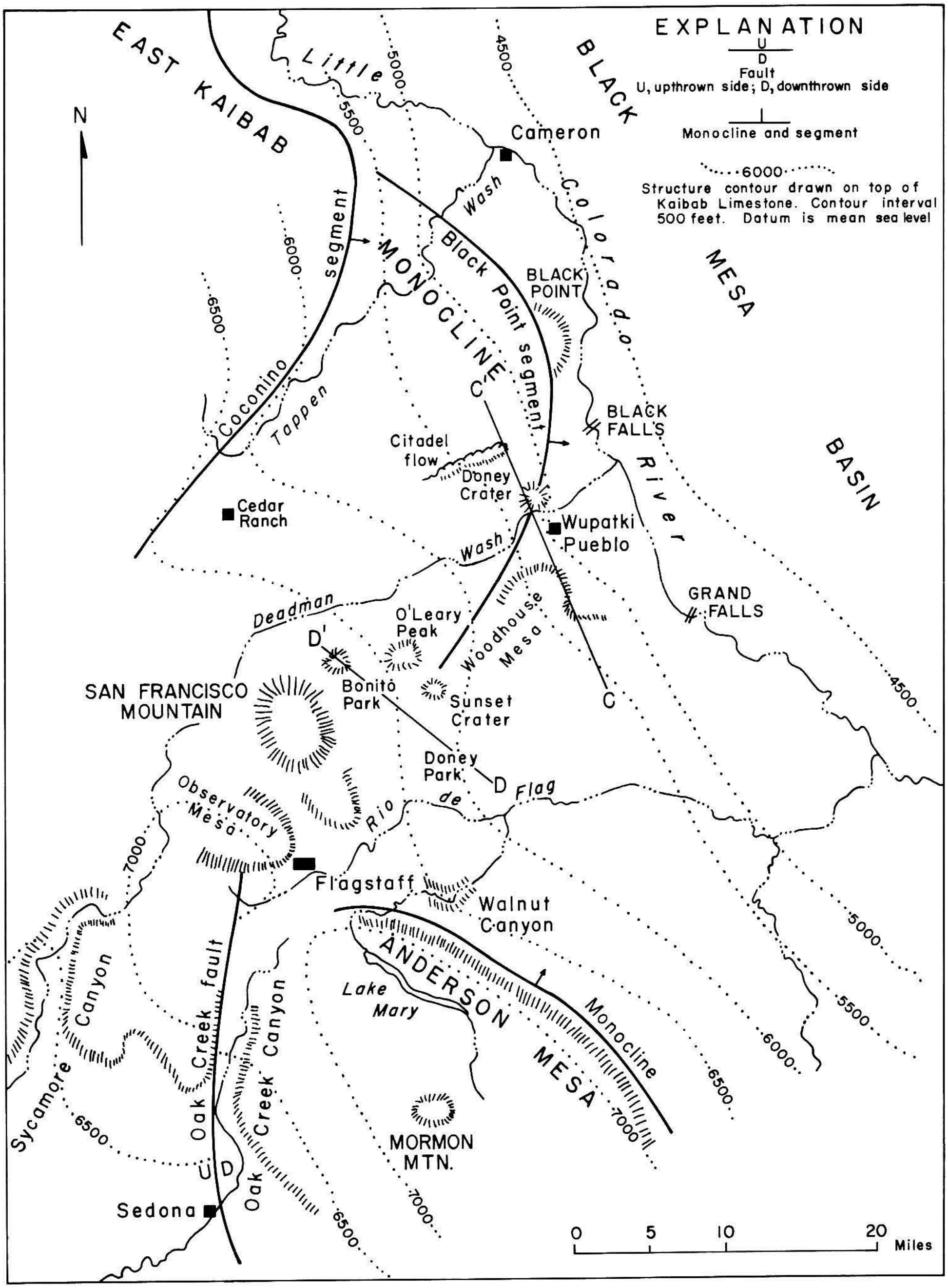


Figure 8. 5. --Sketch map of San Francisco Mountain area, Arizona, showing major structural features and structure contours on the top of the Permian Kaibab Limestone. (For location of area, see fig. 8. 1)

basaltic flows having a combined thickness of about 300 feet; and (4) sandy and gravelly deposits between 200 and 300 feet thick. The four units are exposed in sequence only in the Sycamore Canyon area; elsewhere, one or more of the units are missing. Near Oak Creek only the upper three units are present, and these have been mapped in an area 20 miles in length. The units are recognized easily in good exposures on both sides of and have been offset by the Oak Creek fault. Near Cedar Ranch the youngest unit overlies the oldest unit, and on Anderson Mesa only the youngest unit is present.

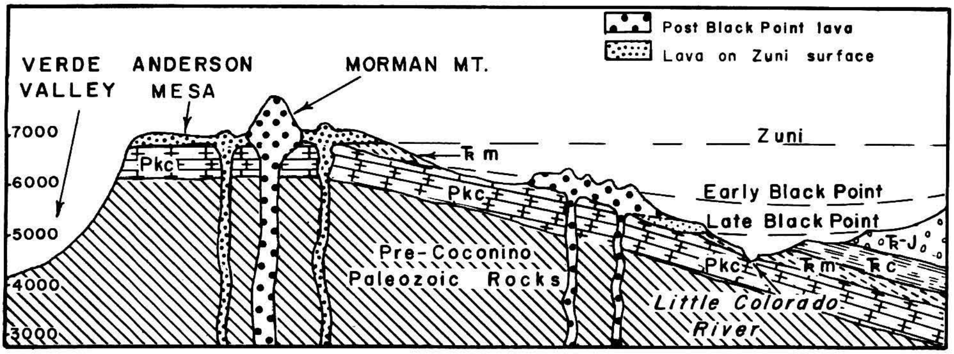
The "pink" sandy unit is composed chiefly of silty sandstone, tuffaceous sandstone, and tuff, laid down in streams or in shallow lakes. The color ranges from a pale red to a grayish orange pink and sharply contrasts with the dark grays and blacks of the basalts. Between 100 and 200 feet of sediments believed to be the middle member was described briefly by Price (1948, p. 80-81) in Sycamore Canyon. Lenses of similar sediments, mostly less than 25 feet thick, are interbedded between the flows of the lower unit. These sediments represent residual-soil zones and fills of small channels. The sandy sediments are covered generally by slumpage, soil creep, and vegetation but are exposed in cuts along streams and roads.

The gravelly unit (4) is composed chiefly of lenticular thick to very thick bedded layers of silty sandstone to sandy conglomerate. The sediments contain fragments of petrified wood and logs, apparently reworked from the Chinle Formation. Analyses of the gravel show that quartzite is the predominant rock type and that the gravel contains a considerable amount of andesite-rhyolite pebbles. Quartzite cobbles 8 inches in the long dimension were observed, and much of the gravel is more than 5 inches in maximum diameter. Similar gravelly deposits were also described by Price (1948). In contrast, gravel from the nearest outcrop of the Shinarump Member of the Chinle Formation indicates a pebble assemblage composed chiefly of chert, jasper, quartzite, and quartz whose sizes reach a maximum of about 3 inches.

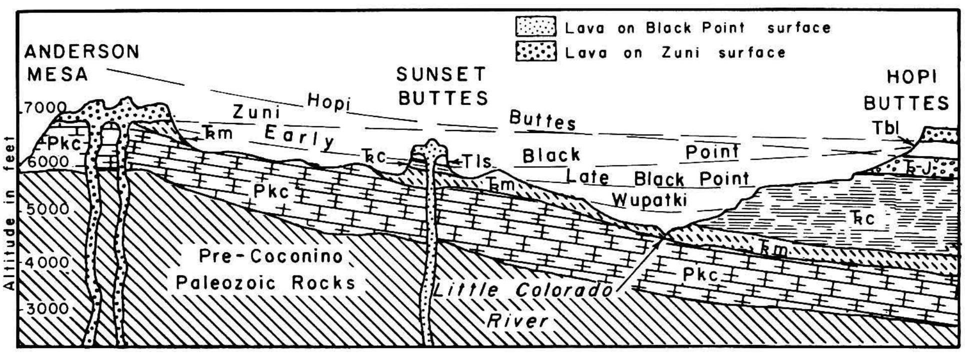
The older basalts and associated sediments overlie an erosion surface consisting of a karst topography and a weathered zone that has been developed on the Kaibab Limestone and Moenkopi Formation. These surfaces are well exposed below the basalts in road cuts about 6 miles south of Flagstaff. The karst zone has a depth of more than 40 feet, and in places a few feet of "pink" sandy sediments lie below the basalt.

On Anderson Mesa the older basalts overlie a flat erosion surface that truncates the Kaibab Limestone and Moenkopi Formation across the monocline along the northeast side of the mesa. The tracing and projection of the early Black Point surface from Black Point, and the late Black Point surface from Woodhouse Mesa and from the area near Grand Falls southward indicate that all the Black Point surfaces lie 500 feet below the summit of Anderson Mesa (fig. 8.6A). Thus, the basalts on Anderson Mesa lie on an erosion surface that had been formed before the Black Point surface or before the entrenchment of the present Little Colorado River valley. The surface beneath the older basalts on Anderson Mesa was correlated with the Zuni surface (Cooley, 1958), and the basalts are believed to be equivalent in age to the Hopi Buttes volcanic field.

Several parts of the erosion surface beneath the older basalts may represent a considerable time of development before burial by the older basalts. The formation of the karst topography on the Kaibab Limestone south of Flagstaff and the deposition of the gravelly sediments in Sycamore Canyon and elsewhere may record events that had begun before the general planation of the Zuni



A. Section A-A', Anderson Mesa to the Little Colorado River at Grand Falls. Ʀ-J, uppermost Triassic and Jurassic rocks; Ʀc, Chinle Formation; Ʀm, Moenkopi Formation; and Pkc, Kaibab Limestone and Coconino Sandstone undifferentiated.



B. Section B-B', Anderson Mesa to Sunset Buttes and the Hopi Buttes. Weakly consolidated sediments deposited on late Black Point surface (Tls), lower member Bidahochi Formation (Tbl), Chinle Formation (Ʀc), Moenkopi Formation (Ʀm), and Kaibab Limestone and Coconino Sandstone undifferentiated (Pkc).

Figure 8.6—Generalized geologic sections showing relationships of the lavas on Anderson Mesa to the erosion surfaces along the Little Colorado River. (For location of sections, see figure 8.1.)

surface, and the Zuni surface may represent the end product of this period of erosion. The initial erosion of parts of the surface cut on the karst topography and beneath the gravelly sediments may extend into late mid-Tertiary time and be contemporaneous with the formation of the Hopi Buttes surface. Therefore, the development of the erosion surface beneath the older basalts may have begun as early as the late Miocene, but most of the surface that has been preserved represents planation during the middle Pliocene.

The older basalts and associated sediments suggest that the deposition of all the units must have taken a considerable amount of time. This conclusion is based on the total number of individual flows, locally at least five, the total thickness of 300 feet, and the fact that the top of each flow was subjected to a period of weathering. Also, the deposition of the middle sandy member must have taken a relatively long period of time. From the above data and from the relationships to the Zuni surface, the age of the older basalts is considered to be middle Pliocene for the most part, although parts of the formation may have been deposited during the early Pliocene or even in the late Miocene.

Younger Volcanic Rocks

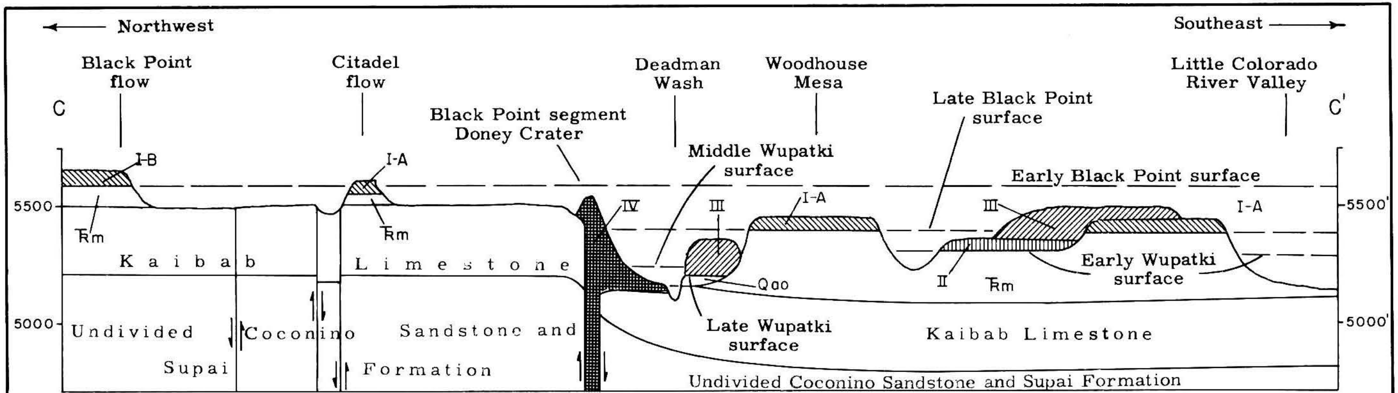
Basaltic Stages and Associated Deposits

The younger basalts, stages I to V, and the flows of intermediate composition, flowed out in valleys which were formed during the entrenchment of the present Little Colorado River valley. These volcanic rocks lie chiefly on the Black Point and Wupatki surfaces. Basalts stages IV and V are only local in extent and have no relationship to the regional erosion surfaces. Alluvial deposition is associated with stages II, III, and IV and with the intermediate flows, because the flows of these stages had partly blocked drainages and alluvial deposits were laid down behind the volcanic barriers. The relationships of stage I-IV flows, igneous rocks of intermediate composition, and associated alluvial deposits are shown in figure 8. 7.

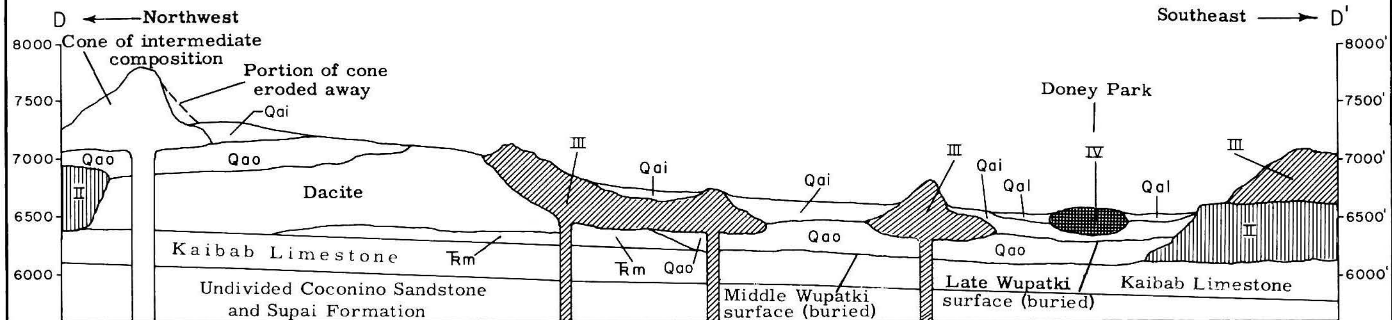
Stage I basalts.--The stage I basalts, stages IA and IB, as defined in this paper, are the lavas that flowed out on the Black Point surfaces. Stage IB basalts are older than stage IA basalts.

The stage IB basalts overlie the early Black Point erosion surface that formed broad valleys of low relief. These valleys sloped gently northeast to the Little Colorado River from a few miles north of Flagstaff to Black Point, and they include the Black Point and related flows. The Black Point flow extends across the Black Point segment of the East Kaibab monocline without changing gradient; thus, no recurrent movement along this monocline has been indicated since the formation of the lava. Several small faults, chiefly graben structures, offset the Black Point flow.

The stage IA basalts were deposited in valleys which were formed during the earliest stage of development of Deadman and Tappen Washes. These flows have been mapped as part of the late Black Point surfaces (Cooley, fieldwork in progress). The late Black Point valleys were partly adjusted to the structural troughs; the valleys were formed on the east sides of the Coconino and Black Point segments of the East Kaibab monocline. Some of the stage IA



A. --Section C-C', Wupatki Pueblo area, showing relationships of the basaltic stages to the Black Point and Wupatki surfaces.



B. --Section D-D', Doney Park area, showing relationships between the volcanic rocks, alluvial units, and the Wupatki surfaces.

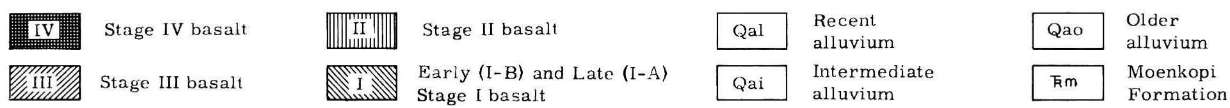


Figure 8.7.--Generalized geologic sections showing relationships of stage I-IV basalt flow, igneous rocks of intermediate composition, and associated alluvial deposits in the San Francisco Mountain area. (For location of sections, see fig. 8.5.)

flows appear to have followed small, recently formed grabens. In many places a small amount of later movement along the same structures has offset these stage IA flows. In the upper part of Tappen Wash the stage IA flows were confined in canyons cut into Paleozoic rocks and are similar in form to the later stage II flows.

Stage II basalts.--On the San Francisco Plateau downcutting became more severe after the planation of the late Black Point valleys. The cutting of Walnut Canyon and other canyons is believed to have been started at the end of late Black Point time. During this period of downcutting and during the Wupatki cycle, all the drainages became more entrenched in shallow canyons and in valleys. Planation continued to be the predominant process near the Little Colorado River with the formation of five Wupatki surfaces near Wupatki Pueblo. The stage II flows, overlying the Wupatki surfaces, are on low terraces near the Little Colorado River or occupy shallow canyons and valleys on the summit of the San Francisco Plateau.

Near the Little Colorado River east of Wupatki Pueblo, stage II lavas overlie the two highest or oldest Wupatki surfaces. Near Cameron the stage II Tappen Springs flow, along Tappen Wash, lies on the middle or third highest Wupatki surface. This flow had partly blocked the canyon of the Little Colorado River below Cameron, and it is partly responsible for the formation of the middle Wupatki surface. The middle surface has been mapped from Cameron to a few miles upstream from Black Falls (Cooley, Akers, and Hardt, in preparation), and it is the Wupatki B "pediplain" of Childs (1948).

Near the Little Colorado River the stage III basalts flowed down valleys which had been cut below the level of the middle Wupatki surface and below the level of all stage II flows. A stage III flow a mile southwest of Wupatki Pueblo along Deadman Wash overlies gravels that were deposited on the youngest or lowest Wupatki surface.

Near Wupatki Pueblo gravels deposited on the middle surface are chiefly of intermediate igneous types derived principally from the San Francisco Mountain area. The intermediate igneous types form a large amount of cobble and boulder size gravel; the gravels on the Wupatki surfaces along the Little Colorado River are generally pebble and small cobble size with the cobbles composed chiefly of quartzite. Similar bouldery gravels have been deposited as alluvial fans and on pediments along the base of the San Francisco Mountain. These gravels make up most of the alluvial area that was mapped by Robinson (1913). The gravels, informally called the older alluvium in this report, were laid down in the valleys of Deadman Wash and Rio de Flag. In the valley of Rio de Flag near Flagstaff the older alluvium overlies two stage II basalt flows and the Kaibab Limestone. The older alluvium is believed to have been deposited on the Wupatki surfaces, and a probable correlation exists between the surface at the base of the older alluvium and the middle Wupatki surface near the Little Colorado River. Thus, the interrelations of the stage II flows and the older alluvial deposits make it possible to extend the Wupatki surfaces into the headwater areas of Deadman Wash and Rio de Flag around San Francisco Mountain. This extension of the Wupatki surfaces may make it possible to establish the ages of many later flows in the area west of San Francisco Mountain.

Stage III basalts.--The configuration of the base of the stage III flows indicates that these lavas occupy shallow valleys cut into the older alluvium.

The stage III flows blocked these valleys and caused the accumulation of a younger alluvial unit, informally called here the intermediate alluvium. These alluvial relationships are shown in the Doney Park, Bonito Park, and Deadman Wash areas by both the stage III basalts and the intermediate-type flows. The relationship between the stage III lavas and the alluvial sediments was brought out by Sharp (1942) who indicated that the oldest glacial outwash in the San Francisco Peaks(?), correlative with the older alluvium, underlies the stage III basalts. This was later confirmed by Cosner (1955) who shows, in a cross section through Bonito Park, stage III and younger volcanic rocks overlying the glacial outwash. Further evidence is shown near the northwest side of Bonito Park where a flow and cinder cone of intermediate composition (Cosner, 1955) has been eroded as much as the stage III basalts. The lava contains embedded cobbles and boulders that are similar in composition and general roundness to the gravel comprising the older alluvium; the lava apparently had been intruded through the older alluvium. Lateral cutting around the base of the cone by streams depositing the intermediate alluvium has destroyed the southeast portion of the cone. Here the present slope is steeper than the dip of the bedding which is exposed in roadcuts near the top of the cone.

Stage IV basalts.--Relationships of the stage IV lavas indicate that they flowed in channels or in narrow valleys cut below the youngest Wupatki surface and are overlain by the younger or Recent alluvium. The short flows extending from Doney Crater near Wupatki Pueblo have diverted the arroyo of Deadman Wash. The arroyo had been cut below the level of the youngest Wupatki surface which underlies the stage III flow a mile southwest of Wupatki Ruin. At Grand Falls the shallow canyon of the Little Colorado River had been filled by lavas of stage IV flows. The river was diverted northward and formed the falls on the resistant Kaibab Limestone (Gregory, 1917). These flows followed the channel of the Little Colorado River from Grand Falls downstream into the Wupatki Pueblo area and formed Black Falls. The lava barrier caused the accumulation of Recent alluvium which formed broad alluvial flats in the area above Grand Falls. Here the alluvium attains a thickness of more than 250 feet and has overlapped the lower slopes of gravels deposited on an early Wupatki surface. In the Black Falls area the depth of the alluvium is not as great, but near the mouth of Deadman Wash the youngest Wupatki surface is partly concealed by the Recent sediments.

Stage V basalts.--The stage V Sunset Crater and associated flows are too young in age to show extreme association with the regional geomorphic units. These volcanics have blocked the lower end of Bonito Park and have allowed some accumulation of late Recent alluvium. However, this has been only a small amount of the total alluvium because the park is underlain chiefly by the intermediate alluvium. The unique dating of the eruption of Sunset Crater by dendrochronological studies shows the eruption occurring between the growing seasons of A.D. 1064 and 1065 (Smiley, 1958).

Age of Basaltic Flows

The ages of all the flows of stages I-IV, based upon geomorphic dating, range from late Pliocene to the Recent (fig. 8.4). The Black Point surfaces range from late Pliocene to early Pleistocene, and the overlying stage I lavas are considered to be of the same age. The stage IB lavas may have been formed primarily during the late Pliocene, and the stage IA lavas may have been deposited during the early Pleistocene. The Wupatki surfaces have an age range from middle to late Pleistocene. Therefore, the early stage II flows on the early Wupatki surfaces are probably of the middle Pleistocene. The later stage II flows lying on the middle Wupatki surface are middle or late Pleistocene in age, and the stage III flows overlying the youngest Wupatki surfaces are late Pleistocene. The stage IV flows, deposited in valleys formed by post-Wupatki erosion, range from very late Pleistocene to early Recent.

Igneous Rocks of Intermediate Composition

The intermediate volcanic types, Robinson's (1913) second general period of eruption, composed principally of dacite, latite, andesite, and rhyolite, overlie stage I and older basalts in all areas of the San Francisco field. The older latite and dacite of San Francisco Mountain, eruptive stages I to III of the second general period of Robinson (1913), underlie the older alluvium whose major sources of material were these rocks. Part of these flows are believed to have formed more or less contemporaneously with the latest stage I and early stage II basalts because some cobbles, similar to the pyroxine dacite of the peaks, were found on an early Wupatki surface near Wupatki Pueblo. At Flagstaff the prehistoric valley of Rio de Flag, which contains a stage II basaltic flow that is partly buried by the older alluvial materials, was eroded around the thick latite of Observatory Mesa. The latite overlies a basalt that flowed out on the Zuni or an early Black Point surface. These relationships, although only generalized, confirm Robinson's statement that the Observatory Mesa latite belongs to the oldest group of intermediate rock types near the San Francisco Mountain.

Following the first eruptive stage of San Francisco Mountain, streams depositing the older alluvium built up a large alluvial fan to the east and northeast of the mountain. The fan occupied the area of Bonito Park and extended northward to Deadman Wash and was formed probably during much of the interval indicated by Robinson (1913, p. 48) between the eruptions of stages I and II. The andesitic stage V and the early Wisconsin glaciation of Sharp (1942) apparently diverted the drainage between the peaks of San Francisco Mountain from the east to the north nearly to its present position. The late Wisconsin glaciation of Sharp (1942) occurred after this diversion had been effected. The broad alluvial fan was partly dissected and some of the newly formed valleys were filled with stage III basalts. Some of these basalts near Deadman Wash are overlain by dacite and rhyolite from flows flanking O'Leary Peak. The intermediate alluvium, correlative to the early Wisconsin outwash of Sharp (1942), was deposited against the intermediate flows. It was also during this time that the lava of the cone near the northwest side of Bonito Park discussed in the section on stage III basalts was formed in the time interval between the deposition of the older and the intermediate alluvial units.

In summary, the main mass of San Francisco Mountain probably had been formed between the basaltic stages I and II, but the other flows of the mountain and the intermediate flows in the adjacent area may consist of several eruptive stages. The age and physical relationships in the formation of the intermediate-type volcanic rocks of the San Francisco field indicate that they can be divided into several eruptive stages which continued intermittently from possibly early Pleistocene to late Pleistocene (fig. 8.4).

SUNSET BUTTES FLOWS

The west and the east mesas of Sunset Buttes, about 15 miles northeast of Anderson Mesa (fig. 8.1), rise prominently above the adjacent low plains. They are composed of a basaltic caprock overlying steep slopes that are formed on weakly consolidated light-buff sediments and the reddish-purple Chinle Formation. The weakly consolidated sediments, consisting of about 50 feet of sandy silt and silty sand partly cemented by caliche, lie unconformably on the Chinle Formation. These sediments are similar to the upper member of the Bidahochi Formation or younger sediments which preserve the Black Point surfaces. The lavas originated from at least three individual vents associated with cinder cones which are located in the central part of the buttes, one on the east butte and two on the west butte. The vents lie between altitudes of 6,000 and 6,400 feet, and the eruption may have caused a slight doming effect because the flows dip gently to the north and to the south away from the vents.

The altitudes of the lavas and the base of the weakly consolidated sediments indicate that the lavas and sediments were deposited on an early Black Point surface (fig. 8.6B). The cinder cones on the Sunset Buttes are partly dissected, but their general shapes are still outlined. In contrast, the cinder cones associated with lavas of middle Pliocene age in the Hopi Buttes volcanic field to the northeast have been completely removed. This suggests that the flows in the Sunset Buttes area are younger than middle Pliocene because both areas have been subjected to similar erosional conditions. The time of eruption of the Sunset Buttes flows and cones, based upon the geomorphic evidence, is probably late Pliocene or possibly earliest Pleistocene.

MESA REDONDO AREA OF THE WHITE MOUNTAINS FIELD

In the northwestern border region of the White Mountains volcanic field near Taylor and Concho, Arizona (fig. 8.1), there is a broad tableland that is covered by several basaltic flows which lie approximately at 6,000 feet above sea level. The lavas overlie unconsolidated sediments consisting of crossbedded gravel, flat-bedded silty sand and silt of possible lake origin, and some caliche. Locally, as in a roadcut a mile east of Shumway, the lava lies on the Moenkopi Formation, and near Mesa Redondo, 10 miles west of Concho, the basalt was deposited on the Chinle Formation. Mesa Redondo is the only landmark that rises above the ancient lava-covered plain. On its summit there are two basaltic flows separated by a gravel bed which are remnants of an earlier volcanic stage in the White Mountains field.

The unconsolidated sediments underlying the basaltic flows of the tableland represent a partly graded fluvial environment in which the streams were constantly meandering across flood plains. These streams deposited gravel in channels and finer material in quiet-water areas. About 100 feet of gravel is exposed 2 miles east of Concho in a gravel pit along U.S. Highway 260, and about 75 feet of sandy and gravelly material is exposed in small gravel-capped buttes between Taylor and Shumway. In other areas the deposits are less than 50 feet thick.

The ancient plain, whose level is preserved by lavas, formed a low rolling surface. Near Taylor and Concho the surface contained north-trending valleys which in the Mesa Redondo area were separated by a broad ridge of older rocks. From Concho the plain can be traced northeastward to the Little Colorado River where it joins the Black Point surfaces. The lavas and sediments in the Concho and Taylor areas are interpreted as equivalent deposits laid down in separate valleys which are part of the Black Point surfaces.

Near Taylor part of a camel found in unconsolidated sand beneath the gravel by C. A. Repenning and J. F. Lance was identified by Lance (oral communication, 1955) as being of Blancan age. The probable age of these gravels is therefore late Pliocene or early Pleistocene, and the overlying lavas and the Black Point surfaces are considered to be of about the same age.

FLOW ALONG THE ZUNI RIVER

A small flow, not connected to any of the major volcanic centers in the southern portion of the Colorado Plateau, originates near the Zuni River at the Arizona-New Mexico State line (fig. 8.1). Here the course of the Zuni River occupies a canyon-valley carved below the Black Point surfaces which bevel the Bidahochi Formation. The valley is walled by steep bluffs composed of the Dakota Sandstone, and the valley floor is cut on the Chinle Formation. From the point of origin at the base of a cinder cone, lava spread fanlike out to the edge of the Black Point plain, and then into the prehistoric valley of the Zuni River, down which it flowed 25 miles to the Little Colorado River. The lava, by blocking the valley of the Zuni River, caused the accumulation of 50 to 75 feet of alluvial material in the upstream area, and remnants of this deposit form low terraces as far east as Zuni Pueblo, New Mexico. Fossils in these sediments occurring 2 miles south of Zuni Pueblo can only be dated as post-Blancan or Pleistocene in age. In the area of confluence of the Little Colorado and Zuni Rivers the Wupatki surfaces were cut in a valley below the base of this lava flow. These geomorphic relationships restrict the deposition of the lava flow to the general period of downcutting which occurred during the middle Pleistocene between the formation of the Black Point and Wupatki surfaces.

CONCLUSION

In the San Francisco field the relationships of the several volcanic flows to the erosion surfaces and alluvial deposition show the buildup of the field by a sequence of events which can be correlated throughout the volcanic field. Here, a framework containing the geologic history of the area can be fitted into a regional geomorphic history of the Little Colorado River. Preliminary observations in the northern part of the White Mountains volcanic field show similar associations of the volcanics to the erosion surfaces. Thus, based on geomorphic relationships, it is believed that all flows of the White Mountains field could be correlated with the flows of the San Francisco field, Hopi Buttes, and other volcanic areas in the Little Colorado River drainage area.

The reconstruction of the erosion surfaces at the time of eruption of the Sunset Buttes flows shows an association of the flows with the regional Black Point surfaces but no relationships to the older Zuni surface which underlies the lavas on Anderson Mesa and the Hopi Buttes and to the younger Wupatki surfaces. The placing in time of a volcanic event like the flow along the Zuni River that had not been deposited on either the Black Point or Wupatki surfaces can be established as occurring between these two periods of planations.

The four types of volcanic areas discussed in this report suggest that, where no other dating controls exist, it is feasible to use the regional erosion surfaces developed along the Little Colorado River as an aid in the determination of the age and the correlation of many volcanic areas of flows in the southern part of the Colorado Plateau.