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GEOLOGY OF THE SAN FRANCISCO PEAKS NORTHERN ARIZONA

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FINAL REPORT

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13. ABSTRACT

This report summarizes an investigation to study and map in detail the geology of the San Francisco Peaks. The investigation includes (1) Bedrock geology of the volcanic rocks and ash and (2) surficial geology, the study of the unconsolidated fluvial, glacial, periglacial and mass movement sediments derived from the San Francisco Peaks volcanics. The study of the consolidated and unconsolidated rocks provides the basis for inferences on the Quaternary and Holocene geologic events of the area as well as the environmental geology of this mountain region.

14. KEY WORDS

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FINAL REPORT

GEOLOGY OF THE SAN FRANCISCO PEAKS OF NORTHERN ARIZONA

by

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and

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June 30, 1973

The present report has been prepared to summarize a major research project inaugurated in 1966 by Troy L. Péwé and Randall G. Updike in the San Francisco Peaks area of northern Arizona.

Contents

INTRODUCTORY STATEMENT

The San Francisco Peaks occupy a central position in the San Francisco Volcanic Field. They are the eroded remnants of a composite volcanic cone rising to elevations in excess of 12,600 feet. These peaks, together with several lesser cones and domes, form an imposing mountain mass visible throughout much of the southern part of the Colorado Plateau. The variability of the lavas and their modes of eruption, together with the interrelated sequence of sedimentary rock units of fluvial, glacial, periglacial, mass movement, and laharic origins makes this a distinctive region of late Cenozoic geology.

SCOPE OF THE PROJECT

The prime objective of this investigation is to study and map in detail the geology of the San Francisco Peaks. The project consists of two phases: (1) Bedrock geology of the volcanic rocks, and ash, and (2) surficial geology, the study of the unconsolidated fluvial, glacial, periglacial, and mass movement sediments derived from the San Francisco Peaks volcanics. The study of the consolidated and unconsolidated rocks provides the basis for inferences on the Quaternary and Holocene geologic events of the area as well as the environmental geology of this mountain region.

LOGISTIC SUPPORT

The principal investigators have been assisted by several groups. To the Grantee, the U.S. Army Research Office, Durham, North Carolina, provided two grants, Grant No. DA-ARO-D-31-124-G928 for the fiscal year 1967-68, and Grant No. DA-ARO-D-31-124-G1027 for the period from 1968 to 1970. To Randall Updike, the Museum of Northern Arizona, Flagstaff, Arizona, has given two grants for the years 1967 and 1968. Other funded support to the Grantee came from the National Park Service, Washington, D.C., for drilling in 1968, and from the Research Corporation, Burlingame, California, for work in 1971.

Arizona State University, Tempe, Arizona, and the Museum of Northern Arizona have also provided much needed logistical support in the form of vehicles, laboratory and field equipment, office and storage space, and field and laboratory assistants.

METHODS OF INVESTIGATION

As of this date the basic field mapping phase of the project has been completed. An area of 210 square miles has been mapped at a scale of 1:24,000 utilizing the Humphrey's Peak, O'Leary Peak, White Horse Hills, Sunset Crater West, and Flagstaff West U.S. Geological Survey Quadrangle maps (fig. 1). Parts of the area were mapped at a much larger scale including the Interior Valley at 1:12,000 (fig. 2) and the Sugarloaf Mountain area at 1:8160 (fig. 3). The mapped region is bounded by the south edges of the Humphreys Peak and Sunset Crater West Quadrangles, except for a one-mile wide strip on the north side of the Flagstaff West Quadrangle. The area is bounded on the west by the edges of the White Horse Hills and Humphreys Peak Quadrangles and on the east by U.S. Highway 89, the Sunset Crater lavas, and the O'Leary Peak lavas. Deadman Wash and Kendrick Park form a natural limit to the north (fig. 1). The mapping involved five summer field seasons as well as several shorter visits in the fall and spring of each year since 1966.

Previous to our study the only major geologic work done on the San Francisco Peaks proper was by H. H. Robinson in 1913, on the volcanic rocks. Other papers were published by Colton (1967) and Sharp (1942) as well as a few additional papers referring in part to the San Francisco Peaks themselves.

As a result of our project, nearly 65 distinct geologic units have been mapped in the described area. This does not include subdivisions of the basaltic lavas and cones, nor of various ash falls. Our work on the volcanic sequence began in 1966 with the assistance of Dr. C. B. Moore

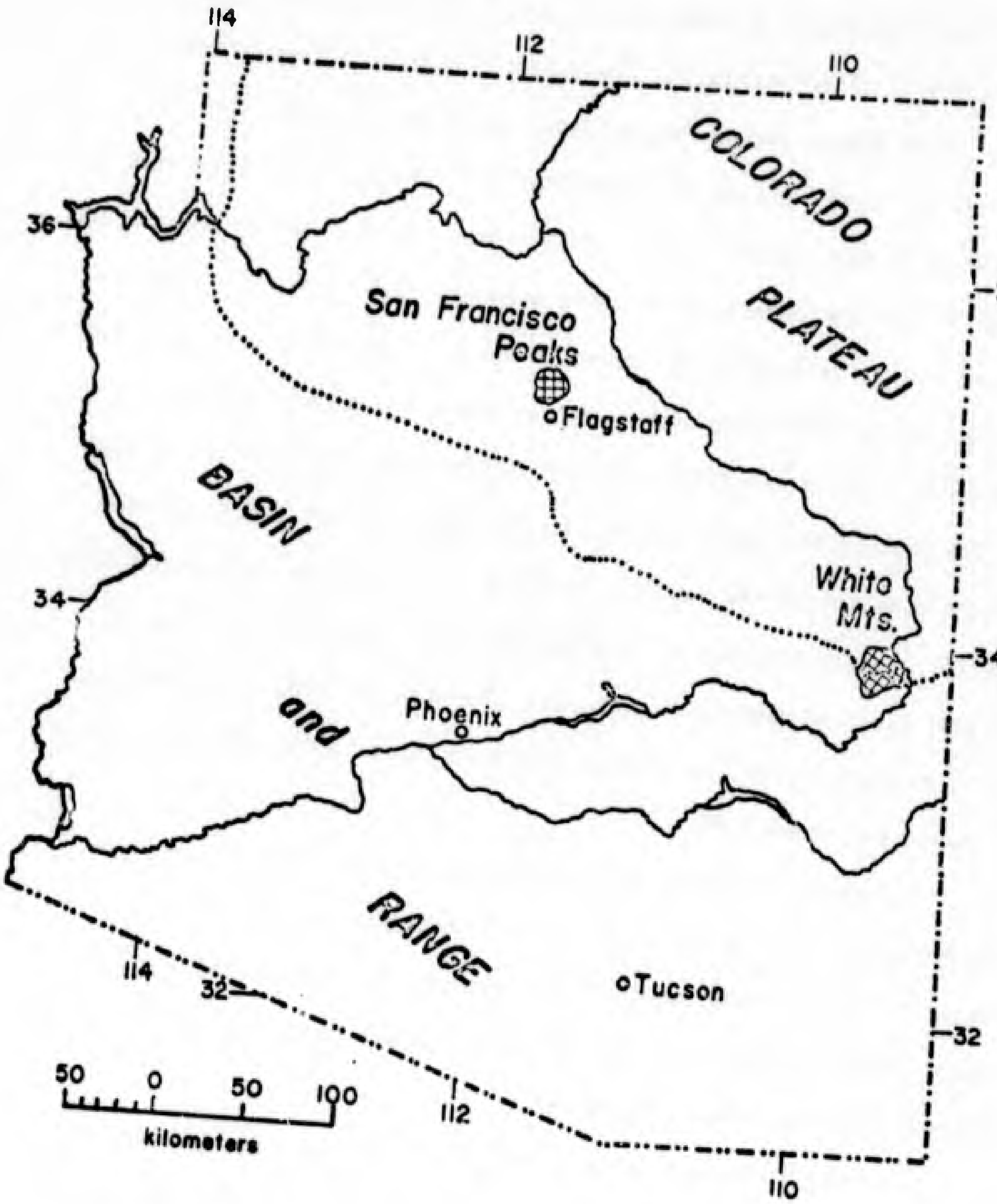


Figure 1. - Location of the San Francisco Peaks and the White Mountains, the two areas of late Quaternary alpine glaciations in Arizona.

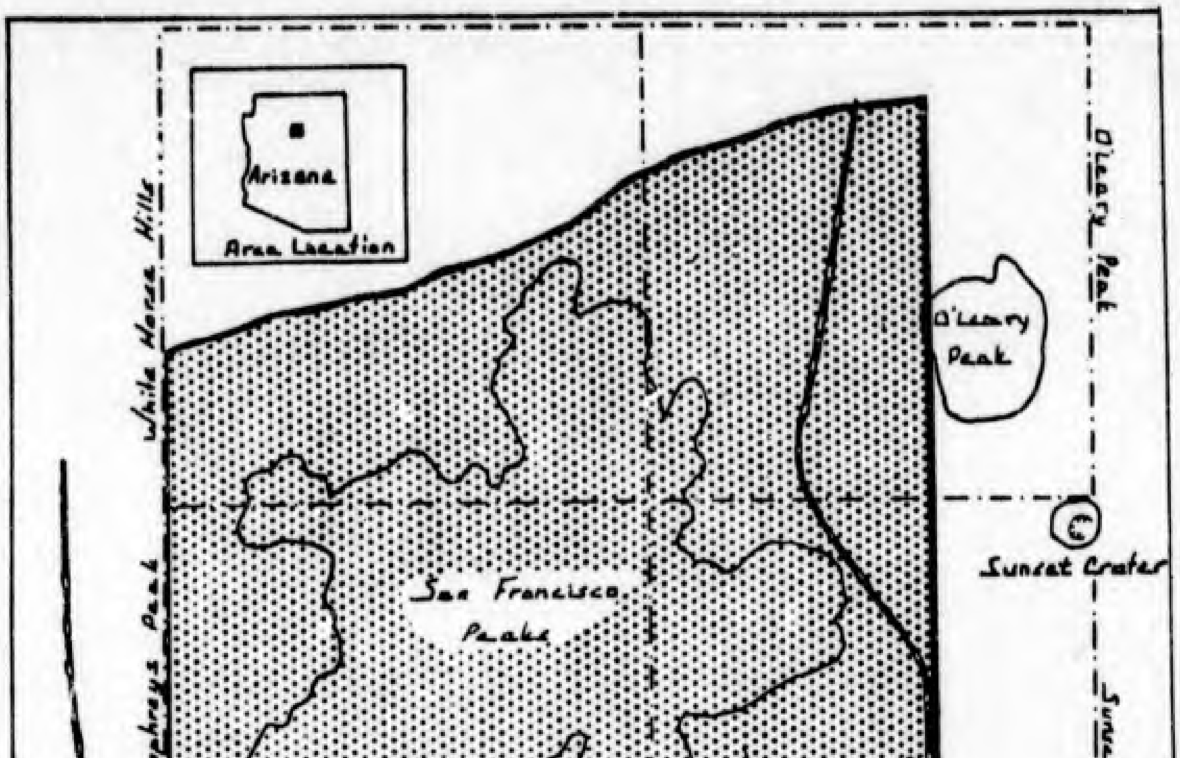
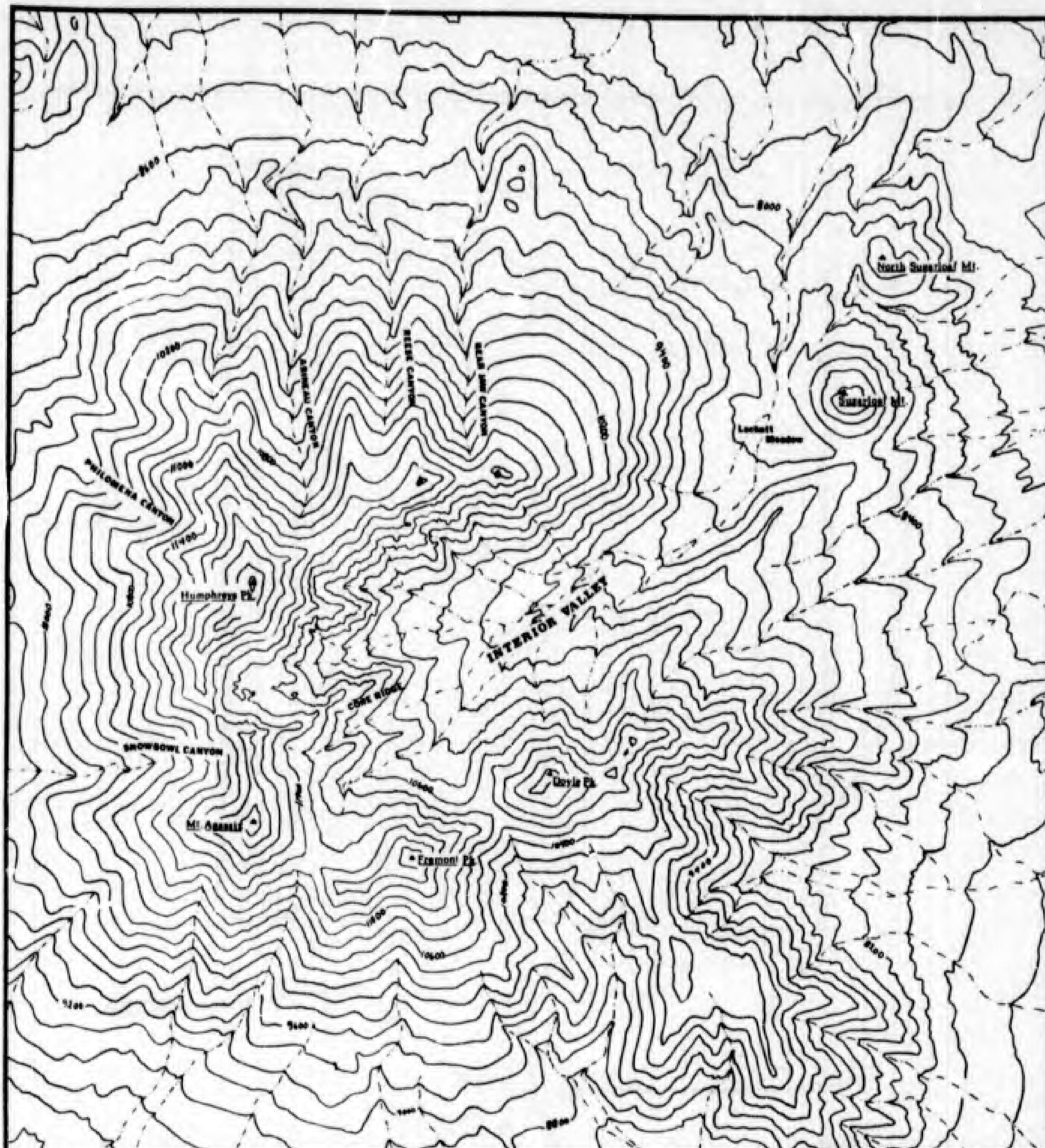


Figure 2. - Index map of the San Francisco Peaks, Arizona showing location of the U. S. Geological Survey topographic map quadrangles, major physiographic features, and area mapped at the scale of 1:24,000.



TOPOGRAPHY OF THE SAN FRANCISCO PEAKS, AZ.

Contour Interval 200 Feet

0 1 2 Miles
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Modified from parts of U.S. Geological Survey Base Maps: Humphreys Peak, O'Leary Peak, Sunset Crater West, and White Horse Hills Quadrangles

Figure 3.

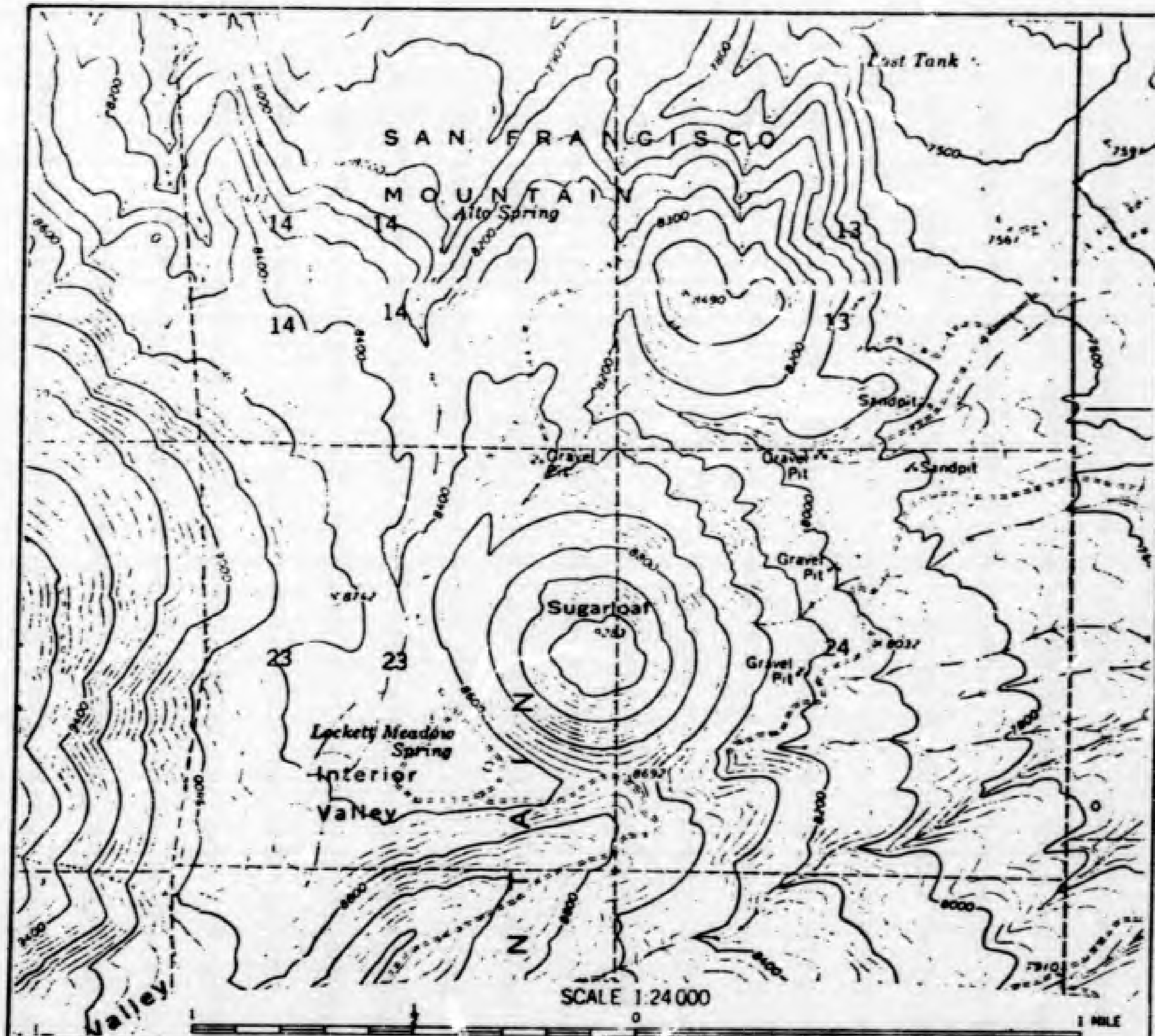

Figure 4. - Topographic map of the Lockett Meadow-Sugarloaf Mountain area of the San Francisco Peaks. Bedrock, volcanic ash, glacial, fluvial, mudflow, and periglacial deposits in this area mapped at a scale 1:8160.

and Dr. M. F. Sheridan.

Carleton Moore, Arizona State University, and Edmond Deal, Arizona State University, conducted a detailed mapping and petrologic study of the upper Interior Valley and Core Ridge Areas, during part of the summer of 1967 (Deal, 1969). They also did considerable geochemical work on the Interior Valley lavas and their contributions have been incorporated into the present project. In addition, Dr. Moore has initiated a geochemical survey of the dacite lavas of Mount Elden.

In addition to mapping the numerous volcanic units and establishing a relative chronology, absolute dating of eruptions has been pursued. Dr. Allan Cox, Stanford University, conducted a reconnaissance paleomagnetic study on some of the peripheral silicic and basaltic lavas. Dr. Paul Damon, Geochronology Laboratory, University of Arizona, consulted in the field and collected samples for radiometric dating. Samples of particular lavas have been submitted by us to Geochron Laboratories, Cambridge, Massachussetts, for potassium-argon dating.

Detailed study of silicic tephra related to the Sugarloaf Mountain eruption was conducted by Dr. Sheridan, Updike, and Péwé. Pyroclastics from silicic eruptions in the mapped area were examined by Dr. G. W. Smith and John Westgate, University of Alberta, for this project using the electron microprobe on glass shards. These data were utilized in the correlation of isolated pyroclastic deposits with eruptive centers.

More than 1500 bedrock samples have been collected from the area. Selections were made of typical or key specimens and more than 160 thin sections were prepared. Petrographic analyses of these sections is nearly complete including modal analysis, orientation studies. One hundred samples have been processed for silica content using the refractive index method. More than 20 wet chemical analyses for silica, sodium and potassium have been performed and additional 55 samples are now processed by atomic absorption analysis. The primary goal of this phase of our study is to specifically characterize each of the eruptions within the area. We are also utilizing the previously published chemical and radiometric data obtained for San Francisco Peak lavas and for those of surrounding areas.

Dr. Dietrich Barsch, University of Basel, Switzerland, Dr. John Blagborough, Albequerque, New Mexico, and R. D. Reger, Kenai, Alaska, consulted on glacial and periglacial features.

Related to the Pleistocene and Holocene climate of the area, a subproject was conducted with Dr. George Batchelder, San Francisco State University, in which several cores were taken from lake basins for the purpose of pollen stratigraphic analyses and carbon-14 dating. The samples from these cores are presently being processed. Another study that was partially supported by the project was one in which the pollen and molluscan fauna of the nearby Winona and Meteor Crater basins were collected and analyzed by Reger and Batchelder of Arizona State University.

With the assistance of Ed McGavock of the Water Resources Branch of the U. S. Geological Survey, Flagstaff, Earl Komie, Bureau of Reclamation, Phoenix, and William Breed, Museum of Northern Arizona, we have been able to accumulate abundant sub-surface data on the Interior Valley and surrounding lowlands of the peaks. These include more than 30 well logs, seismic surveys, and resistivity surveys as well as hydrologic data on the successful wells drilled. In addition, with funding by the National Park Service, we were able to drill four 8-inch diameter cased bore holes at critical localities to establish stratigraphic relationships between sedimentary units and basaltic flows and cinder cones (Péwé and Updike, 1970). Nearly one hundred mechanical analyses were conducted on typical samples of alluvium, glacial till, and pyroclastic deposits. These were conducted with the assistance of Drs. C. F. Royse and M . F. Sheridan of the A.S.U. faculty.

During the fall of 1970 the fifteenth annual field conference of the Rocky Mountain Section of the Friends of the Pleistocene was held in the San Francisco Peaks, under our leadership. This provided an opportunity for approximately 70 Pleistocene scientists from the United States and Canada to review our findings as of that date. Several new concepts came out of the discussions at those meetings.

In addition to the specific persons named above, other individuals associated with the following organizations have lended consultation and assistance either in the field or office regarding the project: Arizona State University, University of Arizona, Northern Arizona University, U. S. Geological Survey (Surface Planetary Exploration Branch, Astrogeologic Studies Branch, Water Resources Branch), Museum of Northern Arizona, University of Oregon, and the Bureau of Reclamation.

PROJECT RESULTS

The San Francisco Peaks volcanic field occupies a broad area of the southwestern part of the Colorado Plateau. Because the sedimentary and volcanic units associated with this field are quite thick, the pre-Cenozoic sequence is concealed throughout most of the region. However, information on these older rocks has been derived from exposures directly adjacent to the mapped area (Walnut Canyon, Sycamore Canyon, Oak Creek Canyon and the Valley of the Little Colorado River), as well as around local laccolithic intrusions where the older rocks have been uplifted. Well logs for drill holes which have penetrated into the underlying units have also been utilized. The sequence thus recognized includes schists, gneisses, and granite (Precambrian), Redwall Limestone (Mississippian), Supai Formation (Permian-Pennsylvanian), Coconino Sandstone (Permian), Toroweap Formation (Permian), Kaibab Limestone (Permian), and Moenkopi Formation (Triassic).

Structurally, the region may be characterized by flat-lying to gently-dipping Paleozoic and Mesozoic strata resting unconformably on the Precambrian complex. The central part of the volcanic field occurs in the crestal area of a large anticlinal feature which consists of the Kaibab uplifts, the Mormon Mountain anticline, and part of the broad Mogollon slope. The axis trends northwestward from the east side of the Verde Valley to the area west of the San Francisco Peaks, and thence north to the Grand Canyon. Regional dip is to the east and northeast toward Black Mesa Basin. Faulting ranges in magnitude from a few centimeters to more than 50 meters and are primarily high-angle normal types. The position of the faults as well as joint sets in the pre-Cenozoic rocks have controlled the position of volcanic vents throughout the field.

Cenozoic Volcanism

For at least the past six million years the San Francisco Peaks region has been an area of extensive volcanic activity up through historic times. Lavas of two general categories have been extruded, basaltic and intermediate to silicic, the two being essentially mutually exclusive. The basaltic eruptions are found as relatively thin, but extensive, flood types covering hundreds of square kilometers and often several are superposed on each other. Also, the basalts have erupted as pyroclastics forming cinder cones, usually as single, short duration events. In contrast, the intermediate to silicic lavas are more limited in aerial extent but attain great thicknesses. Generally, these lavas occur as multiple extrusions to build composite volcanoes, the most massive being the San Francisco Peaks themselves, with other examples being O'Leary Peak, Sitgreaves Peak, Kendrick Peak, and Bill Williams Mountain. The present project is primarily concerned with the San Francisco Peaks proper and eruptions directly adjacent to the main volcano.

At least four previous investigators studied the local volcanic history: Robinson (1913), Colton (1967), Childs (1948), and Cooley (1962), although none treated the area with the depth or variety of approaches possible at present. Although each of these authors developed a series of eruptive periods or stages for eruptions of lavas the present have recognized that such schemes are artificial and the production of magma has been essentially a continuum since late Tertiary times. Future investigators may well find a variation trend within the basaltic lavas with respect to time, but presently such a trend is not apparant. Two observations have been made to be generally true for basalts of the field: (1) there is a general trend toward younger eruptions from south to north in the field, and (2) pyroclastic eruptions (cinder cones and explosion craters) are much more prevalent among the younger eruptions.

Within the project area basalts range from pre-San Francisco Peaks age to 900 years B.P. The older basalts appear to have formed a platform upon which the intermediate to silicic lavas were extruded. Later basalt eruptions, i.e., those contemporaneous with or post-dating the main volcano were at least 2-3 km distant from the base of the strato-volcano. These later eruptions are characterized as limited quiescent flows and numerous cinder cones which often occur in clusters, often showing strong lineation apparantly caused by local structural controls.

The basalts are typical calc-alkaline olivine basalts having abundant olivine, entirely lacking quartz, and having very little or no potash feldspar. This contrasts sharply with the trachybasalts typical of the White Mountain volcanic field to the east and the basaltic volcanic fields south of the Colorado Plateau in Arizona. Table 1 contains representative chemical analyses of the various lavas discussed in this report, including the olivine basalt.

Table 1. Representative chemical analyses of San Francisco Peaks lavas, Arizona.

Rock type Sample No.	Basalt 155A	L.Andesite 52A	L.Dacite 187A	Schultz rhyod. 7A	Bio.Hnd.Dacite 223A	Rieb.Rhyolite 23B
Oxides						
SiO_2	48.81	54.90	60.15	64.47	64.60	73.08
TiO_2	1.56	0.96	0.77	0.38	0.69	0.52
Al_2O_3	16.17	18.78	17.73	16.83	17.64	13.67
Fe_2O_3 FeO	10.10	8.78	7.07	4.90	4.25	2.47
MnO	0.19	0.16	0.13	0.14	0.09	0.05
MgO	6.78	3.10	1.48	0.35	0.47	0.00
CaO	13.20	7.56	3.38	2.57	3.20	0.00
Na_2O	3.38	3.76	5.00	5.51	4.62	5.24
K_2O	0.00	1.32	2.62	3.62	3.16	2.15

Table 1. (cont.) Representative chemical analyses of San Francisco Peaks lavas, Arizona.

Rock type Sample No.	U.Andesite 178A	U.Dacite 71A	Wh.Horse Rhyol. 156B	Elden Dacite 97A	Dry Lake Dacite 16A
Oxides					
SiO_2	57.74	64.52	72.35	62.16	61.2[illegible]
TiO_2	0.98	0.37	0.32	0.46	0.52
Al_2O	19.06	17.01	13.63	17.49	17.38
Fe_2O_3 FeO	5.36	[illegible]	1.13	5.2[illegible]	.74
MnO	0.13	.13	0.01	0.12	0.0[illegible]
MgO	1.68	.84	0.10	0.85	1.23
CaO	5.79	2.[illegible]	0.87	2.93	[illegible]
Na_2O	4.58	5.18	4.53	4.73	4.99
K_2O	1.83	3.15	4.11	3.34	3.01

The initial eruption of lavas from the San Francisco Peak volcano was that of multiple andesitic extrusion. The aerial extent of this series of eruptions was the greatest of any stage for the mountains. Exposure is primarily restricted to the Interior Valley (the caldera of the volcano), the distal end of the flows, and tilted sequences in the White Horse Hills and Elden Mountain laccoliths. Up to a thickness of 535 m of the pyroxene andesite is exposed in canyon walls of the Interior Valley, consisting of massive volcanic breccia, thin lava flows, and interbedded ash and lapilli. Later eruptions of the volcano were also andesitic and for this reason this initial eruptive phase is referred to as the lower pyroxene andesite, having been intruded by dikes of younger dacite and andesite lavas. In some areas (e.g., the Core Ridge, a central ridge 1.5 km in length extending northeast across the southwestern half of the Interior Valley) the andesite occurred as a shallow intrusive of the presumed vent area.

Because this was the earliest stage of development of the volcano topographic relief was lower than at a later time. However, the evidence indicates that multiple lower andesite flows extended further from the control vent area than any subsequent eruption. This fact, together with the relatively low relief of the flow front scarps and high degree of surface vesiculation suggest a relatively low viscosity for this lava. It appears that the early volcano was first built up of volcanic breccia accumulating around the vent area, followed by quiescent lava flows with less pyroclastic activity. These flows, which originated from a central vent and radial dike swarm, extended primarily southwest, southeast, and east of the vent area, and, to a lesser extent, toward the northwest.

The result was an asymmetrical cone with flows built up primarily to the south half of the present volcano.

Chemical analyses and silica analyses showed the rock to be a typical pyroxene andesite with a silica content ranging from 53 to 59%, but with a systematic variation from one stratigraphic position to another (see Table 1).

Unconformably overlying the lower pyroxene andesite is the lower hypersthene dacite. This dacite has the greatest total volume of any lava extruded from the San Francisco Peaks center. The lava is exposed on virtually all flanks of the mountain as well as the inner walls of the Interior Valley. Often at the base of the dacite a glassy horizon lies in contact with the underlying andesite. The irregular contact between the two lavas indicates an extensive period of erosion of the andesite prior to the eruption of the dacite.

No primary vent was located for the massive eruption of the dacite magma. A series of dacite dikes up to 15 m in width cross-cut the Interior Valley (including the Core Ridge) and appear to be massive feeder dikes. Thus, it is probable that the dacite was extruded through a system of fissure eruptions, through the earlier andesite. No exposures of pyroclastic material were found associated with the dacite favoring quiescent extrusion from linear vents. There is one exception to this generalization, that being on the south side of the volcano in the Weatherford Canyon area. Weatherford Canyon is a over-enlarged, amphitheater-shaped canyon which appears to have formed as an explosive, flank eruption during the lower dacite phase. Such an explosive eruption should have produced an extensive pyroclastic deposit of essentially dacitic composition and such a unit is present, referred to as the Orion member of the Sinagua Formation. This unit is entirely composed of coarse angular dacite blocks up to 15 m in diameter contained in an ash matrix also of the same composition. The stratigraphic and physiographic relationships with other lava flows indicates that the cratering and ash expulsion must be contemporaneous with the lower dacite phase. The character of the Orion member negates either a mudflow or traditional Nuée ardente origin but the depositional environment must have been (A) spontaneous in time, (B) relatively high temperature as indicated by high glass shard content in the ash, and (C) high viscosity to transport large blocks several kilometers. The lower dacite lava is a prophyry containing phenocrysts of plagioclase, hypersthene, augite, hornblende, and magnetite. Table 1 gives a representative chemical analysis; silica percentages range from 59 to 66% with systematic variation about the volcano.

Following the lower dacite eruptions, three distinct, localized eruptive phases occurred. Successively these were: rhyodacite, biotite-hornblende dacite, and riebeckite rhyolite. The rhyodacite occurs on the on the southeastern flank of the main volcano as a parasitic cone eruption, formed on the lower hypersthene dacite. The primary topographic feature of these lavas is Schultz Peak, a flat-topped mountain rising from about 8000 feet elevation to just over 10,000 feet elevation. A second, smaller cone formed directly to the north, has lesser aerial extent but reaches 10,569 feet elevation. Both vent areas are marked by a series of agglomeratic dikes which radiate from the presumed final vent area. These dikes are located in similar eliptical canyons which may have been volcanic craters. Silica content is higher for this lava than for the lower hypersthene dacite, but petrographically, the two lavas are quite similar.

The San Franciscan lava of most limited extent is a biotite-horneblende dacite which post-dates the lower hypersthene dacite and pre-dates the upper pyroxene andesite. The rock type was found in only two areas, first as radial dikes within the Interior Valley, and secondly as an isolated mass between two peaks along the northern crater rim. This second locality may well be an intrusive plug due to its eliptical configuration, relationship to older rocks, and lack of feeder dikes typical of surrounding lava flows. This dacite is a very light grey-color porphyry distinguishable from several kilometers away because of its contrast with the surrounding darker lavas. Chemically, the dacite is similar to other San Franciscan dacite lavas (Table 1).

The most distinctive lava of the San Francisco Peaks is the riebeckite rhyolite, a high silica rock (72-73%, see Table 1), containing the amphibole riebeckite. Distribution is limited to three areas in the southern part of the mountains. as flows and a shallow intrusive (at the vent). The rock varies from holocrystalline to autoclastic breccia to vitrophyre and obsidian. At one locality the rhyolite rests directly on the lower hypersthene dacite and is intruded by dikes of the upper pyroxene andesite. The rock is quite important due to its distinctive appearance in hand specimens (usually light blue with large Sanidine phenocrysts) and to its limited extent, which gives it value as a provenance indicator when found as clasts in sedimentary units. A potassium-argon radiometric date (by Paul Damon, University of Arizona), provides an age of about 900,000 years for this lava.

With the exception of the northeastern part of the San Francisco Peaks, another andesite, the upper pyroxene andesite, is the youngest lava to have been erupted. The unit consists of lavas and shallow intrusives within the Interior Valley and flows capping about 65% of the outer slopes of the peaks proper. Commonly, this eruption is represented by thick sequences (up to 130 m thick) of alternating thin flows and pyroclastics (each averaging 2 to 5m thick). This andesite is found stratigraphically overlying every previously erupted lava. The upper andesite is distinctly different in hand specimen from the lower andesite, in both texture and color. Although the chemistry of the two andesites is similar (Table 1) and range of silica content is nearly identical, the average silica content is slightly higher in the upper andesite. In the opinion of the authors the sequence from lower andesite through riebeckite rhyolite represents a normal differentiation sequence of an andesitic magma and that with the eruption of the second andesite a second differentiation sequence begins. It is notable that in both sequences the intermediate andesite and dacite lavas are several times greater in volume than the later, more silicic differentiates (rhyodacite and rhyolite).

The upper hypersthene dacite occurs as a single massive flow on the eastern slope of the peaks. This is the single most extensive and thickest flow to be extruded from the volcano and appears to have been a flank eruption from a vent high on the eastern side of the main cone. Axial length of the flow is 5.4 km and maximum relief at front scarp is about 136 m. This dacite is similar to the lower hypersthene dacite being a porphyry containing phenocrysts of plagioclase and a silica content of 65% (Table /), although this lava post-dates the lower dacite as well as the upper pyroxene and the Schultz Peak rhyodacite.

In the northeastern part of the main volcano two distinct latite flows were extruded as a final eruptive phase, occurring also as flank eruptions. Both lavas were extruded from approximately the same vent and followed the same flow path to the northeast. Both flows are distinctive in having a glassy ground mass, and have similar mineralogy and textures, although the lower flow has a silica content of 62% and the upper flow has a content of 59% silica.

The three major phases of flank eruptions, i.e., the Schultz Peak rhyodacite, the upper hypersthene dacite, and the latites occurred on the eastern side of the volcano, indicating that this is an area of structural weakness to allow venting. This interpretation is supported by the lack of a crater rim in the northeast segment of the cone due apparently to collapse. Further evidence is provided by two silicic domal eruptions in the northeast sector of the volcano: the North Sugarloaf Mountain rhyodacite and the Sugarloaf Mountain rhyolite. The rhyodacite is 2.7 million years old (potassium-argon date by Paul Damon), formed as an exogeneous dome about 320 m high. Silica content is 68% and texture is aphanitic except for euhedral phenocrysts of biotite.

In contrast, the Sugarloaf rhyolite is 550 thousand years or less in age (radiometric dates of 530,000 and 214,000 years for pyroclastic and lava respectively). The eruption of this rhyolite (silica percentage of 72%) occurred in two stages. As the magma intruded near to the surface it encountered large volumes of groundwater which were being transported in weakly consolidated aquifers. As the magma contacted this groundwater, violent explosive eruptions ensued, building up a tephra ring composed of rhyolitic ash and lapilli mixed with fragments of country rock (this is termed a phreatomagmatic or base surge eruption). As the magma continued to be emplaced, quiescent eruption of lava ensued and the dome was built up in the center of the tephra cone.

Studies were also made of intermediate to silicic eruptive centers peripheral to the main volcano. The White Horse Hills, about 5 km northwest of the San Francisco Peak caldera, are the eroded remnants of a rhyolitic laccolith in which a sequence of units ranging from the Redwall Limestone, through the Supai Formation, Coconino Sandstone, Kaibab Limestone, early basalt flow, lower pyroxene andesite, and lower hypersthene dacite have been faulted and tilted symmetrically around the central intrusion. Considerable time was involved in mapping the complex structure and contact metamorphism of this laccolith.

The Elden Mountain area southeast of the San Francisco Peaks was another structurally complex area in which a dacite magma faulted and tilted a similar sequence of strata, but which, in a later phase, was extrusive to form an exogeneous dome. In this case, two major fault blocks were produced on either side of a linear intrusion and the riebeckite rhyolite and upper pyroxene andesite were included in the deformation.

Directly adjacent to the west of (and post-dating) the Elden Mountain complex is the Dry Lake Hills complex. These hills are unique in that they consist of a series of six exogeneous dacite domes and cones erupted in close proximity (both physically and in time) on a base of andesite and dacite flows. The chemistry of each volcano is essentially identical and overlie, in part, the Elden Mountain dacite.

Second only to the volcanic pile itself in aerial extent, a series of sedimentary units having a radial-fan morphology encircle the San Francisco Peaks and adjacent eruptive centers. These fans consist of weakly consolidated to unconsolidated, poorly-sorted sediments derived from the volcanic rocks and older sedimentary basement rocks. Transportation and deposition of these sediments was restricted to the intermediate gradient, lower slopes of the peaks themselves. Although the composition of these fans is quite variable, gross physical characteristics are uniform enough so that all are collectively referred to as the Sinagua Formation (Updike, 1969; Updike and Péwé, 1970a). Work subsequent to first introduction of the formational name has required subdivision into six members of distinctive origins and characteristics: Orion, Schultz Creek, Espil, Little Elden, Hochderfer, and White Horse members.

The formation has been mapped over an area of approximately 110 square km. It is typically a clastic sedimentary unit consisting of sediment ranging from clay-sized particles to boulders in excess of 3 m in diameter. It could be termed either a silty-bouldery gravel, paraconglomerate, or weakly indurated fanglomerate. On the undissected surfaces of the various fans boulders are commonly observed in various stages of burial or exhumation. Some of the largest of these protruding boulders are greater than 5 m. maximum exposed diameter. The sediments of the formation are everywhere poorly sorted, and poorly stratified to unstratified. Gravel-sized and coarser fragments are quite angular compared to adjacent stream gravels. The formation, in some areas, must be at least 50 m. thick as indicated by deep valley dissection, broad, fan-shaped extent, and partial to complete burial of older lava flows.

Origin varies among the members. The Orion and Schultz Creek members are directly related to volcanism. The Orion member, as mentioned earlier, is a product of viscous pyroclastic eruption (perhaps a lahar) of the lower hypesthene dacite lava from a lateral vent in the Weatherford Canyon area. The Schultz Creek member is younger than the Orion member, having been produced during the andesite phase of eruption of the Dry Lake Hills. This member was a small-scale lahar (or volcanic breccia) which flowed northward from the Dry Lake Hills, onto the Orion member.

In contrast, the Espil, Little Elden, Hochderfer and White Horse members are essentially sedimentary units related to subaqueous and/or visco-elastic mediums of transport (fluvial and/or mudflow). The members are differentiated on the basis of composition and morphology. The Espil member is the most extensive member forming the series of fans around the perimeter of the main volcanic pile. Eight major fans were formed, each being composed of fragments of the various volcanic units of the San Francisco volcano. Variation of rock types occurs from fan to fan based upon the variety of rock types exposed in the source area.

The Little Elden member consists of fans derived from the Elden Mountain laccolith/dome complex. A mixture of Elden dacite and Paleozoic sedimentary rocks has resulted, with erosion producing an extensive dendritic drainage pattern. The Hochderfer member is related to a peripheral volcanic complex northwest of the San Francisco Peaks. Here, a central rhyodacite volcano is encircled by basaltic cinder cones which have provided sediment containing the two lithologies, and which occurs as steep-gradient fans extending into the project area. The White Horse member has been produced by erosion processes in the White Horse laccolith complex. Fans consisting of clasts from the San Francisco lavas, plus basalts, the White Horse Hills rhyolite, and the upturned Paleozoic sedimentary rocks, radiate out over older basalt and intermediate lava flows as well as the Espil member.

Age of the members is still being ascertained. Present data indicates that the Espil member must date between 1 million and 500,000 years B.P. based on the presence of fragments of the riebeckite rhyolite and absence of the Sugarloaf rhyolite in the member. The Orion and Schultz Creek members must be contemporaneous with the associated periods of volcanism. The other members have been bracketed between various volcanic eruptions but absolute age dates are presently unobtained. It appears that in all cases the various members have been stable and subjected to erosion since early Holocene times, and, in part inactive since late Pleistocene times.

Three major glacial advances occurred during late Pleistocene time in the Interior Valley and the canyons on the outer slopes of the San Francisco Peaks. Well-defined cirques, U-shaped valleys, side-glacial channels, and unstratified deposits which can only be interpreted as glacial tills confirm the glaciations. In addition, broad outwash plains occur beyond the morainal topography.

The most extensive and oldest glacial advance recognized is delimited by glacial deposits and erosional topography in the Sugarloaf Mountain area (see fig. 5) Till of this glaciation we've termed the Lockett Meadow Glaciation, was first noted by Sharp (Illinoian Glaciation, 1942) and later by Péwé and Updike (Sugarloaf Glaciation, 1970b).

During this period a composite valley glacier flowed from seven cirques to a maximum extent of about 6.25 km. and thickness of 200 m. Morainal topography is preserved, although deeply dissected by erosion (Table 2, Fig. 5). Moraines of this age occur in the saddle between an andesite ridge bounding the Interior Valley and Sugarloaf Mountain. These moraines terminate 0.5 km. beyond the saddle to the east in a series of nested arcuate terminal moraines. On the south side of the Interior Valley till has been plastered against an andesite bedrock ridge. At the northeast end of Lockett Meadow, directly west of Sugarloaf Mountain, another terminal moraine is preserved, forming an arcuate-shaped ridge. Additional patches of till occur on bedrock knobs and terraces in the Lockett Meadow area. Till distribution suggests that a glacier descended from the Interior Valley and bifurcated against Sugarloaf Mountain, nearly at the terminus of the glacier. Morainal-shaped landforms are preserved on the northwest and north sides of Sugarloaf Mountain and "erratics" can be found on the flanks and summit of North Sugarloaf Mountain and were interpreted as being glacial in origin by Sharp (1942) and Updike (1969). Work under the present project has demonstrated that these features are a product of the pyroclastic phase of eruption of Sugarloaf Mountain. Erosion and differential winowing out of the finer ash and lappilli have caused the pseudo-glacial deposits.

The Core Ridge Glaciation, named for a large medial moraine which occurs at the lower (northeast) end of the Core Ridge, produced the most impressive moraines of the San Francisco Peaks. Two sets of terminal and lateral moraines are usually preserved, the second and innermost set appearing to have been superimposed on the first set. Thus, two advances appear to have occurred, each being approximately equal in extent. The two sets of terminal moraines completely fill the Interior Valley for nearly a kilometer of length consisting of approximately 0.5 square kilometers of terminal moraine topography. The relief above the present valley floor at the terminal area is about 65 m. The form of the moraines is quite well preserved, although subsequent drainage has cut several channels through the till. There has been little modification of the original glacial topography; the terminal moraines contain several closed or poorly-drained depressions. The maximum extent of ice from the seven contributing cirques was about 4 km., ice thickness was about 125 to 150 m at a midpoint between the cirques and terminal moraines. Four valleys on the outer slopes of the peaks were of sufficient altitude and aerial extent to produce glaciers during this episode of glaciation.

The best preserved but most limited glacial moraines of the San Francisco Peaks were produced by the Snowslide Spring Glaciation, named for a small canyon with well-preserved moraine of this age. Glaciers which formed in the seven Interior Valley cirques varied in length from less than 0.4 km to slightly more than 2 km, dependant upon size, elevation, and exposure of the cirques. These glaciers were little more than cirque glaciers so that no collescing of ice from adjacent canyons occurred. In most instances, two sets of lateral and terminal moraines are preserved in each canyon indicating multiple advances of ice or a major still-stand during a single glaciation, the former being most favored. Maximum ice thickness in these canyons was 65 to 75 km.

Of the four canyons on the outer slopes of the peaks that were glaciated during Core Ridge times, only two held small cirque glaciers during the Snowslide Spring Glaciation. The present elevation of the nine cirques active during snowslide spring times ranges from 3535 to 3800 m (10,600 to 11,400 feet) giving a mean value of 3,670 m (11,100 feet), which indicates the approximate snowline at this time.

Subsequent to the Snowslide Spring Glaciation the San Francisco Peaks remained free from further glaciation. However, the valleys, cirques, and ridge crests have been modified by Holocene periglacial, fluvial, and colluvial activity producing extensive protalus ramparts, protalus block fields, solifluction, alluvium, colluvium, and other mass movement phenomena.

In conjunction with the mapping of the geologic units within the region an additional set of the four quadrangle maps has been prepared to demonstrate the environmental geology and land use planning of the area. A text has been prepared to accompany these maps and includes evaluation of units on the basis of trafficability, construction, natural resources utilization, hydrology (surface and groundwater) agriculture, and recreational potentials.

SUMMARY OF GEOLOGIC EVENTS

The San Francisco Peaks were formed as a result of extensive intermediate to silicic volcanism. The volcanic pile developed on a pre-existing sequence of Paleozoic and Mesozoic sedimentary units capped by middle to late Tertiary basalt lava flows. The lack of basaltic lavas associated directly with the volcano strongly suggests that the parent magma was intermediate in character, of andesitic composition. This magma progressively differentiated to produce dacite, rhyodacite, and rhyolite lavas, each having successively decreasing volumes. A second andesite magma was generated, again with differentiates of dacite, latite, rhyodacite, and rhyolite composition. Wereas the more mafic lavas erupted from vents associated with the main caldera of the volcano, the more silicic lavas were extruded peripheral to the volcano, through zones of structural weakness. The result was the production of both exogenous and endogenous domes, pyroclastic ash and lapilli, phreatomagmatic eruptions, lahars, and laccoliths. Basaltic erruptions occurred contemporaneously in the surrounding area, resulting in intercalation of the different lavas and ashes. Potassium-argon radiometric dates indicate that the intermediate to silicic eruptions, at a minimum, span geologic time from in excess of 2 million years to 200,000 years B.P. Basaltic eruptions continued to occur up until about 900 years ago.

During and subsequent to the eruption of the various San Franciscan lavas, deposition of the extensive fanglomerates and epiclastic volcanic breccias proceeded about the mountains. The resultant units are collectively referred to as the Sinagua Formation. This formation has various origins including volcanic lahar, ash flow, mud flow, fluvial, periglacial, and colluvial.

At least 100,000 years after cessation of volcanic activity in the San Francisco Peaks, three major glaciations occurred within, and on the flanks of the volcano, causing considerable modificatbn of the preexisting morphology. These glacial intervals would represent pre-Wisconsinan (Illinoian?), early Wisconsinan, and late Wisconsinan stages, and excellent correlation with the Rocky Mountain, Sierra Nevada, and White Mountain, Arizona, glacial stratigraphy (Table 3).

During Holocene times, periglacial activity affected the intermediate and higher elevations, producing solifluction, protalus ramparts, and small rock glaciers. Attending the periglacial activity, fluvial erosion and deposition, and mass movement occurred throughout the project area. Thus, the last 200,000 years, and particularly the last 10,000 years, have been a time of great modification of the volcanic terrain.

Table 3 Correlation of Late Quaternary Glacial Events in the Southwestern United States.

				Rocky Mountains (Richmond, 1965)	Sierra Nevada (Wahrhaftig and Birman, 1965)	White Mountains, Arizona (Merrill and Péwé, 1972)		San Francisco Peaks, Arizona (This Report)	
Holocene				Gannett Peak Arikaree Temple Lake	Matthes Recess Peak	2,800* Mount Ord		Holocene periglacial activity	
Pleistocene	Wisconsinan	Pinedale	Late		Hilgard 9,800±800 **	Baldy Peak	Late	Snowslide Spring	Late
			Middle		Tioga				
			Early		Tenaya		Early		Early
		Bull Lake	Late		Tahoe 90,000±90,000**	Smith Cienega		Core Ridge	Late
			Early						Early
	Pre-Wisconsinan			Sacagawea Ridge Cedar Ridge Washakie Point	Mono Basin θx 710,000 Sherwin McGee Deadman Pass 2.7-3.1my øx	Purcell		Lockett Meadow 214,000 x(Sugarloaf rhyol 530,000 x(Sugarloaf Ash)	

** C-14 date from Sharp, 1972

x K-Ar date

* C-14 date from Merrill and Péwé, 1972

θ Dalrymple, et al., 1965

ø Curry, 1966

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Updike, R.G., and Péwé, T.L., Geologic map of the Sunset Crater west quadrangle, Arizona.

Possible Publications

Updike, R.G., and Péwé, T.L., Geologic map of the White Horse Hills quadrangle, Arizona.

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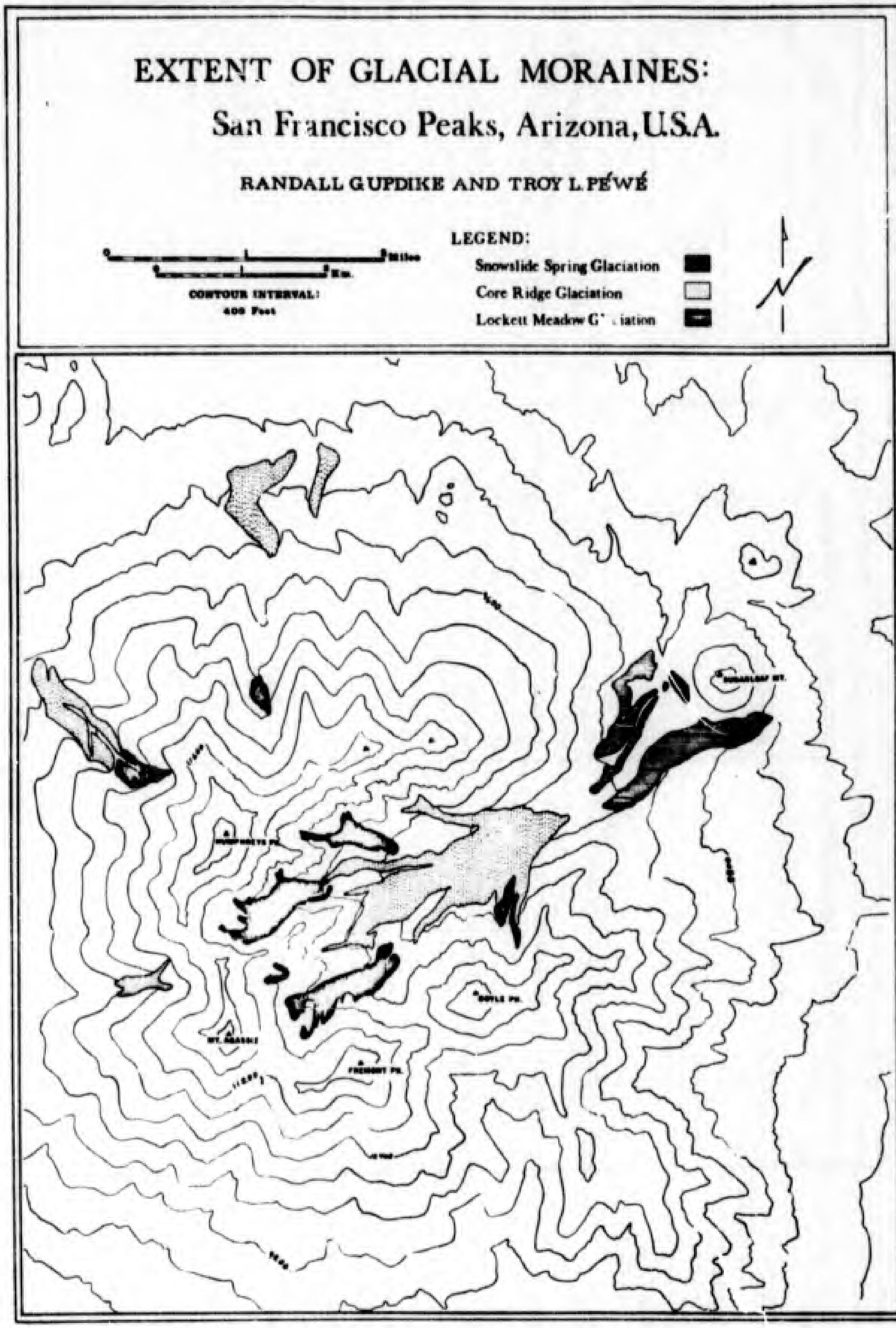

Figure 2. Extent of glacial moraines: San Francisco Peaks, Arizona, U.S.A.

TABLE 2. General characteristics of glacial deposits and landforms in the San Francisco Peaks, Arizona

	Lockett Meadow Glaciation	Core Ridge Glaciation	Snowslide Spring Glaciation
Ice Extent	6.2 km	4.2 km	2.1 km
Maximum relief	N.D. remnants only	90 m	40 m
Surface form	Morainal form essentially destroyed; till occurs in isolated remnants and a veneer on bedrock slopes; Weakly indurated; surface boulders scattered; partially buried by colluvium and alluvium.	Lateral, medial, and terminal morainal forms preserved but modified by stream erosion, slope wash, and colluviation; narrow, deep, and slightly deranged erosion channels through terminal areas; numerous boulders exposed, primarily on moraine crests; modified kettle depressions.	Lateral, medial and terminal morainal forms well-preserved; axial erosion channels only; abundant boulders on all morainal surfaces.
Weathering	Deep on exposed boulders; soil up to 50 cm thick developed on moraine crests.	Weathering rinds up to 2 cm thick on dacite boulders; solution pits common; soil development: 7.6-10.2 cm for A-horizon and 17.7-29.9 cm thick for B-horizon, as developed on moraine crests.	Thin weathering rinds; occasional shallow solution pits on dacite only; soil development: 4.3-5.6 cm for A-horizon and 10.2-15.5 cm for B-horizon, developed on moraine crests.