



## *Mogollon rim volcanism and geochronology*

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# MOGOLLON RIM VOLCANISM AND GEOCHRONOLOGY

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## INTRODUCTION

A remarkable vista into the late Cenozoic history of northern Arizona is offered to the observer from the southern city limits of Camp Verde, in the Verde Valley, Arizona (Figure 1). To the southeast, where the Black Hills Range seems to merge with the Mogollon Rim of the Colorado Plateau, the skyline of a remnant volcano stands out in about ten miles distance. The volcano seems to connect the features of the Plateau and the Basin and Range. About eight prominent blocks comprise the remnant crater wall, some being part of the Mogollon Rim, and some being part of the Verde Valley, deeply breached by faulting and erosion. The road from Camp Verde to Pine leads diagonally across the two mile wide crater, separating the northern undeformed portion (Mogollon Rim, Thirteen Mile Rock) from the southern part (Hackberry Mountain), which was considerably tilted and eroded. Vitric tuff in excess of 1,500 feet thickness in its original position is exposed in the inner, northern crater wall, overlain by the basic cinders and numerous basaltic lava flows of the San Francisco-Verde Valley volcanic fields. Within the crater, about twelve acidic-volcanic orifices stand out. Sabels (1960) proposed the name Thirteen Mile Rock Volcano for this remarkable source of vitric tuff. From micaceous separated from coarse tuff breccia at the base of the exposed tuff section, he obtained an age of 14 million years for the base of the volcano (Arizona-Lamont K-Ar date on sample BES-282-1959).

Because of shortage of sedimentary evidence on the Plateau, there are no clear ideas as to the time and rate of Plateau uplift. Models of uplift utilizing phase changes at depth automatically bring basaltic lavas into the process. Tectonic movement and basaltic volcanic activity seem to be linked together. Acidic volcanic activity, however, must be interpreted as a by-product of these processes, created at shallow depth, probably by absorption of heat from tectonic or basaltic magmatic activity.

Fortunately, the eruption of a huge amount of vitric tuff in the Mogollon Rim is not only of local significance. Fine-grained glass shards spread far and wide through the atmosphere, leaving a stratigraphic record of the volcanic activity that provides a time plane. As a result, correlation of tuff-bearing deposits with each other, and with the age-dated volcano, seems feasible. A concentrated effort was made (Sabels, 1960) to locate and identify possible fragments of the Thirteen Mile tuff blanket in northern Arizona as an aid to interpretation of the late Cenozoic geochronology of the Mogollon Rim country.

## VITRIC TUFF IN NORTHERN ARIZONA

Mahard (1949) identified the Hackberry Mountain volcanic rocks with the lava dam that impounded Verde Lake. From the 1,500-foot section of tuff exposed in the Mogollon Rim opposite Hackberry Mountain, a tuff layer of decreasing thickness can be traced along the Black Hills Range on the other side of the Verde Valley. Within the Verde Valley, the uppermost portion of the tuff has been reworked in various places, and contaminated with lake sediments, basalt cobbles and pyroclastics, so that no sharp boundary against the younger Verde formation can be established. From a thickness of about 200 feet near Clear Creek, southeast of Camp Verde, the tuff band thins

to 75 feet in the Government Pass area of Mingus Mountain, about 15 miles to the northwest of the tuff source.

Anderson and Creasey (1958) named the volcanic and sedimentary rocks that unconformably overly the Supai formation in the Black Hills the Hickey formation. The white tuff band discussed herein lies in the upper part of this formation, underneath the capping basalt flows. Along the northern boundary of the Mingus Mountain quadrangle at Woodchute Mountain, the Hickey formation is 1400 feet thick, all but 50 feet of which is basalt. The Black Hills were uplifted along the Coyote and Verde faults after deposition of the Hickey formation, and the Verde formation was deposited subsequently in the newly formed valley between the Plateau and the Black Hills.

Other tuff deposits have been listed by Lehner (1958) for the Clarkdale quadrangle, and also have been found in Sycamore and Oak Creek Canyons. Drill logs of the Arizona Land Department contain numerous records of vitric tuffaceous sections underneath the basalt of the San Francisco volcanic field. Conspicuous sequences of tuff beds are known from Cedar Ranch in the northern part of the San Francisco volcanic field, and from the Hopi Buttes area. Howell (1959) described vitric tuffs in the Navajo country further eastward in Arizona and New Mexico. To the west, extensive tuff deposits are exposed in the Williams and Floyd volcanic fields.

Shoemaker (1956) and Howell (1959) suggested that vitric tuff might be used as an indicator of a time plane. However, the porosity and instability of tuffs make correlation work rather difficult. Chemical leaching, absorption, and alteration, as well as erosion and redeposition, are facilitated by the character of the tuffs, and any analytical results must be interpreted with great caution. Therefore, a number of techniques that check and supplement each other were applied in this study.

## CORRELATION OF TUFFS IN THE VERDE VALLEY AREA

Cyclic sorting of vitric tuff is evident in many places in Thirteen Mile Volcano. This may be due to the pulsating eruption and "breathing action" known from modern, active volcanoes. Most grading cycles are 3 feet thick, with coarse tuff grains of centimeter size at the base grading upward into much finer material a few tenths of a millimeter in diameter. These grading cycles cannot be seen at every tuff face; it is conceivable that conditions in the volcano were not always favorable for graded deposition. At greater distances from the source, the processes of tuff deposition are more uniform. In the 75-foot thick Government Pass tuff section at Mingus Mountain, south of the Phoenix-Camp Verde highway, grading cycles ranging from one to several inches in thickness (averaging about two inches) are well developed throughout.

Some interesting parallels connect the two tuff sections mentioned, despite differences in their distances from the source vents, and in absolute thicknesses of the tuff beds. In both the Government Pass section and the Mogollon Rim tuff opposite Hackberry Mountain, the number of tuff cycles is about 500. The condition of complete representation of the volcanic record of Thirteen Mile Rock Volcano is well met at Government Pass, because the bottom of the tuff contains granite, schist, and obsidian fragments, and the top is formed by 10 feet of pyroclastics

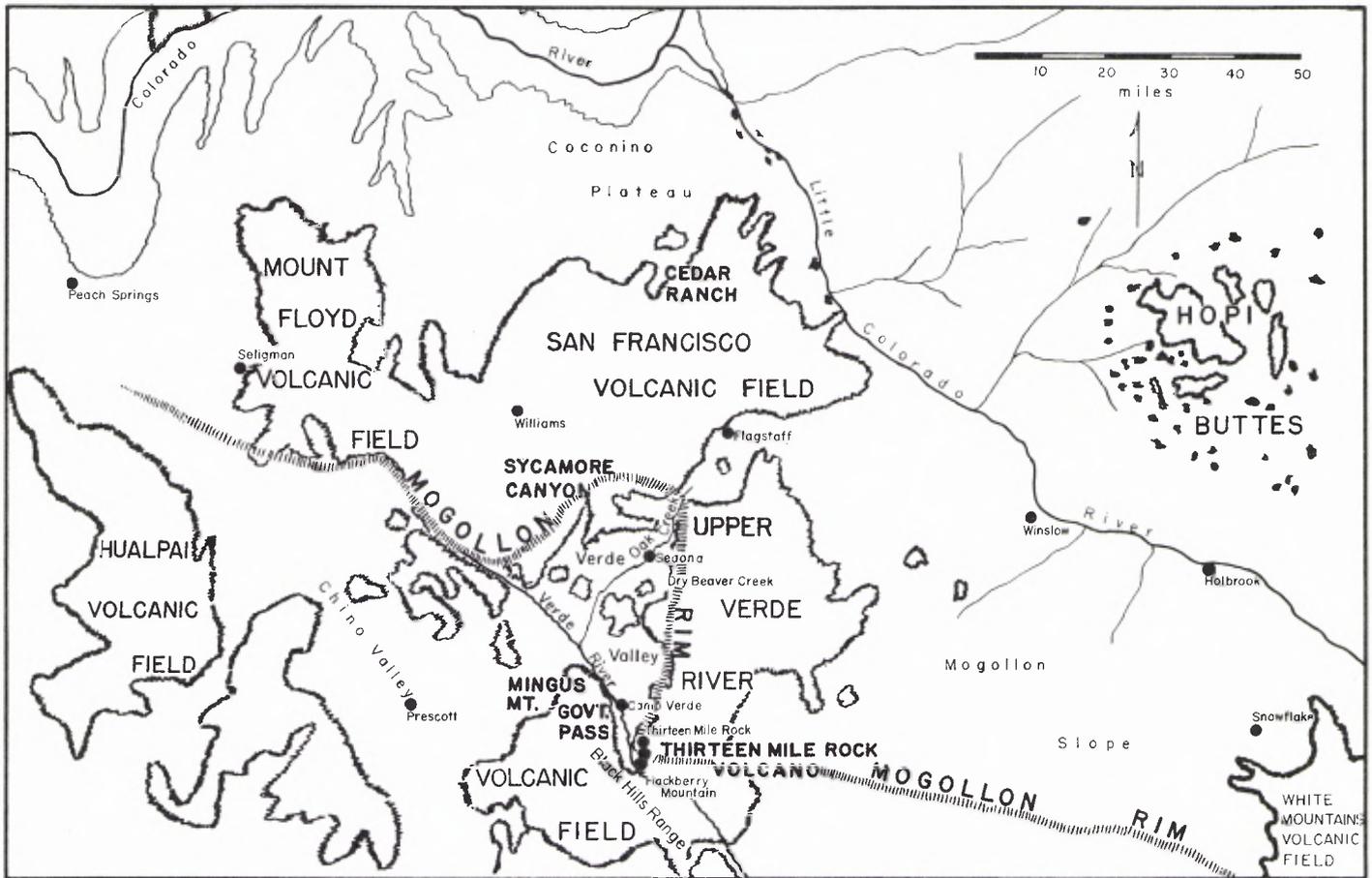


Figure 1.-- Index Map of North-Central Arizona

and 6 feet of basaltic cinders in the same way as in the Mogollon Rim. In the latter place, the two basic ash deposits are about 100 feet thick. The ratio in unit thickness of 100 to 6 at Government Pass is again roughly equivalent to the ratio of 1500 to 75 for the Mogollon Rim section. This proportionality of the two ash and tuff deposits, together with their internal textural features, suggests that the Thirteen Mile Rock and Mingus Mountain tuffs and ashes were deposited in one cast. One more conclusion is permitted. The Thirteen Mile tuff section obviously cannot be bottomless. Judging from the proportionality of cycles, there can be only a few hundred feet of additional tuff underneath the (K-Ar dated) bottom of the valley.

Further similarities between the two tuff outcrops are revealed by microscopic examination. Both tuffs contain biotite and hornblende. The distribution of gray and black glass (perlite and obsidian), and of quartz and feldspar, show similar trends.

The Thirteen Mile Rock tuff beds disappear beneath the lake beds of the Verde formation in the Verde Valley. On the east side of the valley, in the Dry Beaver Creek area, they emerge again and can be seen beneath basalts of the San Francisco - Verde River volcanic fields. In the Sedona area, the tuff has been redeposited. Red and white alternating layers, deltaic crossbeds, and intercalated gray lake beds were laid down before the whole section was dismembered and highly faulted along an east-trending fault zone that dictates the modern topography.

Evidence from faulting indicates that the tuff was deposited before severe deformation set in along the Mogollon Rim. Similar evidence was noted at Mingus Mountain, and at the Hackberry Mountain-Mogollon Rim complex. The covering basalt layers, which are the last components of the Hickey formation, had to be emplaced before severe deformation led to upward movement of the Rim and the Mingus Mountain Range, and to collapse of the Verde Valley. The vitric tuffs were, of course, laid down before the basaltic sheets poured out on top of them.

**EXTENT OF THE HICKEY FORMATION TO THE EAST AND NORTH**

It appears from the evidence given above, that the lava flows of the Upper Verde River volcanic field and of the San Francisco volcanic field, as far as they correspond to the upper unit of the Hickey formation, should rest on top of tuff sections correlative with the Mogollon Rim tuff source. In this chapter, a few tuff sections will be discussed which possibly are parts of this "tuff blanket."

**Mooney Trail Tuff**

In the Sycamore Canyon area, along the new power line leading over the Rim, numerous coarse gravel deposits have been opened up by construction work. Some of these gravels on top of the Mogollon Rim are associated with tuffs, either fragmented and redeposited or relatively well preserved as layered tuff. The overlying basalts are believed to be part of the upper unit of the Hickey formation. This assumption is strengthened by the existence of

numerous inclusions of quartz and potassium feldspar in the olivine basalt. Similar inclusions have been found during this study in the upper Hickey basalts of Mingus Mountain, and above the Thirteen Mile Rock tuff section. They are probably caused by the partial assimilation of vitric tuff in basaltic lava passing through tuffaceous deposits. The tuff from one gravel deposit exposed on Mooney trail near Casner Mountain was studied by thermoluminescence and emission spectrography, and found to be very similar to the bottom tuff of Thirteen Mile Rock Volcano. Therefore, it is believed that the activity of the Mogollon Rim volcano commenced at a time when coarse gravels were being transported in the Sycamore Canyon area from a southerly source, following a northerly drainage system. At that time, the older basalts of the lower Hickey formation were already elevated some 400 feet above the valley floor, which was being continuously lowered by erosion. The lavas and gravels of the Sycamore Canyon area can be arranged in the sequence given in Table 1:

Table 1. Lavas and Gravels of Sycamore Canyon, Arizona

Basalt	Gravel	Characteristics
Lower Hickey fm.	type 3	Elevation 7000 feet; labradorite-olivine basalt, no potassic feldspar enclosed. Gravel angular, 45% schist, 35% granite.
Upper Hickey fm.	type 2	Elevation 6600 feet; quartz and potassic feldspar inclusions in basalt. Gravel coarse, up to 10 inches, containing up to 20% volcanic rocks and tuff.
Verde fm.	type 1	Elevation 6000 feet; potassic feldspar encl. Gravel almost pure chert, quartz, with petrified wood.

#### Cedar Ranch Tuff

Cedar Ranch lies in the northern part of the San Francisco volcanic field, just outside the basalt-covered area which forms jagged, picturesque cliffs to the south. This basalt was chosen by H. H. Robinson (1913) as the type basalt for the older basaltic lavas in the San Francisco volcanic field. Robinson (p. 150) described a mineral enclosure of unidentified character in the basalt, which was probably a baked potassium feldspar from underlying vitric tuff.

In the Cedar Ranch tuff section, about 12 tuffaceous layers of varying degrees of purity, preservation, and mineral content were encountered overlying the Chinle pebble horizon, and underlying the capping basalt flow. The tuffaceous unit is about 250 feet thick, and can be subdivided into 2 subunits along a pebble zone approximately in its middle. These pebbles consist of well-rounded quartzite, jasper and chert, sandstone, rhyolite and aplite. The latter constituents distinguish this pebble zone from the lower zone beneath the tuffs which is believed to be a pebble zone in the Chinle.

Among the tuff layers of the upper subunit, one stands out because of its hornblende and biotite content. Potential hornblende-biotite tuff sources are rare in the San Francisco volcanic field, perhaps with the exception of Bill Williams Mountain. In the Mount Floyd area, several volcanoes could have produced limited amounts of hornblende-biotite tuff. The Thirteen Mile Rock Volcano is about the same distance from Cedar Ranch as the Mount Floyd Volcano, 50 to 60 miles. With its greater productivity, the Rim volcano also has a higher probability of having been the source of the hornblende-biotite tuff discussed here.

The lower subunit of the tuff section is probably of Miocene age, and the upper subunit is probably of Pliocene age. The lower subunit of the tuff section from Cedar Ranch is tentatively correlated with the Miocene tuffs and sediments of the Chetoh country, as described by Howell (1959). The upper subunit is tentatively compared with the Bidahochi formation, lower member. Absolute dating of easily extractable micas will add more certainty to this correlation.

#### Lower Bidahochi Tuffs

The first detailed study of the vitric tuff beds in the lower part of the Bidahochi formation was made by Shoemaker (1956). He described 12 individual thin beds of white, medium- to very fine-grained, water-laid tuff, which occur interbedded in the claystone, silt, and sandstone sequence of members 1 to 4 of the Bidahochi formation (usually combined in the lower member of the Bidahochi formation). Many of the shard beds are continuous for many miles, despite the fact that some of them rarely exceed 0.1 feet in thickness. A few are traceable over the known extent of the containing member.

The question of the age of the tuffs hinges on the dating of the lower Bidahochi lake beds themselves. The only fossils found to date in any of the lower beds of the formation are fragmentary remains of freshwater mollusks, apparently gastropods. A mammalian fauna discovered by Howell near Saunders, Arizona (Lance, 1954), occurs in beds that are probably equivalent in age to the lower Bidahochi beds. According to Lance, a Clarendonian (lower Pliocene) or Barstovian (upper Miocene) age is suggested by the fauna.

The fifth, or White Cone member, also termed middle member of the Bidahochi formation, contains claystone and volcanic rocks of the Hopi Buttes. A Hemphillian (Middle (?) Pliocene) age is indicated by fossils found in this unit by Stirton (1936) and Lance (1954). The uppermost member of the Bidahochi formation consists of sandstone with interbedded claystone.

On the basis of the faunal evidence, a time interval from late Miocene-early Pliocene (Barstovian) to middle Pliocene (Hemphillian) appears to have been available for the deposition of the lower Bidahochi lake beds in Hopi Lake, a name proposed by Williams (1936).

#### SPECTROGRAPHIC CORRELATION OF TUFFS OF THE HICKEY FORMATION

Thirteen Mile Rock Volcano is located in the prevailing upwind direction from the Hopi Buttes at the time of eruption. The situation accordingly was favorable for the preservation of ejected vitric tuffs in the Bidahochi formation, provided that eruption was synchronous with Bidahochi deposition.

A semi-quantitative spectrographic analysis of vitric tuffs and comparison with quantitative-spectrographic analyses of acidic lavas from the San Francisco field (through

the courtesy of Dr. E. M. Shoemaker, U. S. Geological Survey) reveals that the trace-element content of the water-laid vitric tuffs is higher than that of all potential volcanic source rocks. It is quite possible that the alkaline environment in the Hopi Lake not only preserved the original trace-metal content of the tuffs, but in addition led to the precipitation of metals arriving in solution in acidic, meteoric waters, and to their absorption by clay impurities deposited with the tuffs. This hypothesis is supported by the finding that most pure vitric tuff beds have a lower trace-metal content than impure, montmorillonitic beds. In impure beds, the elements barium, strontium and lanthanum show particular enrichment.

If tuff analyses from the Hopi Buttes are compared with available analyses of acidic lavas, it turns out that only dacitic lavas approach compositional requirements for a genetic relationship with the Hopi tuffs. A typical San Francisco field rhyolite would have supplied adequately the following chemical elements to a Hopi Buttes tuff of either the clean or the contaminated variety: beryllium, niobium, lead, yttrium, ytterbium, zirconium. Sufficient barium also is available if the source rock was rhyodacitic.

Impure tuffs from the Hopi Buttes cannot possibly have been supplied with the following elements from rhyolitic sources, but must have collected them later by clay absorption: cerium, cobalt, chromium, copper, lanthanum, strontium.

The following chemical elements are insufficiently represented in any San Francisco field rhyolite to explain their abundance in Hopi Buttes tuffs: boron, barium, nickel, scandium, vanadium.

Several elements are little or not at all influenced by the addition of impurities. Their abundances seem to be independent of contamination. These are gallium, ytterbium, and zirconium.

Dacitic source rocks would eliminate deficiencies for several elements, and reduce the deficiencies for others. In particular, dacitic tuffs contain a greater abundance of the following elements: barium, cobalt, chromium, copper, scandium, and vanadium. Therefore, a tuff of dacitic composition would have a greater probability of having been the source of the Hopi Buttes tuff beds, than would a rhyolitic tuff. The same general results were obtained by analyses of purified micas from tuffs and rhyolites.

In a specific comparison of Thirteen Mile Rock tuff, Hopi Buttes tuff, and San Francisco rhyolite, it was found that Thirteen Mile Rock tuff shows a greater abundance of barium, cobalt, chromium, copper, and vanadium (scandium not analyzed for), than San Francisco rhyolite. The latter is superior in gallium content. The data do not, however, explain the enrichment in boron, nickel and vanadium in Hopi Buttes tuff. For these elements, secondary enrichment by clay absorption must be assumed. It is concluded that for reasons of chemical similarity and of volume of tuff output, Thirteen Mile Rock Volcano was most likely the source of the vitric tuff shards in the lake beds of the Bidahochi formation.

#### THEMOLUMINESCENCE CORRELATION OF TUFFS

Thermoluminescence analysis was applied to basalts from northern Arizona with the intention of determining the age of the rocks. The glow areas registered on a recording device during heating of a standard sample of pulverized lava were previously believed to be proportional to the age of the samples. However, the relationship is not so simple; the glow areas turned out to be related to the alpha activity and to other intrinsic variables of each

sample. Indeed, so many different factors enter into the shape and area of a glow curve that it would seem improbable to find two different materials with the same glow curve. Therefore, thermoluminescence analysis should be applicable to correlation problems in geology. Vitric tuffs of a high degree of preservation turned out to be quite suitable for such work. There is a wide range of glow curve shapes and sizes for tuffs from different sources, and it is helpful that up to 100 glow areas can be determined by one investigator in one day.

It was found that the distance between glow maxima and glow minima is highly reproducible for any sample (Figure 2), independent of the glow intensity. This distance is so characteristic for a sample that even complete annealing will not destroy it. Irradiation with soft x-rays will build up glow response centered around the same maxima and minima. This distance between glow peaks seems to be a useful parameter for the characterization of tuff samples. A second parameter can be obtained from the ratio of glow intensities for the maxima and minima, as indicated in Figure 2. The two parameters may be written as follows:

$$T_{cm} = (T_{max} - T_{min}) \text{ cm}$$

$$I = (I_{max}/I_{min})$$

The two parameters were used to characterize the glow areas produced from several hundred tuff samples. Test samples taken from the same stratigraphic layer revealed that glow characteristics are reproducible and independent of the particular sample taken, and that the glow peak distribution is not accidental. It cannot be destroyed by annealing at 600° C, and therefore probably cannot be created or changed by the effects of collection, storage and preparation.

Agreement in glow areas constitutes a necessary condition for correlation, although not an independently adequate one. In each case further evidence must be sought and obtained before a correlation can be considered valid. Good agreement is suggested by samples falling within a coherent grouping with related samples, distinct from other unrelated groups, as shown in Figure 3. In addition, microscopic, spectrographic, radioactive, petrographic, and other data must be obtained and checked against the field evidence in order to validate a correlation.

In Figure 3, all analyzed tuffs are plotted in a T-I plot. It can be seen that the parameters of all tuff samples from the Hopi Buttes, Sedona, Mingus Mountain, and Thirteen Mile Rock areas are sufficiently similar to cause a concentration of the samples in the narrow intervals between T equal to 4.9 to 5.9, and I equal to 0.7 to 2.0. There are no other samples from a different area or source that fall within the area outlined by these coordinates. However, the possibility must be left open that such samples may be found in the future. Therefore, other conditions must be established which samples grouped together must fulfill.

#### FURTHER EVIDENCE OF DERIVATION OF HOPI BUTTES TUFF FROM THIRTEEN MILE ROCK VOLCANO

The extent of agreement in trace-element content and glow areas of samples from the Hopi Buttes tuff beds, from Sedona and Mingus Mountain tuffs, and from the Mogollon Rim Volcano is quite remarkable. For the sake of brevity, many tables and other data given by Sabels (1960) have been eliminated here. Only a few important remarks will be added.

The lowermost tuff bed from the Hopi Buttes (Shoemaker's alpha layer) and the lowest tuff sample available

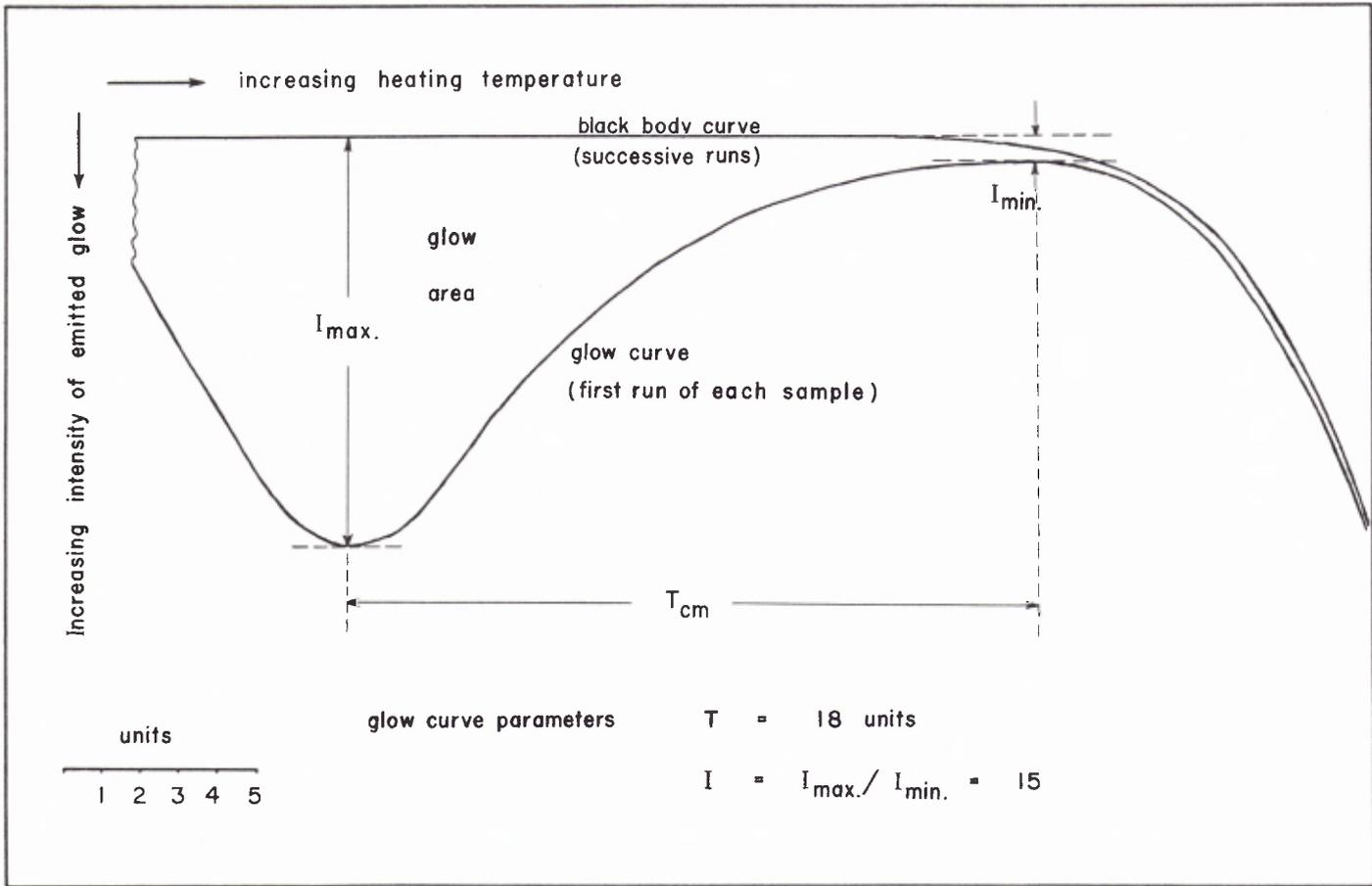


Figure 2. -- Thermoluminescence Glow Curves and Parameters

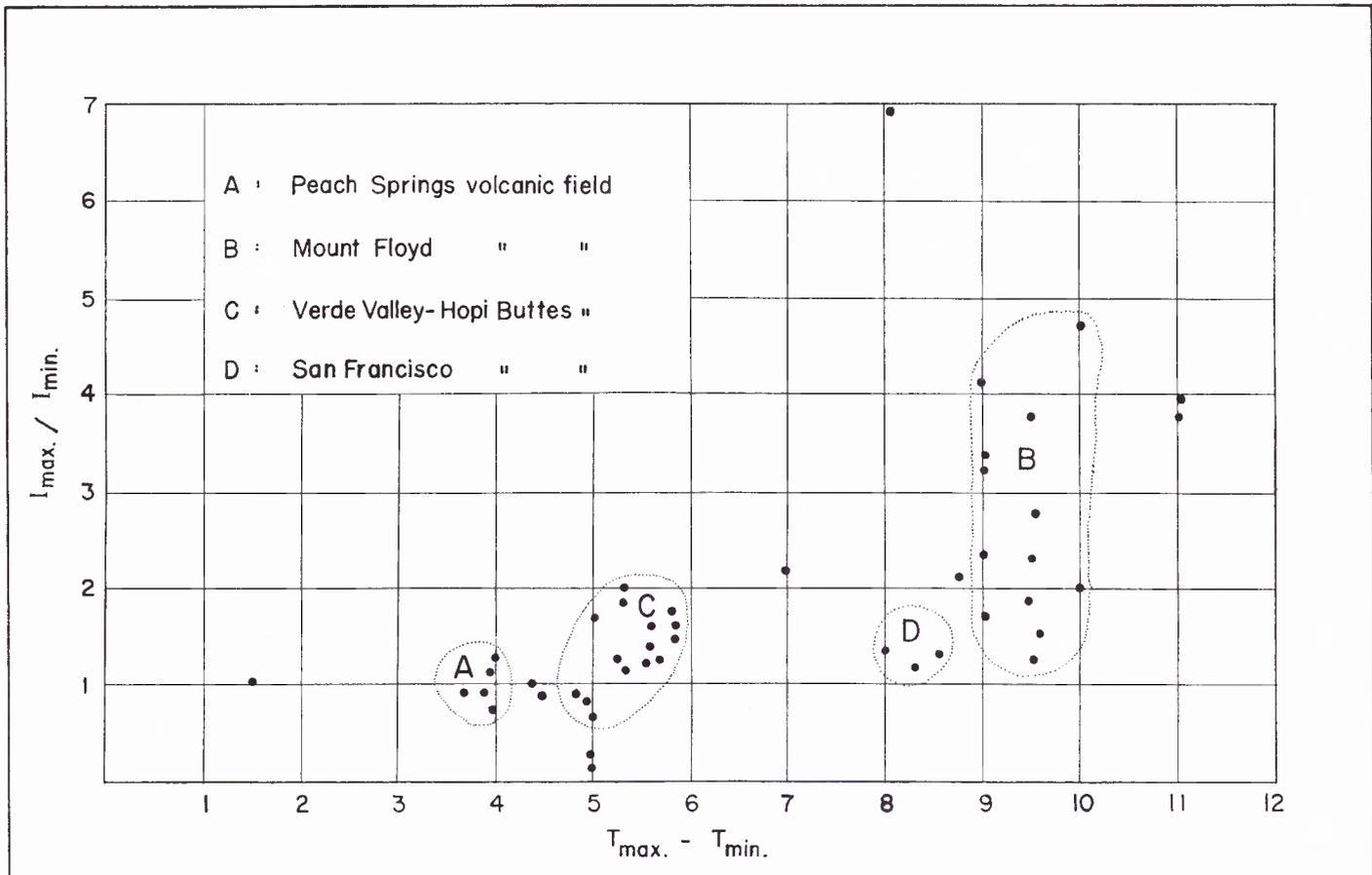


Figure 3. -- Thermoluminescence T-I Plot of Northern Arizona Tuffs

from the Thirteen Mile Rock Volcano were analyzed for potassium content and alpha activity. It was found that the samples contain 2.32 and 2.39 percent potassium, respectively, and that the alpha activities are 0.80 and 0.75 alphas/mg,h.

Accessory minerals were studied in each tuff sample. Some tuff samples from outcrops of the Bidahochi formation at Castle Butte contain hornblende and mica crystals embedded in glass shards of 0.1mm size. In general, the hornblende content of tuff decreases considerably with the distance from the source, while mica flakes tend to be carried along with glass shards. These observations corroborate the analytical findings listed above.

Shoemaker (1956) listed the index of refraction of glass shards from the lower Bidahochi tuffs. In the lower tuff beds, the indices range between 1.498 and 1.501. In the uppermost beds, the indices increase to 1.508, and in the top tuff layer to 1.532. Abundant accessory biotite was observed in some of the samples. It is noteworthy that there seems to be a high degree of similarity between the twelve tuff beds, suggesting that they may have come from one source, or at least from a number of similar sources. This suggestion is not easy to accept, if one considers the time table involved.

If the K-Ar date for the bottom of Thirteen Mile Rock Volcano is taken as the lower age limit of the Bidahochi tuffs, and if the fossil dates by Stirton and Lance on the middle member of the Bidahochi formation are taken as the upper age limit of the Bidahochi lake and tuff beds, then an interval of several million years was available, during which the lake beds could have been deposited and the tuffs spread over northern Arizona. It may appear bold to invoke one tuff source for the deposition of a dozen tuff beds spread over an interval of activity of several millions of years. The nature of acidic lavas, and their high viscosity and dependence on magmatic waters are, in general, incompatible with such a suggestion. The acidic volcanoes in the San Francisco volcanic field, certainly had but a short life span, as indicated by the lavas they produced. However, Thirteen Mile Rock Volcano is a different matter. This tuff volcano is situated on the Mogollon Rim, along which occurred uplift of the Colorado Plateau. The uplift process is known to have taken place over an extended interval of time, probably of the order of magnitude of millions of years. A step-like accumulation and release of tension and connected volcanic activity are quite feasible. Such a mechanism would explain the similarities between individual tuff beds presumably derived from Thirteen Mile Rock Volcano and spread all over northern Arizona. The similarity of tuffs, both in lateral and chronological extent, have been documented by chemical analyses, thermoluminescence study, and determination of characteristic trace metals and indices of refraction. The tuff beds of the lower Bidahochi member should show a great deal more variation in mode of deposition and grain size, had they come from different sources. Such variation is shown in some of the Cedar Ranch tuff beds, for which, consequently, several sources are invoked.

The Thirteen Mile Rock Volcano seems to be the most reasonable source of the lower Bidahochi tuff beds. The possibility that it erupted a dozen times is strengthened by the existence of about a dozen neck-like features in and about the volcano. The tuff beds between the various necks slope against one another. Marginal bouldery agglomerates were observed, which suggest erosion and de-

struction of the volcano between renewed periods of activity.

#### CORRELATION OF LATE MIOCENE AND PLIOCENE EVENTS IN NORTHERN ARIZONA

The various events of tuffaceous volcanism, deposition of lake beds, emplacement of andesitic and basaltic lava flows, uplift of the Plateau, and formation of the Verde Valley are not independent of one another. Each event puts a number of restrictions on other events.

For the base of the Thirteen Mile Rock Volcano, an age of 14 million years was found. The base of the lower member of the Bidahochi formation is, according to Lance (1954), of upper Miocene or lower Pliocene age, and it was shown that there is good evidence that these two bases are correlative.

At the top of the middle member of the Bidahochi formation is the White Cone member, for which a mid-Pliocene age is indicated (Stirton, 1936; Lance, 1954). Paleontological evidence therefore indicates that the interval of deposition of tuff beds among the accumulating lake beds of the lower member of the Bidahochi formation, and subsequent volcanic activity during the deposition of the lavas of the middle member of the Bidahochi formation, extended from late Miocene or early Pliocene to middle Pliocene time.

It was established in the preceding chapter that the time interval of deposition of the Bidahochi tuff beds is believed to be identical with the time interval of Thirteen Mile Rock volcanism. Complications arise because Thirteen Mile Rock activity must be completed, and the covering basaltic lavas emplaced, before Basin-and-Range block faulting set in during late Miocene to early Pliocene time. Further complications arise from uplift of the Plateau and the establishment of the northward drainage, which seems incompatible with the existence of Hopi Lake and deposition of the lower Bidahochi beds.

According to Dr. J. F. Evernden, University of California (oral communication, February, 1960), most evidence by K-Ar dating for Basin-and-Range block faulting and Plateau uplift in Nevada and Utah suggests an age of 9 to 11 million years. This figure should be applicable to the present problem. If valid, it allows 2 to 3 million years for the build-up of Thirteen Mile Rock Volcano and deposition of the lower Bidahochi beds, and allows time in the order of magnitude of another million years for emplacement of the basaltic lava flows capping the tuff section of the Mogollon Rim, and perhaps also in the Bidahochi formation. Then, about 10 million years ago, Hopi Lake, which also should have embraced the eastern part of the Verde Valley and Cedar Ranch sections, should have been drained by progressive Plateau uplift. The Verde Valley would have appeared at that time, together with the other basins and ranges; the erosion cycle would have set in, and volcanism continued in the San Francisco field and adjacent areas, including the Hopi Buttes.

Stream deposition and erosion would have been active during the major part of the remaining Pliocene time. Stream beds of middle Pliocene age have been recorded in the Hopi Buttes (White Cone member) and the Verde Valley. Stream deposits also are intercalated with basaltic lava flows in the San Francisco volcanic field. In the Mount Floyd area, coarse tuff blocks have been redeposited by stream action.

Stream deposition gave way to erosion at an early date in the Hopi Buttes area, probably post-middle Plio-

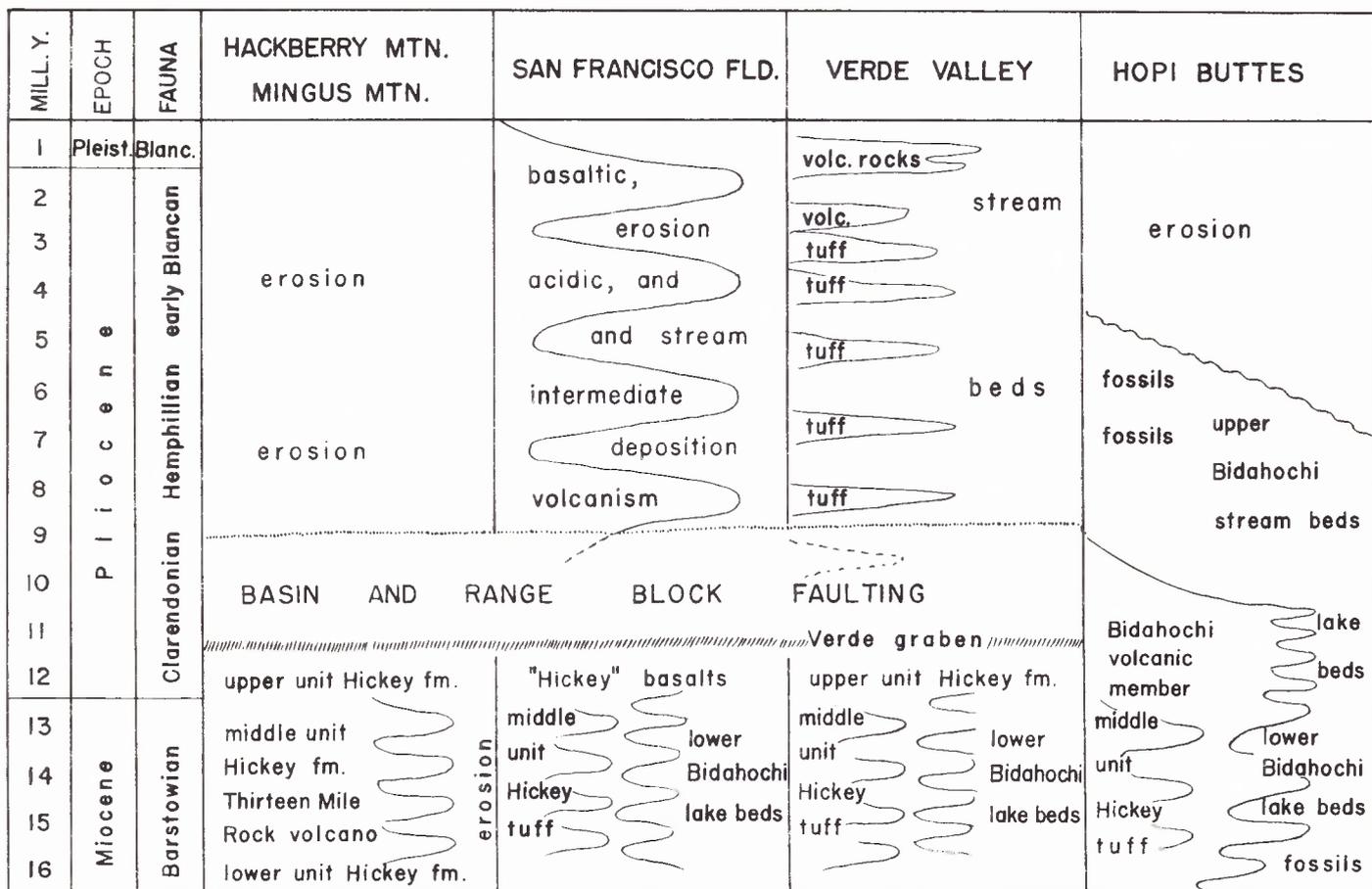


Figure 4. -- Late Cenozoic Geochronology of North-Central Arizona

cene, while deposition prevailed in the Verde Valley area throughout Pliocene and Pleistocene time. The latter statement is supported by relationships of the House Mountain lavas near Montezuma Castle, which are sandwiched between Verde lake beds, and are believed to be of Wisconsin age (Sabels, 1960).

Figure 4 depicts the model for northern Arizona late Cenozoic geochronology as outlined in this report.

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