ARIZONA GEOLOGICAL SOCIETY

SOUTHERN ARIZONA GUIDEBOOK III

1968

EDITED BY

SPENCER R. TITLEY

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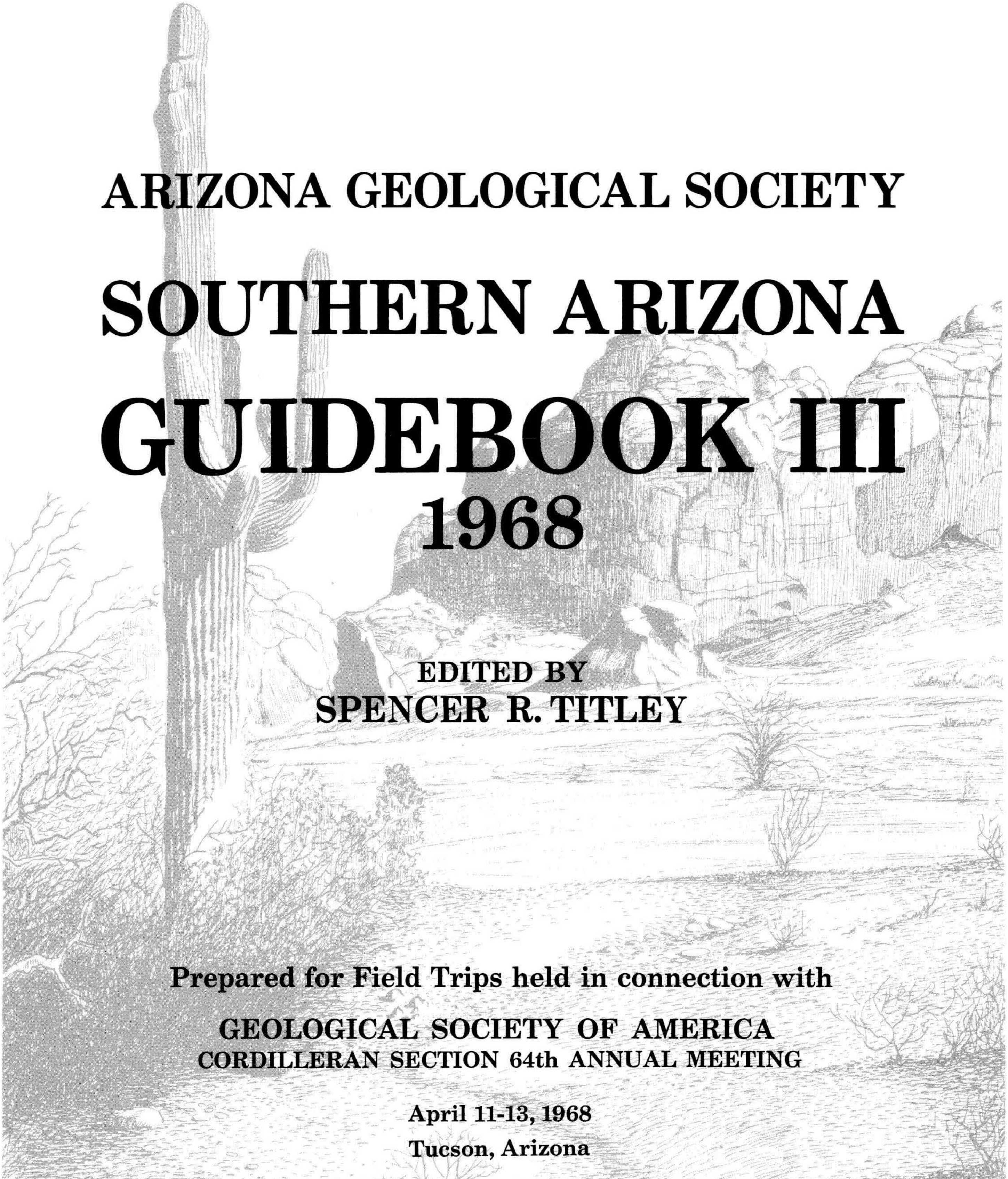

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EDITED BY
SPENCER R. TITLEY

Prepared for Field Trips held in connection with

GEOLOGICAL SOCIETY OF AMERICA
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THIS GUIDEBOOK IS RESPECTFULLY DEDICATED TO THE

MEMORY OF

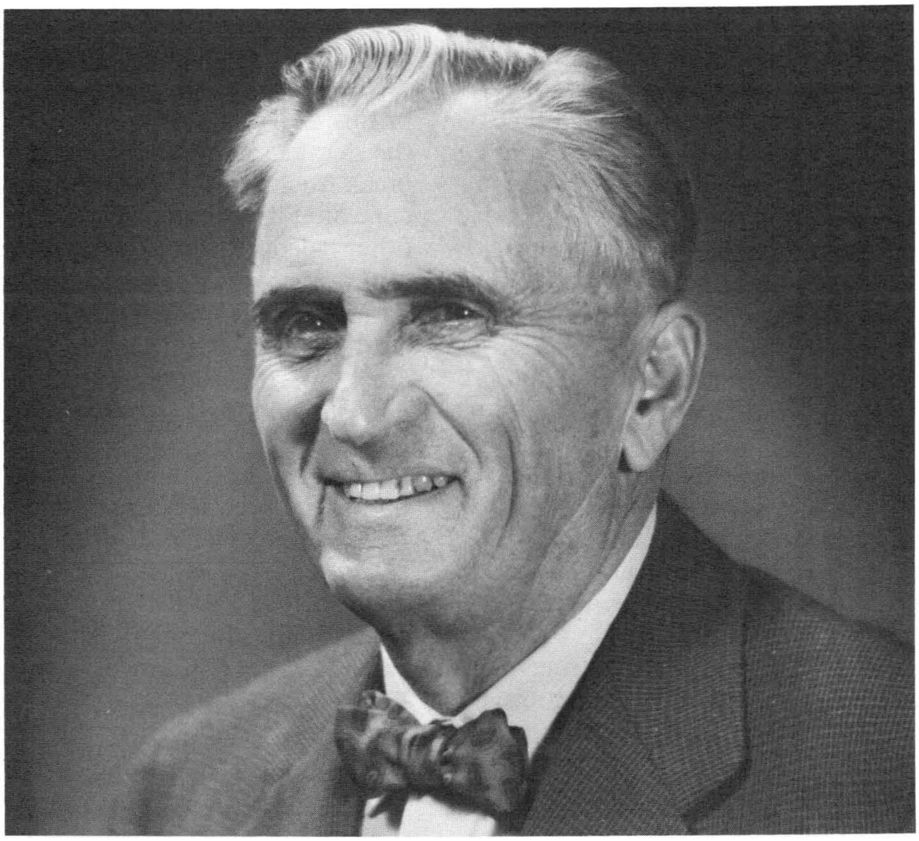
HARRISON ASHLEY SCHMITT

Scientist, Geologist, and Scholar

by

HIS MANY COLLEAGUES AND FRIENDS

IN THE SOUTHWEST



MEMORIAL OF HARRISON ASHLEY SCHMITT

"As I look back on four decades in mining geology I am impressed by the magnitude of the changes that have taken place. Many have said that change is often mistaken for progress and to some extent this has been true especially during the last decade. Much of the change, however, has resulted in real improvement."

Harrison Schmitt – 1964[1]

By

H. H. SCHMITT
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Houston, Texas

Harrison Ashley Schmitt was one of a generation of geologists who developed the art and science of mining geology into a leading factor in the unprecedented growth of mineral exploitation in the last thirty years. Loosely allied with such men as Augustus Locke, Hugh McKinstry and many others, he joined in branching from the footsteps of Waldemar Lindgren toward the application of detailed ore deposit studies to the exploration for new mines. Our generation, in the spell of great advances in exploration geophysics and geochemistry, has in part turned away from the path of applied ore deposition blazed by these men. However, the continued linking of Harrison Schmitt's name with recent porphyry copper developments in the Southwest–Christmas, Esperanza, Mineral Park and Battle Mountain–suggests that we have strayed too far. In the same manner that Harrison Schmitt and his generation combined the logic of chemistry and physics as they knew it with the descriptive philosophy of Lindgren, it is up to us to combine their concepts of applied ore deposition with the new techniques of geochemistry and geophysics.

1. Presented to the Arizona Geological Society, March 3, 1964. This memorial will be published in part by the Mineralogical Society of America in the March-April 1968 issue of the American Mineralogist.

"The Doctor" was born June 11, 1896, in Mankato, Minnesota, into the family of Harrison Lincoln and Esther Grannis Schmitt, a lawyer's family only one generation removed from the frontier. Although the necessity to be a carpenter, a smithy, or a hunter was rapidly disappearing, he nevertheless acquired these and related skills to his and his families' lasting pleasure and benefit. After graduating from Mankato High School he entered the University of Minnesota at Minneapolis apparently intent on studies foreshadowed by his boyhood "excursions" into chemistry. Upon the completion of his second year of university study he volunteered for duty with the Marine Corps where he and his fellows took part in another of our continuing attempts to preserve liberty on this planet. This period of national service during World War I appears to have fertilized a deep concern for the long term health of our society, a concern about which he continued to speak and write throughout his life.

It was also during his tour with the "Horse Marines" that his reading in geology and his affection for nature led him eventually to return to the University of Minnesota where he obtained a doctorate in geology in 1926. His thesis work in the Parral District of Chihauhua, Mexico, (1931) and other investigations in that country for the American Smelting and Refining Company began the first of two major phases in his studies of ore deposits. He continued this phase of detailed field studies with work on the vein, manto and pipe types of ore deposits in Mexico from 1922 to 1926, in southern Arizona, Virginia and the Central Mining District of New Mexico from 1927 to 1931 and subsequently as a consultant throughout Mexico and southwestern United States. This work gave him extensive if not unique knowledge of the structure, mineralogical associations and ore finding techniques related to pyrometasomatic and hypogene ore deposits and supergene alteration (1933a, 1933c, 1938, 1948). He generalized some of his early thoughts on the localization of ore deposits in the Southwest by writing (1933a):

> "...The universal association of the ore deposits of this province with sharp or localized features of structure supports a theory of occurrence in which the influence of such features is given first place. Preparation of the ground—that is, breaking and brecciation—is considered essential. Temperature doubtless has important influence in the separation and classification of the elements; the importance of chemical reactions with the wall rock is debatable; the influence of pressure, although minimized, must be considered where critical phenomena exist; the position of ore relative to the source hinges upon theories of the location of the source. But the need of an opening to start with cannot be escaped. Furthermore, judging from the conditions in this province this opening must connect with the depths of the earth's crust by a crosscutting break such as a high-angle fault, dike, breccia cone or chimney or a deep-cutting stock, neck or other igneous form.

"A theory of occurrence that emphasizes ground preparation explains why ore deposits are limited to the first mile or two of the earth's crust, for the volume of the broken ground in many mineralized areas appears to diminish with the depth... Many have been impressed by the rapid downward diminution in the size of orebodies, of brecciated rock and the tendency for fissures, faults and dikes to focus in depth... In places where deep development has been done, many of the so-called stocks are seen to narrow to a focus also; that is, have the form of a funnel... In other words, some 'stocks' behave like ore; i.e., they tend to constrict downward in the first 1,000 ft. or so of the earth's crust.

"The theory that most 'stocks' are truncated cupolas of batholiths has become so firmly established that it is heresy, perhaps, to suggest that the probabilities are good that many 'stocks' with which contact pyrometasomatic deposits are associated in this province and in adjoining areas have 'floors'. If such a condition is verified, the current theory for the origin of the contact pyrometasomatic and associated ore deposits will need revision for this province at least. There is already a large body of evidence showing that the deposition of many of the contact pyrometasomatic deposits in western United States was later than the consolidation of the adjacent exposed intrusives and if these intrusives are not the cupolas of batholiths the question of the source of the mineralizing fluids seems even more complicated than current theory suggests.

"It seems likely that the primary factor in the localization and association of 'stocks', contact pyrometasomatism and ores, is a deep-cutting break of one sort or another in the earth's crust, (and) that the contact pyrometasomatic deposits are not derived from the 'stock' but that their association is the result of localization along mutual outlets to the earth's surface.

"In conclusion, it is perhaps significant that mining geologists whose living depends on their success in applying geology, and especially those who have had good success in finding ore, continually emphasize the importance of studies of structure in solving the problems of ore occurrence, particularly the careful measurement of the rocks by large-scale methods of mapping. The successful application of mining geology in the past has been largely the result of such work. The writer believes, however, that specialized studies of outcrops and the less obvious surface expressions of ore, the alteration jackets or halos of orebodies, vertical zoning, oreshoot extension and the character of the roots and branches of orebodies will have a proportionately greater success in the search for ore in the future."

Dr. Schmitt's 1939 paper on the Pewabic Mine of the Central Mining District (1939b) is considered by many to be one of the foremost illustrations of the application of systematic field and laboratory investigations to a problem in ore deposition and mining. In the abstract of this paper he concluded:

"The Pewabic mine is in the southeastern part of the zone of pyrometasomatism which surrounds the intrusive quartz monzonite at Hanover, New Mexico. Extensive development has proved that the south lobe of the intrusive is floored and that the sedimentary rocks, chiefly limestones, shales and intercalated quartz diorite sills, were thrust aside laterally by the magma. The overthrust, a minimum of 500 feet, was expressed by close folding accompanied by rock flowage of the bedded rocks in the upper plate of a flat thrust fault.

"The less intense effects of the exomorphism resulted in marbleization of the limestone and hornstonization of the shales; the stronger effects were epidotization of the aluminous rocks and andraditization of the limestones. The lower plate was mildly metamorphosed. The sphalerite ore bodies, essentially uncontaminated by lead and copper, are localized by the intersection of the thrust fault with nearly vertical post-silicate northeast fault zones resulting in flatly pitching chimneys and ore blankets.

"The facts indicate that the rocks were metamorphosed without volume change and that large amounts of silicon, iron, and zinc were brought in. Much of the silica can be accounted for by epidotization and chloritization of the aluminous rocks, and a question discussed is whether the silica, largely older than the sphalerite, may not have been derived from alterations by gaseous volcanic emanations."

During this period of detailed field studies he also wrote extensively on the use of systematic geological techniques in ore search and mining (1932b, 1932c, 1933b, 1936). He recognized and deplored the early stages of the current trend to deemphasize training in geologic mapping at the college level, writing in 1936:

"Most recent discoveries of ore by geologic methods resulted from detailed studies of structural conditions and these had detailed large-scale mapping as their base. Few recent college graduates seem to have had training in mapping methods known to be effective... The student is expected to acquire the needed skill somehow after graduation; yet it may mean his bread and butter for several years. Indeed he may never learn to map well and therefore be ineffective in exploration."

His concern in this area continued throughout his career as reflected in this statement in 1960 (1960):

"Many mining geologists avoid geological studies and mapping in the exhaustive detail necessary for success in many mining districts. Short-cuts are commendably sought, but are seldom successful in the hands of the inexperienced. This lack of accomplishment further spurs the drive to short-cut panaceas. But, ironically, the very short-cuts looked for are the dividends from many years of detailed outcrop and mine mapping. Beginners seldom can be convinced of this."

Soon after the end of the Second World War Dr. Schmitt's interests followed those of the mining industry into the exploration for disseminated, or "porphyry" copper deposits. This second phase of his study of ore deposits culminated in one of the most impressive string of successful mining property developments of which I am aware. Of particular note is his involvement in the discovery and development of ore bodies at the Christmas, Esperanza, Mineral Park and Peach mines in Arizona, and at Battle Mountain in Nevada. As part of his work with the Defense Minerals Production Agency of the Federal Government he was also involved in evaluation of the Bor Mines in Yugoslavia in 1951 and the Toquepala, Peru, copper deposit in 1952. Several other properties which he recommended in recent years show promise of becoming major producers in the near future. In 1960 he outlined the factors involved in the search for porphyry copper deposits, saying in part:

"As for the more detailed outcrop inspection in a given district, many of the cappings of the copper-molybdenum disseminated deposits are characteristic enough to permit an efficient, quick, on-the-spot decision as to action. These are the cappings that have been said to be of low to moderate temperature hypogene origin and are characterized by silicification, argillization, sericitization, biotitization and rarely chloritization...

"Other than the above more general type with which most of us are familiar, at least three others occur in Arizona:

"(1) With the above general type of alteration still evident there is often enough jarosite to result in a high yellow outcrop as contrasted with the normal geothite brown. We generally correctly interpret this as representing high pyrite-non-commercial copper. But in recent months an enriched chalcocite zone of unknown size has been found under such an outcrop where some copper was visible in the form of turquoise. I confess that I have passed up similar outcrops in the past because most of them previously drilled had yielded high pyrite and low copper even when copper stains were common in the outcrop. In such outcrops we probably are overlooking some clue or clues as to the copper-pyrite ratio.

"(2) There is the oxidized capping derived from a hypogene mineralization that has the appearance of sulphides in 'fresh' rock, that is, in rock that is not argillized, quartzified, sericitized or chloritized. There may or may not have been chalcocite enrichment. The hypogene secondary minerals, besides the sulphides, may include biotite and feldspar. This would seem to represent high temperature mineralization. Bagdad, Arizona, represents this type... There is abundant hypogene secondary biotite and feldspar associated with chalcopyrite, molybdenite, and pyrite. There is not much clay...

"The above described types of occurrence are likely to give cappings that depart from the norm. Nevertheless, it should be possible to judge them. There must be enough discrete 'limonite' to make possible a commercial amount of copper in depth and the 'limonite' should in part represent chalcocite, and/or chalcopyrite and/or bornite. As noted earlier a predominance of jarosite may not rule out possible commercial copper in depth, but normally it is less favorable. Furthermore, we like to see some copper staining in the outcrop and should not forget Locke's admonition to look for relict sulphides...

"(3) Another type of disseminated copper deposit is presumed 'high temperature' mineralization in sedimentary and igneous rocks including a high proportion of limestone. Garnet and other silicates are characteristic. This type includes the Pima-Banner, Mission-Palo Verde and Peach ore bodies in the Sahuarita, Arizona, area. The Pima-Banner out-crop is really a wide lode and is largely covered by gravel. The exposed part contains silicates at the surface associated with unreplaced limestone. Copper stains are prominent and oxidized copper ore is found in pockets. The mineralization of the Peach ore body is similar. Veinlets and spots of brown 'Limonite' a millimeter or more in thickness are conspicuous.

"There are probably other types of outcrops that are significant in terms of ore. Experience indicates, however, that if the outcrop represents a section of the original protore, enriched or hypogene ore...it will be characterized by discrete veinlets and/or spots of 'limonite' and hematite. This is the essential ingredient. Paper thin veinlets or very small dots of original sulphides are not enough volume-wise to suggest an ore body. 'Limonitic' paint is not enough. In those few cases where all the iron is leached out, the walls are likely to be inert and the pyrite ratio high.

"We have been saying for some time that if we are to give a specific out-crop more than passing notice it must be well altered in the sense that the character of the original rock must be greatly modified. The normal cappings, as have been often described, present the aspect of an area of dirty white to gray coloration modified by 'limonite' and hematite of several colors and distributions. This type of capping is always brecciated and broken. We don't necessarily need to look for 'structure'; it is always there. The boundary or walls of the capping may be defined by the lack of any appreciable 'structure'.

"The question of copper staining of the outcrop is usually important although the outcrop over the ore body may have less visible copper than that over waste. That is, leaching may be thorough over the ore and some of the capping copper may migrate a long distance. Outcrop and plant sampling can be misleading. Sometimes secondary ore bodies are formed in the neighboring talus slopes, outwash and stream gravels. Molybdenum on the other hand, appears to be relatively stable and since it is nearly always present in the porphyry coppers of the Southwest it is a fair metallometric anomaly guide...

"A few...geological features of the...(More usual)...bulk-type ore bodies may be of interest:

"(1) Copper enrichment resulting in chalcocite blanket ore bodies is not the exclusive type of gross copper disseminated ore body in Arizona. As is well known, primary chalcopyrite ore predominates at Ajo, but it also predominates or is important at the Pima-Banner, the Mission-Palo Verde and the Esperanza ore bodies at Twin Buttes; in the Bagdad, Ray and Safford copper ore districts and at Helvetia, Arizona.

"(2) At the Esperanza mine and the Mineral Park copper mineralization areas where the chalcocite blanket form is well developed, the ore bodies are on topographic highs. These thin deposits are depressed and usually die out in the adjacent lower slopes and arroyos where either protore or primary ore is exposed in places. In detail the upper surfaces of the blankets though sub-level are fairly smooth-topped. They dip down and thin rapidly as the lower topographic elevations are approached...

"(3) I cannot adequately evaluate the cup or inverted cone theory of Pennebaker. Since most of the bulk-copper deposits are in intensely brecciated ground, in contrast to most of the surrounding walls, they seem to have the aspect of permeable sponges. There seems to be supporting theory that in the ore body block of ground circulation of both hypogene and supergene fluids would be more active, penetrate deeper and spread out farther. The end result would be more elevated and lower grade protore sulphides outside of the 'cup' country. This should significantly aid in evaluating the best blocks of ground.

"(4) Apparently, in some cases where sulphides are deposited in holocrystalline igneous rocks, without low temperature alteration such as argillization, upon oxidation the resulting copper minerals are concentrated in the outcrop. No chalcocite blanket is formed. This has been attributed to the easy availability of free alkali as a neutralizer from the partial breakdown of the originally fresh feldspar.

"(5) In the Southwest there are many occurrences where primary sulphides outcrop over wide areas. This is the result of recent exposure through rapid erosion. The exposures are often protores, but are usually wholly barren pyrite. The suggestion is that possibly hypogene chalcopyrite exposures of commercial grade may have been overlooked because they have not been expected. They may be marked by superficial oxidation not over a few inches in thickness."

The broadening of Dr. Schmitt's experience with the ore deposits of the Southwest led him to think and write about his cumulative knowledge of these deposits. He was among the first to document the importance of the hot spring environment in epithermal mineral deposition (1950). Summarizing his thoughts as follows:

"The postulated formation of the 'epithermal' ore bodies in the meteoric-water shell appears to simplify the explanation of several features of these deposits:

"(a) They show a nearly universal shallow bottoming. This bottom often may well be at the base of the vadose-water zone. In some districts a belt of primary ore bodies of a given vein parallels the present topography.

"(b) The delicate layering of the vein minerals may be due to seasonal and longer climatic changes, i.e., changes largely in the quantity of water entering the meteoric-water shell.

"(c) The difficulty of classifying many 'epithermal' minerals as hypogene or supergene is explained as the result of the intimate intermingling of the hypogene and supergene environments.

"(d) 'Epithermal' ore bodies commonly do not outcrop, but the apex of the ore is at shallow depth. This is possibly explained by the rapid change in conditions near the original surface. Such a change is evident in the hot-springs areas.

He also continually reemphasized the importance of wall-rock alteration as a possible source of vein silica stating in 1954 that -

"The known facts on the distribution of the silica in and associated with many ore deposits suggest that only a small proportion of this oxide is imported into the ore zone from distances measured in thousands of feet or more. Most of it appears to be derived from the desilication of alumino-silicate walls and transported for distances often measured in inches, and rarely more than hundreds of feet.

"This belief suggests a unique approach to the theory of the character of the ore-forming fluids, and further, following Knopf, that the 'magma' need not be called upon to supply much of the silica and perhaps none at all for many ore deposits.

"Speculation on the nature of the ore-making fluids leads to the further suggestion that they are similar to volcanic emanations. The original environment of the ore body could be a mass of structural open ground of one form or another that is the site of a pool or reservoir of condensate, connate, meteoric or sea water. This is activated by the 'volcanic emanations'. The alumino-silicate walls are attacked particularly by hot water and carbonic acid and the silicates broken down to form lower silica species and other minerals. The excess silica is moved to the more open ground. In the form of quartz, chalcedony, etc., it is progressively fractured and forms the channel and locus of deposition for most of the sulphides."

In more recent years the implications of subcontinental structure in the localization of and search for ore deposits (1959, 1966) attracted Dr. Schmitt's attention.

"The ore deposits of the West...and some of the larger igneous intrusives are associated with, and presumably genetically related to, the major fault zones, orogens, and tectogenes. Intersections are particularly sensitive, as noted by Billingsley and Locke long ago. Triple or more complex intersections are especially potent as localizers for ore districts and smaller mineralized units.

"The chief copper-producing area is in southern Arizona and just over the borders of neighboring states. It is clustered in or near the intersection of the Texas fault zone, a 'Precambrian' northeast lineation, and the Wasatch-Jerome orogen. Most of the copper deposits of the West occur along the Wasatch-Jerome orogen, and a large proportion of these appear to be a little east of a median line on or near a central 'channel'...

"An hypothesis is proposed that the metals are broadly zoned in the earth's crust and mantle and that they were originally derived from the meteoric material of the original earth. Presumably, copper, nickel, cobalt, and iron would be most abundant at the deepest levels; lead, zinc, silver, and gold at the next shallowest; and mercury, antimony, and arsenic near the surface. With such zoning, an especially deeply penetrating structure, such as a tectogene or geosuture, could release the deeper metals along with basic and ultrabasic rocks. Moderately deep orogens could remobilize copper and associated metals; whereas shallow remobilizations of the crust would be likely to deposit and concentrate the other base and the precious metals. Mercury and antimony may be especially susceptible to fumarolic and hot-spring shallow leaching and still shallower precipitation. The active agents of remobilization and collection and transfer of the elements are thought to be heat and gases from the degassing and (or) metamorphism of the earth.

"The persistence of copper metallization in the Southwest from Precambrian to possibly upper Tertiary is explained as the result of continued deep faulting of the crust, and it is suggested that in many places there has been a penetration of the lower crust or even to the mantle."

In the few years just prior to his death Dr. Schmitt had begun to compile his data and impressions on ore deposition and leached cappings related to disseminated copper and molybdenum deposits. Most of the papers have not yet been formally published although they were presented orally on numerous occasions (see, however, 1953a, 1959, 1960, 1961a, 1961b, 1962).

In spite of his positive successes in ore search and development, he wrote in a personal note in 1965 "I feel that an important contribution to the mining industry especially in the Southwest has been my rejection of hundreds of prospects that would otherwise have absorbed and wasted a good deal of exploration money". To this contribution we can add the on-the-job training of numerous young mining geologists and engineers who worked with him during nearly forty years of supervisory activity. His legacy to these men was the example of success resulting from the combination of professional knowledge and professional ethics.

As we look back on the development of Schmitt's studies of ore deposits there is a trend from the detailed to the general, but always with a clear rationale for these studies, namely, our need for the long term exploitation of the earth's mineral resources. As we look forward into the future that includes many new technological advances in field and laboratory methods, including exploration by remote sensing from space, we must not forget the need to understand as fully as possible what we are looking for. This is the lesson we should learn from Harrison Schmitt and his generation.

Dr. Schmitt was a Fellow of the Mineralogical Society of America and the Geological Society of America, and a member of the Society of Economic Geologists, the American Association for the Advancement of Science, the American Geophysical Union, the Geochemical Society of America and the American Institute of Mining and Metallurgical Engineers. He served on the councils of both the GSA and the SEG. He was a member of Sigma Xi, Sigma Gamma Epsilon and Gamma Alpha. His social fraternity at the University of Minnesota was Beta Theta Pi.

Harrison Schmitt was prominent throughout his professional career in the Arizona and New Mexico Geological Societies and local chapters of the AIME. He was an honorary life member of the New Mexico Geological Society and served as its president from 1951 to 1952. He was president of the Silver City AIME at the time of his death. In 1962 he was elected Man of American Mining for that year by Mining World.

His chief clients after becoming a consultant included Duval Sulphur and Potash Company; Lewisohn Copper Corporation; Banner Mining Company; American Smelting and Refining Company; Black Hawk Consolidated Mines Company; American Zinc Company; Kennecott Copper Corporation; Kerr–McGee Corporation; New Jersey Zinc Company; Peru Mining Company; U.S. Smelting, Refining and Mining Company; Quintana Petroleum Company. During the Depression years he organized the Shingle Canyon Mining Company and developed a small lead-zinc mine near Fierro, New Mexico. This mine was later sold to the U.S. Smelting, Refining and Mining Company.

Although El Paso, Texas, was the center of this early consulting activity he moved to Hanover, New Mexico, in 1933 where he had lived previously while working for New Jersey Zinc Company. The family then moved to nearby Silver City in 1937. Next to his beloved Minnesota lakes, Silver City remained "home" through the following years of travel.

Dr. Schmitt's interest in civic activities, education in particular, was reflected in his tenure from March 1961 to April 1964 as president of the Board of Regents of Western New Mexico University at Silver City. He was also in demand as a speaker not only in his profession but with civic groups who wished to hear about other of his varied interests, including archaeology, meteorology and economics. He was an honorary life member of Rotary International, an honor he valued as highly as any.

Harrison is survived by his wife, Ethel Hagan, a Tennessee-born teacher whom he married in 1929; by three children, Alexandra (Mrs. B. E. Decker, known as Sandra) of Woodland Hills, California, Harrison Hagan (Jack) of Houston, Texas, and Armena of Tucson, Arizona; two granddaughters, Janis and Linda Decker; and by three sisters, Mrs. Helen Staples of Wausau, Wisconsin, Mrs. Gretchen Strong, of Silver City, New Mexico, and Mrs. Wilhelmina Palmen of Wabasha, Minnesota. A daughter, Paula, died at age two in 1939.

"The Doctor" died of a first heart attack on October 26, 1966 at the age of 70. The week before his death he took his last trip with a client through Nevada and California examining several properties in some of the most beautiful mountain country in the world. He received "...as much pleasure from that trip as from any in recent years". This was the retirement he talked of for many years.

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FOREWORD

Guidebooks Number I and II, published by the Arizona Geological Society in 1952 and 1959 presented broad systematic information related to geology of this part of the Basin and Range Province. This Guidebook, the third, represents a departure from the previous broad outline format. The information presented is intended to update the previous volumes in those areas of study in which considerable advances have been made, and in which new data have been acquired. I believe that the general articles in the book reflect a fair sample of the proportion of efforts devoted to various geological studies in this region since publication of Guidebook II.

Perhaps the greatest amount of geological field and laboratory research work devoted to fundamental topics has been given over to intensified efforts at unraveling the problems of the Mesozoic and Cenozoic Eras and the nature of the Laramide Revolution. Such an evaluation is not intended to slight the work carried out in other subject areas as much fundamental geological field and laboratory study continues to be carried out across the broad spectrum of geological problems that exist in the region. While prior decades witnessed the development of present concepts of Paleozoic history, for example, preliminary solution of the complex problems of the Pennsylvanian and Permian, and evolution of working concepts of Precambrian history, the past decade of work has resulted in the gradual emergence of ideas of the history of the Mesozoic and Cenozoic Eras in this southern part of the Basin and Range Province.

Several factors have probably contributed to the heightened interest in this portion of the geologic column. Increased recognition of the importance of the Cenozoic as a consequence of its water potential and source of certain building materials has resulted in much study and a considerable body of new information. The search for copper and other metals in the Province has spurred interest in the events and the time that gave rise to these deposits. The acceleration of data gathering as the result of increasing numbers of geologists studying the problems, and the advent of new research tools has enabled workers to attack problems of volcanic stratigraphy hitherto considered too complex for solution by field methods alone. Such an example is the establishment of a chronologic framework for the Mesozoic–Cenozoic volcanic stratigraphy and thus the sedimentary stratigraphy at the Era boundaries. As another, new geophysical measurements have provided information useful to reinterpretation of the nature of structural evolution of the region.

I have attempted to select papers for the general part of the Guidebook that, although reflecting new interpretations also represent contributions or compilations of factual information relative to the problems which exist here. It is the hope of the Arizona Geological Society that the users of this book will find much stimulation from its content.

ACKNOWLEDGEMENTS

Many persons have contributed to the preparation and publication of this third Guidebook, not the least of whom have been the authors themselves. The cooperation of all who have contributed and their parent organizations is gratefully acknowledged. Dr. Evans B. Mayo, General Chairman of the 64th Annual Meeting of the Cordilleran Section of the Geological Society of America has materially assisted in organizing the Guidebook. Mr. Steven Congdon has overseen the matters of business management. Mr. J. David Lowell has organized the field trips. Drs. John W. Anthony and Esther A. Holm and Mrs. J. K. Percious have assisted in editing and proof reading.

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S.R. Titley
Tucson, Arizona
March 1, 1968

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GENERAL ARTICLES

ROAD LOGS

RECENT DEVELOPMENTS IN THE GEOLOGY OF THE RAY AREA

By

R.A. Metz, C.H. Phillips
Ray Mines Division, Kennecott Copper Corporation

and

C.R. Caviness
Arizona District, Bear Creek Mining Company

INTRODUCTION

The Ray porphyry copper deposit is located in southeast central Arizona in the Mineral Creek Mining District of Pinal County. It is approximately 70 miles north of Tucson and about 75 miles east of Phoenix on Mineral Creek.

Mining activities began as early as 1870 with the location of claims in the search for gold and silver. From 1870-1906 sporadic attempts at mining by several companies were economic failures. In 1906 D. C. Jackling and associates acquired control of part of the deposit. They began an ambitious, well-directed exploration program which led to the profitable production of copper.

From 1911-1955 mining was by a combination of shrinkage and block caving methods. Since 1955 all mining has been from two connecting pits, the Pearl Handle Pit and the West Pit. The present production rate is more than 25,000 tons of ore per day in addition to dump leaching of the caved areas.

Since 1911 the Ray deposit has produced over one and one-half million tons of copper, 40,000 ounces of gold, and 4 million ounces of silver. Gross value of this production is in excess of half a billion dollars.

Objective in Presentation

The purpose of the paper is to update the general knowledge and developments in the geologic undertaking of the Ray District since the April, 1952 edition of the Arizona Geological Society *Guide Book for Field Trip Excursions in Southern Arizona (1).* In that edition, Otis M. Clarke, Jr. presented the paper, "Structural Control of Ore Deposition at Ray, Arizona." Since 1952 considerable additional knowledge has been gained from detailed field and pit mapping, new exposures in mining, and by drilling. These recent developments and concepts will be emphasized in this presentation.

MAPPING PROGRAM

A detailed geologic mapping program was initiated in 1954 and completed in 1963. Nine square miles around the pit area were mapped at a scale of 1 inch equals 100 feet. The mapping, in general, covers an area of from one to a little over two miles from the pits (Figure 1). In some areas mapping extends farther out to include important geologic features.

In the field, outcrop geology was plotted directly on topographic sheets with alteration and mineralization plotted on transparent overlays. Interpretation at the field scale followed and this was reduced to 1 inch equals 500 feet for the district map. Alteration overlays were also prepared for the district geologic map. From the compiled district geologic map and the drill hole information, cross sections were constructed and interpreted.

For the initial mapping in the pits a scale of 1 inch equals 100 feet was used. For pit progress mapping 1 inch equals 200 feet is used. Initially, mapping of the pit benches was done by compass and tape with the aid of survey points, power poles, and other features previously plotted on the engineering department's pit topographic progress maps. However, this method had many limitations. One can imagine trying to tape around an active shovel and its trucks. A plane table method utilizing two-way radios was developed which allowed the plotting of rapid changes of benches in the more active areas as well as plotting the new geologic exposures at the same time. As a result, almost all pit mapping has been done with the plane table. Level maps, one for every 50-foot bench, were made with all available underground geologic data included.

GEOLOGY

One of the most comprehensive publications on the Ray District is the U.S. Geological Survey Professional Paper 115 by F. L. Ransome (1919-1923). Although this work contains an excellent description of the Ray deposit, emphasis is on the geology of the Ray Quadrangle. Other works on the Ray deposit are by Spurr

Plate I – Aerial photograph of the Ray Mine area (fall, 1967) showing (1) West Pit, (2) Pearl Handle Pit, (3) Emperor Hill, (4) Silicate ore area, (5) Kennecott mine shops, (6) silicate ore leaching plant site, (7) state highway 177, (8) visitors observation point.

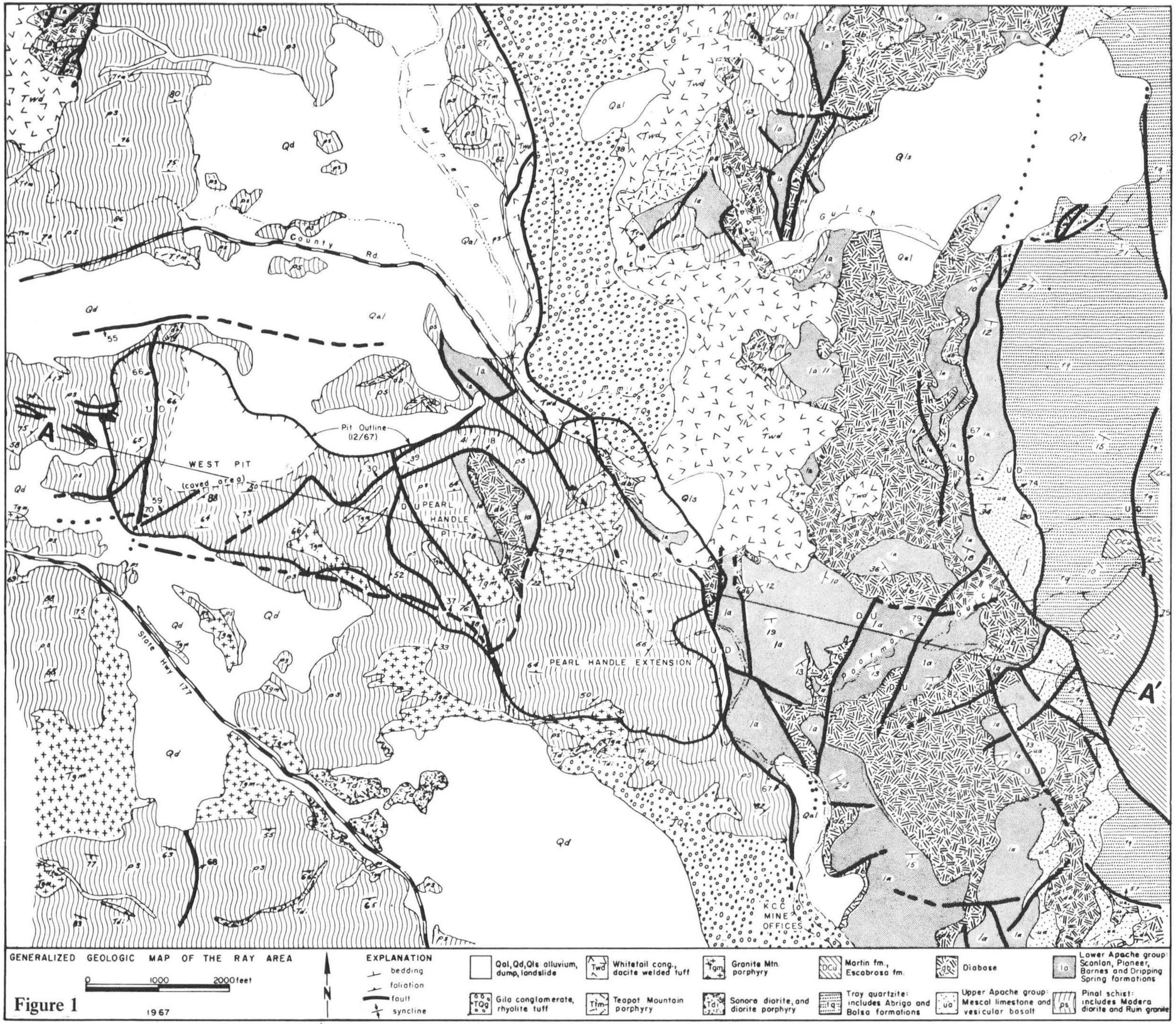
GENERALIZED GEOLOGIC MAP OF THE RAY AREA
0 1000 2000 feet
1967
N
EXPLANATION
bedding
foliation
fault
syncline
Qal, Qd, Qls alluvium, dump, landslide
Gila conglomerate, rhyolite tuff
Whitetail cong., dacite welded tuff
Teapot Mountain porphyry
Granite Mtn. porphyry
Sonora diorite, and diorite porphyry
Martin fm., Escobrosa fm.
Troy quartzite: includes Abrigo and Bolsa formations
Diabase
Upper Apache group: Mescal limestone and vesicular basalt
Lower Apache group: Scanlan, Pioneer, Barnes and Dripping Spring formations
Pinal schist: includes Madera diorite and Ruin granite
WEST PIT
(caved area)
Pit Outline (12/67)
PEARL HANDLE PIT
PEARL HANDLE EXTENSION
KCC MINE OFFICES
County Rd.
State Hwy 177
A
A'

Figure 1

and Cox (1909); Otis M. Clarke, Jr. (1952), and R. A. Metz and A. W. Rose (1965). Many other authors of company reports have contributed greatly to the knowledge of the Ray deposit.

The following general description of the geology is largely summarized from the presentation by R. A. Metz and A. W. Rose, which appears in the *Geology of the Porphyry Copper Deposits Southwestern North America* (1966).

Rock Types in the Mine Area

Precambrian Rocks. Both Older and Younger Precambrian units are present in the mine area (Figure 3). The Older Precambrian is represented by the Pinal schist, which is derived from clastic sediments and some igneous rocks, the Madera diorite, and the Ruin (Oracle) granite. The Younger Precambrian rocks are the Apache group, which was deposited unconformably on the schist, and the Troy quartzite. The Apache group is divided into the Scanlan Conglomerate, Pioneer Shale, Barnes Conglomerate, Dripping Spring Quartzite, Mescal Limestone, and vesicular basalt. These were in turn intruded by diabase as thick sills, dikes, and irregular masses.

Paleozoic Rocks. The Paleozoic rocks have been removed by erosion in the immediate mine area; however, about a mile east of the deposit, in the Dripping Spring Mountains, the following Paleozoic rocks crop out (Figures 1, 3): the basal Cambrian Abrigo(?) Formation, and possibly the Bolsa Quartzite (M. H. Kreiger, oral communication), which overlie the Troy Quartzite. Conformably above the Abrigo is the Devonian Martin Limestone, which is overlain by the Mississippian Escabrosa Limestone.

Cenozoic Rocks. The Cenozoic rocks are represented by a series of six Tertiary intrusive rocks ranging in composition from diorite to quartz monzonite.

The intrusive rocks, in order of decreasing age, are: quartz diorite, diorite porphyry, Granite Mountain (quartz monzonite) porphyry, andesite, Teapot Mountain (quartz monzonite) porphyry, and a quartz diorite porphyry. The diorite porphyry was thought, at one time, to be a phase of the quartz diorite, however, recent detailed work shows it to be a separate intrusive.

Of the above intrusive rocks, the most abundant in the mine area is the Granite Mountain porphyry, considered to be the "mineralizer" for the Ray deposit.

The youngest strata deposited were the younger Cenozoic Whitetail Conglomerate, dacite welded tuff, Gila Conglomerate, and rhyolite tuff.

GENERAL FEATURES OF MINERALIZATION

The mineralization at Ray occurs in an area that is about two miles long east-to-west and one and one-half miles long north-to-south. The bulk of the copper produced from Ray has come from secondary deposits of enriched chalcocite ore. The chalcocite ore forms an irregular blanket of from a few feet to several hundred feet thick. Capping this "blanket" was an average of over 200 feet of leached and hematite-stained Pinal Schist. Although most of the production to date has been from Pinal Schist, the primary ore in Schist averages between 0.1 and 0.2 percent copper as chalcopyrite. Without enrichment the Schist seldom contains ore grade mineralization. This is also the case with the Granite Mountain porphyry. Only the diabase contains abundant primary ore grade mineralization. At one time ore intercepts in diabase were dismissed as unreliable and were deleted from ore reserve calculations. The diabase is now recognized as having been the most important primary host rock in the district. Where mineralized, the diabase has a distinct gradient in copper content. The upper portions of the sills usually contain the higher grade copper, the tenor decreasing with depth. Successively deeper sills exhibit a similar gradation, although the overall grade is low.

Mineralization Controls

Controls for the hypogene mineralization were structure, including rock permeability, and rock type. Controlling factors for supergene mineralization were structures and available pyrite to be replaced as chalcocite. Better grade primary mineralization occurs in highly fractured zones in the vicinity of the porphyry stocks. Less intense fracturing generally is followed by a drop in copper grade as well as intensity of quartz veining and alteration. Diabase apparently was the most reactive and intensely fractured of the pre-ore rocks, thereby accounting for its importance as a host rock.

The zone of supergene enrichment shows a marked relationship to several major structures as well as to lithology and location of primary sulfide concentrations. Copper rich solutions came from areas of high pyrite (hence high acid formation) content with appreciable copper content. These solutions moved down and laterally along structures through the chemically unreactive rocks (schist and porphyry) to replace pyrite and chalcopyrite.

One of the most important structural controls for supergene ore is the Emperor fault which is a low-angle fault zone containing up to thirty feet of gouge along its trace. It is along this zone, and in the footwall, that the higher grade chalcocite ore was developed.

STRUCTURE

The Ray deposit is believed by the writers to be among the most structurally complex of the porphyry coppers; no doubt this opinion is shared by many of those who have studied it for even a short while. The deposit occurs in an area which has undergone major structural disturbance during several periods ranging from Precambrian to post-Miocene. More often than not, the same major faults have been active during more than one of these epochs and both direction and magnitude of displacement are likely to have been different in each recurrence. For this reason age relationships of intersecting faults are often quite obscure.

Detailed surface mapping has helped unravel a number of such problems, but, just as often, has complicated what had been thought to be a rather simple situation. Frequent mapping of new exposures in the pit has been most helpful in defining important faults and related problems. Notable among these are the School-Ray-Diabase fault system and the Emperor fault which will be discussed below.

The major faults in the district as interpreted from the detailed mapping are shown in Figure 2 as well as Figure 1. The arrangement and distribution of these faults defies any concise, comprehensive description. The School-Ray-Diabase and Broken Hill fault zones might be thought of as reflecting Basin and Range type faulting, and the Porphyry break, North End and Rustler faults conjugate to these, but both systems have been found to pre-date what is generally thought of as Basin and Range faulting. The gross surface relationships suggest step faulting which is progressively down to the east (Figure 1), the throw on the Broken Hill fault being over 1000 feet. The reverse movement on the School-Ray-Diabase zone (now recognized as one continuous structure) may be variously interpreted from outcrop information as having a throw of from 300 feet north of the mine to in excess of 1500 feet near the south end. This fairly simple picture was greatly complicated with the identification of Apache group strata beneath the Emperor fault (Figure 5). Improvements in diamond drilling and careful geologic mapping guided by a background of detailed study in the district have made possible the documentation of the Apache strata and the diabase sill which intrudes them in the area between the Pearl Handle Pit and the Ray-Diabase fault zone and along strike from the North End fault southward to the limit of information. Directly above the diabase sill in the pit in the hanging wall of the Emperor fault a minimum of 1000 feet of Pinal Schist was formerly present. In other words, had erosion proceeded at a much faster rate, or the surface mapping delayed a few million years so that everything above the Emperor fault were stripped off, the Ray-Diabase fault zone would to all appearances be a normal fault. The evidence of reverse movement persists, though, in the offset of the dacite and rhyolite tuff beds and the resultant syncline in the rhyolite north of the pit. This intriguing relationship has given rise to a number of hypotheses, all deficient in some respects, regarding the relative movements on the Emperor and School-Ray-Diabase faults. From the present state of information, it appears that 1) part of the movement on the Emperor fault was post-enrichment, and 2) the Emperor fault has been offset by the School-Ray-Diabase fault which had in part been intruded by Precambrian diabase. The solution of this problem has a direct bearing on mining problems inasmuch as the intersection of these structures occurs near the geographic center of mineralization.

In the block between the School-Ray-Diabase and the Broken Hill fault zones, a low-angle east-dipping fault zone has been detected which offsets the Pinal Schist and lower Apache Group (Figures 1, 2 and 4a). The zone has been intruded by diabase. Because it cuts the schist almost perpendicular to the schistosity, the fault is felt to be pre-diabase, rather than a result of the diabase intrusion, and is referred to as the pre-diabase thrust. Detailed mapping and drill hole information have made it possible to trace this zone through several offsets from the Rustler fault to the south boundary of the area mapped.

The Rustler fault is similar in several ways to the School-Ray-Diabase fault zone. Its attitude is apparently steep and displacement is about 1500 feet putting Dripping Spring Quartzite in juxtaposition with Pinal Schist; it appears to have both pre- and post-diabase movement, but does not cut the Tertiary strata. Detailed mapping shows the fault to have been intruded by diabase and quartz diorite porphyry, the oldest and youngest intrusives in the district. A small vein system of sub-economic base metal mineralization striking parallel to the Rustler fault crops out a short distance to the southeast, but there is no indication of mineralization northwest of the fault.

Another recently defined structure is the Teapot Mountain fault in the extreme northwest corner of the area. This fault separates the relatively undisturbed Pinal Schist from a chaotic assemblage of outcrops of thoroughly brecciated Apache Group and diabase on the west. The Apache Group rocks, although thoroughly broken, are arranged in general stratigraphic sequence from south to north; in many places the fault zone is occupied by shattered Madera diorite. S. C. Creasey (oral communication) has suggested that this may be a megabreccia resulting from a huge collapse structure centered beneath the Whitetail Conglomerate to the west, an interpretation which is compatible with the field data.

One of the most interesting structural features discovered during the detailed mapping program is the Calumet breccia pipe (Figure 1). At the surface the

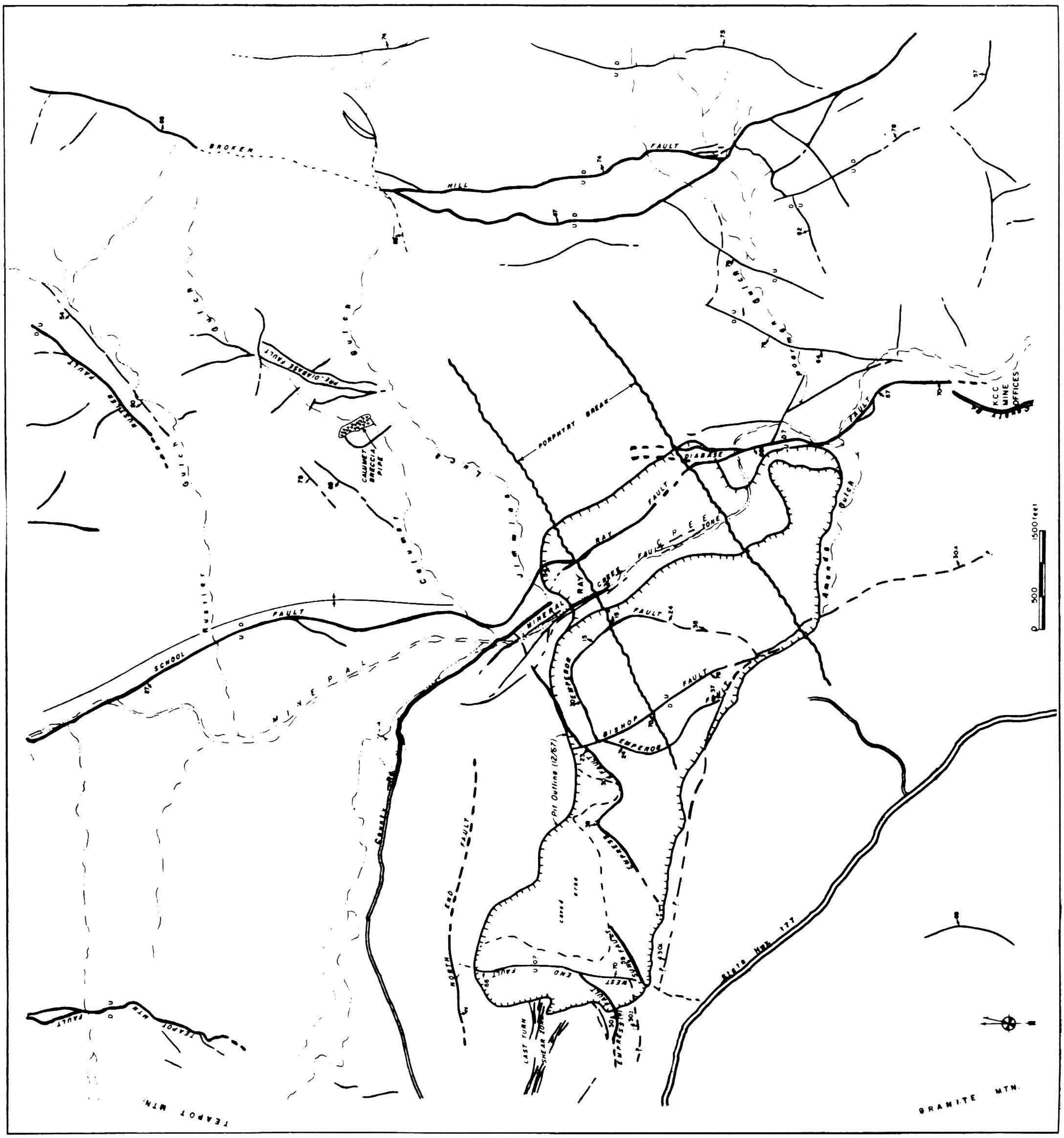

Figure 2 — Map showing major faults in the Ray District

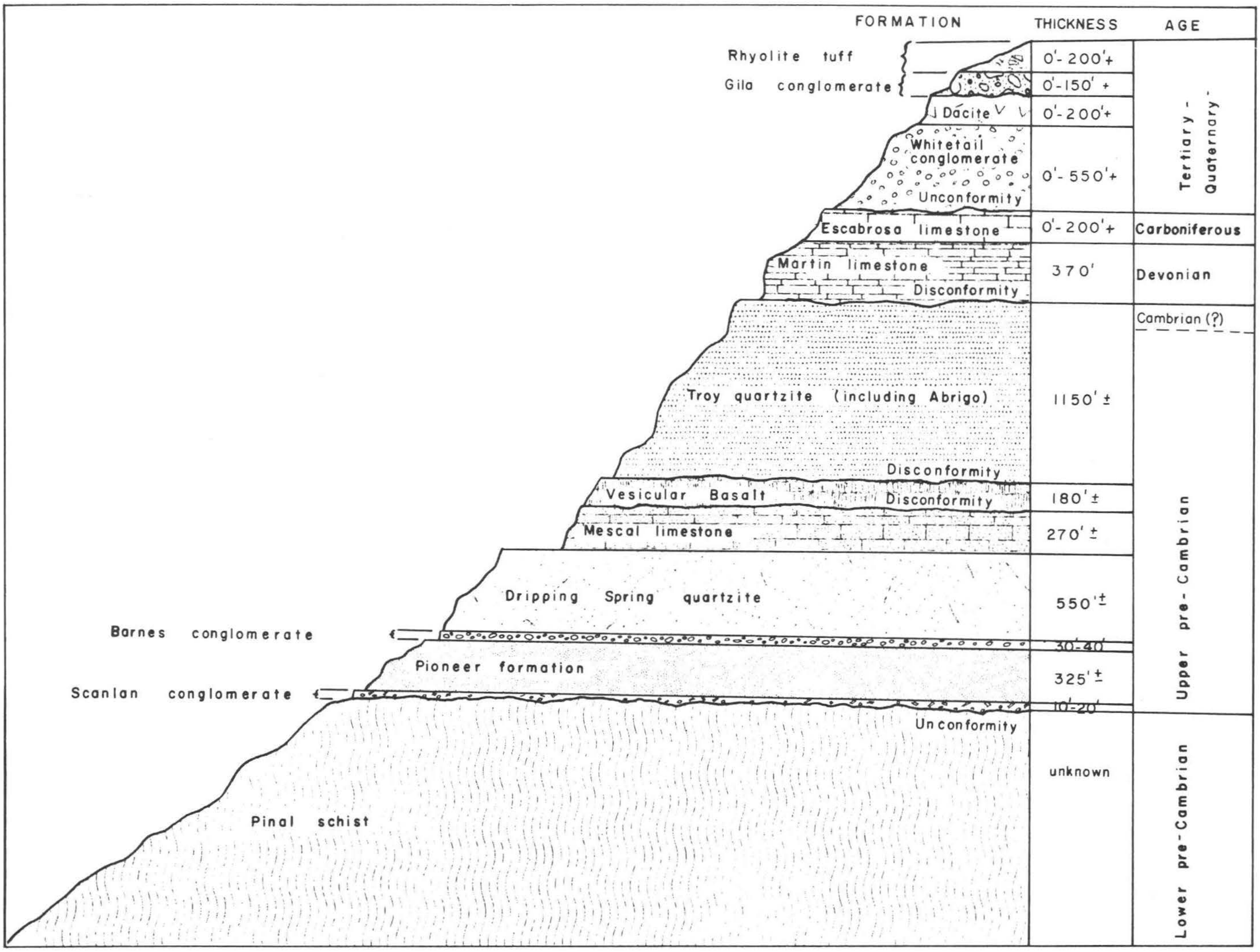

Figure 3 – Stratigraphic Section, Ray, Arizona

pipe covers an elliptical area whose maximum dimensions are 200 feet by 600 feet. The component rock types are those immediately adjacent to the pipe: diabase, Pinal Schist, Pioneer Shale, and the Scanlan member. The most competent of these, the Scanlan, occurs in fragments up to 15 feet in diameter. Spatial distribution of the fragments indicates a general collapse movement, presumed to have been caused by a magmatic pulsation and subsequent withdrawal. The breccia is pre-mineral and locally contains copper oxides and silicates at the surface which give way to primary sulfides (chalcopyrite, pyrite, and molybdenite) at depths of 20 to 400 feet. The pipe has been cut by a dike of quartz diorite porphyry and several small pebble dikes, all of which are post mineral. The latter have been found to contain pebbles of Granite Mountain porphyry, brought up from an unknown depth, which is thought to be responsible for the mineralization. Early attempts at mining in the pipe from three shafts and several drifts and crosscuts were unsuccessful due to the erratic nature of the mineralization.

Test drilling has indicated the possibility of another such breccia pipe west of the Calumet pipe beneath post-mineral cover. This has not been confirmed, nor are any details of the structure known.

ORE DEVELOPMENT

A program of detailed study such as that outlined above would be of little value if it could not be profitably applied to the development and exploitation of the orebody. This has been the main objective at Ray and a fair measure of success has been attained.

Fundamental to the development of the deposit was the recognition of the ore controls. These are both structural and lithologic. For example, the Porphyry break is interpreted as a deep-seated structure which controlled the intrusion of the Granite Mountain porphyry; the intrusion reactivated old faults and produced new ones which allowed the later ore fluids access to the diabase, schist, and other well prepared host rocks. Faults, shattered porphyry contacts, and the diabase sills themselves served as conduits for the hypogene fluids. The diabase was a major controlling factor in localizing ore deposition. After studying the district it can safely be said that more copper has been added to the diabase than all other rocks combined (3). Complications result from post-ore faulting in various directions and distances, often offsetting the ore. The embryonic knowledge of these controls played a major role in developing large tonnages of silicate and sulfide ore east of Mineral Creek during the middle and late 1950's; the improved knowledge of ore controls continues to play a vital part in ore development. As in other districts, a number of intriguing possible ore loci have been suggested by detailed study.

THE SILICATE OREBODY

A few years ago, Ray Mines Division was faced with limited ore reserves. It was known at that time that the diabase beneath the Emperor fault had some ore grade mineralization of unknown extent and also that there were scattered showings of oxides in the diabase east of Mineral Creek. A drilling program undertaken on the basis of this knowledge subsequently expanded the sulfide reserves sufficiently to justify construction of a smelter and turned up an anticipated tonnage of silicate ore east of Mineral Creek; however, the silicate copper was not recoverable without the development of a special plant (Plate 1). Several years of study and pilot plant operation have culminated in the plant presently being constructed.

Structure and Origin

The silicate orebody is irregular in plan and varies greatly in thickness though most of it occurs in the diabase sills (Figure 4b). It is elongate parallel to the strike of the sills, extending across the Porphyry break (Figure 2) and beyond about 500 feet to both north and south. It sometimes overlies primary ore but is in part exotic. The exotic ore is found in the dacite, the Whitetail Conglomerate and possibly in the diabase and in other rocks of the Apache Group. Four factors are considered to have been of primary importance in localizing the orebody: 1) reactivity of the diabase, 2) strong shear zones, 3) high relief of the pre-Whitetail Conglomerate erosion surface, and 4) lack of a high pyrite content throughout much of the silicate area. Deep oxidation was facilitated by both the structure and the deep pre-Whitetail erosion while the chemical reactivity of the diabase tended to fix the copper within the diabase. The lack of a high sulfide content in much of the silicate area might be considered a permissive factor in non-removal of the copper since a higher sulfide content normally results in greater acid production as weathering progresses and much greater leaching of copper. There is evidence that hot spring activity supplied or mobilized silica locally, and this may have contributed to the precipitation of copper from ground water. Exotic mineralization in post-mineral rocks is evidence that some copper was transported either from the high sulfide area west of Mineral Creek or from the diabase east of Mineral Creek. Silicate ore in pre-ore rocks overlying lower grade or nil primary copper mineralization also may be due in part to oxidation of a pre-existing chalcocite enrichment blanket instead of, or in addition to, oxide enrichment.

Mineralogy

At the inception of development work on the silicate orebody, the mineralogy was thought to be quite simple, mainly chrysocolla with minor copper-manganese oxide, cuprite, malachite and native copper. As time passed and research progressed, the mineralogy became less and less simple. In the Dripping Quartzite and Pioneer Shale, there are small amounts of cuprite, malachite and native copper, but most of the copper, particularly in the diabase, is tied up in a complex of oxides and silicates. Chrysocolla is the predominant silicate. Other copper bearing minerals that have been at least tentatively identified are the clays montmorillonite and halloysite, lampadite, possibly tenorite, cupriferous wad, and extremely finely divided native copper.

Copper halloysite is an important ore mineral, its copper content ranging up to 17 percent (7). The copper halloysite distribution follows that of chrysocolla, and its identification is best made in the laboratory as its appearance is often similar to that of the chrysocolla. Copper montmorillonite is also common but of less significance as an ore mineral because the copper is more difficult to extract from the montmorillonite. The copper content of the mineral may exceed 8 percent, nonetheless, the strongest color shown by copper montmorillonite is very pale green in contrast to the deep blue-green of some copper halloysite.

Also of interest are unusual, though far from economic, amounts of cobalt and nickel within the exotic secondary copper minerals. The most probable source of cobalt and nickel is the diabase, which suggests that some portion, if not all, of the exotic mineralization came from the diabase to the east of Mineral Creek.

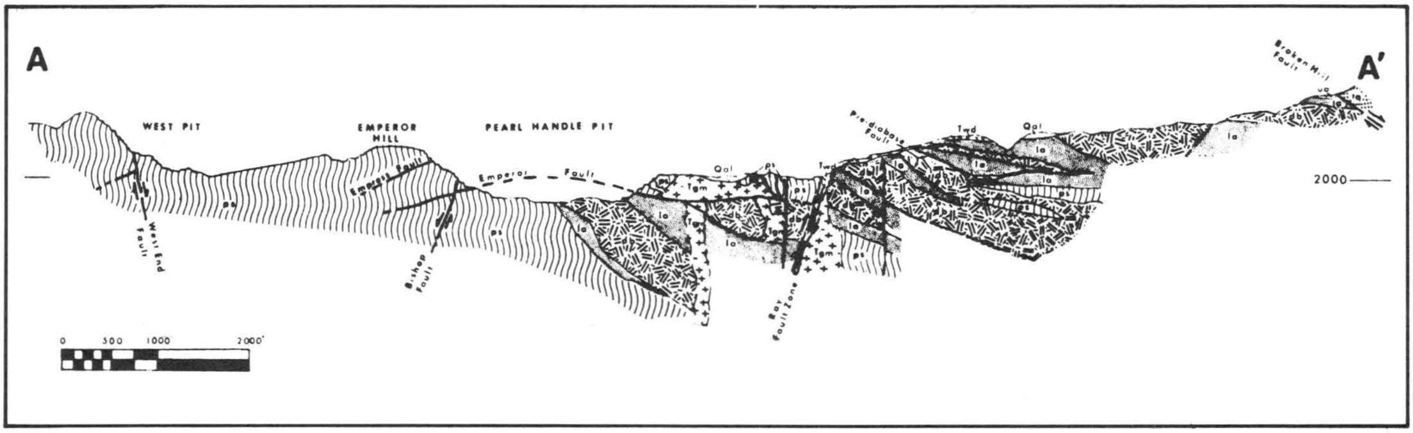

Figure 4a – Geological Section A-A'

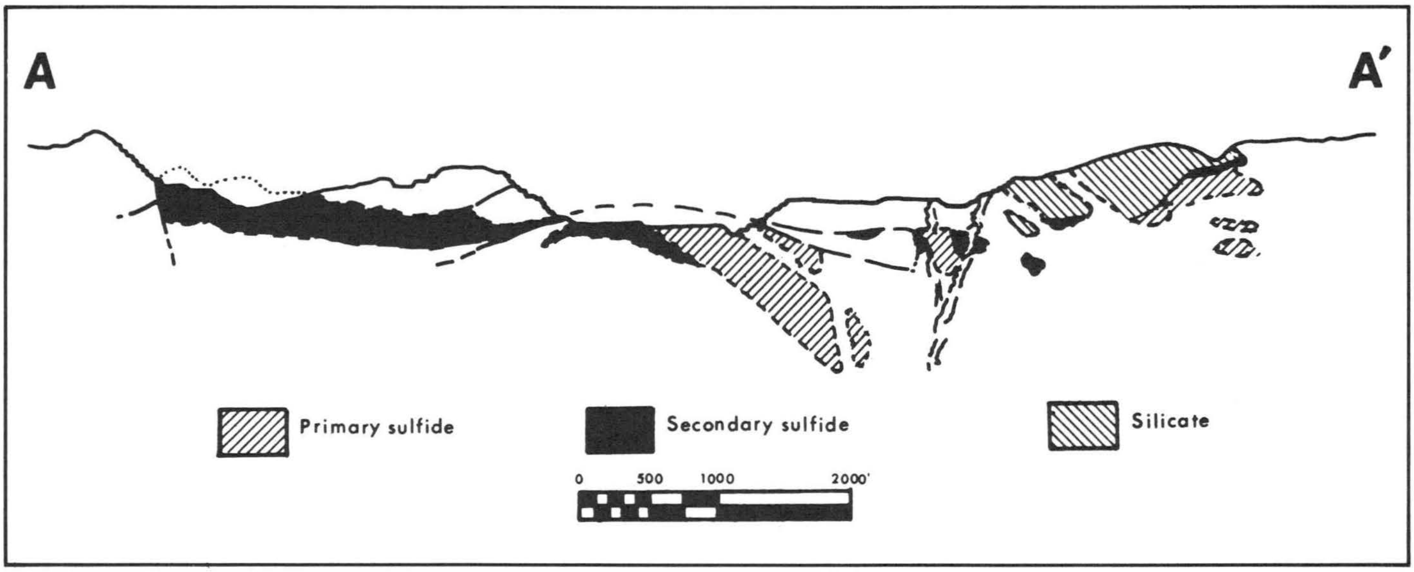

Figure 4b – Section A-A' Showing Mineralization Types

Treatment

The silicate ore leaching plant now being constructed at Ray Mines Division will cover an area of 28 acres and cost more than 35 million dollars. It will process 10,000 tons of ore per day and produce 24,000 tons of copper annually. Treatment of the ore will consist of three crushing stages, after which the sand and slimes will be split. The sand will then go through a ten-day counter-current vat leach and the slimes through an agitated leach. Final recovery of the copper from solution will be by electrowinning. Acid for the leaching process will be produced from smelter gasses by a special plant at the Hayden smelter. This plant will serve the dual purpose of acid production and atmospheric pollution control.

Stripping of the silicate ore began in mid-1967. Silicate ore mined from the Mineral Creek channel cut and other areas has been stock-piled pending completion of the leaching plant in the latter part of 1968.

SUMMARY

The foundation laid by previous workers and detailed geologic study of the Ray (Mineral Creek) District have resulted in several new concepts of ore control and deposition in this very complex porphyry copper deposit. Among these are the following:

1) In the proper environment diabase and other basic intrusives may contain extensive ore grade copper mineralization.

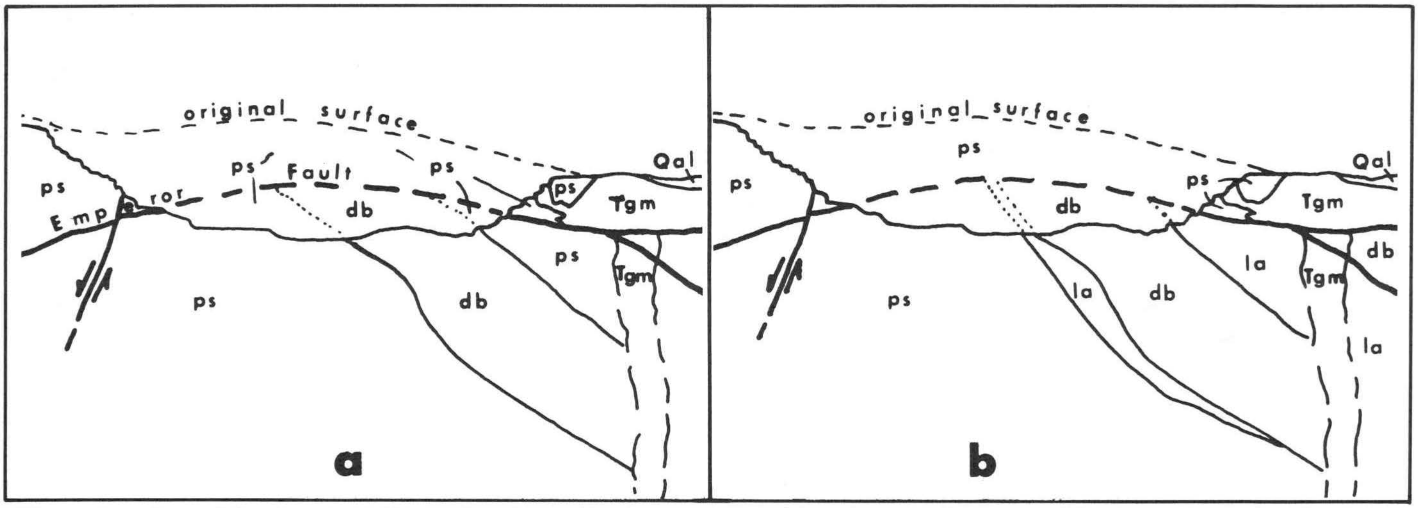

Figure 5 – Part of Section A-A' illustrating the earlier interpretation (a) and presently known (b) relationships of rocks above and below the Emperor fault in the Pearl Handle Pit. Pinal Schist (ps), diabase (db), Granite Mountain porphyry (Tgm), and lower Apache group (1a) [Scanlan and Pioneer formations below and Pioneer and Dripping Spring formations above the diabase sill].

2) Because of its chemical composition, diabase is likely to contain supergene enriched sulfide ore only in areas of high pyrite content. It may, however, undergo supergene oxide enrichment resulting in copper silicate ore.
3) In exploring diabase sills the upper portions will probably contain the better grade mineralization.
4) Successive underlying sills of diabase can be expected to be of lesser copper content.
5) The Granite Mountain porphyry, Pinal Schist, and Apache Group quartzites are not likely to contain large tonnages of primary copper ore.
6) Strong low-angle faulting occurs extensively in the district. Both pre- and post-mineral movement may have occurred on these as well as the high-angle faults.

The above statements represent the state of the writers' present knowledge. Because the Ray deposit has a reputation for repeated destruction of geological hypotheses, it is not unlikely that these too will undergo extensive alteration before the orebody is mined out.

Acknowledgments

Acknowledgment is due Messrs. Donald D. Smythe and Allan H. James, supervising geologists of the Kennecott Operating Properties Division, 1954-60 and 1960-67 respectively for their able direction and assistance in the geologic study of the Ray area. In addition to those cited in the references, credit is due the following for "breaking trail" in Ray geology: J.B. Wertz, senior geologist, 1954-59; and geologists D. LeBiondo, 1954-56; D. Newberg, 1956-57; and D. Marksbury, 1957-58.

The active interest of Messrs. A. P. Morris (deceased) and I. G. Pickering, general manager of Ray Mines Division, Kennecott Copper Corporation, has been a valuable stimulus to the geologic program.

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INTRUSIVE VOLCANIC PHENOMENA IN SOUTHERN AND CENTRAL ARIZONA

By

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INTRODUCTION

In recent years the attention of field and laboratory geologists in Arizona has been shifting from Paleozoic and younger Precambrian stratigraphic sections to those areas in which are exposed Mesozoic-Cenozoic volcanic rocks and clastic sedimentary rocks. This changing emphasis of study has been brought about, in part, by interest in volcanic rocks and their associated sedimentary rocks, and, in part, by economic incentive—the realization that much of Arizona's copper was emplaced in Late Cretaceous-early Tertiary (Laramide) times.

Many of the areas of Mesozoic-Cenozoic rocks are structurally complex, and the origins of various of the rock units are in question. A general lack of knowledge concerning volcanic processes has, in the past, caused study of these areas to be by-passed in favor of the less complex and better understood older rock sections.

The writer has been involved in the study of Mesozoic-Cenozoic volcanics for several years and has recognized a phenomenon which he believes to be widely. present in southern and central Arizona. Certain igneous rock units which are megascopically and petrographically volcanic exhibit indisputably intrusive relationships with adjacent stratigraphic units. These intrusive volcanic rocks, where encountered, might have led to the confusion of workers in volcanic stratigraphy in the past, and it is hoped that a description of some of these phenomena will assist future geologic mapping and interpretation.

This paper will describe first the intrusive volcanic units studied in the detail by the writer in the Silver Bell Mountains. Following are brief geologic summaries of each of the other localities in which the definite or possible presence of intrusive volcanic phenomena has been discerned.

INTRUSIVE VOLCANIC ROCKS IN THE SILVER BELL MOUNTAINS

Dacite Porphyry

The dacite porphyry is exposed over large areas in the southern, southwestern, and western portions of the Silver Bell Mountains (30 airline miles west-northwest of Tucson). The porphyry is underlain by Paleozoic sedimentary rocks on the southwest and overlain by Late Cretaceous Claflin Ranch sedimentary rocks and Silver Bell andesite breccia to the north and northwest. The following description has been abstracted from a detailed study of the dacite porphyry given elsewhere (Watson, 1964, p. 26-42, 139-143).

Field Description The most distinctive feature of the dacite porphyry is the presence of numerous small, rounded to subrounded, quartz "eyes" (.04 to .15 inch in diameter) which, along with small white feldspar phenocrysts and a few biotite flakes, are set in an aphanitic matrix. Also distinctive are the numerous xenolithic fragments frequently up to an inch in diameter. Limestone fragments are plentiful near the base of the unit and schist fragments are prevalent in the uppermost 100 feet. Pieces of quartzite, a bedded or banded shaly material, and a homogeneous silty or arkosic material are common to all exposures of the dacite porphyry.

Flow structure within the upper portion of this unit is shown by a platy layering which is emphasized by weathering. This layering consistently strikes northwest and dips 20-35° to the northeast. A visible foliation, as shown by alignment of fragments and phenosrysts, is locally present near the base of the dacite porphyry with strikes and dips similar to those of the platy layering. These indications of a consistent flow structure allow a thickness computation—approximately 3,400 feet—for the main body of the porphyry.

Petrographic Description Significant petrographic features of the dacite porphyry as determined from the study of many thin sections are the presence of rounded and embayed quartz phenocrysts, large fragments of quartz, distinct shards in the matrix, a generally consistent flow structure, and presence of about 3% of sanidine and orthoclase phenocrysts (see Figure 1). The rather high potash feldspar content of the rock shown by the sanidine phenocrysts and by positive reaction of much of the matrix to staining by cobaltinitrite solution strongly suggests that the dacite porphyry is more truly a quartz latite porphyry.

Also noteworthy is the fact that the ratio of phenocrysts to matrix appears to decrease upward in

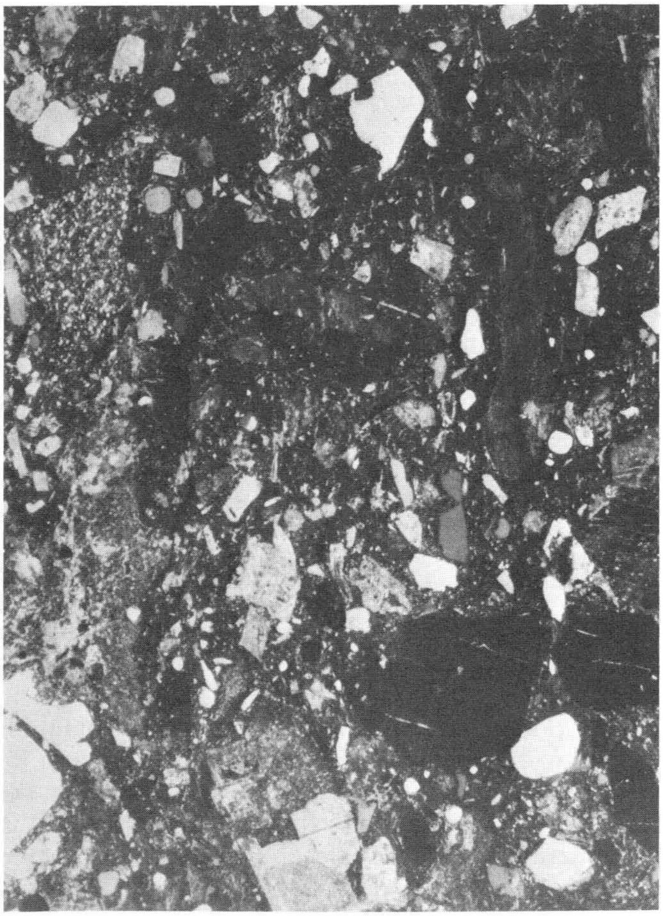

Figure 1 – Photomicrograph (crossed nicols) of dacite porphyry, showing flow structure. Slivers of quartz and a stretched lapillus indicate flow north-south across the photograph. The volcanic nature of the rock is apparent. (W 15.)

the unit. The quantity of xenoliths however, does not reflect such a distribution. Fragments are most numerous near the base of the dacite porphyry, least numerous in the central portions, and abundant in the upper portions.

Structural Relationships Mapping of the basal contact of the dacite porphyry (Figure 2a) shows the unit to deeply embay the Paleozoic sedimentary rocks and to intrude them forceably along parallel bedding planes east of El Tiro pit and north of Oxide pit. In a few places intact beds of limestone up to 15 feet long are engulfed in porphyry 5 to 10 feet from the contact. In the El Tiro pit area drilling data show that the dacite porphyry invades the Paleozoic strata as dikes and sills.

The dacite is generally overlain by sedimentary rocks of the Claflin Ranch Formation, and the contact between the two units is so gradational that neither field mapping (Figure 2b) nor petrographic study can locate it more closely than 6 feet. Indirect evidence suggests that this contact is intrusive, but conclusive evidence is found in the form of dacite dikes–petrographically nearly identical to the main body of dacite porphyry –intruding the overlying Claflin Ranch Formation. Assimilation of schist-fragment-bearing Claflin Ranch beds by dacite porphyry is indicated by the large number of schistose xenoliths in the upper portion of the dacite.

The contact between the dacite porphyry and the later Silver Bell andesite breccia is erosional.

It is of further interest to note that the 5000-foot thickness of Amole-type arkoses described by Clarke (1965) in the West Silver Bell Mountains are absent in the main Silver Bell range. Both the arkose to the west and the dacite porphyry at Silver Bell occupy the interval between Paleozoic units and the Claflin Ranch Formation. Local pre-Claflin Ranch erosion in the Silver Bell Mountains can be hypothesized to explain in part, the disappearance of the arkoses.

Interpretation The combined evidence presents a picture of the dacite porphyry as a large sill or laccolithic body, with a source of the southwest in the Silver Bell porphyry copper fault zone. The main body of this sill was generally floored by Paleozoic sedimentary rocks and roofed by strata of the Claflin Ranch Formation.

An explosive history is strongly suggested by the numerous xenoliths, the large fragments of quartz, and the shards of former glass in the matrix. The quartz phenocrysts can be interpreted as volcanic, with rounding produced by gas action. The nature of the rock is believed to reflect emplacement by fluidization, and the writer visualizes the intrusion of fluidized dacite porphyry in the manner explained below.

The gas- and fragment-charged dacite porphyry magma (actually quartz latite in composition, suggesting greater viscosity and more explosive potential) rose along the Silver Bell fault zone into Paleozoic strata. The higher the porphyry magma ascended, the more the confining pressure decreased, causing exsolution of gases and thus lending an explosive and dilative nature to the intrusive material.

Its extension to the southwest blocked by a large body of alaskite, the dacite porphyry welled up, sending small dikes and sills northeastward into the Paleozoic limestones, quartzites, and shales. Damp Amole-type Cretaceous (?) sediments were reached and more gas evolved. The magmatic material, expanding constantly, spread laterally to the northeast in the weak Cretaceous (?) sediments. Dilation occurred, as did the incorporation of fragments broken by churning gas action.

The dacite porphyry probably surfaced in one or more places, venting gases as it did. Gas also escaped laterally through the just-formed sill and vertically into overlying Claflin Ranch sediments. The heat and vapor altered the immediately overlying quartzofeldspathic clastic sediments, making them somewhat similar in appearance to the intrusive porphyry.

As the intrusive material cooled, differential movement within the newly formed sill gave rise to the flow structures seen in many places and the platy layering found in the upper portions. Such a platy parting within quartz latite sills is seen also near Pando, Colorado (Tweto, 1951, p. 507).

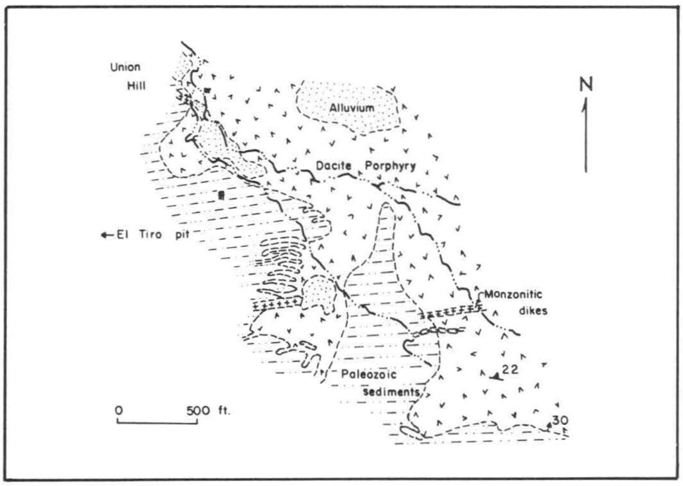

Figure 2a – Basal contact of dacite porphyry with Paleozoic strata just east of El Tiro pit, Silver Bell, Arizona.

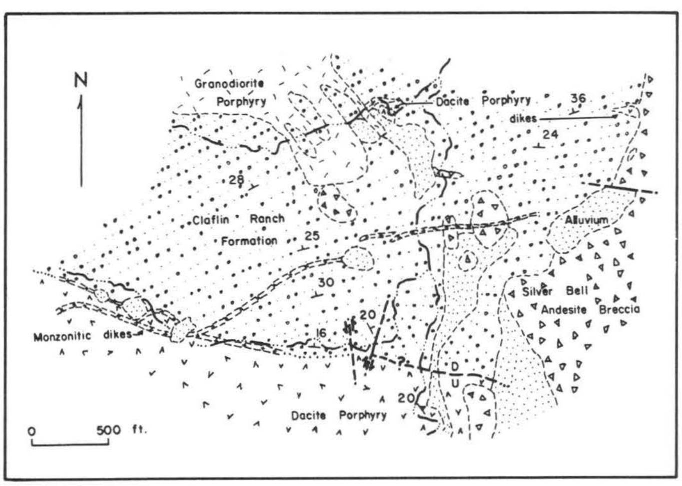

Figure 2b – Contact between dacite porphyry and overlying Claflin Ranch strata in the Silver Bell Mountains is gradational where not obscured by other structure. Note the dacite dikes cutting the sediments at the upper right.

Mount Lord Ignimbrite

The Mount Lord Ignimbrite is a quartz latitic pyroclastic flow breccia which overlies the Silver Bell andesite breccia and caps the Silver Bell Mountains. It strikes generally northwest with an average northeasterly dip of 30°–the dip a result of post-depositional regional tilting. This welded ignimbrite is lithologically similar to, and stratigraphically a near time equivalent of, the Cat Mountain Rhyolite of the Tucson Mountains as described by Kinnison (1958).

Sill- and dike-like intrusive ignimbrites related to the main body of the Mount Lord Ignimbrite are found in stratigraphically lower and older formations. One such sill is described here. A more detailed account of these intrusive ignimbrites is given elsewhere (Watson, 1964, p. 75-82, 145-148).

Field Description A sill of ignimbrite with a 200-foot maximum thickness is found several hundred feet below the extrusive welded ignimbrite along the dacite porphyry-Silver Bell andesite breccia contact northeast of Oxide pit. Well-developed eutaxitic structure in the central and upper portions of this sill indicates some locally turbulent conditions during the time of emplacement, but a northwest strike and northeast dip of about 40° represent an average orientation.

Xenoliths are common within the sill, and a peculiar type of andesite porphyry fragment characteristic of the extrusive ignimbrite is present. Megascopically the extrusive and intrusive ignimbrites are identical.

Petrographic Description The petrography of the sill ignimbrite just northeast of Oxide pit is like that of the extrusive welded ignimbrite with but few exceptions. Closer to the porphyry copper alteration it is more highly altered, with epidote partially replacing drawn-out lapilli and volcanic bombs. Devitrification has progressed to a greater extent, and a slightly larger percentage of crystals is present.

Common to both extrusive and intrusive (Figure 3) ignimbrites are the usual petrographic features of an acid vitric-crystal tuff. The crystals, which constitute about 25 percent of the rock, include quartz (~15 percent, subrounded to angular with many slivers, up to 2 mm., embayed and corroded), sanidine (~4 percent, subhedral, .3 to 1.5 mm., 2V = 0° to 5°), plagioclase (sodic andesine, ~5 percent, subhedral, up to 2.2 mm., sometimes twinned), and magnetite (~1 percent, euhedral to anhedral, up to .5 mm., oxidizing). The glassy matrix has devitrified.

Xenolithic material constitutes 10-20 percent of extrusive and intrusive ignimbrite. Numerous brown flattened pumice fragments have devitrified, with feldspar spherules forming in large quantities. A large amount of incipiently devitrified brown glass is seen under the microscope to be flattened, and nearly planar devitrified glass shards are visible.

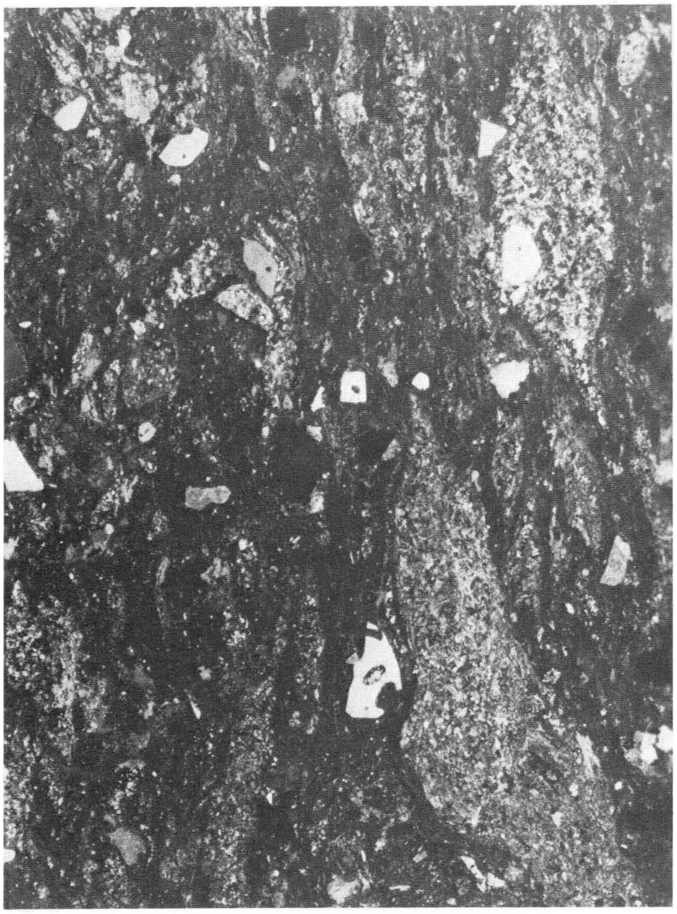

Figure 3 – Photomicrograph (crossed nicols) form a sill of intrusive Mount Lord Ignimbrite. Drawn-out lapilli give the rock a strong eutaxitic structure. (X 15.)

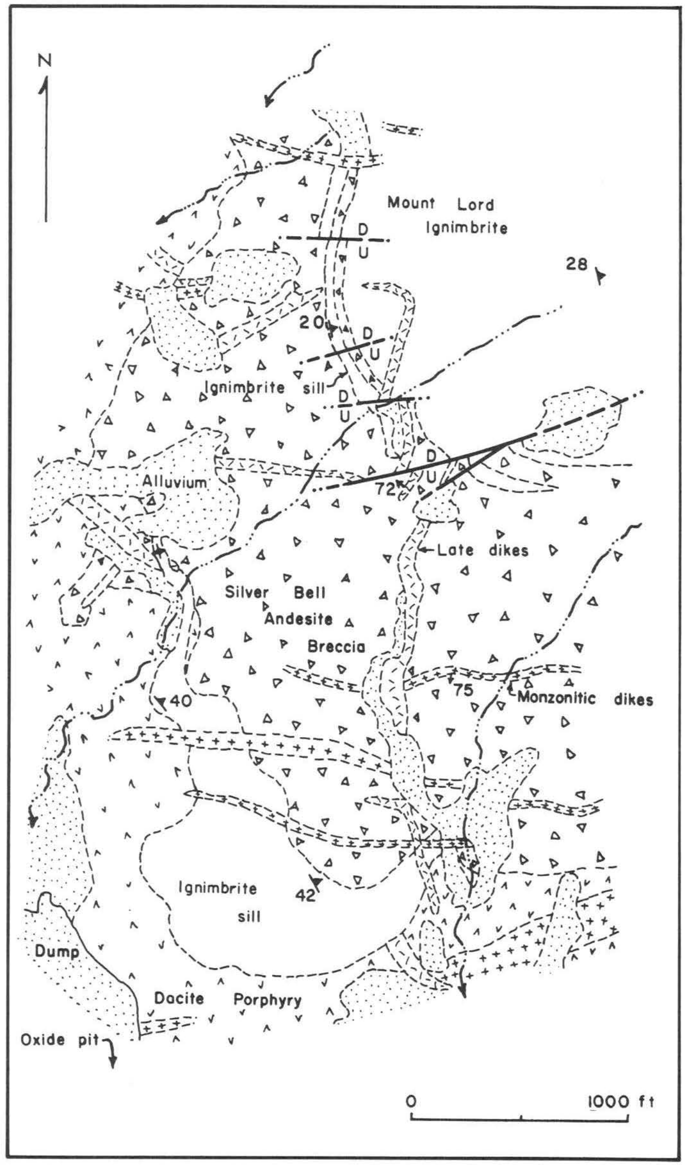

Figure 4 – Structural setting of the sill of intrusive Mount Lord Ignimbrite just northeast of the Oxide pit, Silver Bell, Arizona.

Structural Relationships The geologic setting of the ignimbrite sill is shown in Figure 4. The upper contact of the sill with well-indurated andesite breccia of the Silver Bell Formation is fairly sharp. The basal contact with dacite porphyry is, in one place, a 30-foot zone of intrusion breccia, whose character as a breccia is indistinct in the field but recognizable under the microscope.

The sill tapers in both directions. In a deep gully 1,100 feet to the east of the maximum thickness, the sill is but a few-inch thickness of tuffaceous material along the andesite breccia-dacite porphyry contact. Some 2,000 feet northwest of the maximum thickness, the sill narrows to 25 feet, then gradually steepens, becoming a cross-cutting, steeply dipping, 20-foot thick feeder dike in dacite porphyry. This feeder dike shows faint flow structure but contains none of the stretched pumice fragments seen in the sill.

Interpretation It is not unreasonable to suppose that the ignimbritic material in its gas-charged and dilative state, rising in dike-like vents, could have spread laterally along weak planes and contacts in the rock in the form of sills. Formation of such sills could also have occurred toward the end of pyroclastic activity if one or more of the feeder vents were to become choked with solidifying ignimbrite, forcing the magmatic and gas-charged material still rising to spread out beneath the thick ignimbrite sequence already deposited. At Silver Bell these surging intrusive ignimbrites took advantage of flow contacts existing within the Silver Bell andesite breccia as well as the Silver Bell breccia-dacite porphyry contact.

INTRUSIVE VOLCANICS ELSEWHERE IN ARIZONA

Described briefly below are examples of intrusive volcanic phenomena from 8 other mountain ranges in southern and central Arizona (see also Figure 5). Most of these examples have been verified in the field; however, several require additional study in order to substantiate them as intrusive volcanics. Further instances of these phenomena, known to exist in the western Silver Bell and West Silver Bell ranges, will not be covered here.

Figure 5 – Map of Arizona showing locations of intrusive volcanic exposures discussed in this paper.

TUCSON MOUNTAINS

Piedmontite Hills

In his study of the Piedmontite Hills section of the Tucson Mountains Evans B. Mayo (1963) notes that a large body of ignimbrite has "local steep to vertical contacts and flow structure. . . . Some parts of this large body appear to have been intruded in a sill- or laccolith-like manner into the stratified fragmental volcanics. Some of the ignimbrite may have flowed out on the surface, but no convincing evidence of this has yet been found. . . . Several of the smaller bodies of ignimbrite in the southern part of the hills obviously occupy steep, or vertical, fissures." (p.73).

The ignimbrite is identified as the tuff member of the Recreation Red Beds Formation. The host rock which consists of fragmental volcanics belongs to the volcanic conglomerate member of the same formation.

Tucson Mountain Chaos

The Tucson Mountain chaos was a name given by John E. Kinnison (1958) to a tabular megabreccia which overlies Amole Arkose and underlies Cat Mountain Rhyolite (ignimbrite) along a 14-mile length of the axis of the Tucson Mountains. Kinnison believes that the chaos came about through sedimentary processes, utilizing landslides and mudflows to carry the large blocks included therein.

More recently Mayo (1963, 1966) has suggested a fluidized origin for the chaos, and Bikerman (1963) suggested the chaos to be a nuée ardente member of the Cat Mountain Rhyolite sequence.

Drewes (personal communication 1966), has mapped a megabreccia in the Santa Rita Mountains south-southeast of Tucson which he refers to as a "chaos." This breccia unit is apparently in the same stratigraphic position as the Tucson Mountain chaos, and Drewes ascribes a landslide block origin to it. Certainly, megabreccias would seem credible in a terrane undergoing volcanic upheaval.

The writer has seen exposures on the south side of Cat Mountain where tuff appears to have flowed around and cut through boulders within the Tucson Mountain chaos. This could be explained as ignimbrites of the Cat Mountain sequence intruding an already formed sedimentary megabreccia either laterally or upward from vents, or oozing down into the chaos as the flows poured over the surface. Perhaps an "intrusive volcanic" as herein suggested would help explain some of the features of the chaos which led Mayo and Bikerman to volcanic hypotheses of origin.

Little Ajo Mountains

The Little Ajo Mountains are directly southwest of the town of Ajo and are of particular interest as they contain Phelps Dodge's New Cornelia porphyry copper orebody. Reference is made herein to geologic maps by Gilluly (1946).

A light-colored tuff intrudes the andesite breccias of the Upper Cretaceous (?) Concentrator volcanics on the western slopes of Pinnacle Peak (T12S, R6W, Section 28). This intrusive volcanic is clearly visible from the Gibson Arroyo road.

The tuff has dilated a considerable portion of the volcanic sequence as dikes, sills, and irregular masses.

Clear intrusive contacts with the andesite breccias are abundant. The largest body of this tuff has the apparent shape of a laccolith—a massive southeast-striking dike terminates upward as a southeast-dipping sill along a Concentrator bedding horizon. Within this stratigraphic unit numerous offshoots of the tuff extend into the surrounding volcanics.

Most of the intrusive volcanic has the appearance of a fragmental tuff with a siliceous matrix. Flow structures are seen locally. Two thin sections cut from tuff specimens show decidedly volcanic textures. The tuff, quartz latite in composition, has been devitrified and recrystallized, and fragments of foreign rocks, quartz and feldspar are plentiful. Weak, superimposed sericitization and kaolinization with incipient iron-staining are reminders of the proximity of the New Cornelia orebody.

Gilluly apparently saw this tuff (p. 51) but did not point out its intrusive characteristics.

Patagonia Mountains

Tuffs, ignimbrites, and flow-banded rocks with intrusive relationships occur in the vicinity of the Flux mine within the Patagonia Mountains, southeast of the town of Patagonia. J. H. Courtright has mapped the surface geology of the Flux area for the American Smelting and Refining Company and has logged core from sub-surface exploration.

Courtright's "ribbon rock" or intrusive volcanics occur within portions of his Lower Conglomerate, Middle Grits, and Upper Grits—all probable Cretaceous sediments—and within the overlying Laramide Chief Formation conglomerate. Drilling data and surface mapping show these volcanic-appearing rocks to be cross-cutting in relation to the enclosing sediments. Courtright (personal communication 1966) rules out a megabreccia explanation for this occurrence because of the distribution of the ribbon rock throughout several stratigraphic units, and its continuity over considerable distances as well as its continuity with enclosing sediments as shown by drill core.

A large number of thin sections cut from the ribbon rock all show volcanic textures, ranging from devitrified and recrystallized tuff to finely flow-banded latite. Quartz veinlets and sericitic bands parallel the flow structure attest to the superimposed alteration in the Flux mine vicinity.

A Laramide extrusive volcanic sequence caps the Patagonia Mountains.

Sierrita Mountains

The Sierrita Mountains are located south-southwest of Tucson and contain several notable porphyry copper deposits. The southern end of the range is composed, in part, of Laramide volcanic units similar to, and possibly time equivalents of, volcanic formations known at Silver Bell.

Cooper (personal communication 1966) verifies the presence, on a small scale, of intrusive rocks of volcanic appearance in the Sierrita Mountains. J. H. Courtright (personal communication) has noted several localities in the southern Sierritas which evince intrusive volcanic phenomena similar to that known at Silver Bell.

The complex geology at the Esperanza mine of the Duval Corporation has been worked out by Lynch (1965), whose maps indicate a Laramide rhyolitic welded tuff overlain by andesitic breccias and welded tuffs. This is the reverse situation of the normal southern Arizona Laramide volcanic stratigraphy. Lynch's geologic cross-sections suggest a cupola shape for certain occurrences of the rhyolitic welded tuff unit. In one cross-section a block of Cretaceous quartzite is shown overlying the younger welded tuff. These anomalous situations could be explained if the rhyolitic welded tuff were, at least in part, a near-surface intrusive.

Vulture Mountains

The Vulture Mountains southwest of Wickenburg are characterized by Tertiary rhyolitic to andesitic outpourings over a Precambrian basement. Along the Vulture mine road and straddling the line between Sections 6 and 7, T6N, R5W, a possible vent for both rhyolitic tuff and andesite is well exposed.

At the surface, the tuff occurs in the form of a thin ellipse with a long axis of 1500 feet. Pronounced flow structure shows a dip of 65°. Completely surrounding this tuff is a sheath of andesite which is, in turn, enclosed in Precambrian gneiss. Andesite dikes cut the gneiss outward from the volcanic center. There is no structural solution for this occurrence other than to call these volcanic-appearing rocks intrusive.

Big Horn Mountains

Like the neighboring Vulture range, the Big Horn Mountains south of Aguila are composed of Tertiary rhyolitic and andesitic volcanic rocks overlying a Precambrian basement. The U. S. mine in the northeast corner of T4N, R8W lies on the contact of a massive north-northwest trending rhyolite dike. Southwest of the mine Precambrian schist is criss-crossed by a large number of tuffaceous dikes which undoubtedly were feeder structures for the ignimbrites capping the geologic column in the area.

Galiuro Mountains

East of the San Pedro River and around 32°30′ N. Latitude, the abruptly rising western flanks of the

Galiuro Mountains expose a thick, layered sequence of Tertiary volcanics. It is not unusual to see an apparently conformable flow unit suddenly change stratigraphic horizons. Both basaltic (or andesitic) and rhyolitic sills are present.

Ajo Mountains

The Ajo Mountains northeast of the Organ Pipe National Monument headquarters also exhibit a thick pile of Tertiary flows. Large scale examples of seemingly tuffaceous rocks cross-cutting andesitic volcanics are visible from the Ajo Mountain drive.

CONCLUSIONS

Some of the intrusive volcanic rocks described herein fit in the category of rhyolitic or andesitic dikes – a type of occurrence recognized for many years and widely excepted as valid. However, some of the descriptions and suggestions made in this paper imply the existence of large bodies of intrusive tuffs, ignimbrites, etc.

No doubt terminology is partly responsible for lack of credence in intrusive volcanic phenomena. Terms such as "tuff," "welded tuff," "ignimbrite," and "volcanic rock" all were originally coined and are almost exclusively used to refer to igneous extrusive materials. But is it necessary to invent new nomenclature to describe rocks that are megascopically and petrographically an ignimbrite, or a tuff – just because these volcanic-appearing rocks can be shown to be intrusive? The writer has chosen not to do so. Consideration might, however, be given to the term "sub-volcanic" (not listed in the major science dictionaries) to describe the type of occurrence represented by these intrusive volcanics.

The fact remains that intrusive volcanics do exist in a number of localities, and that individual rock bodies can be of a rather large scale – as witness the dacite porphyry at Silver Bell. It has become apparent that petrographic and megascopic volcanic textures do not *necessarily* qualify a rock as extrusive, and that structural relationships are of the utmost importance. Southern and central Arizona should be favorable for the recognition of the sources that fed the volcanic outpourings as much of the Laramide and later Tertiary extrusive cover rocks have been eroded away.

Near-surface intrusive volcanic phenomena should be expected in a volcanic province. Dikes and more circular vents would act as feeders. Certain stratigraphic horizons would, at times, allow easier access to rising volcanic materials than would very hard or plastic overlying formations – thus sills or laccoliths would form. In a like manner large amounts of gas-charged fluids could be temporarily impounded beneath a particularly impervious barrier, and the intrusive volcanic body formed could assume any of a variety of shapes. If a fluidized column vented forth at the surface, the pressure decrease could affect other portions of the fluidized system, and rising volcanic materials might stop and cool in place.

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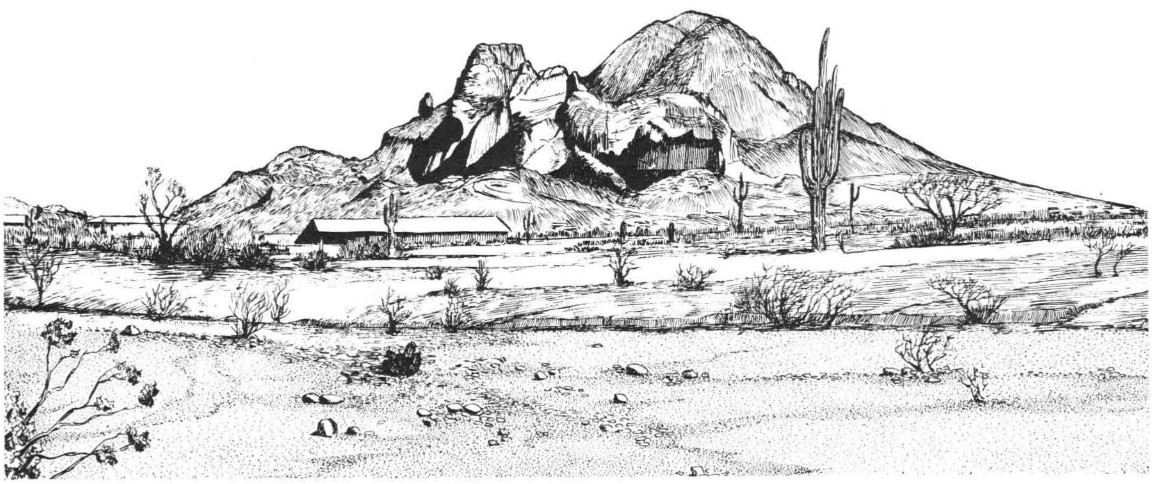

A HISTORY OF GEOLOGIC INVESTIGATION IN THE TUCSON MOUNTAINS, PIMA COUNTY, ARIZONA

By

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INTRODUCTION

The story of geologic studies in the Tucson Mountains reveals a swing, from the early interpretations based directly on observation, to popular tectonic theory, and back again.

Sixty-three years ago F. N. Guild mentioned "remnants of the original quartzites and limestones through which this great mass of lava has broken." Then, in 1920, Jenkins and Wilson wrote of a great upheaval in the central part of the range, from which the flanking flows dipped away. In 1939 there was substituted for these earlier interpretations, based on what could be seen, an hypothesis of vast overthrusting followed by intrusion, volcanic outpourings and block faulting.

Reaction to the overthrust hypothesis began in 1958, when J. E. Kinnison defined the Tucson Mountain chaos and assigned to it a sedimentary origin. Subsequent field work by University of Arizona students and by the present writer seems to point the way back toward something like the original ideas of magmatic breakthrough and upheaval.

Radiometric dating by P. E. Damon and his students has helped greatly to fix the times of geologic events, but important problems remain unsolved. If a proper understanding is to be attained of this mountain range on our very doorstep, investigative work now in progress must continue and should be augmented.

For valued suggestions received during preparation of this manuscript, the writer gratefully acknowledges his indebtedness to Professors Donald L. Bryant, Paul E. Damon, Edgar J. McCullough, Jr. and Spencer R. Titley all of the Geology Department, University of Arizona.

GEOGRAPHICAL SKETCH

The trend, size, elevation and shape in plan of these mountains are represented on figure 1 together with the names of some local features.

The trend is about north 20 degrees west. The length of the range is some 23 miles and the width is about seven miles at the widest place. The maximum relief, from the summit of Wasson Peak to the bed of the Santa Cruz River, is about 2,450 feet. The shape, in plan, is not easy to describe.

The central, longest and widest portion trends northwest. From its southeast end a shorter southern part extends southwest. A line of dark hills, including Black Mountain, which trends west-south-west, forms the southernmost fringe of the range. At the north, starting at Safford Peak with a width of about two miles, a long, thin arm, scarcely more than a quarter of a mile wide, extends northward. The fingers of the hand are bent abruptly westward.

The principal named summits along and near the crest of the range are, from north to south, Safford Peak, Wasson (Amole) Peak, Tower Peak, Bren Mountain, Golden Gate Mountain and Cat Mountain. As mentioned, Black Mountain is on the southernmost fringe.

Separated from the main mass of the mountains are on the west from north to south: The Twin Peaks (Picachos de Calera) and the small, isolated hill north of them, Busterville Hill, the Red Hills, the Piedmontite Hills (Brown Mountain), the Sedimentary Hills, Snyders Hill, Saginaw Hill and Beehive Peak. On the eastern side of the range, almost directly opposite the junction of the central and southern parts, is a bud-like eastward projection that includes Tumamoc Hill and "A" Mountain; the Twin Hills and Coyote Peak are other isolated masses on the eastern side.

The map (fig. 1) which shows further local features of topography and culture should guide the reader through the following narrative. No further reference will be made to it.

NARRATIVE

Descriptions, Upheaval, and Volcanic Break-Through, 1905-1939

The earliest report dealing with geologic features in the Tucson Mountains seems to be that of F. N. Guild, (1905). His essay, entitled "Petrography of the Tucson Mountains, Pima County, Arizona" contains descriptions of the volcanic rocks. In order of abundance,

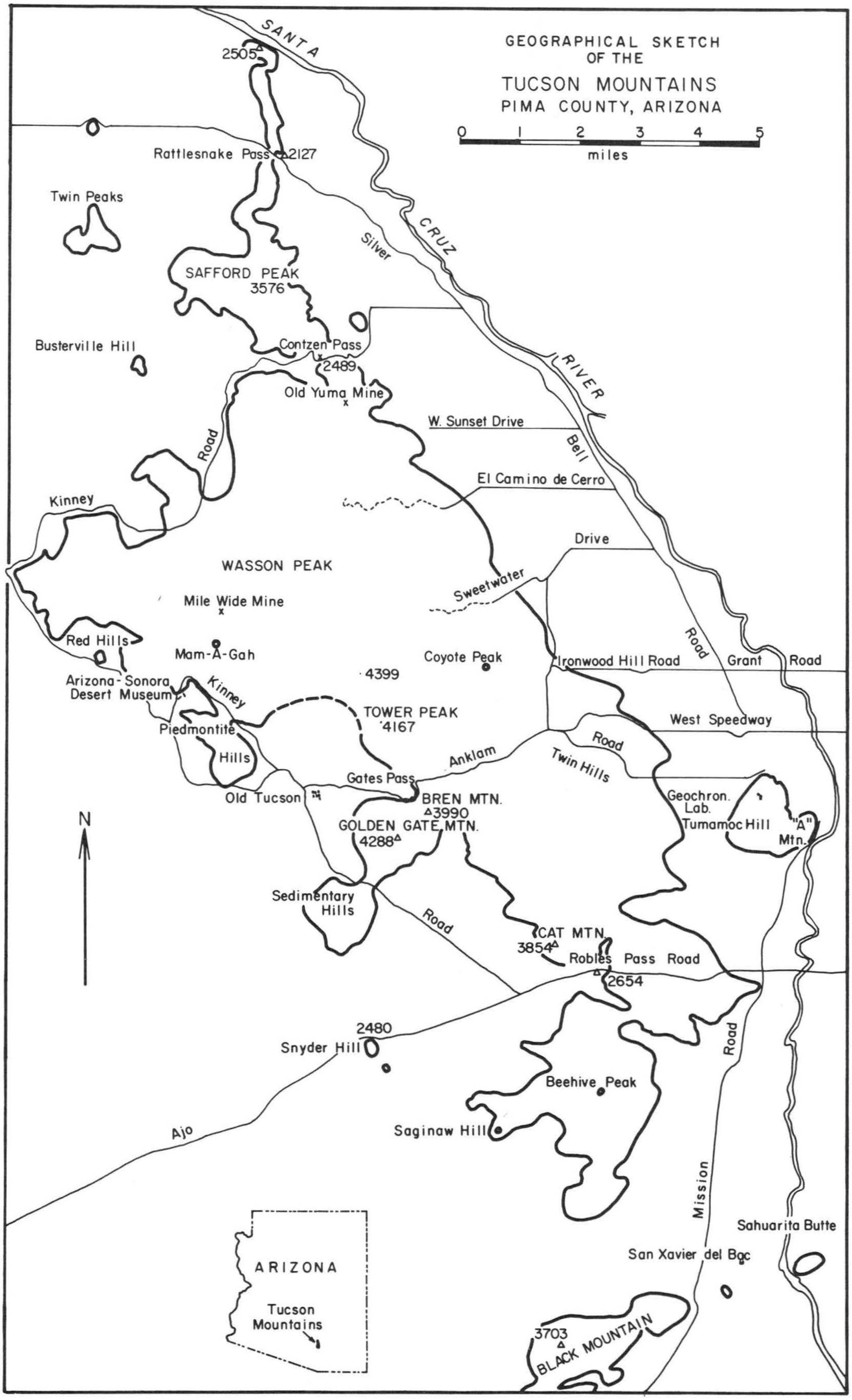
GEOGRAPHICAL SKETCH
OF THE
TUCSON MOUNTAINS
PIMA COUNTY, ARIZONA
0 1 2 3 4 5
miles
SANTA CRUZ RIVER
2505
Rattlesnake Pass 2127
Twin Peaks
Silver
SAFFORD PEAK
3576
Busterville Hill
Contzen Pass
2489
Old Yuma Mine
W. Sunset Drive
Bell
Road
Kinney
El Camino de Cerro
Drive
WASSON PEAK
Sweetwater
Mile Wide Mine
Red Hills
Mam-A-Gah
Coyote Peak
Ironwood Hill Road
Road
Grant
Road
Arizona-Sonora
Desert Museum
Kinney
4399
TOWER PEAK
4167
West Speedway
Piedmontite
Hills
Anklam
Road
Twin Hills
Gates Pass
Old Tucson
BREN MTN.
3990
GOLDEN GATE MTN.
4288
Geochron.
Lab.
Tumamoc Hill
"A"
Mtn.
N
Sedimentary
Hills
Road
CAT MTN.
3854
Robles Pass Road
2654
2480
Snyder Hill
Road
Beehive Peak
Saginaw Hill
Ajo
Mission
Sahuarita Butte
San Xavier del Bac
ARIZONA
Tucson
Mountains
3703
BLACK MOUNTAIN

Figure 1

Guild lists rhyolite, rhyolitic tuff, andesites and basalts. He subdivides the basalts, least abundant of the volcanic rocks, into three major classes, –fine-grained olivine basalt, porphyritic basalt and quartz basalt. Areas of exposure of these basic rocks are mentioned near the Desert Laboratory (now the Geochronology Laboratory) on Tumamoc Hill, and on Black Mountain. As a matter of fact, the entire southernmost fringe of hills, plus Tumamoc Hill and "A" Mountain are composed dominantly of these sombre materials.

Although no discussion is attempted of the geologic relations, the following statement is made (Guild, 1905, p. 313): "There occur, however, in places, remnants of the original quartzites and limestones, through which this great mass of lava has broken." It would seem that Guild thought magma had broken on a grand scale through the underlying older sedimentary sequence. He mentions that much more petrographic work remains to be done and he refers to the Tucson Mountains as a favorable field for geologic research. His inference and his remarks apply today.

Three years later, a brief discussion of the geology of the entire range is said (Jenkins and Wilson, 1920, p. 7) to have been published by W. P. Blake (1908). Unfortunately, I have been unable to locate this early report, which might be of great interest.

In 1909, C. F. Tolman wrote about the "Geology of the vicinity of the Tumamoc Hills." His paper contains evidence of five separate flows of basalt, of a rhyolite tuff floored and capped by "older gravels," and of an underlying biotite andesite. Tolman recognized intrusions into the upper volcanic pile. The rocks resting on the andesite were considered to be "probably Quaternary" in age in spite of the lack of volcanic forms. The report includes a chapter on the petrography by Guild, and it is accompanied by a geologic map at the scale of 1:6,000.

There followed a period of eleven years during which nothing seems to have been published about Tucson Mountain geology. Then there appeared the report on "A geological reconnaissance of the Tucson and Amole Mountains," (Jenkins and Wilson, 1920). The reconnaissance, which formed the basis of the report, had been done in preparation for publication of the first Geologic Map of Arizona (Arizona Bureau of Mines, 1924). The field work was, therefore, much generalized; yet the reader sees, for the first time, an emerging picture of the composition and structure of the entire range.

At the Twin Peaks (Picacho de la Caleria of the authors) the older Precambrian Pinal Schist is exposed. Above this there follow 200 feet of fractured, iron-stained quartzite, 271 feet of thin-bedded limestone with a ridge of quartzite and cherty, yellowish limestone, 60 feet of vesicular, epidotized basalt (?) and 75 feet of chert-banded limestone. All of these sedimentary rocks are assigned tentatively to the Cambrian. Then follow in sequence Devonian and Carboniferous rocks consisting of 330 feet of blue-gray fossiliferous limestone, overlain by 600 feet of thick-bedded, massive, ridge-forming, blue-gray limestone that is "undoubtedly Carboniferous."

The sedimentary rocks southwest of Amole (Wasson) Peak are assigned tentatively to the Mesozoic. They consist of 900 feet of brick red, sandy shale, not generally fissile, calcareous in places, and interbedded with layers of sandstone and conglomerate. These rocks form the Red Hills. Overlying them are 1240 feet of arkose and quartzite, gray to brown sandstones, interbedded with layers of limestone that "weather to fine, sharp, parallel bands." On the black on white geologic map, at the scale of about 2-1/2 miles to the inch, the Paleozoic and Mesozoic (?) sedimentary rocks are represented by a common symbol.

In the Amole Peak area, and to the northwest, intrusions of granite, granodiorite and rhyolite are recognized and are assigned provisionally to the Mesozoic.

Resting unconformably on the Paleozoic and Mesozoic sedimentary rocks is a thick volcanic accumulation. To this is assigned, tentatively, a Tertiary age, although the authors state (Jenkins and Wilson, 1920, p. 12): "Blake, however, refers to the andesitic and rhyolitic flows as of pre-Tertiary, or Cretaceous age." In the vicinity of Yuma Mine (Chaco de Yuma) the Tertiary rocks consist of 2,200 feet, more or less, of "rhyolites, andesites and tuffs, volcanic extrusions, flows, eruptions (sic.) and agglomerates." Unconformably on the Tertiary (?) rocks at the Tumamoc Hills are the basalts that Tolman thought were "probably Quaternary."

Regarding the structure, the authors write (Jenkins and Wilson, 1920 p. 9): "The structure, therefore, consists of a tremendously upheaved and intruded region about the center of Amole Peak with a flanking rim of extrusive volcanic flows . . . ." As a first approximation, this is an excellent statement. It reaffirms the idea of magmatic break-through expressed by Guild fifteen years before, and it adds the concept of upheaval.

Fifteen years later F. N. Guild (1935) published a second paper, on "Piedmontite in Arizona." This essay consists mostly of beautifully illustrated descriptions of occurrences of the manganesian epidote in the Piedmontite Hills. "A dense, pinkish rock of rhyolitic composition, perhaps best designated as felsite" is considered to be the source of the manganese. Guild points out, however, that chemical analyses show the felsite to be no more manganese-rich than most normal rhyolites, or than the other rocks of these hills.

Here again a statement by Guild (1935, p. 681) is of unusual interest. "The intrusion of this volcanic mass is probably the direct cause of the sandstone hills." The Piedmontite Hills are not best described as "sandstone hills," but the reader can begin to visualize their structure as a miniature of the greater Tucson Mountain structure. At this point it seems that a somewhat sketchy, but good, foundation has been laid for understanding the Tucson Mountains. All that remains is to study more thoroughly the stratigraphic and volcanic geology and to fill in details of the structure.

In a report on "Correlation of Arizona Paleozoic formations," A. A. Stoyanow (1936) refers to some localities in the Tucson Mountains. In the Picacho de Calera (Twin Peaks) section he recognizes the Paleozoic formations established by Ransome (1904) at Bisbee, and he sub-divides some of these into additional units. In the Cambrian section he describes in ascending order the Bolsa Quartzite of Ransome, the new Pima and Cochise formations, and the Abrigo Formation of Ransome, which he says (1936, p. 471) is overlain by the new Upper Cambrian Rincon limestone. As Devonian, in addition to the Martin Limestone of Ransome, he recognizes the Picacho de Calera formation which rests disconformably on the Rincon limestone. As at most localities in southern Arizona, the Ordovician and Silurian are not represented.

In the discussion of Mississippian and Pennsylvanian rocks, he does not mention specifically the Tucson Mountains, but he refers to Snyder Hill as the type locality of the new Permian formation of that name.

Systematic Geology, Great Overthrust, and Fault Block Mountains, 1939

In view of the considerable interest shown in the geology of the Tucson Mountains, it might be expected that a reasonably detailed account of the geology of the entire range would eventually appear. Such an account was that by W. H. Brown (1939) entitled "Tucson Mountains, an Arizona Basin Range type." This report, which is still the standard reference on the geology of this range, is divided into three main parts, –physiography, descriptions of the rocks, and structure. There is also a brief discussion of mineralization.

As reported previously by Jenkins and Wilson, the older Precambrian Pinal Schist crops out at the western end of the Twin Peaks. The younger Precambrian Apache group has never been recognized in this range.

The Paleozoic section of the Picacho de Calera Hills is described in some detail, and Stoyanow's units are adopted. In the Cambrian System, in ascending order, the Bolsa Quartzite, Pima sandstone, Cochise formation, Abrigo Formation and Rincon limestone are described and reported to have a cumulative thickness of 1,444 feet. In the Devonian System, five members of the Picacho de Calera formation and four members of the Martin Limestone are described. Their combined thickness is reported to be 334 feet. No detailed section of the Mississippian System is available, but the statement is made that Stoyanow correlated these rocks with the Escabrosa Limestone of Ransome and gave 600 feet as their thickness. Brown also states that Stoyanow assigned a thickness of 1,000 feet to strata of the Pennsylvanian System and correlated them with the Naco Formation of Ransome. He also says (1939, p. 712): "The Pennsylvanian also occurs in a small limestone hill two miles (sic) north of the Picacho, where it is thrust onto the Permian."

Under the "Permian System," Stoyanow's type locality at Snyder Hill is mentioned, and Brown adds the following significant statement: "Among the limestone blocks on the great thrust those containing the Snyder's Hill Formation are most abundant. Especially fossiliferous blocks are found along the base of the escarpment near the Silver Lily dike system."

Three Mesozoic units are recognized and are assigned to the Cretaceous. The oldest of these is named the Cretaceous volcanic rocks. This unit, which according to Brown may reach a thickness of 2,000 to 5,000 feet, consists mostly of fragmental andesites, but includes some flows and intrusions, and some rhyolites. The Cretaceous volcanic rocks crop out in the Piedmontite Hills, as well as on both sides of the crest over much of the length of the range.

Mostly overlying the Cretaceous volcanic rocks, but to some extent interlayered with them in the Piedmontite Hills, are red siltstones, sandstones, and minor conglomerates that Brown names the Recreation Red Beds. He measures in this unit a section 1,265 feet thick, and the base of the unit is not exposed.

Resting with apparent conformity on the red beds is the Amole Arkose, an assemblage of feldspathic sandstones, siltstones, shales and thin limestones, in which Brown measures a partial section 2,275 feet thick.

In late Cretaceous time the above mentioned rocks were folded. In order to explain the seeming geologic anomaly of huge Permian limestone blocks "resting on" Amole Arkose, an extensive imbricate thrust sheet is postulated to have advanced from the southwest, across the site of the present mountains. This overthrust carried Cretaceous volcanic rocks, together with slices of Paleozoic rocks, northeastward across the Amole Arkose. In time, erosion reduced this overthrust sheet to remnants.

In late Cretaceous or early Tertiary time the rocks and structures were invaded from below by siliceous magmas. The largest of the resulting intrusive masses, the Amole Quartz Monzonite and Amole Granite, is a composite stock some four miles in diameter, located northwest of Wasson Peak in the northern half of the range. Similar, but smaller intrusive masses are found in the Sedimentary Hills and at Saginaw Hill. Granite, probably of late Cretaceous or early Tertiary age, also crops out beneath the Pinal Schist at the southwest base of the Twin Peaks. A fine grained to aphanitic intrusive rock, the Amole Latite, is found as dikes and irregular masses in the northern part of the range, especially on and near Amole (Wasson) Peak. This is the rock spoken of as rhyolite by Jenkins and Wilson, and the area of its greatest concentration is the "tremendously upheaved and intruded region about the center of Amole Peak . . . ." Brown maps this rock as though it has been cut off by the Amole Quartz Monzonite.

Overlying the Cretaceous rocks in northern, central and southern parts is a sequence of rhyolitic flows, assigned to the Tertiary and named the Cat Mountain Rhyolite. Regarding the relations of this rhyolite to underlying formations, Brown (1939, p. 730) is explicit: "The stratigraphic relations appear to be well established. It usually rests either on the overthrust mass of Cretaceous sedimentary and volcanic rocks or where the thrust has been removed by erosion, directly on the truncated edges of the sedimentary rock . . . ." This relation is shown in section (fig. 2-A of the present paper). (Figs. 2 & 3 at the end of paper.)

In the north a layer of gravel or conglomerate rests with angular unconformity on the Cretaceous volcanic rocks. On this gravel reposes the Rillito Andesite, followed by more gravel, then by the Safford Tuff, in turn overlain by the Upper Andesite. In the central part of the range the Cat Mountain Rhyolite is directly overlain by a tuffaceous unit that Brown correlates with the Safford Tuff. In the southern part, what he identifies as Safford Tuff is overlain by the Shorts Ranch Andesite, followed by the basalts, "older gravel" and rhyolite tuff previously mapped by Tolman and which Brown is inclined to regard as of Tertiary or Quaternary age. In its southernmost extent the Cat Mountain Rhyolite is directly overlain by the Diopside andesite which is succeeded by the Biotite rhyolite.

In the supposed fine-grained, southern continuation of the Safford Tuff there are clays. Near the junction of Ajo and Mission roads, and also in pits north of Anklam Road, these clays contain plant fossils that E. W. Berry considered to belong to the later, rather than the earlier, half of the Tertiary (Brown, 1939, p. 732). On this basis, and on the basis of structure, he ". . . . placed the entire series of volcanic rocks in the Tertiary." The series, of course, begins at the bottom with the Cat Mountain Rhyolite.

Many small rhyolitic, quartz latitic or dacitic masses, intrusive into Cretaceous or Tertiary rocks are also assigned to the Tertiary. Among these are the Silver Lily dikes, the Warrens Ranch Latite sill, the Beehive rhyolite neck, the Spherulitic rhyolite and the Safford Dacite neck.

The succession of Tucson Mountain rocks, as established by Brown, is presented in condensed form in Table 1.

His concept of the post-Cretaceous structure is perhaps best revealed in a series of quotations. He writes (1939, P. 751): "The Tertiary volcanic series rests with marked angular unconformity on the peneplained surface of the complex just described . . . ."

"The lavas dip easterly from 10 to 20 degrees. This tilted lava cap makes the tilted block character of the range so apparent. The lavas are completely block faulted by two systems of faults. One set strikes from east-west to northwest and the other from north-south to northeast . . . ."

He points out that the younger Tertiary or Quaternary basalts have been disturbed much less than the older Tertiary lavas, then writes (1939, p. 707): "The lavas extend continuously around the east side of the peak. It seems almost certain, therefore, that lavas covered Amole Peak and that the range was a completely lava-capped block, with a continuous escarpment which lay miles west of its present position."

The report was accompanied by a colored geologic map and structure sections on the scale of one inch to the mile.

As we have seen, the earlier, simple and sensible notion of upheaval and magmatic break-through was supplanted by an hypothesis of intense compression and large-scale overthrusting. This thrusting took place near the end of Cretaceous. In mid-Tertiary, perhaps, the range was tilted eastward as one huge fault block that broke internally on a network of lesser fractures. This dual concept was to dominate for many years.

Review of Paleozoic Stratigraphy, 1939-1955

In a dissertation on "The geology of the northern Camelo Hills, Santa Cruz County, Arizona," J. H. Feth (1947, p.70-72) presents a measured section, 226½ feet thick of the Snyder Hill formation at Snyder Hill in the Tucson Mountains.

O. B. Coulson (1950) submitted a master's thesis on "Geology of the Sweetwater Drive area and correlations of Santa Cruz valley gravels." The thesis is accompanied by a geologic map to the scale of 1:12,000, and there are two cross sections on the scale of 500 feet to the inch.

Many large and small Paleozoic limestone and quartzite blocks are exposed in the Sweetwater Drive area. On the evidence of fossils, and on the basis of a Permian section measured in the Empire Mountains by Feth, Coulson correlates both the limestones and the quartzites with the Snyder Hill formation. He accepts the

Table 1 – Rock Sequence in the Tucson Mountains, compiled from map and text of W. H. Brown's 1939 report (Silver Lily Dikes and other minor intrusions omitted.)

Age	Northern Part	Central Part	Southern Part	
Quaternary			Basalt and Tuff	
Tertiary	Safford Dacite Upper Andesite Safford Tuff Rillito Andesite Conglomerate	Safford Tuff Cat Mountain Rhyolite	Shorts Ranch Andesite Safford Tuff Cat Mountain Rhyolite	Biotite rhyolite Diopside andesite Cat Mountain Rhyolite
Tertiary or Cret.		Granite & quartz monzonite Amole Latite		
Cretaceous	Volcanic rocks	Amole Arkose Recreation Red Beds Volcanic rocks	Amole Arkose Volcanic rocks	
Penn.-Perm. Pennsylvanian	Naco Limestone	Exotic limestone blocks	Exotic limestone blocks	Snyder Hill formation
Mississippian	Escabrosa Limestone	— —	— —	—
Devonian	Martin Limestone Picacho de Calera fm.	— —	— —	—
Cambrian	Rincon limestone Abrigo Formation Cochise formation Pima sandstone Bolsa Quartzite	— —	— —	—
Older Precambrian	Pinal Schist	—	—	—

overthrust sheet origin of the blocks, and he mentions horsts of Cretaceous rocks faulted up into the overlying Permian. Blocks of Recreation Red Beds (?) are found in the Cretaceous volcanic rocks, and the contacts are described as faults.

Coulson writes of the Cat Mountain Rhyolite (1950, p. 24): "It rests unconformably upon the Cretaceous volcanics and sediments . . ." In spite of this statement, one of his structure sections shows Cat Mountain Rhyolite to dip about 45 degrees under Cretaceous volcanic rocks that are in turn overlain by Cat Mountain Rhyolite with 45 degree dip.

In the Spring of 1952 the Cordilleran Section of the Geological Society of America met on the campus of the University of Arizona. Among the papers prepared for the Arizona Geological Society's Guidebook on that occasion was one by Donald L. Bryant on "Paleozoic and Cretaceous stratigraphy of the Tucson Mountains." Bryant applies Stoyanow's subdivisions of Ransome's units. In the Picacho de Calera section he reports 1340 feet of Cambrian strata, about 350 feet of Devonian, about 600 feet of Mississippian, and 1000 feet of Pennsylvanian. To this is to be added 226 feet of Permian sedimentary rocks exposed in the Snyder Hill section, making the total exposed thickness about 3,516 feet.

The U. S. Geological Survey's Professional Paper 266, by Gilluly, Cooper and Williams, was published in 1954. The authors raise the Naco Limestone of Ransome to group status and subdivide it into the Pennsylvanian Horquilla Limestone, the Pennsylvanian and Permian? Earp Formation, the Permian? and Permian Colina Limestone, and the Permian Epitaph Dolomite, Scherrer Formation and Concha Limestone.

The following year, Donald L. Bryant (1955) in a dissertation on "Stratigraphy of the Permian System in southern Arizona" proposes to place the top of the Naco Group at the top of the Epitaph Dolomite which had been mapped as Naco by Ransome at Tombstone. On this he places the Andrada Formation, recognized in the Empire Mountains. The Snyder Hill formation of Stoyanow is raised to group status. It follows above the Andrada formation and consists, in ascending order, of the Scherrer Formation, Concha Limestone, and a new Permian formation, the Rainvalley.

It now seems that the quartzite blocks reported by Coulson from the Sweetwater Drive area were derived from the Sherrer Formation. The limestones may have been derived from the Concha, or from limestone in the Scherrer.

Terence L. Britt, (1955) carefully re-studied the rocks and structures at the Twin Peaks (Picachos de Calera). His detailed description and measurement of the stratigraphic section are thought to be the best available. Britt employs the old stratigraphic terminology of Ransome, and measures 700 feet of Bolsa Quartzite and 481 feet of Abrigo Formation, giving a total of 1,181 feet of Cambrian strata. The Devonian Martin Limestone is reported to be 268 feet thick, but the measured thicknesses of its units seem to total only 244 feet. The Mississippian Escabrosa Limestone is 408 feet thick, and the exposed thickness of the Pennsylvanian Naco Formation measures 811 feet, according to the sum of the thicknesses of its units. The Naco is perhaps erroneously reported to be 896 feet thick. Using the corrected values, the total Picachos de Calera Paleozoic section is only 2,744 feet thick.

Britt concludes that the Picachos de Calera are not klippen, but are the exposed part of the west flank of a large syncline. He suggests that a down-faulted major anticline might be buried beneath alluvium to the west.

His colored geological map is on the scale of 1:3375.

Studies of Mesozoic Stratigraphy, 1957-1958

Paul J. Bennett, (1957) wrote a master's thesis on "The geology and mineralization of the Sedimentary Hills area, Pima County, Arizona." The thesis is accompanied by a colored geologic map and two structure sections on the scale of one inch equals 400 feet.

Bennett divides the Amole Arkose of the Sedimentary Hills into a northern argillic unit and a southern limey unit, separated by a southward-dipping thrust fault. The northern argillic unit, about 1,400 feet thick, consists of argillite, shale and siltstone, with a number of arkosic inter-beds. Some of the arkose members have associated basal conglomerates.

The southern limey unit, more than 1,000 feet thick, consists of banded limey argillite and banded argillite with a few thin limestone beds and one 150 foot bed of "rather coarse-grained arkosic sandstone." One of the limestone beds contains fossil pelecypods that "were identified by Dr. Donald Bryant as a probable Upper Cretaceous fauna." The total thickness of Amole strata here is in excess of 2,400 feet.

The northern argillic unit has been intruded, near a thrust fault, by a small, composite stock-like body of quartz monzonite and granite porphyry, and the quartz monzonite contains a 20-25 foot, nearly circular, quartz-pegmatite pipe.

Bennett concludes that the intrusions were emplaced previously to thrusting movements, or at least before movement on the thrust had entirely ceased.

In 1963 R. E. Davenport submitted a master's thesis on a "Geophysical investigation of the Sedimentary Hills area, Pima County, Arizona". According to Davenport the results indicate that southwest of the thrust mapped by Bennett there exists a second, parallel, "mineralized thrust zone" concealed by alluvium.

Richard L. Whitney (1957) submitted in a master's thesis the results of his re-study of the Sweetwater Drive area. At that time, the possibility was being considered that the big, exotic blocks of that area, and elsewhere in the Tucson Mountains, might have been emplaced by some sort of gravitational transport.

Whitney's colored geologic map, at the scale of about 360 to 370 feet to the inch, is a beautiful work. He is able to correlate many of the blocks with the late Paleozoic section as described by Gilluly, Cooper and Williams, (1954) and by D. L. Bryant (1955). The oldest formation recognized is the Martin Limestone, but some blocks impossible to correlate might have come from still older formations. Blocks from the Escabrosa Limestone, the Pennsylvanian Horquilla Limestone, and the Permian Scherrer Formation, Concha Limestone and Rainvalley Formation are recognized and distinguished on the map. Blocks, or possibly extensive areas, of Cretaceous Volcanic Rocks, Recreation Red Beds, and Amole Arkose are also indicated. One tiny stock (or block?) of granite is shown. A few small exposures are noted of Cat Mountain Rhyolite with flow structure parallel in strike and dip to steep contacts with older rocks. Whitney suggests (1957, p. 46) that the rhyolite might have erupted from local fissures.

Whitney considers the arrangement of the exotic blocks to be too orderly to have resulted from any kind of gravitational transport! Therefore, he favors their emplacement as an overthrust sheet. The sheet had been much broken, after emplacement, by a network of steep faults. This fault network had also been active before the advent of the overthrust.

In 1958, R. E. Colby finished a study of the Piedmontite Hills and the Red Hills, the type locality of the Recreation Red Beds. Brown (1939) had shown a fault, at the eastern edge of the Piedmontite Hills, to swing westward to separate the Cretaceous volcanic rocks of these hills from the younger Recreation Red Beds of the Red Hills. Colby finds that the fault does not so turn and that therefore no appreciable displacement separates the two older Cretaceous formations. Further, he suggests that the Cretaceous volcanic rocks, which are fragmental, have been deposited in a huge cut-and-fill channel, eroded into the red beds. Red bed blocks, found in the volcanics, are thought to have caved from the banks of the channel, and red beds interstratified with the volcanics are assumed to have been transported from a headwaters source area, or perhaps eroded from the channel banks. The felsite, mentioned by Guild (1935) appears in thin section to be a strongly altered ignimbrite or welded tuff. It is assumed to have travelled as one or more nuees ardentes down the erosional channel from the volcanic source.

These new findings seem to upset the sequence of the two older Cretaceous formations established by Brown. Colby proposes, therefore, to establish a single Recreation Red Beds formation consisting of three members, –a sandstone-siltstone member (the original Recreation Red Beds), a volcanic conglomerate member (the original Cretaceous volcanic rocks) and a tuff member, (Guild's felsite). This suggestion may apply to advantage in the Piedmontite Hills and Red Hills, but it is not known as yet whether it will be useful throughout the Tucson Mountains.

Colby suggests (1958, p. 41-47) that Brown Mountain (the Piedmontite Hills) has been uplifted by magma that was emplaced beneath. This is essentially the idea expressed by Guild (1935) except that Guild specifically attributed the uplift to intrusive emplacement of the felsite. Colby thinks that the fault at the eastern edge of the hills is a thrust, and he infers that a second thrust fault exists at the western edge of the hills.

The thesis is accompanied by a geologic map of both groups of hills, at 900 feet to the inch, a similar map of the Piedmontite Hills alone at 300 feet to the inch, and a 50 feet-to-the-inch map of some intrusions at the northwest end of the Piedmontite Hills. There is also a 900-feet-to-the-inch fence diagram of the entire area.

In 1958 also, John E. Kinnison submitted a very outstanding master's thesis on the "Geology and ore deposits of the southern section of the Amole mining district, Tucson Mountains, Pima County, Arizona." He briefly reviews the Paleozoic section, then describes a probable basal conglomerate of the Amole Arkose, found to overlie "Snyder Hill limestone on an apparently smooth surface" near the Braun shaft, south of Ajo road (1958, p. 13). The clasts in the conglomerate are angular to sub-rounded pebbles and angular cobbles of black, Snyder Hill (?) limestone, brown limestone and varve-like siltstone.

Kinnison proposes to raise the Amole Arkose to group status, and he describes in it the following informal units in ascending order:

Braun formation (1958, p. 15-17) consists of shale and thin to medium bedded arkose and siltstone, in approximately equal amounts, transitional downward into the conglomerate. A very small percentage of thin-bedded, silty limestone is also present. The color tones range from light tan through yellowish brown to light gray. The thickness (1958, P. 16) "must be well over 1,500 feet."

Dead Cow formation (1958, p. 16-19) is "Principally fine-to coarse-grained pure . . . arkose and quartzite, with a characteristic clear white or light gray color. It is predominantly medium-bedded with well-developed stratification in thin bands." The formation contains some tan, gray and olive siltstone, and one thin but persistent limestone bed with ostracodes. These fossils were identified by Peck (Kinnison, 1928, p. 17) "as of an age no younger than early Cretaceous." [1] Kinnison estimated the thickness of this formation to be approximately 2,000 feet.

Mouse House formation (1958, P. 19-21) is distinguished from the others because of its far greater proportion of limestone beds. Other lithotopes are thin-and medium-bedded brown siltstone and brown and black shale. The whole formation is highly incompetent. Its thickness is unknown. Pollen from this formation was tentatively stated by Roger Y. Anderson (Kinnison, 1958, p. 21) to be no older than Upper Cretaceous.

Echo Valley formation (1958, p. 21) is the uppermost unit, identical in appearance to the Braun formation. Its thickness is unknown, but is probably at least 1000 feet.

It seems, then, that the Amole group, as described by Kinnison south of Ajo road, can hardly be less than 4,500 feet thick, and that it may reach, or even exceed, a thickness of 5,000 feet. Does it represent all or most of Cretaceous time, with the possibility that basal portions might be pre Cretaceous? Kinnison suggests (1958, P. 28) that the Amole sedimentation might possibly have ended as late as early Tertiary.

Overthrust Hypothesis Challenged, 1958-1959

Kinnison next proceeds to establish another new formation, the Tucson Mountain chaos. This is precisely the equivalent of Brown's imbricate thrust sheet. Kinnison states (1958, p. 28) that in this unit very large fragments of all the pre-Laramide rocks are present in a chaotic arrangement. This is the case at many places, although, as we have seen, Whitney was impressed with *order* in the chaos in the Sweetwater drive area. Brown, Coulson and Whitney also noted the especial abundance of Permian blocks in the chaos.

The Tucson Mountain chaos is described (1958, p. 29-30) as a tabular unit easily recognized as a distinct formation. Its stratigraphic position is said to be always the same,—above the steeply-dipping rocks of pre-Laramide age and below the Tertiary Cat Mountain Rhyolite. It is pointed out (1958, p. 39) that an interpretation of the history of certain andesites associated with the chaos is critical to a complete analysis of the Tucson Mountain chaos.

Kinnison suggests, and illustrates with diagrams, the origin of the chaos by erosion and slumping of a thrust mass that advanced onto a previously-established erosion surface, the Tucson surface, of Tertiary age. Thus Brown's imbricate thrust sheet is seen as a widespread, coarse, unsorted sedimentary formation.

The Cat Mountain Rhyolite is described as resting with apparent conformity on the Tucson Mountain chaos. Four members of this rhyolite were described at the type locality, Cat Mountain.

In dealing with the Tertiary formations younger than the Cat Mountain Rhyolite, Kinnison proposes to change the name of Brown's Diopside andesite to Ivy May andesite. It is noted that this rock is both intrusive and extrusive.

The structure south of Ajo road is inferred to be a synclinorium or first order fold, on which are superposed second, third and fourth order folds. "East of the Five fault second order folds are asymmetrically inclined and overturned to the east, and west of the Five fault they are overturned and asymmetrically inclined to the west" (Kinnison 1958, p. 84).

A colored geologic map and structure sections on the scale of one inch equals 1,000 feet are part of the thesis.

J. H. Courtright (1958, p. 7-8) states that the Tucson Mountain chaos is "composed in part of material eroded from a formation of the Silver Bell type." He points out (p. 8) the identity of the chaos with Brown's Cretaceous volcanic rocks. From this we may infer that the imbricate thrust sheet, the chaos, and the Cretaceous volcanic rocks are the same unit.

In the Spring of 1959 the Cordilleran Section of the Geological Society of America again met on the University of Arizona campus. Among the papers written for that occasion and published in Guidebook 2 of the Arizona Geological Society was one by John E. Kinnison on "Chaotic breccias in the Tucson Mountains, Arizona" (1959a, p. 49-57). The Tucson Mountain chaos is described again, and its sedimentary origin by erosion, slumping and gliding from some structural feature with considerable topographic relief is reiterated. In a second brief paper in the same guidebook (1959b, p. 146-150) Kinnison writes (p. 150): "If this interpretation is correct, then there is no direct evidence of large-scale overthrusting in the Tucson Mountains." After 20 years of dominance the concept of a great Tucson Mountain overthrust begins to be seriously challenged.

In Guidebook 2, L. A. Heindl (1959, p. 152-159) presents a discussion of the "Geology of the San Xavier Indian Reservation, Arizona." His map (p. 152) shows the basic volcanic and intrusive rocks of Black Mountain and near-by hills to be distributed along an east-northeast-trending zone of probable faults. He adds to the list of geological formations the intrusive

1. Professor Donald L. Bryant has called my attention to the fact that subsequent examination of these ostracodes has led to a less definite result. Apparently, the Lower Cretaceous age of part of the Amole Arkose, reported by Bryant and Kinnison (1954) cannot be maintained on the evidence of the ostracodes.

(?) Speckled rhyolite and the San Xavier conglomerate of possible Middle Tertiary age. W. B. Ferguson (1959, p. 43-47) in a paper on the Cretaceous rocks of southeastern Arizona, briefly discusses the observations and conclusions of Brown, Colby, and Kinnison.

Fluidization and the Intrusive Emplacement of Limestone Blocks, 1959-1961

James B. Imswiler (1959) reported in a master's thesis on the structure of the Safford Peak area. The oldest rocks in this area are the ones that Brown mapped as Cretaceous volcanic rocks. Imswiler finds them to consist of interbedded flows, tuffs, and tuffaceous arkoses. The strike of the stratification is slightly north of east, and the dip is steeply northward. Imswiler proposes the name Safford conglomerate for the Tertiary conglomerate which Brown found to rest with angular unconformity on the Cretaceous volcanic rocks. He also includes in the Safford conglomerate Brown's Safford Tuff. Thus, the Safford conglomerate has a lower, conglomerate member and an upper, tuff member. Where these members are not separated by the Rillito Andesite, they grade into one another. Imswiler retains the name Safford Tuff for what Brown regarded as the bottom, tuffaceous unit of the Upper Andesite. The Safford Tuff, thus defined, is conformably overlain by the Contzen Pass formation, uniformly 20 to 40 feet thick and a vitrophyre from bottom to top. The Contzen Pass formation is separated from the Upper Andesite by from one foot to possibly ten feet of loose, unconsolidated ash.

Imswiler finds that parts of both the Rillito Andesite and the re-defined Safford Tuff are intrusive. Where the tuff is intrusive, it is itself intruded by a network of granophyre, or aplite veins which Imswiler regards as having been emplaced as a fluidized system. So far as I am aware, this is the first reference to fluidization in connection with any geologic feature in the Tucson Mountains.

The trends of some of the faults and the elongation of the dacitic Safford neck seem to follow the structure of the pre-Tertiary rocks. These features are shown on the colored map at 800 feet to the inch and on the structure sections.

In a master's thesis on "Correlation of volcanic rocks in Santa Cruz County, Arizona," Omer J. Taylor (1959) correlated the members of volcanic sequences in Santa Cruz County with the volcanic units of the Tucson Mountains, beginning with the andesites in the Cretaceous volcanic rocks and ending with the basalts. The data and conclusions, in more condensed form, were published the following year (Taylor, 1960).[2]

Kenyon Richard and J. H. Courtright (1960, p. 1-2) write as follows concerning the Tucson Mountain chaos and the Cretaceous volcanic rocks:

"As described by Kinnison the Tucson Mountain chaos is a giant breccia–unusually large blocks in a clastic matrix–that was deposited on an early Tertiary (?) erosion surface (the Tucson surface). Parts of this formation, and also a series of andesite-Pebble conglomerate beds in the Piedmontite Hills, had previously been mapped by Brown as Cretaceous volcanics. A recent study of the Piedmontite Hills was made by Colby who reported the occurrence of a rhyolite tuff in these clastics. The field evidence suggests to us that this rhyolite is an intrusive rather than a pyroclastic."

"At this time none of the volcanics of the Tucson Mountains can be demonstrated to be Cretaceous. Locally, andesite underlies the Tucson Mountain chaos; the relationship to older rocks is not definitely known, but we believe that it is most probably post-Cretaceous."

Nine columnar sections illustrate the authors' regional correlations. It is an impressive fact that at many places the volcanics are underlain by very coarse clastics. Perhaps some process that causes giant breccias has operated regionally.

In the following year was published a description of the structure of an intrusive andesite porphyry southwest of the Arizona-Sonora Desert Museum (Mayo, 1961). Some structural features in the sedimentary rocks surrounding the intrusion seem most readily explained as results of fluidization. Thus, for the second time, the fluidization process is referred to in connection with minor, local structures in the Tucson Mountains.

A postscript states that Carol Halva found this porphyritic andesite to be identical to the turkey track porphyry, which crops out over a large region in southeastern Arizona.

John R. Cooper (1961) published the results of a careful petrographic and petrochemical study of the turkey track porphyry, which the geologic relations indicate to be Miocene in age. Cooper suggests, as hypothesis, that this porphyry, which varies little from place to place ". . . came from the same deep-lying magma chamber during a geologically short interval of time, and therefore . . . is a valid though somewhat rough marker for regional correlations."

Gerald Greenstein (1961) submitted the results of a structural study of the Amole Arkose northeast of the Desert Museum. Brown had shown his great overthrust to pass through this area, but Greenstein finds no evidence of the overthrust. Further, he feels that the evidence exposed in his area favors emplacement of the Permian (?) limestone blocks by rising, viscous masses of Amole Latite. It seems to him that the

2. Professor Paul E. Damon has reminded me that Taylor was the first person to recognize the unusually high potassium content of the Tumamoc Hills and "A" Mountain "basalts."

latite has broken through the Paleozoic section and has lifted the blocks of limestone into the Cretaceous section.

A geochemical investigation was made of "basalts" in southern Arizona by Carol Halva (1961). He finds that the basic rocks of the Tumamoc Hills and Black Mountain are "potassic basaltic andesites" (1961, p. 57). The excess of potash is in the groundmass, not in the phenocrysts. According to Professor Damon (personal communication) Halva also established that the turkey track porphyry and the potassic basaltic andesites were very similar in composition. Further, they often occur together and, in every case studied by Halva, the turkey track porphyry was extruded prior to the potassic basaltic andesites. Apparently, Halva accepts the Quaternary age of these rocks.

Richard Champney (1962) as part of the requirements for the MS degree studied the structural geology of one of the cooling units in the Cat Mountain Rhyolite. The unit is a thick, reddish flow which seems to have been essentially inflated and mobilized Recreation Red Beds. Plates III and V accompanying the thesis are a map and cross sections of a small area in which andesite porphyry appears to have domed up the Amole Arkose, and to have pushed small Paleozoic limestone blocks up into the arkose. These observations lend support to Greenstein's conclusion as to the mode of emplacement of the limestone; but we should not forget that this emplacement mechanism had been visualized by Guild, many years before.

Radiometric Dates from Tucson Mountain Rocks, 1962-1965

During this period were published (Damon, 1962-1965) a number of radiometric dates of Tucson Mountain rocks. The list below has been compiled from the annual reports from Professor Damon's laboratory to the U. S. Atomic Energy Commission.

Sample	Rock and Constituent	Apparent Age
PED-10-63,	Safford Tuff, biotite	25.2 ± 1.7 m.y.
5A-2,	Contzen Pass Formation, biotite	26.0 ± 1.7 m.y.
MB-2-62,	Upper Andesite, biotite	27.9 ± 1.9 m.y.
PED-9-63,	Rillito Andesite, biotite	38.5 ± 1.3 m.y.
PED-1-64,	Safford Dacite, Biotite	24.5 ± 0.9 m.y.
MB-1-62,	Cat Mountain Rhyolite, feldspar	70.3 ± 2.3 m.y.
MB-3-62,	Cat Mountain Rhyolite, feldspar	65.2 ± 2.0 m.y.
PED-11-63,	Amole Quartz Monzonite, biotite	72.9 ± 2.2 m.y.
PED-12-63,	Granophyre, biotite	75.1 ± 2.2 m.y.
PED-3-64,	Amole granite, biotite	68.1 ± 2.7 m.y.*
PED-15-62,	Short's Ranch Andesite, biotite	56.8 ± 1.9 m.y.
PED-19-62,	Biotite Rhyolite, biotite	60.5 ± 1.9 m.y.
PED-16-63,	"A" Mtn. Turkey Track Andesite, plag.	28.0 ± 2.6 m.y.
PED-17-63,	"A" Mtn. basalt, whole rock	27.0 ± 1.2 m.y.
PED-7b-63,	"A" Mtn. grey tuff, sanidine	25.8 ± 0.9 m.y.
PED-17-62,	"A" Mtn. grey tuff, sanidine	29.7 ± 0.9 m.y.

*This rock, when re-analyzed, gave a date of 71.4 m.y.

The above dates demand rather considerable changes in previous age assignments. For example, according to Kulp, (1961, p. 1011) the Cat Mountain Rhyolite would be Maestrichtian in age, therefore it cannot rest on a Tertiary erosion surface. Moreover, andesite beneath this rhyolite cannot be Tertiary unless the andesite is intrusive. The "basalts" (Potassic basaltic andesites) and the tuff of "A" Mountain are, according to the same authority, lowermost Miocene or Upper Oligocene in age. They are much older than Quaternary.

It seems that in Upper Cretaceous time igneous activity resulted in emplacement of the composite mass of Amole Quartz Monzonite and Amole Granite, and in eruption of the Cat Mountain Rhyolite. In the southern part of the Tucson Mountains, volcanic activity continued into the Paleocene and perhaps into Lower Eocene. In the northern part of the range post Cat Mountain volcanism began with intrusion and extrusion of the Rillito Andesite in Upper Eocene or Lower Oligocene time, and it continued in the northern, central and southern portions into lowermost Miocene. There appears to have been no Pleistocene, Pliocene, or even Upper or Middle Miocene volcanic activity.

Volcanic Orogeny, 1962-1966

In 1962 Michael Bikerman submitted a master's thesis entitled "A geologic-geochemical study of the Cat Mountain Rhyolite" and in the following year he published a brief paper dealing with the thesis subject (Bikerman, 1963). He points out that Kinnison and Taylor had assigned to this formation a nuee ardente origin, and that Kinnison had supposed the underlying Tucson Mountain chaos to be of sedimentary-tectonic origin. Bikerman proposes, as a result of his studies, that the chaos represents an initial phase of the volcanic activity which gave rise to the Cat Mountain Rhyolite, and which terminated with emplacement of the Spherulitic rhyolite. He writes: (1963, p. 84-85) "The chaos unit is a pyroclastic flow breccia . . . of probable nuee ardente-type origin."

Simultaneously there was published (Mayo, 1963) a preliminary report on "Volcanic orogeny of the Tucson Mountains." This report is based principally on a detailed re-study of the Piedmontite Hills. There it is found that certain parts of the fragmental volcanics have *intruded* other parts as well as the red siltstones. The resulting mixture has in turn been intruded by probable rhyolitic ignimbrite (Colby's tuff member, Guild's felsite). There is no longer need to assume a cut-and-fill channel; the observed relations are more readily accounted for by intrusion and fluidization.

On the assumption that the Piedmontite Hills might provide the key to Tucson Mountain structure, a section is walked out across the Sedimentary Hills, Golden Gate Mountain and Bren Mountain and shorter sections are made in the Gate's Pass area. A surprising observation is that, as the Cat Mountain Rhyolite is approached over the Amole Arkose, the arkose begins to dip toward the rhyolite, and this dip steepens toward the contact. Further, near and in contact with the rhyolite, the steeply-dipping Amole Arkose appears to have become disaggregated and mixed with foreign elements, including fragments of andesite, pieces of apparent Pinal Schist, and a few large blocks of limestone. The structure of this chaos appears to be steep, and the flow structure of the rhyolite in contact with the chaos is steep also. In the area sectioned, the chaos cannot be observed to rest on an erosion surface. In fact it appears that arkose, chaos and rhyolite may be essentially conformable, and all are steep.

The section across Golden Gate Mountain (fig 2, B) seems to show a funnel of Amole Arkose lined on the inside by a thick or thin shell of Tucson Mountain chaos. The Cat Mountain Rhyolite forms the core of this inverted cone. It seems that the chaos is indeed related genetically to the rhyolite, but both the sedimentary and the nuee ardente origins of the chaos are questioned. The structures resemble, on a huge scale, those reported by Hans Cloos (1941) from the Swabian tuff pipes.

S. M. Assadi (1964) reported in a master's thesis on the "Structure of Golden Gate Mountain, Pima County, Arizona." The excellent 500-feet-to-the-inch, colored geologic map accompanying this thesis confirms, with minor exceptions, the above-mentioned interpretation that the Amole Arkose dips funnel-like into the mountain. Assadi's discussion strongly suggests a premonitory period of upward bulging at the site of Golden Gate Mountain, followed by collapse, formation of a core of Tucson Mountain chaos (which he calls brecciated Amole) and intrusion of the chaos by Cat Mountain Rhyolite.

At the same time as Assadi, P. A. Geiser (1964) made a study of the Gates Pass area and part of Bren Mountain. Geiser finds that Bren Mountain is partially surrounded by a steep, inward-dipping collar of Amole Arkose, with an inner collar of Tucson Mountain chaos. Within the inner collar, in turn, is the Cat Mountain Rhyolite. The semi-circular, inward-dipping structure of these collars is reflected inward by the flow structure of the rhyolite. Geiser concludes that the central mass of Bren Mountain has been emplaced as an endogenous dome. On the basis of field and petrographic studies he suggests that the Cat Mountain Rhyolite was generated by the partial fusion of Amole Arkose by rising andesitic magma.

Mayo and McCullough (1964) published the results of a brief study of some limestone and other basement blocks in the Tucson Mountain chaos. At every place examined, there is associated intrusive andesite that could have lifted the block. The writers conclude that, of six theories proposed to date for emplacement of the blocks, the most probable is uplift by intrusive magma, perhaps aided by fluidization of the overlying Cretaceous deposits. Essentially the same conclusion is reached independently by Scott McCoy (1964). The problem of the emplacement of these blocks is, of course, very closely related to the problem of the origin of the Tucson Mountain chaos.

J. E. Mielke (1964; 1965) reported on a "Trace-element investigation of the turkey track porphyry, southeastern Arizona." He finds the composition of this porphyry from widely separated localities to be surprisingly constant and to be close to that of doreite, as suggested before by Cooper (1961). The various occurrences seem to be parts of a single unit, emplaced (Mielke, 1964, p. 92) ". . . all within the span of a few million years." It is suggested (p. 93) that the turkey track porphyry was emplaced within the interval of 25-30 million years ago.

F. Richard Yeatts (1964) wrote "On the orientation of crystals in porphyritic rocks." The subject of this study was the porphyry near the Desert Museum. Yeatts concluded that during emplacement of this body an early affine deformation may have gone over into incipient fracturing to which many of the phenocrysts became aligned.

In 1965 John Horton submitted a master's thesis on "The geology of the Man-a-gah picnic area, Tucson Mountains, Pima County, Arizona." Horton suggests that the Silver Lily dikes and the Amole Latite are of the same age. He also reports "rare small xenoliths" of the Amole Quartz Monzonite in the Amole Latite, and intrusive contacts of the latite against the quartz monzonite. He regards many of the limestone "blocks" in the area as lenses in the Amole Arkose. Only one block, south of the Mile Wide Mine, is admitted as being possibly of Paleozoic age.

The results of a structural study of the Museum Embayment (Mayo, 1966a) have been published in preliminary form. The embayment is defined as the low area that contains the Arizona-Sonora Desert Museum and the village of Old Tucson, and that is enclosed by the cliffs of Cat Mountain Rhyolite on the east, the Amole Mountains of Jenkins and Wilson (1920) on the north, the Red Hills and Piedmontite Hills (Brown Mountain) on west and southwest, and by the Sedimentary Hills and Golden Gate Mountain on the south and southeast.

The geologic formations and structures in and marginal to the embayment are discussed and it is concluded that the structure is the result of emplacement at depth of magma. From time to time this magma has approached or gained the surface to form the Cretaceous volcanic rocks of Brown, or the Tucson Mountain chaos, the Amole Latite, the Cat Mountain Rhyolite, and related intrusive rocks. Additional observations and some inferences are presented on the Tucson Mountain chaos and the Cat Mountain Rhyolite, but definite conclusions on the mechanism of emplacement of these units are deferred pending further field work.

Expressing a growing conviction of the present writer, the statement was made (1966a p.30) that ". . . the burden of proof rests on any geologist who glibly speaks of the 'compressional phase of the Laramide orogeny' in these mountains."

The above report was followed (Mayo, 1966b) by a paper on "Paleocurrents in the Museum Embayment, Tucson Mountains, Arizona." From measurements on directional current structures in the Amole Arkose and in sandstones of the Recreation Red Beds, it is concluded that in general the paleocurrents flowed from northwest to southeast. However, there are marked deviations, and even reversals, of flow direction, thought to have resulted from instability of the surface of deposition. Comparison of the pattern of paleocurrents with the pattern of fold axial traces discloses such close agreement that it seems as though deformation had already started at the time the Recreation Red Beds and Amole Arkose were being deposited.

Damon and Mauger (1966) on the basis of accumulated radiometric dates on Mesozoic and Cenozoic intrusive and extrusive rocks in the Basin and Range province, point to orogeny as a restricted, exothermic process, superimposed on the much broader, primary process of epeirogeny. In the Tucson Mountains, two orogenic maxima have been established, the Laramide one in uppermost Cretaceous and Paleocene, and the Basin and Range Orogeny in Upper Oligocene and Lower Miocene.

Figure 3, based on all available data as of 1966, is an attempt to represent Tucson Mountain rocks and history from the beginning of Cretaceous time to the end of the Basin and Range Orogeny. Units that have been dated radiometrically are shown in capital letters; those dated by other means are shown in lower case letters.

Some Results of Current Investigations, 1967-1968

A steep contact, discovered some years ago by P. A. Geiser, between intrusive Cat Mountain Rhyolite and highly disturbed Amole Arkose, has recently been the subject of detailed study (Mayo, 1967). The disturbed sedimentary rocks bend down to form the walls of a steep funnel of which the rhyolite forms the core. The field and thin section study suggests that this part of the rhyolite was emplaced at rather low temperature as a fluidized particulate system. The sedimentary walls, likewise were fluidized. The funnel structure is thought to result from collapse, caused mostly by expulsion of material to the surface, but in part also by post eruptive compaction.

Louis J. Jansen (1968) is making a geologic study of the Sus Hills, the westernmost outcrops in the Tucson Mountains, bordering the granite phase of the Amole Pluton in the Sahuaro National Monument. Here an east-facing sequence, beginning with probable Permian formations, followed by intrusive Cat Mountain Rhyolite, then by Amole Arkose, dips on the whole steeply eastward under the pluton. Where the succession is complete the Amole Arkose borders directly the granite, but in the northern part of the hills rhyolite and arkose are missing and the granite is in contact with the supposed Permian.

The above two examples seem to represent a frequently observed case in which the wall rock, with few exceptions, dips steeply toward the intrusive or eruptive center.

A detailed study of the Cat Mountain Rhyolite and the Cretaceous volcanic rocks in the northern part of the range, southwest and south of the Old Yuma Mine has been completed by Louis H. Knight (1967). Brown (1939) had shown on his map in this area east trending strips of Cat Mountain Rhyolite faulted down into his Cretaceous volcanic rocks. Knight finds that the rhyolite is actually part of a very steeply north-dipping and north-facing sequence that includes Cat Mountain Rhyolite at the base, overlain by a new formation, the Cam-boh rhyolite, perhaps 2,000 feet thick, in turn overlain by another new formation, the Old Yuma

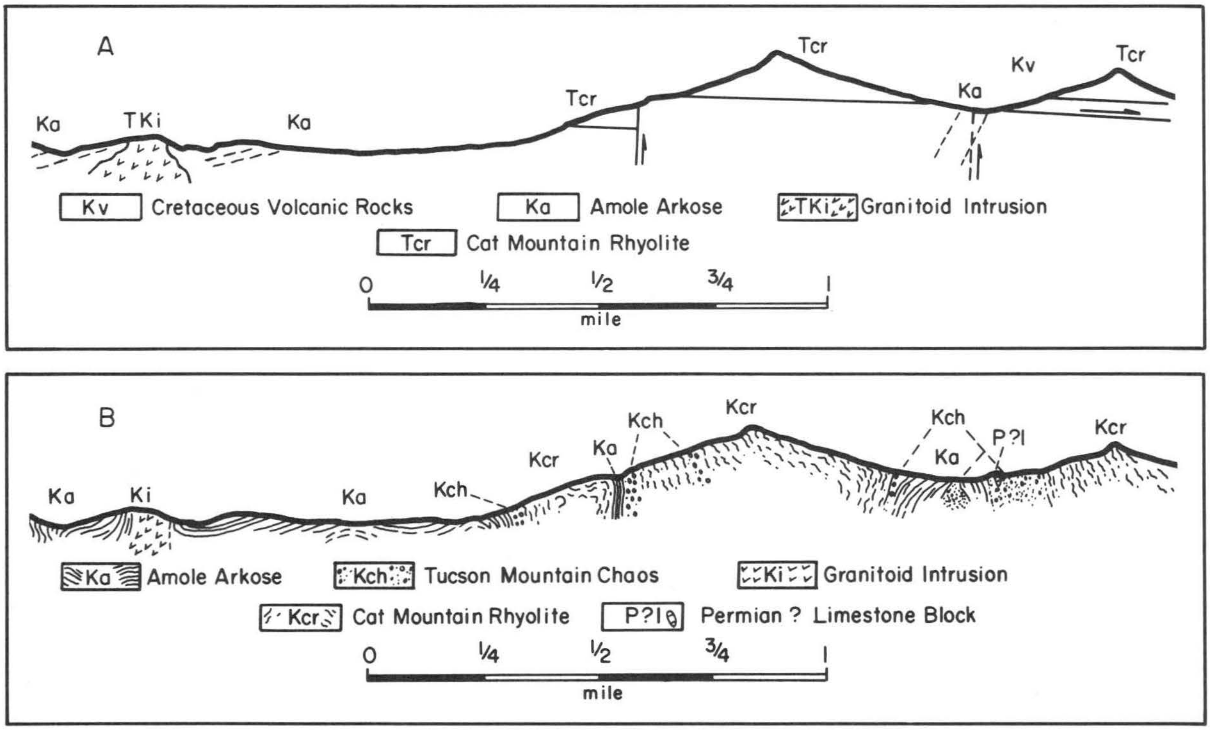

Figure 2 – Sections, trending northeast across the Sedimentary Hills, (left) Golden Gate Mountain, (right of center) and Bren Mountain (extreme right). A–after Brown, (1939); B–after Mayo, (1963).

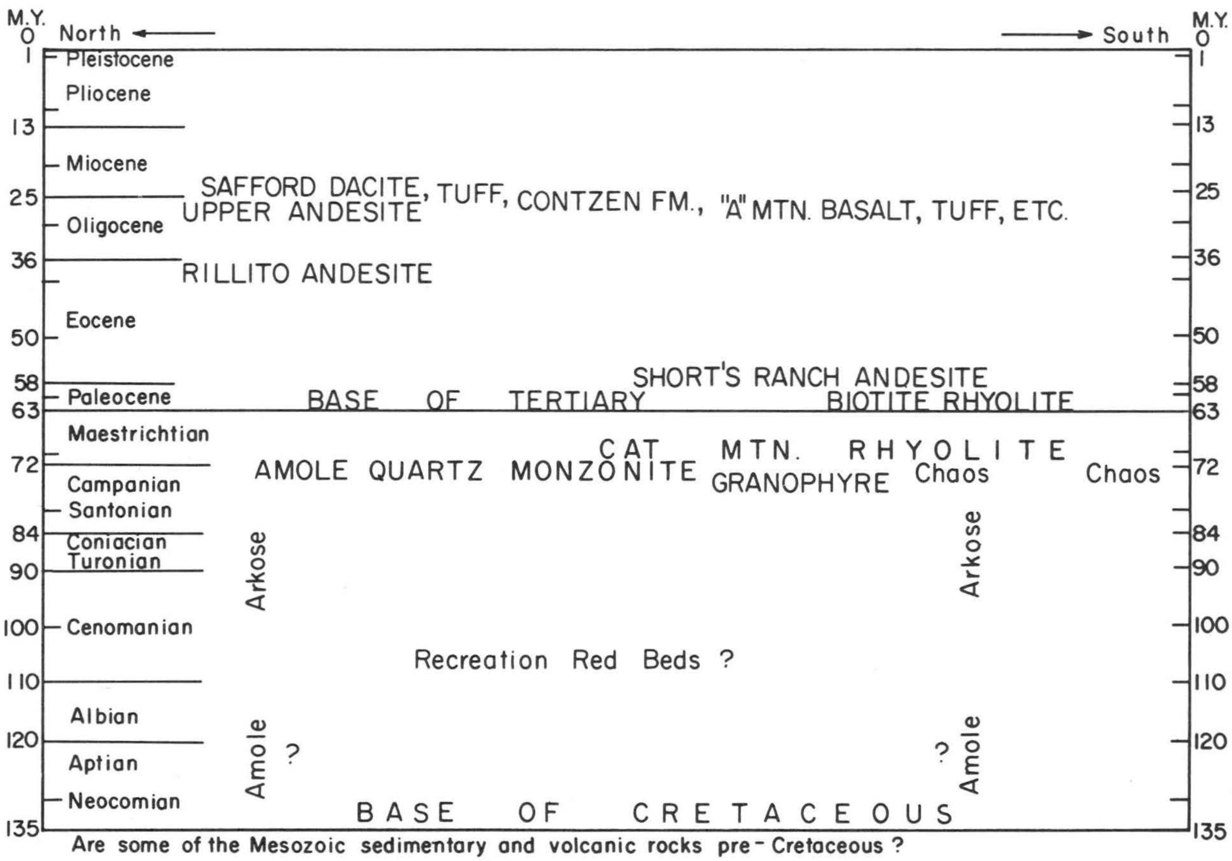

Figure 3 – Tucson Mountain rocks and geologic time, based on the time scale of Kulp (1961) and all data on Tucson Mountain rocks available as of 1966.

andesite, which may be 1,000 feet thick. This interpretation is based on primary ash flow features in the rhyolites, on the presence of an apparent weathered erosion surface on top of the Cat Mountain, and on graded bedding in thin sedimentary units.

Unless there is an undetected error in the above, it has to be accepted that several thousand feet of volcanic and sedimentary rocks overlie the Upper Cretaceous Cat Mountain Rhyolite and are truncated by the surface on which was deposited the Safford Conglomerate. Further, the easterly strikes and steep northward dips of the pre-Safford rocks persist northward for at least two miles beyond Knight's map area. Obviously, present information in this part of the range raises a number of important problems.

Coming on the heels of Knight's findings is another surprising discovery made by a worker in Professor Damon's laboratory (P. E. Damon, personal communication). Suspecting, on chemical evidence, that the "coarse phenocryst porphyry" near the Desert Museum (Mayo, 1963) was not the same as the turkey track porphyry, Damon asked graduate student Peter Kuck to analyze radiometrically, by the K-Ar method, a fresh specimen of this rock. The apparent age so obtained, and carefully checked, is approximately 150 m. y. The porphyry, then, would appear to be Upper Jurassic in age, according to Kulp (1961). Because this rock intrudes the Recreation Red Beds, the age of these beds must be greater than that of the porphyry. The red beds may be Jurassic, or *even Triassic* in age. Such an assignment would accord with the findings of U.S.G.S. geologists in southeastern Arizona (Simons, Raup, Hayes and Drewes, 1966, p. 1-12).

In view of the above it seems well to look again at figure 3. The question stated at the bottom of the figure is, of course, now answered in the affirmative, and the Recreation Red Beds should be placed below the base of the Cretaceous; in fact they belong somewhere below the lower part of the Upper Jurassic.

The status of the "Cretaceous volcanic rocks" is now seen to be very unsatisfactory. Parts of this complex appear to be pre-Cretaceous in age, whereas other parts of it seem to be younger than the Upper Cretaceous Cat Mountain Rhyolite. Probably nothing effective can be done about this situation until much more is known about the geology of these volcanic rocks, and until more radiometric dates are available.

Judith K. Percious (1968) has just completed a field study of the turkey track porphyry and the potassic basaltic andesites of Black Mountain and nearby hills. The related geochemical investigation is still in progress.

She finds that a large dike of turkey track porphyry extends east-northeast along the axis of Black Mountain and beyond as far as Mission San Xavier del Bac. On Black Mountain there is an eruptive center of turkey track porphyry which may be the source of a turkey track flow present on "A" mountain. At Martinez Hill (Sahuarita Butte) a new road cut has exposed several superimposed flows of potassic basaltic andesite, separated by gravels. All of the flows, on Black Mountain as well as on Martinez Hill, are tilted northward as though by movement on an east-northeast trending normal fault or zone of normal faults.

CONCLUSION

The above narrative, terminated as of 1967-68 is obviously far from finished. Geology has to be built up from details, as an edifice is erected, brick by brick. Years of field and laboratory work still remain if we wish to achieve a proper understanding of the geology of the Tucson Mountains. Future workers, warned by history, will demand good, substantial evidence for every statement. Let us avoid basing any further conclusions on quicksand.

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VOLCANIC STRATIGRAPHY AND STRUCTURE OF THE PENA BLANCA AND WALKER CANYON AREAS, SANTA CRUZ COUNTY, ARIZONA

By

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INTRODUCTION

The area discussed in this paper is part of the Coronado National Forest, and lies about 15 miles west-northwest of the city of Nogales, Santa Cruz County, Arizona. The area is bordered on the south by the United States-Mexico Boundary along a line from a point one mile east of International Boundary Monument no. 127 to a point midway between Boundary Monuments no. 128 and no. 129. Lines bearing true north from these points form the eastern and western limits of the area mapped. The northern border is a line parallel to and six miles north of the east-west bearing portion of the International Boundary.

Geology of the Pena Blanca And Walker Canyon Area

The geology of the Pena Blanca and Walker Canyon area is characterized by a complex of volcanic and interbedded sedimentary rocks, which are believed to range in age from Upper Cretaceous to Recent. Volcanic rocks in southeastern Arizona are usually considered Cretaceous and older if they are badly faulted and folded, Tertiary if they are tilted, and Quaternary if they are flat-lying (Taylor, 1959). Since no dateable strata were found, ages have been assigned to the formations studied by using these suppositions, as well as the principle of superposition.

Extrusive rocks, comprised of tuffs and lava flows, range from rhyolite to basalt in composition. Conglomerates and breccias are the most common sedimentary rocks, with some small interbedded lenses of arkosic sandstone.

There are four recognized formations in the Pena Blanca and Walker Canyon area (Wilson and others, 1957). Three of these, the Pajarito Lavas, the Montana Peak Formation and the Atascosa Formation, were named by Webb and Coryell in 1954. The fourth formation, the Oro Blanco Conglomerate, was named by G. Fowler in 1938. On the basis of field evidence discussed later in this report, a fifth formation can be recognized. This unit, which for the purpose of this report will be called the "Pena Blanca formation", contains the youngest rocks found in the area.

Pyroclastic Terminology

The terminology used in this report to describe pyroclastic rocks is based on a paper by C. K. Wentworth (1932). The following is a list of some of these terms and Wentworth's definitions of them.

Tuff: Indurated pyroclastic rocks of grain generally finer than 4 mm.; i.e., the indurated equivalent of volcanic ash and dust.

Sedimentary tuff: A tuff containing a subordinate amount of sediment introduced either during or after deposition, e.g., the finer deposits of volcanic mud flows, or rocks produced by the erosion and redeposition of pyroclastic ejecta admixed with nonvolcanic materials.

Volcanic conglomerate: Sedimentary, coarse pyroclastic material containing an abundance of large, chiefly rounded, water-worn fragments. In most cases they result from the erosion and redeposition of old volcanic rocks, but they may also be formed by volcanic mud flows and by the action of running water on freshly fallen ejecta.

Volcanic breccia: More or less indurated pyroclastic rocks, consisting chiefly of angular ejecta 32 mm. or more in diameter. If the fine tuff matrix be abundant, the term "tuff-breccia" seems appropriate.

Agglomerate: Contemporaneous pyroclastic rocks containing a predominance of rounded or subangular fragments greater than 32 mm. in diameter, lying in an ash or tuff matrix and usually localized within volcanic necks or at a short distance therefrom. The form of the fragments is in no way determined by the action of running water, as in volcanic conglomerate, but is a primary feature determined by the actual eruption.

Lithic: An adjective applied to any pyroclastic deposit in which the fragments are composed of previously formed rocks.

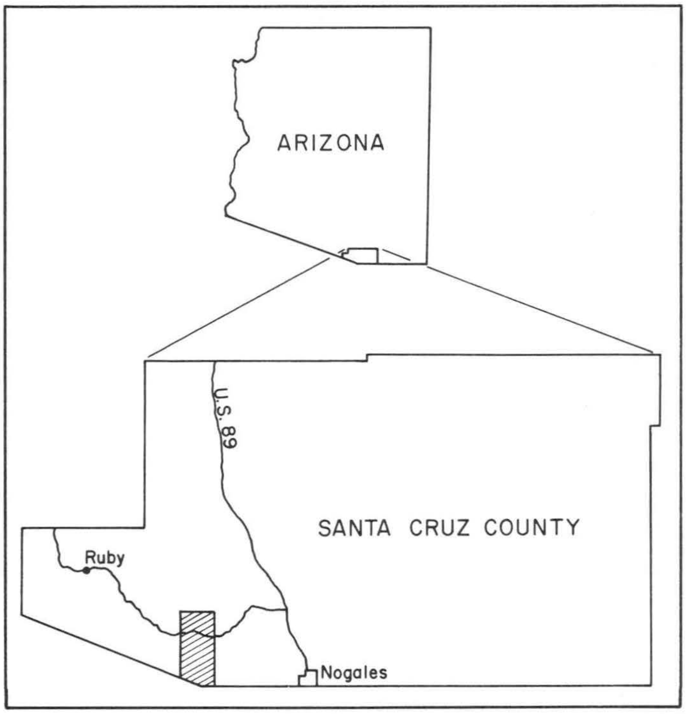

Figure 1 – Location of Pena Blanca and Walker Canyon area

Essential: Pyroclastic detritus, whether loose or indurated, which is of immediate, juvenile, magmatic origin.

Accessory: An adjective denoting pyroclastic materials derived from previously solidified volcanic rocks of consanguineous origin, i.e., the debris of earlier lavas and pyroclastic rocks from the same cone.

Accidental: An adjective used to designate pyroclastic materials derived from volcanic rocks, non-consanguineous with the magma involved during an eruption or from other igneous, metamorphic or sedimentary rocks through which the vent was developed.

STRATIGRAPHY

Cretaceous Rocks

Pajarito Lavas The oldest rocks that crop out in the Pena Blanca and Walker Canyon area belong to the Upper Cretaceous(?) Pajarito Lavas. Webb & Coryell (1954) assigned these rocks to the Mesozoic on the basis of their badly faulted and jointed character. On the geologic Map of Pima and Santa Cruz Counties, Arizona (Wilson, et al, 1960), rocks in this area are shown to be Cretaceous and Laramide in age. In a complete section, the Pajarito Lavas underly the Cretaceous (?) Oro Blanco Conglomerate. Locally the lavas are unconformably overlain by the conglomerates and tuffs of the Tertiary (?) Atascosa Formation and the Quaternary Pena Blanca formation.

The Pajarito Lavas occupy most of the southern half of the mapped area, where they form the Pajarito Mountains. This massive flow probably extends for ten miles or more south into Sonora, as mountains with similar appearance to the Pajaritos of Arizona can be seen from higher points along the International Boundary.

One of the best exposures of this formation occurs on the east side of Walker Canyon, about a half mile north-northwest of Pajarito Peak. Here over 800 feet of the lavas can be seen, outcropping on the 50 degree

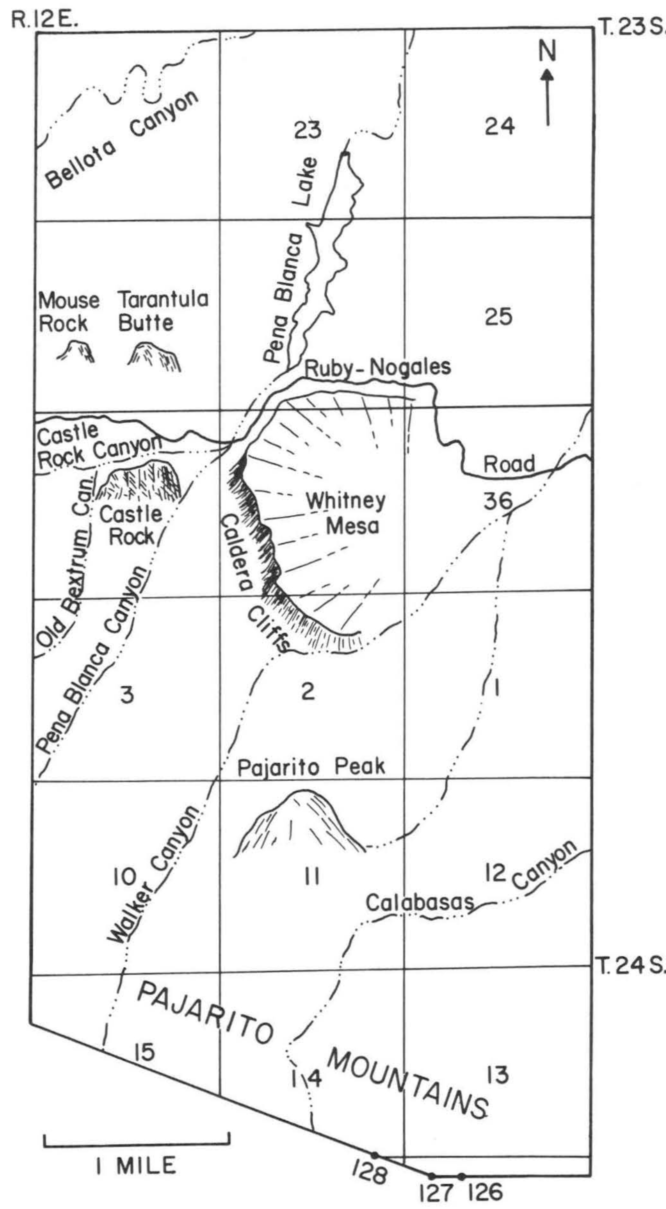

Figure 2 – Detail of area

slope of the canyon wall. The formation is also well exposed in the deeply cut upper parts of Pena Blanca, Walker, and Calabasas Canyons, and in most of their higher tributaries.

It is difficult to determine the exact thickness of the Pajarito Lavas, as no underlying formations have been observed and the whole unit is extremely faulted and broken. At least 1,300 feet are exposed in the Pajarito Mountains, generally dipping to the northwest and increasing in thickness toward the southwest.

Newly exposed outcrops have a blocky, angular appearance the result of closely spaced, intersecting joints that cut the rock in many directions. The lavas are usually deeply weathered, giving a rounded symmetrical shape to the mountains of the Pajarito Range.

The formation is composed of massive, porphyritic quartz latite, which varies in color from reddish pink to light grey. Phenocrysts of quartz and pink feldspar are abundant, and can readily be seen with the unaided eye. A few minor intrusions cut the formation, and include quartz latite porphyry and andesite porphyry. Veinlets of quartz transect the Pajarito Lavas in all directions. Some of them are more than ten inches wide and usually contain miarolitic cavities. Occasionally pale amethyst crystals occur in these cavities.

Oro Blanco Conglomerate The Oro Blanco Conglomerate was first named and described by G. Fowler (1938), who tentatively regarded it as Mesozoic age. It was named for the Oro Blanco Mining District, in which its type locality, the Montana Mine, is located.

On the Geologic Map of Pima and Santa Cruz Counties, Arizona (Wilson, et al, 1960), these rocks are shown to be of Cretaceous age. In the Pena Blanca and Walker Canyon area, the Oro Blanco Conglomerate rests disconformably upon the Cretaceous(?) Pajarito Lavas, and is unconformably overlain by the Cretaceous(?) Montana Peak Formation. An irregular layer of silicified tuff locally separates the Pajarito Lavas from the Oro Blanco Conglomerate. This tuff layer probably was deposited upon an old erosion surface of the lavas, as its thickness varies greatly in different exposures. The tuff is usually apple-green with scattered patches of pink, and is cut by many veinlets of vuggy quartz.

Except for a few tilted and deformed blocks, the conglomerate dips toward the northeast at steep angles. It is a hard, well indurated rock, although not generally a cliff-former. Outcrops appear as low, irregular hills and occasionally as steep canyon walls.

The best exposure of the Oro Blanco Conglomerate is found in the Montana Mine at Ruby, about fifteen miles west of the area discussed in this report. It is the host rock for the lead-zinc-gold ores of the mine, and covers a large area in the western part of Santa Cruz County (Fowler, 1938). This formation is widespread northwest of Ruby, with isolated outcrops east and south. In the Pena Blanca and Walker area it is represented by two relatively small outcrops, one in Castle Rock Canyon, and another southeast of Castle Rock.

Fowler (1938) noted that this formation occupied depressions in the underlying rock to a depth of "many hundred feet". In Castle Rock Canyon the outcrop of Oro Blanco Conglomerate averages approximately 200 feet in thickness.

Color of the conglomerate varies from bright red to dark greyish purple. It has a mottled appearance in some places due to included fragments of green, silicified tuff. The formation shows the effect of what may be hydrothermal alteration, principally the staining of fragments and cementing material by iron oxides. This red staining is most pronounced where the conglomerate is nearest Castle Rock, and grades to sporadic areas of grey colored rock further away.

Classification of the Oro Blanco Conglomerate is difficult, as it combines characteristics of a conglomerate and a sedimentary breccia. It contains angular, subangular and rounded fragments, which range from less than an inch to over twelve inches in diameter. Interstices are filled with sand-sized particles. Lenses of arkosic sandstone are abundant, interbedded between layers of conglomerate. Webb and Coryell (1954) mention that the formation locally contains thin limey beds.

Stratification of this formation is pronounced, and is primarily due to concentrations of similar sized fragments. Differences in the degree and type of cementation have been brought out by differential weathering.

The fragments are badly weathered, and consist primarily of igneous rocks, mainly subangular boulders of the Pajarito Lavas. Quartzite and silicified tuff fragments also occur, and are commonly smaller and more rounded than the lavas. The cementing material is generally silica and exceptionally calcium carbonate.

Montana Peak Formation The Montana Peak Formation was named by Webb and Coryell (1954), who considered it to be late Cenozoic in age. Its type locality is Montana Peak, a prominent mountain 1½ miles southeast of the town of Ruby. On their reconnaisance geologic map, Webb and Coryell indicate that some rocks of the Pena Blanca and Walker Canyon area are contained within the Montana Peak Formation.

E. Wilson (1962) noted that these rocks had a lithology common to the Cretaceous, and that they lie with pronounced angular unconformity beneath strata of supposed Tertiary age. These features have been observed in the field in the present study. Therefore, in this report the Montana Peak Formation is considered to be Upper Cretaceous(?).

In a complete section this formation is underlain by the Cretaceous (?) Oro Blanco Conglomerate, and is unconformably overlain by the Tertiary (?) Atascosa Formation. Locally the Montana Peak Formation overlies the Cretaceous (?) Pajarito Lavas. In a few places it is covered by the Quaternary Pena Blanca formation.

The Montana Peak Formation is well exposed in Pena Blanca Canyon, particularly along the shores of the lake north of the dam. Around the lake the best exposures are on the east side, directly across the lake from the boat dock, and on the west shore about 600 yards north of the dock. In the canyon north of the dam the Montana Peak Formation forms steep cliffs, 50 to 100 feet high. Except for a few deeply cut washes, the formation in the rest of the area is covered by slope-wash, with only the more resistant layers exposed.

It is not possible to accurately measure a complete section of the Montana Peak Formation in the Pena Blanca and Walker Canyon area, owing to extreme faulting within it. At Montana Peak the unit is 800 feet thick, and probably thins to about 600 feet in the area studied. The formation generally dips steeply toward the south, although faulted blocks can be found at nearly any attitude from horizontal to vertical.

The Montana Peak Formation is usually a red, purple or tan color, with some grey, buff brown and greenish colored rock locally exposed. The unit is characterized by the extreme variety of its layers, which cause it to outcrop as cliffs in some places and as gentle slopes in others.

The formation consists mainly of andesite agglomerates, breccias and tuffs, with numerous ash layers and flows of porphyritic lava. Stratification is distinct throughout the unit except for some hills of massive tuff. The agglomerates, breccias and conglomerates are by far the most important units of the Montana Peak Formation.

The agglomerates are commonly a deep red or purple color. They consist of angular to subangular blocks of porphyritic andesite that vary from less than an inch to over five feet in diameter. The blocks are set in a matrix of red ashy tuff which is quite soft and easily removed by erosion. As a result the agglomerate is rarely exposed as cliffs except in recently cut canyons.

Volcanic breccias and conglomerates occur interbedded with the agglomerates, usually distinctly separated, but occasionally mixed in a chaotic manner. Contacts between the beds are often gradational, with agglomerates grading into breccias and both into conglomerates.

Most breccia layers have fragments that average from a few inches to three feet in diameter. A few layers are extremely coarse, containing boulders up to twelve feet in diameter. The fragments consist most commonly of large angular to subangular pieces of porphyritic andesite and tuff. Porphyritic quartz latite, probably derived from the underlying Pajarito Lavas, is found as fragments throughout. The breccias usually grade upward into obviously water-laid conglomerates, which contain rounded fragments with the same lithologies as those in the breccias. These rocks are generally red or purple, although some exposures of grey conglomerate occur.

The breccias and conglomerates are hard, well indurated rocks, and are usually found as steep cliffs. Softer, less resistant fragments of tuff in the breccias have been largely removed by weathering and erosion, giving the breccia a rough, almost "vesicular" appearance.

Tuffs are the most variable rock type of the Montana Peak Formation. They vary from well indurated, rather pure layers of bright red color, to masses of tan colored sedimentary tuffs full of included fragments. The fragments include both accidental and accessory rocks in the lowest tuff layers, with an obvious increase in accessory material higher in the section.

The purest tuffs are usually less than ten feet thick, and form small cliffs of wide lateral extent. On close observation many of these layers are seen to be banded, with definite zones of red, tan, yellow and grey.

Other tuffs, which were probably water-laid, contain a large amount of fine-grained sediment. Along the east shore of Pena Blanca Lake there is a good exposure of this type of rock. There the tuffs are very well stratified, some layers even showing a "shaly" type of parting. From a distance this outcrop has a "barber-pole" appearance, as a result of the alternating layers of red and white rock. These layers vary from a few inches to over thirty feet in thickness, and probably represent oxidation of the tuffs during a period of sporadic volcanic eruptions.

A mass of reddish-brown tuff about 200 feet high is exposed one mile north of Castle Rock. This mass, locally called Tarantula Butte, is composed of sedimentary tuff with a high content of sand and gravel-sized accidental fragments. The rock is strongly fractured on the west side of the butte. Bedding is almost completely absent, suggesting that this tuff was deposited as one continuous unit.

The lavas of the Montana Peak Formation usually contain abundant fragments, similar to those within the breccia and conglomerate layers. Occasionally the lavas occur as aphanitic or porphyritic flows, completely devoid of foreign material.

TERTIARY ROCKS

Atascosa Formation The Atascosa Formation was named by Webb and Coryell in 1954. They suggested that it is the youngest formation outcropping within the area covered by the Ruby Quadrangle. In the present study the upper half of Webb and Coryell's Atascosa Formation is called the "Pena Blanca formation". It is considered to be Quaternary age as it is generally flat-lying and has a lithology common to the Quaternary. The lower half, which is tilted and fractured, is called the Atascosa Formation in this report, and is considered to be of Tertiary age.

This formation unconformably overlies the Cretaceous(?) Montana Peak Formation. The angular unconformity that separates these two formations can best be seen in Pena Blanca Canyon, north of the lake. There the Montana Peak agglomerates and lavas dip steeply toward the south, and are covered by the tuffs of the Atascosa Formation which dip at shallower angles toward the northeast. A few pieces of petrified wood have been found at one exposure, along the contact between the Montana Peak Formation and the Atascosa Formation. Small tree stumps were found which were most likely in place, as they were all properly oriented with the swollen base down, and the trunk vertical. This petrified wood probably represents part of a forest which once grew on the old erosion surface of the Montana Peak Formation. The forest was killed by the falling ash that formed the tuffs of the Atascosa Formation, and was eventually partially petrified by the high silica content of the ash. Locally the tuffs of this formation unconformably overlie the Cretaceous(?) Pajarito lavas.

The generally flat-lying Pena Blanca formation overlies the Atascosa Formation. Inside the semi-circle formed by the "Caldera Cliffs", and in a few other places, these formations meet with obvious unconformity.

Best exposed in the Atascosa Mountains north of Bellota Canyon, the Atascosa Formation covers approximately two square miles of the area covered by the present study. It crops out along the north and northwestern borders of the area mapped, where it appears as cliff-bounded cappings to a number of hills and ridges. The formation also crops out east of Pena Blanca Lake, and forms the Caldera Cliffs between the Ruby-Nogales Road and Walker Canyon. A few isolated erosional remnants of the Atascosa Formation form stack-shaped buttes along ridges of the Montana Peak Formation.

In the Atascosa Mountains this formation, as mapped by Webb and Coryell (1954), is about 800 feet thick. In the Pena Blanca and Walker Canyon area the Atascosa Formation varies in thickness from 100 to 400 feet, probably due to the topography of the old surface of deposition. This thickness does not include the uppermost 300 feet of Webb and Coryell's Atascosa Formation, as this uppermost unit has been mapped as the Pena Blanca formation for this report.

The Atascosa Formation consists mainly of lithic and vitric tuffs, with interbedded lenses of conglomerate. The whole formation is rather well indurated, and is usually exposed as vertical cliffs of distinctive white color. Bedding is pronounced, and in places the unit is broken by numerous joints and faults. The rock weathers into rounded shapes which look very much like weathered granite rocks from a distance. In a number of localities the tuff forms terrain that is extremely difficult to cross. The vertical joints have been widened by weathering and erosion, which created a maze of deep fissures and jumbled boulders. One of the best examples of this terrain is found on the southernmost part of the Caldera Cliffs, just north of Walker Canyon. The formation there is cut by numerous erosion fissures, many more than fifty feet deep and from five to twenty-five feet wide. The bottoms of the fissures are covered with fallen blocks and are virtually impassable.

The tuffs of the Atascosa Formation, which have a rhyolitic to quartz latite composition, are for the most part well-bedded, and were probably deposited directly in lakes, or were washed into bodies of standing water soon after their original deposition on land.

The tuff layers are quite variable in their relative resistance to erosion, and in the amount and type of their included fragments. Lithic tuffs full of accidental inclusions are the most common, although many thin vitric tuff layers occur. Ash layers are numerous and are soft and easily eroded. Near the base of the formation the layers have a baked appearance. These beds are usually very hard and exhibit a "shaly" type of parting. Most of the tuff layers are full of blocks of pumice, some more than twelve inches in diameter. One layer, about 25 feet thick, is composed almost wholly of accretionary lapilli. These hard spheres of tuff, also called pisolites or mud pellets, exhibit concentric structures, each formed around a nucleus fragment as it rolled along the ground (Wentworth and Williams, 1932).

The most common type of inclusion in the tuffs of the Atascosa Formation are the angular fragments of welded tuff (ignimbrite). These fragments are usually purple or grey color, often are spherulitic, and have the banding and streaking typical of welded tuffs. They probably represent pieces of a welded ash-flow that was deposited as one of the first layers of the Atascosa Formation. Since no layer of ignimbrite is exposed within the Pena Blanca and Walker area, it is also possible that the source of these fragments was outside the boundaries of the area. Lithic fragments include pieces of all the older formations discussed in this paper, most typically lavas, silicified tuff and quartzite.

QUATERNARY ROCKS

Pena Blanca Formation For the purpose of this report the upper part of Webb and Coryell's Atascosa Formation is called the Pena Blanca formation. It is considered to be of Quaternary age, and can be distinguished from the underlying Atascosa Formation by differences in lithology and structure. A sequence of rocks similar to the Pena Blanca formation occurs in the Santa Rita Mountains, overlying lake deposits that are thought to be late Pliocene or Pleistocene (Schrader, 1915). Locally the Pena Blanca Formation unconformably overlies the Montana Peak Formation and the Pajarito Lavas, both of supposed Cretaceous age. Overlain by unconsolidated alluvial material, the Pena Blanca formation represents the youngest rocks exposed in the area.

This formation covers most of the northeastern quarter of the Pena Blanca and Walker Canyon area. It is particularly well exposed along the Ruby-Nogales Road, and in the east branch of Walker Canyon. Along the eastern side of Pena Blanca Canyon, north of the lake, this formation occurs as a prominent cliff cresting a fault-line scarp.

The Pena Blanca formation is approximately 350 feet thick near the western limit of its outcrop area. It dips eastward at very shallow angles, and appears to thin in the direction of dip. In a few places the attitude of these rocks is anomalous, owing to several strong faults which have tilted large blocks of the formation.

The formation consists of a sequence of distinctly bedded conglomerates, with interbedded layers of tuff and basalt. Heindl (1952) included these rocks within the Gila Conglomerate. Except for the layers of tuff and basalt, these sedimentary rocks appear to have been deposited under conditions similar to those existing in southern Arizona today. Numerous deep, narrow ravines cut the rock, most of them formed along a series of joints. A dense growth of lichen covers most of the formation, giving it a characteristic greenish color when viewed from a distance.

Conglomerate beds of this formation are well consolidated, and stand in vertical to overhanging cliffs. The conglomerate is generally very coarse, although layers of well-sorted, finer grained conglomerate, and lenses of arkosic sandstone are common. Fragments in the conglomerate represent all the older rocks of the area, as well as some types not exposed anywhere nearby. Sub-angular to rounded boulders of ignimbrite, andesite and quartz latite are most abundant, and are accompanied by smaller, rounded fragments of arkose and rhyolite. The conglomerates are tuffaceous and are cemented by both silica and calcium carbonate. Chalcedony is found in numerous veinlets, and as a veneer on many fragments through the formation.

There are many distinct layers of tuff within the Pena Blanca Formation, measuring from a few inches to over six feet in thickness. They vary from thin almost pure beds of vitric tuff, to layers of sedimentary tuff with a high content of accidental fragments.

The tuff layers are usually well-bedded and lens-shaped, indicating that they were probably deposited in ponds. A few short, relatively thick beds have a baked zone along their base. They probably formed by ash-flows that were not hot enough to completely "weld" the glass shards. Other thin, wide-spread beds of tuff are soft and ashy, and often partially altered to greenish bentonite.

Basalt occurs in one short flow near the eastern border of the area mapped. The flow has a thickness of 25 feet, and caps a ridge bordering the east branch of Walker Canyon. This narrow, elongated outcrop is exposed for about 400 yards, and probably represents a reversal of topography. The basalt dips toward the north at about ten degrees, cutting across the conglomerates which are nearly flat-lying. This suggests that the source of the basalt may have been somewhere to the south of the presently exposed flow.

Intrusive Rocks

Only three mappable bodies of intrusive rock are exposed in the Pena Blanca and Walker Canyon area. These rocks occur as two short dikes and one sill, cutting the Pajarito Lavas. They are all oriented roughly parallel to a strong northwest trending system of joints and faults. The two dikes are mineralogically similar to the rocks of the Pajarito Lavas, and the sill is similar to the lavas of the Montana Peak Formation.

The larger of the dikes, 55 feet wide, crops out in Pena Blanca Canyon, about two miles south of the canyon's junction with the Ruby-Nogales Road. It is quartz latite porphyry and is characterized by an abundance of very large phenocrysts of sanidine. Contacts between the dike and the lavas are sharp and distinct. A finer-grained chilled zone a few inches wide occurs in the dike wall.

Another dike is exposed in Calabasas Canyon, about 1½ miles east of Pajarito Peak. This dike, which consists of quartz monzonite porphyry, is about 40 feet thick, and transcects the Pajarito Lavas just south of the fault contact between the lavas and the Pena

Blanca Formation. The dike strikes N. 75 W. and dips northeast at 66 degrees. It is accompanied by a number of smaller parallel dikes of the same composition.

A sill of andesite porphyry five feet thick is exposed in a branch of Calabasas Canyon, ½ mile north-northeast of International Boundary Monument No. 128. It is less resistant than the Pajarito Lavas which it intrudes, and forms the canyon's streambed for about fifty feet. The sill is concordant with the bedding in the lavas, strikes N. 46 W., and dips 38 degrees northeast. Chilled zones less than one inch wide occur on the sill's edges.

Possible Correlations

It is difficult to make any definite correlations away from the immediate area studied because of the abruptly varying nature of the volcanic rocks. The sedimentary rocks were deposited in lakes of unknown extent, or as alluvial material, and being devoid of fossils, are difficult to correlate with other units. Some general similarities do exist however, and may be used to indicate possible regional correlations. The work necessary to prove such correlations is beyond the scope of this paper, and only the more outstanding possibilities are suggested.

Many of the mountain ranges of Santa Cruz County are continuous into northern Sonora, Mexico. It is likely therefore that the most rewarding attempts at correlation will be made by doing further work in these two areas.

O. Taylor (1959) stated that; "An excellent correlation with Santa Cruz County can be found in central Cochise County as mapped by Gilluly (1956). He assigned the oldest volcanic rocks to the Cretaceous but stated that they might be Triassic or Jurassic. The Cretaceous (?) andesite and overlying sequence appear to correlate well with sequences of Santa Cruz County."

Pajarito Lavas Rocks very similar to the Pajarito Lavas crop out just east of Nogales, Sonora. These rocks also form the northern tip of the Sierra de los Pajaritos.

Oro Blanco Conglomerate The Oro Blanco Conglomerate covers a large area in the western part of Santa Cruz County. G. Fowler (1938) states that "... it is probably part of a similar formation that is widespread in south-central Arizona, from west of the Baboquivari Mountains to the Santa Rita Mountains, east of the Santa Cruz River."

The Trincheras Formation of north-central Sonora has a lithology very similar to the Oro Blanco Conglomerate. It rests upon volcanic rocks much like the Pajarito Lavas, and is overlain unconformably by andesite lavas and tuffs (Dumble, 1900).

O. Taylor (1959) suggests a possible correlation between the Oro Blanco Conglomerate and a conglomerate in the Santa Rita Mountains which was first described by Schrader (1915).

Montana Peak Formation Rocks similar to the Montana Peak Lavas, agglomerates and tuffs are quite common in south-central Arizona and north-central Sonora. O. Taylor (1959) suggests a possible correlation of the Montana Peak Formation with the Cat Mountain Rhyolite of the Tucson Mountains, and with "rhyolite clastics and flows" of the Santa Rita, Patagonia and Mustang Mountains.

The Nogales Formation, described by King (1939), includes andesite lavas and tuffs, and probably can be correlated with the Montana Peak Formation. Its type locality is near Nogales, Sonora, just fifteen miles east-southeast of the Pena Blanca and Walker Canyon area.

Atascosa Formation The tuffs of the Atascosa Formation are similar in composition and thickness to the Safford Tuff of the Tucson Mountains (Taylor, 1959). Another possible correlative unit occurs in the Salero area near the Grosvenor Hills, Santa Cruz County (Schrader, 1915).

N. Talliaferro (1933) described a layer of "vitric rhyolite tuff" about 800 feet thick, just south of the International Boundary, near Cabullona, Sonora. Its thickness, composition and stratigraphic relationships suggest that it might be related to the Atascosa Formation.

Pena Blanca Formation As mentioned earlier in this report, the rocks included within the Pena Blanca formation have been considered part of the Gila Conglomerate. Similar sequences of conglomerates, tuffs and basalt flows are common throughout southern Arizona, particularly in the structural valleys of the Gila River and some of its tributaries (Heindl, 1952).

The Báucarit Formation of northern and central Sonora is equivalent in a broad way to the Gila Conglomerate. The Báucarit Formation occurs in valleys between mountain ranges, and is usually flat-lying or dipping at low angles, and contains the same rock types as the Pena Blanca formation.

STRUCTURAL GEOLOGY

Faulting and Jointing

The Pena Blanca and Walker Canyon area is probably located within a zone of recurrent breaking, as all the rocks exposed have suffered some degree of fracturing and movement. Angular unconformities seem to separate almost all the formations. However, owing to the relatively steep angle of repose commonly observed in volcanic rocks, it is often difficult to distinguish between angular unconformities and original bedding.

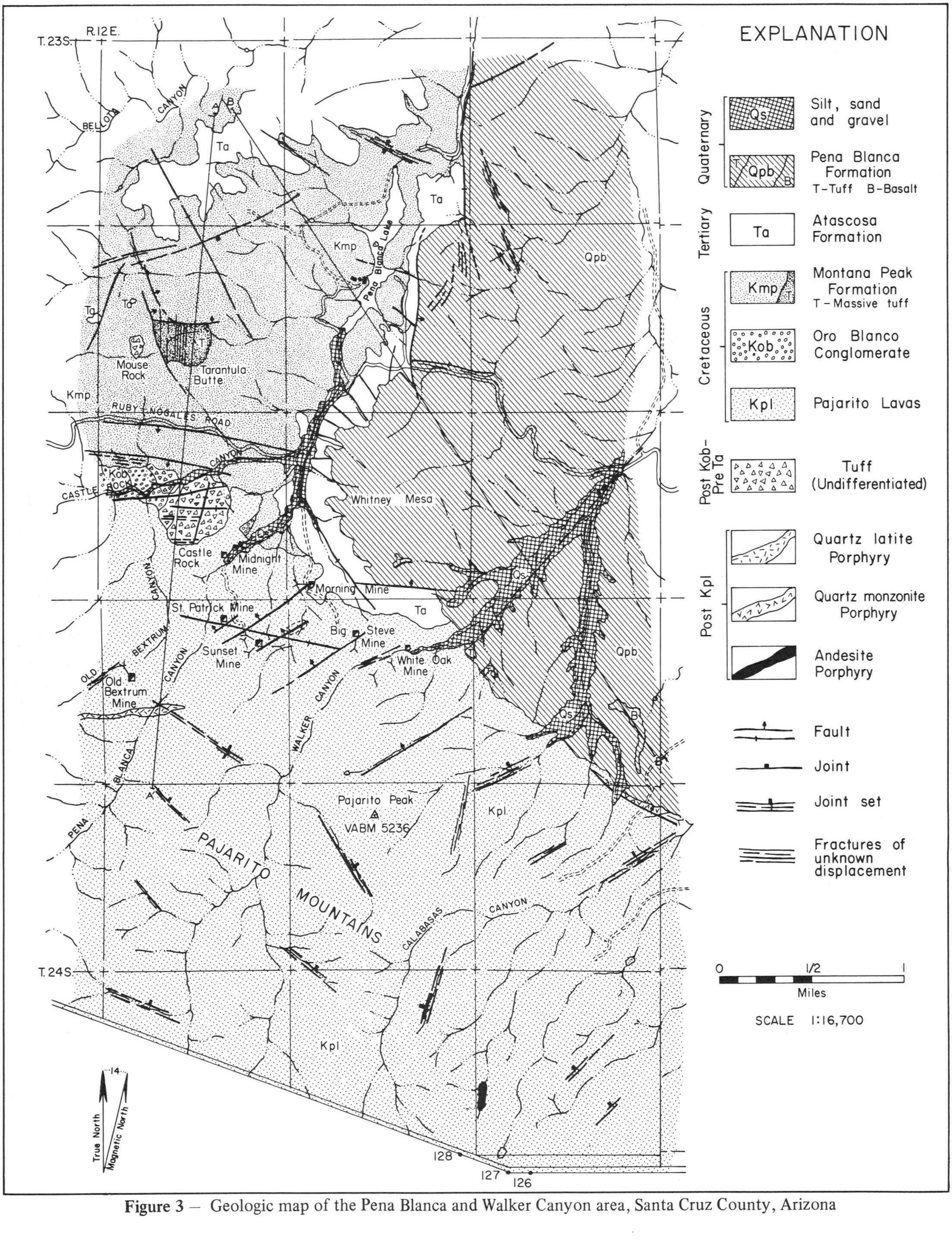

Figure 3 – Geologic map of the Pena Blanca and Walker Canyon area, Santa Cruz County, Arizona

Faults and joints transcect the area and appear to have been formed during a number of intermittent events, throughout a long span of geologic time. Four prominent directions of faulting exist, each accompanied by numerous parallel joints.

One of the longest zones of faults and joints in the area bounds the north flank of the Pajarito Mountains. The fractures along this zone generally trend between N. 70 W. and N. 80 W. They dip at very steep angles toward the northeast, and in some cases are almost vertical. Faulting, where present, is normal. This west-northwest fracture trend is best developed in the southern half of the area mapped.

A strong second direction of faulting and jointing trends generally northeast. Fractures along it usually strike between N. 50 E. and N. 70 E., and are vertical or steeply dipping toward the northwest. Parts of Walker, Pena Blanca, Old Bextrum, Calabasas and Bellota Canyons have been formed along fractures having this northeast trend. Several small mines of the north flank of the Pajarito Mountains follow a number of parallel tension cracks which generally trend northeast.

The third regional fracture set has a prominent north-south trend. It varies in strike from N. 10 E. to N. 10 W., and is characterized by numerous closely spaced near vertical joints, such as those cutting the west side of Tarantula Butte. A line of cliffs east and north of Pena Blanca Lake, as well as the east branch of Walker Canyon, follow strong fault zones having a north-south trend.

An east-west fracture system is important locally, but is not as widespread as the other three systems discussed. Joints and faults with this trend strike between N. 80 E. and east. Parts of Castle Rock Canyon and numerous small ravines cutting the Montana Peak Formation are formed along fractures with this trend.

Folding

The only major folding in the area covered by the Ruby Quadrangle is represented by a broad synclinal structure in the western section of the quadrangle. The axis of this fold trends northwest and plunges gently to the southeast (Webb and Coryell, 1954).

In the Pena Blanca and Walker Canyon area the rocks are either block-faulted or flat-lying, and no large folds occur. Penecontemporaneous folding, due to slumping of partially consolidated tuff, is common. One small fold is particularly interesting, as it may give a clue to the origin of Castle Rock.

This fold is exposed on the north side of Castle Rock Canyon, ½ mile west of the canyon's junction with the Ruby-Nogales Highway. At this exposure there are numerous disconnected layers and lenses of conglomerate imbedded within a cliff of vitric rhyolite tuff. The conglomerate, which is very similar to the Oro Blanco Conglomerate, has been faulted, tilted, and folded.

Layers of the conglomerate vary from 2 to 6 feet in thickness, and are accompanied by lens-shaped pods of conglomerate 2 or 3 feet long and about 1 foot wide. Along the top contact of the layers is a hard, baked zone a few inches wide. This baked zone also surrounds all the isolated pods of conglomerate.

All the larger layers of conglomerate are tabular, and end along numerous small faults or are isolated and wholly surrounded by tuff. The faults follow no particular trend and include both normal and reverse types.

A small anticlinal fold occurs in one of the least disturbed conglomerate layers. The fold is asymmetrical, about 3½ feet high, and has been somewhat separated from the rest of the layer by a small fault.

This folding, the chaotic orientation of large blocks of conglomerate and tuff, and the baked contacts probably are a result of a single sudden event. The event may have been a landslide of hot masses of tuff that flowed into a depression containing semi-consolidated gravels. The force of the rushing blocks of tuff and ash would tear loose slabs of the gravel, finally coming to rest with the slabs oriented at various attitudes. The tuff's unevenly distributed weight would cause squeezing and compression on the soft, probably wet gravels beneath, forming small "diapiric" folds.

The baked contacts indicate that the tuffs might have been quite hot when the landslide occurred. This suggests that the source of the tuffs might not have been too far away.

Other Structural Features

There are three features in the Pena Blanca and Walker Canyon area that may be structural in origin, but are rather difficult to classify. Two of these, Castle Rock and Mouse Rock, are masses of tuff that may have formed as diatremes. The third, Whitney Mesa, is a circular feature that may be the remains of a caldera.

Castle Rock and Mouse Rock Castle Rock is a mass of lithic rhyolite tuff. Its tuffs are very similar to the material surrounding the disturbed conglomerate beds mentioned above. It is roughly elliptical in outline, about 550 feet tall, and covers approximately 80 acres. It lies within a strong zone of east-west trending fractures, a few hundred feet south of the disturbed conglomerates, and is broken by numerous joints and faults.

Formations surrounding Castle Rock include the Pajarito Lavas on the south, west and east, the Oro

Blanco Conglomerate on the north, and the Montana Peak Formation on the northeast corner. Parts of these formations closest to the borders of Castle Rock are stained a deep red color. This color, which may have been caused by weathering or by hydrothermal alteration of the iron oxides, extends into the tuffs inside the periphery of Castle Rock.

The tuffs are mostly well-bedded, with the exception of a "core" of massive tuff which is best exposed on Castle Rock's east face. The core is composed of the same type rock as the bedded layers, but is harder and somewhat more resistant. It extends about 200 feet up the vertical east face, and terminates in a blunt, rounded end. Layers of bedded tuff dip toward it from either side. These layers dip steeply near the base of the cliff and gradually flatten out higher up. They join above the blunt end of the core, and continue to flatten until, near the top, they are flat-lying.

Accidental inclusions in the tuff are very abundant and are generally poorly sorted. Many boulders more than three feet in diameter occur, mixed randomly with gravel and sand-sized fragments. The fragments are angular to well rounded and consist primarily of pieces of ignimbrite and quartz latite. Rhyolite, greenish silicified tuff, granite and quartzite also occur in abundance. The granite fragments are unusual, as they are not found in any other formation in the area. Some of the quartzite fragments are also of a type not found anywhere nearby. The granite and quartzite inclusions may represent basement rocks brought up from depth by volcanic activity.

Castle Rock does not seem to be part of any formation described in this paper. It may be an erosional remnant of a layer that was once much more extensive. It is also possible that it is the remains of an ash-filled volcanic vent or a diatreme. It is difficult to prove any of these possibilities without doing more work. Detailed mapping, combined with gravimetric studies would probably be necessary.

The facts available are far from conclusive, but seem to favor a diatreme origin for Castle Rock. Briefly they are:

1. No rocks exposed that definitely underlie Castle Rock.
2. Accidental fragments are poorly sorted, and include pieces of rock not found anywhere nearby.

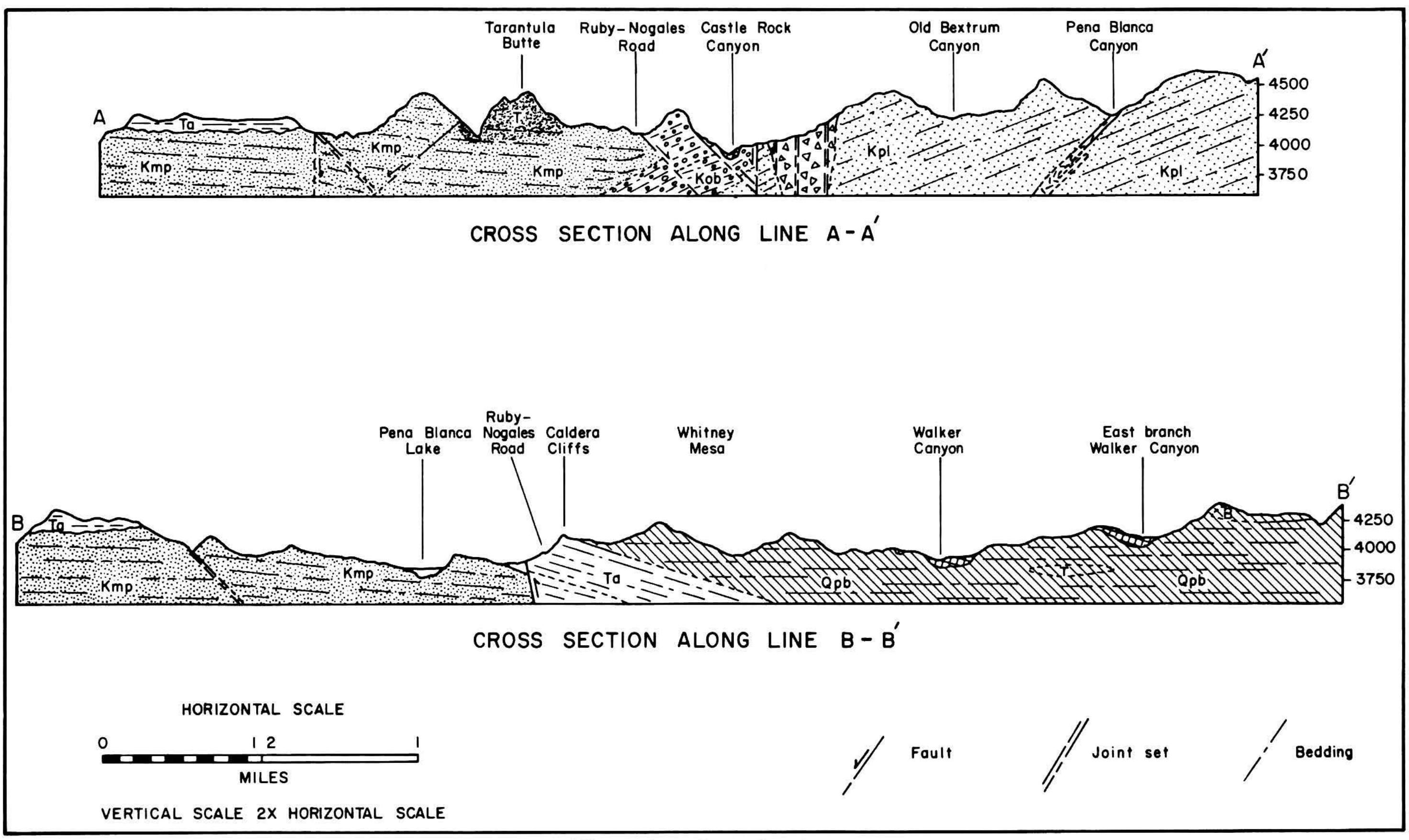

Figure 4 — Cross Sections

3. Massive core, surrounded by dipping beds which look like they were deposited in a steep depression.
4. Location along a fault zone.
5. Severe fracturing of neighboring rocks.
6. Elliptical shape, having rather good symmetry.
7. Chaotic orientation of nearby conglomerate beds, and small "diapiric" fold.

Regardless of whether Castle Rock is a diatreme or an erosional remnant, the pyroclastic activity that formed it probably occurred soon after deposition of the Oro Blanco Conglomerate and before deposition of the Montana Peak Formation. This relative age is suggested by the lack of Montana Peak-type rock fragments in the Castle Rock tuffs. If Castle Rock was the origin of the tuff slides mentioned previously, it must have formed after the Oro Blanco gravels were deposited, and before they were completely consolidated.

A smaller, similar feature occurs about one mile north-northwest of Castle Rock. This structure, locally known as "Mouse Rock", is an elliptical body of lithic rhyolite tuff about 600 feet long and 230 feet wide. It lies just west of Tarantula Butte, in a canyon developed along an east-west fault zone. The canyon cuts through Mouse Rock, forming a steep, narrow defile.

Mouse Rock is completely surrounded by the andesitic lavas and pyroclastics of the Montana Peak Formation. On its southern and western sides it abruptly rises above the surrounding rock, forming vertical cliffs 30 to 40 feet high. The cliffs become lower on the north and east sides, and in places the tuff of Mouse Rock is level with the andesites.

The tuffs are very much like those of Castle Rock and have a similar suite of inclusions except for the occurrence, in Mouse Rock, of Montana Peak-type fragments. Most of the tuffs occur as large, well-bedded blocks which generally dip toward the center of the mass. These blocks enclose a central core of massive, non-bedded tuff, and are surrounded by a "sheath" of similar material.

Mouse Rock may have formed as a diatreme, the massive tuffs emplaced by gas escaping from a vent, and the blocks mis-oriented by sinking. It seems unlikely that this feature is an erosional remnant, as it lies deep in a canyon, well below the general level of the upper contacts of the Montana Peak Formation.

Whitney Mesa

The Caldera Cliffs enclose part of a large structural feature of the Pena Blanca and Walker Canyon area that is locally called "Whitney Mesa". Although this feature is not actually a mesa, but rather a curved escarpment, the local name will be used for the purposes of this report. The cliffs half encircle a structural depression which may be a partly buried caldera.

About 170 degrees of arc are closed by the cliffs, forming a segment of a circle 1½ miles in diameter. The cliffs are composed of large blocks of the Atascosa Formation and are broken by a number of faults. The faults, which are mostly radial to the center of the structure, do not generally enter or affect other formations. Other faults are parallel to the perimeter of Whitney Mesa. Canyons that formed along these faults roughly outline a circular shape, and suggest the location of the borders of the structure where it is covered by younger rocks.

Except for a few blocks which have been rotated and tilted by faulting, the tuff layers that comprise the cliffs obviously dip toward a common center. Dips average from 15 to 30 degrees, the steepest dips occurring on the north and northeast corners of the structure.

The eastern half of the supposed circle of tuff is covered by a thick section of the Pena Blanca Formation. The interior of the circle is also occupied by this formation, which extends almost to the Edge of the Caldera Cliffs. Near the center, the flat-lying conglomerates of the Pena Blanca Formation are at least 200 feet thick, and thin rapidly toward the bordering cliffs.

There is not really enough evidence to be certain that Whitney Mesa is a caldera. It does seem obvious however that this feature indicates a collapsed area or a basin-shaped downfold.

A collapse caldera of the Glen Coe type, as described by Williams (1941) generally has radial and concentric fractures somewhat similar to those of Whitney Mesa. The inward dipping beds of tuff also strongly suggest subsidence of the center of the structure. Since the overlying beds of the Pena Blanca Formation are not disturbed, this subsidence must have occurred before their deposition. It might have been caused by withdrawal of magma which was then deposited as some of the lower tuff beds of the Pena Blanca Formation.

SUMMARY OF GEOLOGIC HISTORY

The geologic history of the Pena Blanca and Walker Canyon area is characterized by recurring volcanic and tectonic activity. Exposed formations range from Cretaceous (?) to Recent in age, and they consist of volcanic and interbedded sedimentary rocks.

The Pajarito Lavas are the oldest rocks in the area. They were formed by a number of flows of porphyritic quartz latite which were probably extruded some time during the Cretaceous (?). The flows thicken to the southwest and probably originated somewhere in the Sierra de los Pajaritos of Sonora. After the rocks cooled, hardened and fractured, they were intruded by dikes of quartz latite porphyry and quartz monzonite porphyry.

An erosion surface developed on the lavas and eventually was partially buried by a layer of ash.

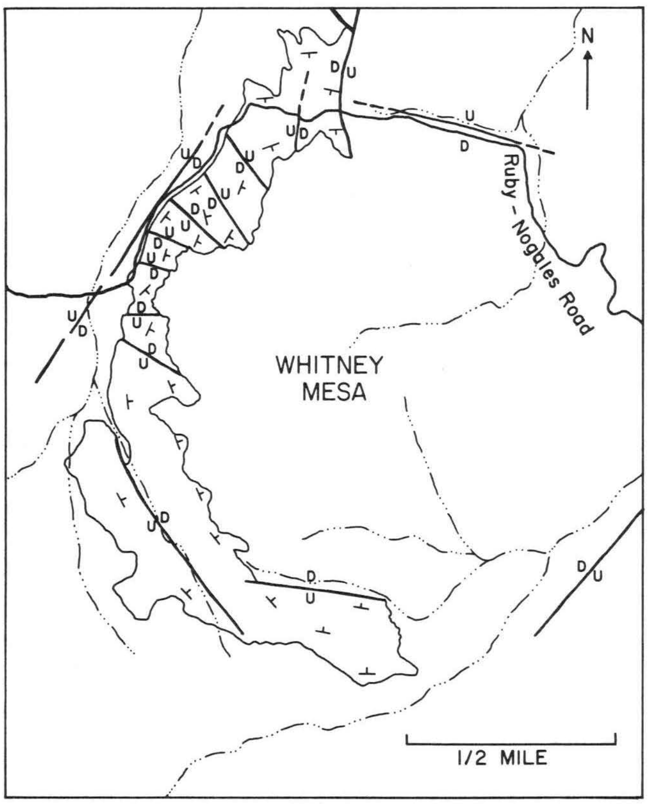

Figure 5 – Sketch map of Whitney Mesa, showing outcrop of Atascosa Formation

Reworked pieces of the Pajarito Lavas and other rocks accumulated as alluvial material and formed the Cretaceous (?) Oro Blanco Conglomerate.

Castle Rock probably was formed during the consolidation of the Oro Blanco gravels. Masses of hot tuff slid into depressions, tearing loose slabs of the gravels and contorting the soft underlying beds. Faulting and fracturing of the area surrounding Castle Rock probably took place about the same time and tilted the otherwise flat-lying beds of the Oro Blanco Conglomerate.

The andesitic lavas, tuffs and agglomerates of the Cretaceous (?) Montana Peak Formation were the next rocks to form. They were deposited on tilted older rocks during a long period of sporadic volcanic activity. Layers of the Montana Peak Formation were eroded, redeposited as breccia and conglomerate beds, and covered again by deposition of lavas and tuffs from repeated eruptions. After the rocks of the Montana Peak Formation solidified they were subjected to severe fracturing and faulting.

A soil layer developed on the erosion surface of these rocks. Trees growing on the soil were killed by ash falls, marking the beginning of the deposition of the Tertiary (?) Atascosa Formation.

Mouse Rock may have been formed about this time. It is possible that it and Castle Rock are diatremes or ash-filled volcanic vents, and, if so, they are the first ones recognized in this part of Arizona.

The ash falls continued, building up a layer more than 500 feet thick. Gravel from higher surrounding areas mixed with the ash or was washed into depressions and covered by new layers of ejecta. These ash layers and interbedded gravels were lithified and formed the tuffs and conglomerates of the Atascosa Formation.

Tilting and faulting of the rocks took place again, during which time the subsidence of Whitney Mesa probably occurred. Whitney Mesa, which may have formed as a collapse caldera, was then partially covered by the conglomerates of the Quaternary Pena Blanca formation.

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THE GEOLOGY OF THE ROSKRUGE MOUNTAINS

a Brief Summary[1]

By

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INTRODUCTION

This paper discusses the geologic setting and history of the Roskruge Mountains. The work leading to this discussion was undertaken to determine the volcanic history and chronology of the range and compare it with the established Tucson Mountain chronology (Bikerman and Damon, 1966). The geochemical dating and related isotopic studies are reported elsewhere (Bikerman 1965, and in prep.) but the general results will be used in this discussion as needed.

This study began with a few reconnaissance surveys in 1961, and intermittently continued through 1965. A total of about 4-5 weeks was spent in the field. All work was done on a base geologic map of the Cocoraque Butte quadrangle kindly supplied by L. A. Heindl, which was the basis in turn of the country geologic map (Wilson et. al., 1960).

Location

The Roskruge Mountains are a predominantly volcanic range lying west across the Avra Valley from the Tucson Mountains, some 20 miles west of the City of Tucson (Fig. 1). The Roskruge Range is in the Basin and Range Province of southern Arizona and geomorphologically is very similar to the adjacent volcanic ranges.

Access to the area is by Arizona Highway #86, Tucson to Ajo, which runs through the southern part of the range and by various ranch and reservation trails. Most of the central part of the range is accessible only on foot. The area studied lies partly within the Papago Indian Reservation, and partly in privately held land.

Previous Work

The area was surveyed by Bryan (1925) and Andrews (1937) in conjunction with groundwater studies, and was later mapped in more detail by Heindl and associates for the Papago Project. Although the map has not yet been published in detail, various short notes and sketch maps are available (Heindl, 1959, 1960, 1965) as well as drillers logs for some of the wells on the Papago Reservation (Heindl and Cosner, 1961).

General Geology

The geology of the Roskruge Range will be treated in three major divisions established in field and laboratory studies, namely (1) the pre Laramide rocks (2) the Laramide rocks and (3) the post Laramide sequence. A generalized geologic map is figure 2 of this paper.

Pre-Laramide Geology

The pre-Laramide rocks have been divided by Heindl (1965) into two main formations, the older Cocoraque Formation and the younger Roadside Formation.

The Cocoraque Formation outcrops (fig. 2) primarily on the northeastern flank of the range around the ranch from which its name is derived. No base for this unit is exposed in the Roskruge Mountains. The Cocoraque Formation consists of folded interbedded arkoses, quartzites, graywackes, mudstones and pebble conglomerates (Heindl, 1965) along with green to purple somewhat altered andesites as tabular interbeds. Heindl notes that the conglomerates contain limestone and quartzite pebbles in the northern portion of the exposure and andesite and felsite pebbles in the southwest. He assigns these pebbles to the Nolia Volcanic Formation of the Comobabi Mountains. In the present study it is thought that some of the "conglomerates" in the southwestern exposures of the Cocoraque Formation may, in reality, be autobrecciated flows (Murai, 1961), or sills, and hence possibly correlatable with the Nolia Volcanic Formation, but absolute proof of this correlation is lacking at present. The brecciated andesites appear as angular pieces in a matrix of similar material. Thin section study indicates that these

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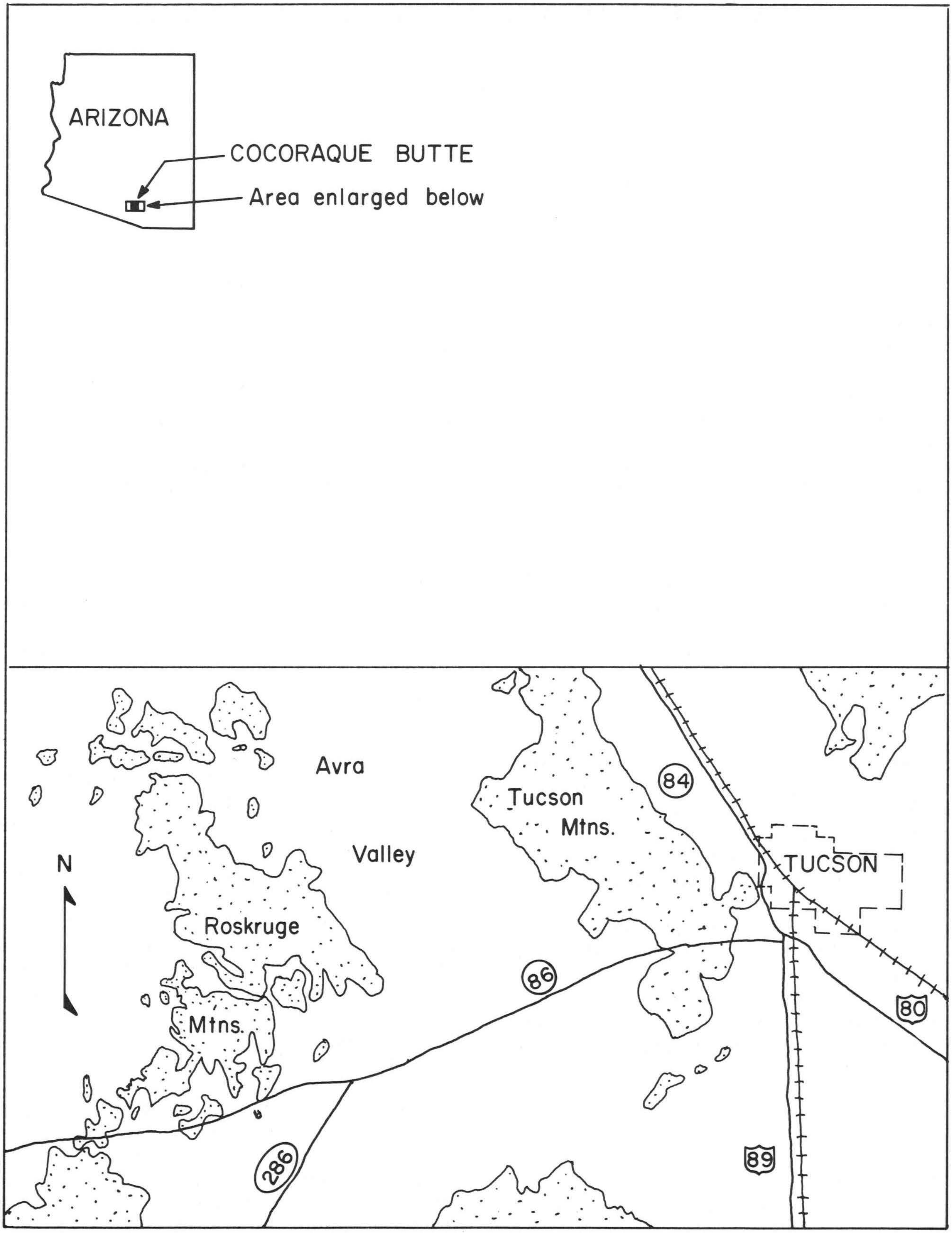
ARIZONA
COCORAQUE BUTTE
Area enlarged below
Avra
Valley
Tucson
Mtns.
84
TUCSON
N
Roskruge
Mtns.
86
80
286
89

Figure 1

rocks are made up of subhedral plagioclase laths of oligoclase-andesine composition, scattered clumps of green or yellowish green hornblende and opaques—probably magnetite and hematite—in a groundmass of finer (.1–1mm) laths of plagioclase and opaque minerals. Some of the feldspars are zoned, with different quantities of sericitization and argillization determining the zones. Optical continuity was maintained through some of the zoned crystals, and in others the zones were discontinuous. In one thin section the opaque minerals were surrounded by fine chlorite which also followed twin planes in some of the feldspars. Veins of magnetite and quartz ranging in size from microscopic to several inches across are found scattered throughout the unit. Concentration of hornblende in the wall rock of a vein was noted in one thin section.

The surface appearance of the andesites varies from common purple and green mottled coloration to occasional black specularite cover. In a few localities the andesite is intruded by very fine grained white rhyolite plugs, with generally well defined contacts. The age of these plugs in relation to the overlying Laramide volcanics is not known, but conceivably could be the same, as similar white rhyolite is found in the younger rocks.

The age of the Cocoraque Formation is not completely defined at present. The oldest rocks in the unit are probably Jurassic or Cretaceous (Heindl, 1965) and older than upper lower Cretaceous or Albian time. This age estimate is based on the fossil evidence quoted by Heindl and by a K-Ar date on a whole rock andesite from the eastern exposure of the unit. The andesite date sets a minimum age on the underlying rocks but further field study is needed to determine the relationship between the dated volcanic and the overlying rocks.

The Cocoraque Formation is overlain by the Roadside Formation unconformably (Heindl, 1965) in the subsurface at the Roadside mine. The surface exposures of the two formations are in contact only in one area in the far northeast part of the Roskruge Mountains according to Heindl (fig. 2, 1965), and in the present study insufficient information was gathered to confirm or change this interpretation.

The Roadside Formation consists of a largely grey to brown fine-grained series of interbedded clastic sediments and andesites in the region of Dobbs Buttes. Elsewhere it is a thick sequence of interbedded and intertonguing coarse clastic rocks and flows of dacitic and andesitic composition.

The sedimentary rocks range from breccias and conglomerates to fairly thick grey claystone, which is well exposed in a wash just south of Bell Mountain. The volcanic rocks are fine-grained and under the microscope one example shows a pseudo diabasic character with randomly arranged feldspar phenocrysts, along with rare ferromagnesian minerals (including calcite pseudomorphic after olivine) in a fine-grained birefringent matrix. Opaque minerals are found as both phenocrysts and in the matrix material.

The Roadside Formation must be upper Cretaceous in age because it lies beneath the Laramide (Maestrichian) Roskruge volcanics and above the Cocoraque Formation which is at least Albian (uppermost lower Cretaceous) (Folinsbee et.al. 1961) in age and possibly even younger in part. The Laramide volcanic rocks lie unconformably on the Roadside formation.

LARAMIDE GEOLOGY

The Laramide rocks in the Roskruge Mountains are the greatest in total exposure in the range (fig. 2). They include the colorful Roskruge volcanics formation and the Cocoraque Butte pluton which is intrusive into the pre-Laramide rocks.

The Roskruge volcanics were named the Roskruge Rhyolite by Heindl (1965) and divided into two members: the Pescadero which he considered to be predominantly flows and the Dobbs Butte which are mostly pyroclastic in nature. In areas where the distinctions blur, no subdivision is made. In this paper the formational name is modified to the Roskruge volcanics because of a wider compositional range in the units than indicated by the term rhyolite, and because the author wishes to avoid a semantic problem such as that associated with the widely known quartz-latitic ash flow in the Tucson Mountains whose name, the Cat Mountain Rhyolite, is well established. The members are distinctive and no change is called for at this time.

The Roskruge volcanic rocks are a series of widespread colorful ashflows and volcanic breccias which are by far the dominant exposed rock in the range.

The general section from the base up includes (1) the Viopuli red ignimbrite (Damon et.al. 1964) and related pyroclastics (2) two or more brown to purplish-grey welded tuffs with their related ash and agglomeratic beds and (3) finally a thick sequence of coarse, brecciated grey to red volcanic agglomerates associated with many small white rhyolite sills, plugs and probably flows.

Units 1 and 2 above together approximate Heindl's Dobbs Butte Member, and unit 3 his Pescadero Member. Estimates of total thickness of the formation range from 2,800 to 3,300 feet (Bikerman, 1965) to a possible maximum of 4,000 feet (Heindl, 1965). The difficulty in determining the thickness lies in the lack of an upper contact as the younger rocks are on an erosional surface cut on the Roskruge volcanics, and

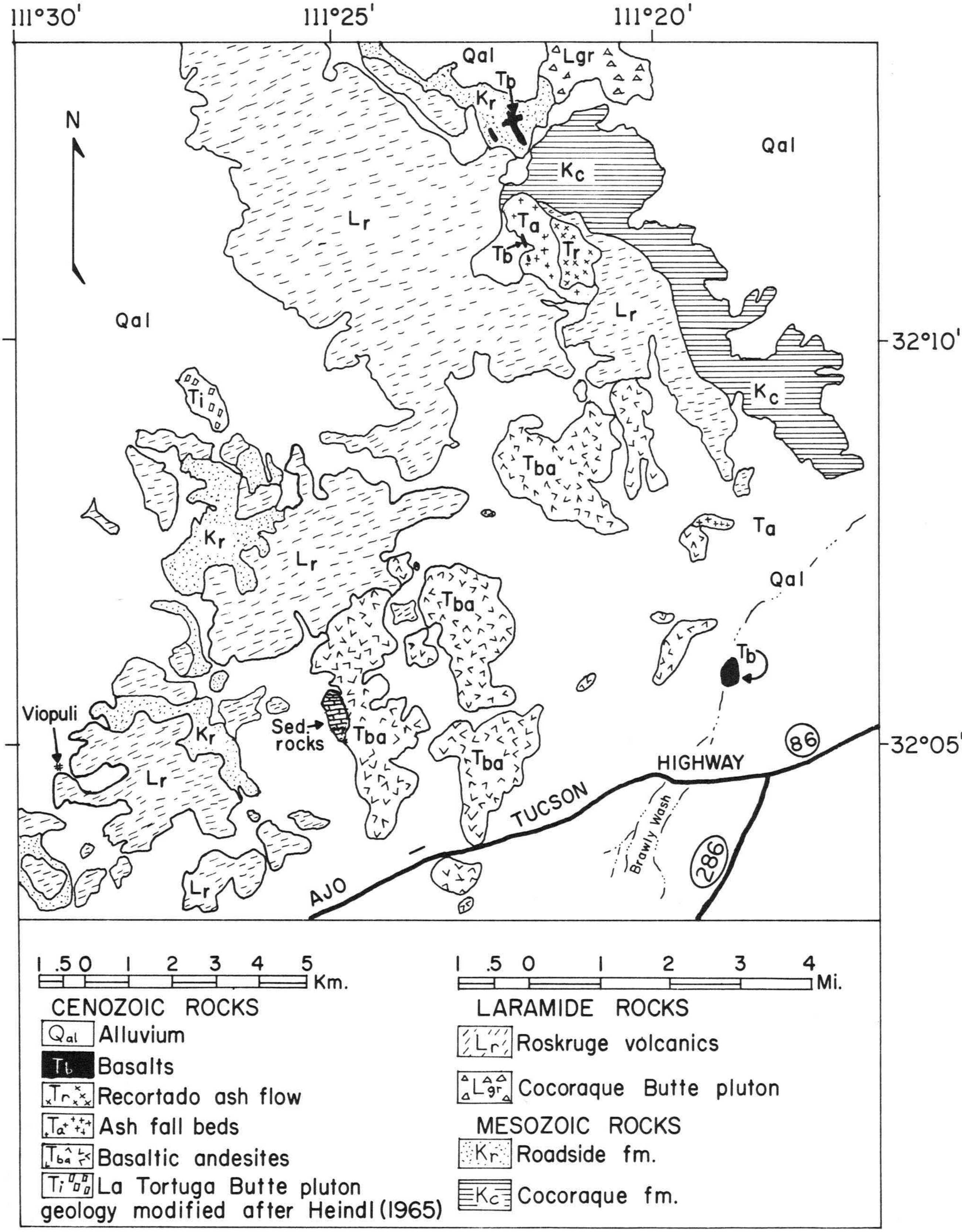

Figure 2 – Geologic map of the Roskruge Mountains, Arizona

on the variable attitudes and lack of lateral continuity of the units. The lower series of ash flows and agglomerates is estimated to be on the order of 1,800 feet thick, with the upper agglomerates making up the remainder of the formation.

The Roskruge volcanics strike predominantly east-northeast and the dips measured mostly 11°-40° southeast. Jointing is common with steeply dipping joint planes striking preponderantly north-northeasterly or northeasterly with less common strike directions north-northwest and west-northwest.

Petrographic examination of the Roskruge volcanic rocks discloses that the majority of the rocks have a phenocryst composition in the quartz latite to dacite range. The groundmass is generally fine-grained devitrified glass or ash, often somewhat altered or opaque, and of undetermined composition. Using Bowen's rule the net composition of the ashflows and volcanic breccias would be somewhat more acidic than that determined from phenocryst analysis (Ross and Smith, 1961).

The ashflows show varying degrees of welding and development of eutaxitic texture. The Viopuli red ignimbrite is flamboyantly eutaxitic both in hand specimen and under the microscope – the younger ashflows less so. The rocks tend to be highly porphyritic aphanites with phenocrysts of subhedral embayed sanidine, oligoclase-andesine (often sericitized), biotite and quartz with various amounts of magnetite in a matrix of altered and devitrified often red or brown volcanic glass. Squashed pumice fragments showing frayed ends are also found on occasion. Most of the pumice has been converted to a birefringent mass of quartz and feldspar. Xenoliths are common, and include many rock types with a predominance of andesites.

The other textures found range from the highly welded eutaxitic tuffs above to the equivalent unwelded ash fall tuffs. The sequence parallels the ideal or theoretical sequence as shown by Smith (1960a) except that no vitrophyre is known. The position of the breccias in the sequence is not clear, but apparently they are separate flows probably of nueé ardente type, involving less juvenile magma and more pre-existing or xenolithic material. In all the volcanic breccias of the Roskruge formation the major xenolithic fragments are acidic volcanic rocks with the types found ranging from varyingly altered pumice to hard, finely banded flow rhyolites. The flow rhyolite fragments are chiefly red in color and often show orange colored alteration products; they range in size from microscopic to several inches across. Other materials found as xenoliths are andesites and various sedimentary rocks most of which are quite similar in appearance to the pre-Laramide rocks in the adjoining outcrops. The definition of volcanic breccia follows the usage of Fisher (1958).

The white rhyolite intrusions show branching and bending of the main tabular bodies around portion of the breccia. Under the microscope the white rock is found to consist of a very fine to moderate grained birefringent mass of intergrown quartz and feldspar around sparse phenocrysts of plagioclase and quartz. One exposure of the white rhyolite that intrudes breccia showed a phantom breccia structure in a thin section taken at the contact. The xenoliths appeared as progressively more vague until in the maximum preserved distance from the contact (about 2 cm) they were indistinguishable from the remainder of the rock.

In one hill, located just northeast of La Tortuga Ranch, a vertical pair of "intrusives" cutting the volcanic breccias was found. These "intrusives" apparently are the result of vertical gas streaming and the resultant fluidization of the country rock, similar to phenomena in the Tucson Mountains described by Mayo (1963). They resemble pyroclastic flows (Smith, 1960b) with their angular to partly rounded xenoliths, lack of sorting and absence of flow characteristics of acidic rock.

The Roskruge volcanic rocks were dated by K-Ar determinations on mineral separates from the various welded tuffs and the period of activity was some 4 to 8 million years in Campanian and Maestrichian time (Folinsbee et.al. 1961) or at the beginning of the classical Laramide interval. The upper breccias were not datable but assuming an equal period of time for their formation, this would extend the total activity of the Roskruge volcanic interval into the lower Eocene (Kulp, 1961) – or the latter part of the classical Laramide. The granodiorite pluton of Cocoraque Butte is contemporaneous with the ashflows and in many ways resembles them chemically.

Post Laramide Rocks

The interval between the last of the Laramide volcanic rocks and first of the basaltic andesites, the next major rock group, is denoted by the intrusion of the small granodiorite pluton of La Tortuga Butte and about ten feet of red arkose and grey conglomerate in an area to the east of the Butte.

The basaltic andesites are shown on the county map as "T_b" (Wilson et.al. 1960) and actually have a field appearance not unlike true basalts on first appearance. Closer study indicates that these flows must have been considerably more viscous as shown by the lobate appearance of the flows with a greater height/area ratio than expected for a basalt. Also their chemical composition (Halva, 1961, Bikerman, 1965) is considerably more alkalic and silicic, with most of the excess alkali such as potassium being concentrated in the groundmass.

The basaltic andesites have shallow dips ranging to a measured maximum of about 30 degrees. Their exposures are in the southeastern portion of the Roskruge Mountains (fig. 2).

Petrographically these rocks are composed of laths of fine grained plagioclase (mostly labradorite), and associated phenocrysts of iddingsite-olivine, augite and magnetite in a matrix of exceedingly fine grained feldspar and ferromagnesian minerals.

Compared to the colorful Roskruge volcanic sequence the mafic flows are drab and uniform. However they express the results of some interesting volcanic phenomena and are associated with the only sediments of any importance in these mountains of the Laramide to Pliocene-Pleistocene interval.

The volcanic features include hornitos with marginal brecciation, varieties of texture from exceedingly massive, through flaggy plates to highly scoriaceous zones and areas. The surficial color of the black andesites ranges from dull yellow or red in some zones to the more common dark greys and blacks.

The associated vitroclastic sediments apparently formed in impounded lakes developed by the bulbous mafic flows. The sedimentary rocks are a fairly flat lying series of limestones and claystones. Table 1 is an approximate composite section of several outcrops northeast of Martina Mountain:

Table 1

Top of section – contact with basaltic andesite or erosion surface.

Unit No.	Description	Thickness
3	One to five thin (3"-8") white to tan limestone beds separated by red purple claystone	3" to 2 ft
2	Red orange or red purple grading to grey rather uniform vitroclastic claystone with occasional shale partings	18 to 20 ft
1	One or two 3" to 8" pale grey to white limestone often interbedded with argillacous unit. No basal contact exposed.	3" or greater

No fossils were found in these beds in any of the exposures examined.

In the areas of exposure the basaltic andesites are not covered by any younger rocks. The age of these mafic rocks is of the Basin and Range orogeny (Damon and Mauger, 1965) or in the transition period between the Paleogene and Neogene periods.

The remaining units to be described in the Roskruge Mountains are the small but significant Recortado ashflow and related tuffs and the various Pliocene true basalts.

The Recortado Ashflow

This unit is sufficiently interesting to warrant more detailed study and a separate paper, but until that is done this short description will have to suffice.

Recortado Mountain is a flat topped mesa located in the northeastern portion of the Roskruge Range. It is surrounded by mountains and ridges of Cocoraque formation, Roskruge volcanics and basaltic andesite. The mesa consists of a valley–filling series of mostly yellow tuffs and agglomerates lying unconformably on older volcanic and sedimentary rocks, and the more resistant capping Recortado ashflow. An approximate composite section in two erosional chutes carved in the tuffs and agglomerates on the northeast face of the mesa is given below (Table 2). Yellow tuffs similar to those discussed here crop out in an apparently intrusive contact in the basaltic andesites some 3½ miles south southeast of Recortado Mountain.

The ashflow shows the vertical and horizontal zonations ranging from a near basal vitrophere through non welded tuff illustrated by Smith (1960a) very clearly. No unwelded ash is preserved on top of the unit which is capped by a partially welded phase, but non-welded material is preserved in several small "micromesas" at the distal end of the flow. The original height of the pre-compaction material is indicated by a "high water" line of thin remnant plaster like cover on the flanks of the pre existing hills in the distal portions of the flow. A compass survey from the top line of the cover towards Recortado Mountain indicates that the decrease in thickness by erosion and compaction is at least 30 feet. Adding the present thickness of the cliff of about 75 feet and combining this with the area now covered or believed to have been covered by the ash flow originally, gives a volume of around 0.15 cubic kilometers or a position in the lower part of Smith's (1960b) class 3. This calculation indicates that the Recortado ashflow must be one of the smallest ever to have produced a vitrophyre. This is particularly emphasized by figures given in Ross and Smith (1961) that at temperatures of 580°C, water pressure of 300 psi and static pressure or load pressure of 500 psi and thicknesses of pre compacted material of 800 feet and density 1.5 g/cc, or 1,000 feet and density 1.0 g/cc, are required to produce welding. This discussion indicates that the Recortado ashflow must have been quite hot and dense on emplacement.

Table 2 – Measured Section of the Recortado Ash Flow

Top of cliff.

Unit No.	Description	Thickness (feet)
6	Recortado ash flow; top is well indurated brown-gray to gray in color with black eutaxitic streaks. Becomes progressively darker until well-welded part is nearly completely black with the eutaxites showing up less distinctly. Sanidine crystals and accidental fragments are found throughout the flow. The basal vitrophyre is a maximum of 3 feet thick and grades into overlying welded tuff either quite abruptly or gradually in different areas. The basal unit is a 1- to 5-foot-thick pink to yellow-pink breccia-tuff, which overlies with apparent conformity the:	~ 75
5	Top unit of the yellow tuff; this part is mostly covered by huge blocks broken off the overlying cliff.	~ 35
4	The erosion scar tops out in a pinkish to white tuff quite massive in aspect. The base of this is a purplish-bedded xenolith-rich zone some 4 inches thick on a white clean 1-inch tuff bed.	~ 35
3	The next group of beds is the major part of the yellow agglomeratic crossbedded to finely bedded xenolithic tuff. Included in this are large andesite and rhyolite accidental fragments, which have bowed the underlying tuffs beneath them. The attitudes of the various units vary quite randomly. In one place what appears to be a channel filled with boulders is found. Pumice xenoliths are found throughout the section. Some units form caves, others are filled with zones of agate xenoliths, and practically none are traceable very far laterally as a local feature. Laramide rhyolite, pumice, older andesites, and a somewhat altered epidotized material make up most of the xenoliths. The bottom of this is a reddish breccia to conglomerate zone, lying on an uneven surface on:	~ 180
2	A rather local roundish in outcrop gray pumice-bearing tuff found only in the northern scour. Under microscope this unit is found to be a mass of glass full of tiny birefringent crystallites and rare larger phenocrysts up to millimeter size of quartz and feldspar and corroded andesitic xenoliths of the same size. Of the entire sequence underlying the ash flow, this was the only sample really amenable for thin sectioning. This has a rather sharp contact with:	~ 17
1	The basal yellow tuff that closely resembles the tuff overlying the gray tuff. This unit has two xenoliths of clean Cocoraque Butte type intrusive, one first size, the other very small. The base is covered by the debris of the erosional chute, but the tuff appears sporadically between boulders to the Laramide rhyolite surface. An additional 20 feet are added to the section to make up:	~ 30
	Covered with boulders to the top of the Roskruge rhyolites	~ 20
	Total	~ 392

Petrographically the Recortado unit is peculiar in its composition of abundant subhedral sodic sanidine phenocrysts showing resorbtion and occasional Carlsbad twinning, rare ferromagnesian phenocrysts, lack of quartz, and its highly eutaxitic red brown to orange and colorless to grey banded glassy matrix. Opaque minerals are common, both oxides and brassy sulphides being represented. Xenoliths of tan tuff and various other fragments are common. The overall composition is judged to be in the rhyolite-trachyte region.

Results of K-Ar dating places the Recortado flow on the Miocene-Pliocene border of the Kulp (1961) time scale. The source of the ashflow is believed to be under the highest portion of the existing cliff on the northeast side of the mesa.

In summary, the Recortado flow is interesting because of its good state of preservation, its unusual sanidine-rich-quartz-poor composition and its age.

Pliocene Basalts

Under this heading are several basalt exposures outcropping in a general north northwesterly linear pattern in the eastern portion of the range. They include the basalt flow (?) exposed in a bulldozer cut in Brawley Wash (also spelled Brawly), several small dikes and stringers cutting through the tuffs south and west of Recortado Mountain, and a prominent dike about a mile and a half southwest of Cocoraque Ranch. This last dike is strongly jointed and many of the smooth joint faces are covered with Indian drawings from which the rock has been named the Pictograph dike.

Pictograph dike reaches a maximum width of 20 feet and the stringers to the south of it often die out from widths measured in inches. The maximum breadth of dikes elsewhere do not exceed three feet. No reliable spatial orientation of the Brawley Wash basalt was possible, but the jointing patterns suggested a flow. Petrographically the basalts are porphyritic with olivine and plagioclase (about An_7) phenocrysts abundant in the Brawley Wash sample, and large augite crystals in the dikes. Both have matrices made up of fine plagioclase needles, augite and opaques.

Whole rock K-Ar determinations placed both units in the early Pliocene. Of particular interest is the fact that the initial Sr^{87}/Sr^{86} ratio of the Brawley Wash basalt indicates (Bikerman, 1965) a deep seated source for this unit, and as the dikes are of similar ratio, this suggests that these units were emplaced during the last profound faulting of the earth's crust in that area, and tapped deep seated magmas.

The latest geologic activity in the range was the deposition and subsequent uplift and partial removal of a widespread alluvial blanket, but this phase of the history of the Roskruge Mountains is beyond the scope of this report.

SUMMARY AND CONCLUSIONS

The general history both of events and their timing in the Roskruge Range closely parallels that previously established in the Tucson Mountains (Brown, 1939; Kinnison, 1958; Mayo, 1963 and Bikerman and Damon, 1966). The pattern is matched most closely in the pre Laramide andesites and sediments and in the Laramide ashflows and intrusives, also in the very similar basaltic andesites found in both ranges.

There is no correlative of the mid Tertiary ashflows of Tumomac hill in the Roskruges, though evidence of their activity is seen in the coeval vitroclastic sediments described above. Of greater import is the lack of any rocks equivalent to the Recortado ashflow or the Pliocene basalts in the Tucson Mountains.

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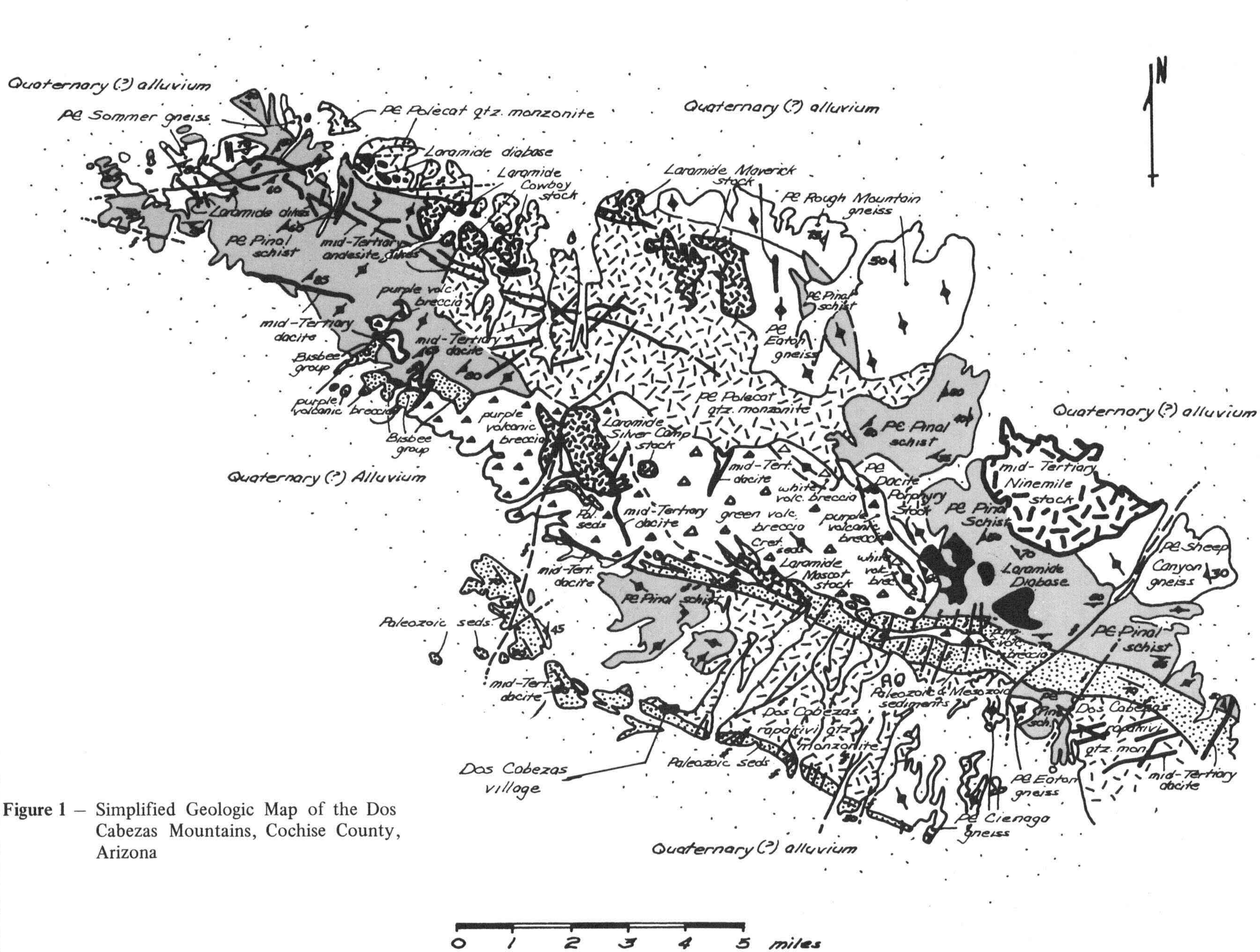

Figure 1 – Simplified Geologic Map of the Dos Cabezas Mountains, Cochise County, Arizona

GEOLOGY AND GEOCHRONOLOGY OF THE DOS CABEZAS MOUNTAINS COCHISE COUNTY, ARIZONA*

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INTRODUCTION

The Dos Cabezas mountains lie in the north central part of Cochise county, Arizona. The mountains are elliptical in plan, have an overall west-northwest trend and cover an area of some 120 square miles. Sixty percent of the range is a complex exposure of Precambrian metasedimentary rocks and granitoid intrusions. These Precambrian rocks were overlain by Paleozoic and Mesozoic sediments; following this, in the Laramide orogeny, the range was broken along west-northwest and then east-northeast trending steeply-dipping faults. The Apache Pass fault, the major structure of the range, was formed at this time. The two parts of the range separated by the fault were tilted to the southwest about west-northwest trending axes. Laramide intrusive events began when late Cretaceous intrusive breccia and dark aphanitic magmatic bodies intruded 16 square miles of the central Dos Cabezas mountains. This was followed by intrusion of Paleocene quartz diorite and quartz monzonite stocks and Eocene basaltic dikes. In mid-Tertiary times, several andesitic and dacitic dike groups, a granodiorite stock, and numerous quartz dikes were intruded into the rocks of the range.

THE PRECAMBRIAN TERRAIN

The Pinal Schist

The Dos Cabezas Mountains contain three separate major exposures of Pinal Schist (see Figure 1). The exposures in the western part of the range reveal the nature of an original premetamorphic assemblage composed primarily of dacitic to basaltic volcanic flows and tuff-contaminated sediments with some interstratified layers of pelitic sediments; in one of the pelitic layers is a small lens of limestone which is the only such body recorded in the Pinal Schist from any area. These previously mentioned units were invaded by numerous basaltic sills during and in the waning stages of metamorphism of the strata.

The premetamorphism units in the Pinal Schist in the eastern Dos Cabezas consisted of several thousand feet of pebble and cobble conglomerate, overlain by several thousand feet of arkose, overlain in turn by pelitic sediments with minor interbedded flows. Cross-bedding is common in the arkoses and conglomerates and shows the above sequence to be upright.

The premetamorphism rocks in the Pinal Schist exposures in the southern Dos Cabezas Mountains were nearly pure quartz sands containing a minor argillaceous pelitic component; a few beds of pelitic sediments were interbedded with them.

Folding of the Pinal sedimentary rocks in the original dynamothermal metamorphic-tectonic event produced large open folds several miles across; the present three major areas of Pinal Schist exposure in the range contain all or part of one anticline or syncline at the most.

Metamorphism accompanied folding of the Pinal rocks. All three exposures show the same metamorphic grade and structure relationships. Foliation is always bedding-plane foliation. Original textures and structures are preserved well enough so that the original character of the now-metamorphosed rocks can be determined. Metamorphic rank is in the chlorite-albite-epidote-quartz or biotite-albite-epidote-quartz facies of the greenschist facies. The entire Pinal Schist terrain in the range evidently underwent a primary dynamothermal metamorphism in which the chlorite-bearing metamorphites were developed, and then underwent a second thermal metamorphism perhaps 200 million years later when Precambrian plutons developed contact metamorphic biotite in place of chlorite in large areas of the present Pinal Schist exposures.

The post-metamorphism rocks are predominantly phyllites, feldspathic phyllites and argillites, and amphibolites throughout the Pinal Schist terrain in the Dos Cabezas, except for the quartzites of the southern exposures and metaconglomerate of the eastern exposures.

The absolute age of the rocks classified as Pinal Schist in the Dos Cabezas Mountains is unknown. No age data on the Pinal Schist have yet been obtained

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from the range. A best estimate of age for at least the western exposures of Pinal Schist is obtained by correlating them with lithologically similar metamorphic rocks in the Johnny Lyon Hills, some 30 miles west of the Dos Cabezas range, where Silver and Deutsch (1961) have shown the age of Pinal sedimentation to be 1720 million years and Pinal metamorphism to be pre-1660 million years.

The Pinal Schist of the eastern and southern parts of the Dos Cabezas Mountains is very tentatively given the same general age as the western exposure; this is merely chosen as the simplest hypothesis in the absence of conflicting evidence. As an alternative hypothesis, the southern quartzite exposures might be equated on lithologic grounds with the Mazatzal Quartzite of Wilson (1937). No presently observed evidence compels or denies the latter interpretation; the former tentative assignment of all the Precambrian metasediments to the Pinal Schist is retained.

Precambrian Gneissic Quartz Monzonites

Five separate Precambrian gneissic quartz monzonite stocks are partially exposed in the Dos Cabezas Mountains (see Figure 1). They have been provisionally named for purposes of discussion. The oldest dated unit is the Eaton gneiss. It occurs in two separate exposures, one on each side of the Apache Pass fault; it is the only igneous Precambrian unit which has been correlated across the fault. In field exposures it is a coarse-grained granitoid gneiss whose foliation is marked by subparallel elongated clots of biotite. It is the only Precambrian gneiss whose foliation is so characterized.

The other Precambrian gneisses are the Sommer, Rough Mountain, Sheep Canyon, and Cienaga gneisses. All four are medium-grained weakly porphyritic gneisses, whose foliation is revealed by planar alignment of feldspar phenocrysts and weak to strong post-crystallization shear foliation parallel to the primary feldspar foliation. All four gneisses are quartz monzonitic in composition, although each has minor petrographic features which distinguish it from the others.

The Eaton Gneiss is 1440 ±30 million years old, based on a four-sample whole rock Rb-Sr isochron study. It intrudes the Pinal Schist and sets an upper limit on the age of the Pinal Schist in the northern Dos Cabezas mountains. The Rough Mountain gneiss is 1425 ±45 million years in age by inference from field relationships to dated intrusions. The Cienaga and Sheep Canyon gneisses are tentatively correlated to the Rough Mountain gneiss on the basis of gross similarity of field outcrops and similar compositions.

The Sommer gneiss is regarded as being older than all the other previously mentioned gneisses. Two main reasons are given; first, it contains a suite of foliated amphibolites whose foliation is not parallel to that of their own long axes but is parallel to foliation in the enclosing gneiss and to foliation in the metasediments and amphibolites of the Pinal wall rocks around the Sommer intrusion; second, the gneiss has marked shear foliation parallel to that in the surrounding Pinal Schist, and the foliation shears are filled with sericite, chlorite, and biotite assemblage similar to that of the schist. These lines of evidence indicate that the Sommer gneiss was dynamothermally metamorphosed along with its Pinal Schist wall rocks after both had been invaded by basaltic sills and dikes. With respect to Pinal folding and metamorphism, the Sommer gneiss is a late-tectonic intrusion whose age probably lies in the interval 1660-1750 million years.

The importance of the ages on the Eaton and Rough Mountain gneisses is that they provide the first geochronologic evidence from Arizona for at least mild tectonism in the 1350-1450 million year interval in which only plutonism has been recorded before (see Damon, Livingston, and Erickson, 1962; Livingston, 1962).

Precambrian Weakly Foliated Quartz Monzonite Plutons

Two Precambrian plutons which occur in the Dos Cabezas Mountains show only weak internal foliation revealed by subparallel orientation of individual tabular euhedral phenocrysts of feldspar. The largest of these plutons is the Polecat quartz monzonite which cuts Pinal Schist and Precambrian gneisses in the northern Dos Cabezas Mountains and which may be equivalent to the Rattlesnake Point Granite of Sabins (1957). The rock is coarsely porphyritic with euhedral tabular potash feldspar crystals up to 3 by 1 cm. lying in a coarse-grained ground mass. A dual west-northwest and north-northeast foliation is present in many outcrops.

The other large Precambrian pluton lies in the southern Dos Cabezas, and is a rapakivi-textured quartz monzonite which cuts quartzite of the Pinal Schist and Precambrian granitoid gneisses. The rock bears mixed rimmed and unrimmed euhedral plagioclase and oval potash feldspars up to 5-6 cm. across, in a coarse-grained ground mass. The pluton is here called the Dos Cabezas rapakivi quartz monzonite.

The Polecat quartz monzonite is around 1400-1450 million years old, depending on the exact value assumed for the initial Sr^{87} Sr^{86} ratio present in the rock at the time of its initial crystallization. A single whole-rock sample, a plagioclase sample, and a biotite sample from one overall sample of this pluton give an isochron 1000 million year age and an initial Sr^{87}/Sr^{86} ratio of 0.85; these data are thought to record marked reequilibration of radiogenic strontium throughout the Polecat, probably due to a strong heating event, at the 1000 million year time. The other pluton, the Dos Cabezas rapakivi quartz monzonite, is 1375 ±40 million years old, based on a four-sample Rb-Sr whole rock isochron.

Precambrian Dacite Porphyry Stock

The last Precambrian intrusion to be described is a dacite porphyry stock in the northeastern Dos Cabezas which cuts Pinal Schist and is cut by Cretaceous volcanic breccia. It has internal flow foliation normal to the foliation in the schist surrounding it. It is believed to be Precambrian, but no age analysis has been made.

K-Ar Chronologic Relationships in the Precambrian Rocks of the Dos Cabezas Mountains

Three K-Ar ages from the westernmost Precambrian areas in the Dos Cabezas Mountains fall into the interval 1000-1200 million years. These are on the Sommer gneiss (1100 ±20 m.y. on biotite), the Polecat quartz monzonite (1010 ±30 m.y. on biotite) and an amphibolite (1180 ±35 m.y. on hornblende). These units are almost certainly from 400 to 600 million years older than their apparent K-Ar ages. These ages are believed to be the result of argon loss from the K-Ar systems in the sampled minerals in the various bodies. The argon loss was due to heating in the 1000-million year event recorded in the Rb-Sr relationships in the Polecat quartz monzonite. The Polecat makes up the larger part of the 1000-1200 million year K-Ar age bearing terrain.

Four K-Ar ages on biotite from Precambrian gneisses and weakly foliated plutons in the central and western Dos Cabezas Mountains are Paleocene, with a group mean age of 53.4 ±3.1 million years for the four samples. A fifth truly Precambrian sample from very near a mid-Tertiary quartz vein gives a mid-Tertiary age (32.7 ±3.3 m.y. on biotite). The Paleocene ages reflect essentially complete argon loss in Paleocene time from the dated biotites. This loss is thought to have been due to heating by Paleocene plutons. Four Paleocene stocks of slightly older (63-59 m.y.) or equivalent (56 m.y.) ages appear in parts of this very young biased area. Independent evidence of a strong reheating of the central and eastern Dos Cabezas range which did not extend to the western part of the mountains lies in the presence of thermal metamorphic effects in the Precambrian amphibolites and Paleozoic limestones of the central and eastern parts of the range; these effects do not show up in the western parts of the Dos Cabezas where K-Ar ages record only the 1000-million year heating previously mentioned. No trace of this older event remains, of course, in the K-Ar data in the rest of the range.

The mid-Tertiary age for a sample of rapakivi near the quartz dike indicates a third very local reheating of the Precambrian rocks in at least one local area, and also serves to establish a mid-Tertiary age for these quartz veins and dikes.

PALEOZOIC AND MESOZOIC SEDIMENTATION

Sabins (1957) discusses the essential features of the Paleozoic and Mesozoic strata of the eastern Dos Cabezas and northern Chirichahua Mountains. The Paleozoic units present are the Cambrian Bolsa Quartzite, Ordovician El Paso Formation, Devonian Portal Formation, Mississippian Escabrosa Limestone, and Pennsylvanian Horquilla Limestone of the Naco group. In addition, Cooper (1960) discovered a small isolated hill of Permian Concha Limestone lying just southwest of the main mass of the range west of Dos Cabezas village; its relations to the other Paleozoic units are unclear. A hiatus is present from upper Ordovician time to lower Devonian time.

Mesozoic units are all part of the Bisbee Group of Lower Cretaceous age; another large hiatus exists for all Triassic and Jurassic time. The Bisbee group is represented by the basal Glance Conglomerate consisting of quartz–cobble and lime–pebble conglomerates, overlain by thick sequences of very thin-bedded pelitic clastic sedimentary rocks.

No older Tertiary sedimentary rocks are known in the Dos Cabezas Mountains. Quaternary alluvium lies in low areas in much of the range.

LARAMIDE TECTONISM

The Dos Cabezas Mountains were broken along at least two major west-northwest trending faults after conclusion of Bisbee Group deposition. On one, the Apache Pass Fault, the movement was right-lateral strike slip and reverse fault dip slip with the upthrown side on the south. Net slip is great, perhaps a mile or more. Paleozoic and Mesozoic strata were tilted to the southwest from sixty to ninety degrees, and were overturned to the southeast along the western part of the Apache Pass fault. Presumably the basement rocks beneath these sedimentary strata underwent considerable tilting of the same type. Vertical north-northeast striking faults then offset the west-northwest trending faults and the tilted blocks. Net slip on these north-northeast striking faults ranges from a few tens to a few hundred feet at most.

CRETACEOUS INTRUSIVE WELDED VOLCANIC BRECCIA

The core of the Dos Cabezas mountains is made up of a complex intrusive mass of dark rocks with aphanitic ground masses and some proportion of mineral phenocrysts or xenolithic fragments of various types and sizes contained within them. Perhaps four-fifths of the mass, which underlies some 16 square miles of the range, is made up of tough, fragment-rich rock which is best called welded volcanic breccia. The non-breccia part of the area is composed of small plugs and dikes of basalt and andesite, intrusive into the breccia. See Figure 1.

There are three main types of breccia, classified on the basis of color of the ground mass and character of fragments; these are the green, purple, and white breccias respectively. Each of these three occurs in several distinct bodies and each of these bodies shows some internal textural variation, especially near contact with the walls. The actual overall composition of the breccias is difficult to determine, but in the green and purple breccias the rocks are dark in color and contain large, predominantly andesitic, fragments in a fragmental dacitic groundmass. In the white breccias, both large and minute fragments are usually white or yellow felsite.

The green breccia makes up most of the eastern part of the breccia exposures and is its oldest member. Average size of megascopic fragments is about an inch. There are gradationally bounded zones in the breccia showing few or no megascopic fragments and other minor zones full of rounded blocks up to several feet across. Most of the breccia fragments of whatever size are andesite or basalt, but numerous fragments of limestone, quartz monzonite, shale, schist, and quartzite are present. Fragments vary in shape from sharply angular to well-rounded, and all degrees of rounding are present in any one outcrop. Internally, the breccia often shows a foliation, which generally trends northwest and dips steeply to vertically.

The groundmass in the green breccia is composed mostly of small lithic fragments grading down to submicroscopic sizes, together with small crystals and crystal fragments of plagioclase, quartz, and potash feldspar. Fragments and crystals alike are fused together into an extremely hard and brittle, welded mass. The microscopic lithic fragments are of the same composition as the larger ones. There is no evidence for a coherent, throughgoing, originally liquid material in which the fragments might have been contained; if any magma was present it was in the form of droplets.

A high-temperature origin for the body of green breccia is indicated by the presence of large amounts of post-formational epidote in the groundmass and fragments of the breccia; the epidote cuts across fragment boundaries and lines of flow in the groundmass, and is found occasionally in good crystals in small cavities in the breccia. Many of the fragments have also suffered some reaction breakdown to new mineral phases around their borders.

The green volcanic breccia has been active in the disruption of the northern part of the Apache Pass fault zone. As can be seen in Figure 1, tongues of the breccia cut into the zone along preexisting north-northeast and west-northwest trending faults, and blocks of sedimentary rocks once bounded by faults in their original setting have now been surrounded by dikes of the breccia. There are several very large masses of Paleozoic and Mesozoic sedimentary rocks wholly contained in and surrounded by the breccia in the western and southern parts of its exposure. In detail, the borders of the blocks are often markedly uneven with dikes and reentrants of breccia cutting into them. In addition to these enormous blocks (tens of feet) there are numerous smaller blocks of Paleozoic and Mesozoic sedimentary rocks throughout the green breccia.

The purple volcanic breccia occurs in the westernmost part of the breccia terrain, and is intimately associated with purple andesite magmatic bodies. The breccia contains fragments of various purple and green andesites and andesite porphyries in a generally purple groundmass of lithic fragments and plagioclase crystal fragments. No fragment-groundmass reaction is noted, nor is epidote present. The units of the purple breccia are quite hard and tough. Xenoliths of materials other than andesite are rare, but numerous fragments of Paleozoic and Mesozoic rocks are present in the breccia in an exposure at the foot of Camelback mountain in the western end of the breccia terrain.

The white volcanic breccia occurs as small plugs and dikes of breccia cutting other breccia units. The fragments in it are almost wholly white to yellow felsite, although a few small rock fragments of various volcanic and basement types are usually present. The groundmass in at least two of these breccia plugs shows eutaxitic texture, which in both cases marks out a west-northwest trending, vertically dipping, internal foliation in the body. These white breccia bodies are thought to be near-surface ignimbrite feeders.

It should be emphasized that the breccia shows none of the characteristics of a bedded deposit laid down as a flow or as air-fall pyroclastic agglomerates. The breccia units often show a vertical or steeply dipping flow foliation as displayed by orientation of layers of fragments, flow lines in the groundmass, orientation of platy fragments, and orientation of crystals in the groundmass. Breccia contacts with surrounding units are steep to vertical; for example, up to 1,000 feet of relief is present along the contact between the green breccia and the Polecat quartz monzonite, and no deviation from an essentially vertical dip is observable.

The breccias cut faulted Bisbee Group strata and are cut by Paleocene stocks; hence they are Mid- to Late-Cretaceous in age.

The breccias originated as a mass of fluidized fragments in a generally rising fluidized bed of great complexity. The bed acted as a rising, penetrating, disruptive mass, and presumably the present exposures represent the solidified throat of an eruption vent of great size. The breccia terrain in the Dos Cabezas Mountains is the largest of its kind in the world yet described, so far as is known.

The breccias have been cut by large numbers of small andesite and andesite porphyry intrusions which are probably representative of the magmas from which much of the gas in the fluidized system arose. These small bodies have a fair amount of modal carbonate in their groundmass, but are otherwise quite ordinary in character.

LARAMIDE STOCKS AND DIKES

Following the intrusion and solidification of the Cretaceous breccia, a group of Paleocene and Eocene stocks, plugs, and dikes belonging to the Laramide pulse of igneous intrusive events invaded the central and western Dos Cabezas Mountains.

Perhaps the first of these were two clusters of diabase and basalt plugs which rose in the northwestern and central eastern parts of the range; internally these show considerable granulation and recrystallization of their constituent mineral crystals which occurred before they reached their present level in the crust. This texture is presumably due to their having been crushed while Laramide tectonism was still active. No absolute age data have been obtained on these plugs, but they are thought to represent the oldest of the Laramide post–breccia intrusions, as none of the others show this crushed texture.

Three stocks of fine-grained quartz diorite intrude the west central Dos Cabezas along a west-northwest trending line which cuts across the range axis. The northwesternmost, here called the Cowboy stock, gives a K-Ar age of 59.0 ± 1.8 m.y. on biotite; the central stock, here called the Silver Camp stock, gives a K-Ar date of 62.4 ± 1.9 m.y. on biotite. The southeasternmost one, the Mascot stock, has not been dated.

North of these three stocks lies a large complex stock of dark medium-grained porphyritic quartz monzonite, here called the Maverick stock. Its age is 55.9 ± 1.7 m.y. on biotite by K-Ar. It may be a sample of the Paleocene plutonic group responsible for the 53 million year old K-Ar age-bearing biased-terrain in the Precambrian rocks of the eastern and central Dos Cabezas Mountains.

The western Dos Cabezas Mountains are cut by perhaps fifty small olivine basalt dikes; a dating sample from the largest of these gave an age of 47.6 ± 1.4 m.y. on whole rock. These dikes are the last Laramide intrusive units to appear in the Dos Cabezas Mountains.

MID-TERTIARY INTRUSIVES

Following the Laramide series of intrusive events, there was a quiet period of some 12 million years before the onset of the mid-Tertiary pulse of magmatic intrusive events; rocks related to this later pulse are represented in the Dos Cabezas Mountains by four dike groups and a stock. The oldest of these units is a nine-mile-long complex dike of plagioclase andesite porphyry of the type called "Turkey Track". This unit is composed of 33 separate small dikes arranged along a line trending west-northwest across the western Dos Cabezas. The dike gives an age of 35.2 ± 3.1 million years by K-Ar on plagioclase.

Parallel to and half a mile southwest of the K-Ar andesite porphyry dike is a thirteen-mile-long series of hornblende andesite porphyry dikes composed of 25 individual segments. Its age by inference from cross-cutting relationships with dated units is 34 ± 2 million years.

The entire Dos Cabezas Mountains have been invaded by a large number of small dacite porphyry dikes and sills and several small stocks of the same unit. One dike of this type cutting the Paleocene Mascot stock gave a whole-rock K-Ar age of 33.9 ± 1.9 million years.

A large granodiorite stock, here called the Ninemile stock, cuts the southeastern Dos Cabezas Mountains. It is a large coarse-grained weakly porphyritic stock, containing numerous associated aplite dikes, quartz pods, and simple pegmatites. It gives an age of 29.0 ± 1.7 million years on biotite.

There is a suite of a large number of quartz dikes in the Dos Cabezas. Some bear pyrite, galena, and gold. They cut mid-Tertiary and Laramide intrusions, and one is associated with a mid-Tertiary age in a biased Precambrian rock. Assuming that all the dikes are of the same age, they can be assigned a post-Ninemile stock age of less than 29 million years. They make up the last recorded igneous event in the history of the Dos Cabezas Mountains.

SUMMATION OF GEOCHRONOLOGY

There are four times of intense metamorphic and intrusive activity and one somewhat mysterious period of heating unaccompanied by intrusion or dynamic metamorphism which stand out on examining geochronologic data from the Dos Cabezas Mountains. The first event is the time of metamorphism of the strata in the Pinal Schist and the intrusion of it by *granitoid magma*. This event is not quantitatively dated in the Dos Cabezas Mountains, but a best time estimate for the metamorphism and plutonism is 1700

± 50 million years. The second major event is the time of intense Precambrian plutonism and tectonism in the interval 1450-1375 million years, in which at least four of the eight known Precambrian granitoid plutons appeared.

The strong 1000 million year heating recorded in the Rb-Sr isochron relationships in the Polecat quartz monzonite and the K-Ar apparent ages in the Precambrian units in the western Dos Cabezas Mountains are not related to observed plutonism; the heating is probably related to deep-seated plutons of this age which did not rise high enough in this area to be exposed by erosion at the present surface.

Between the second and third intrusive events is a span of 1300 to 1350 million years, covering the vast time span of unrecorded events in the later Precambrian, and the relatively quiet deposition of Paleozoic and Mesozoic sediments. This period ends with the Laramide orogeny.

The third event is the time of intrusion of the Cretaceous volcanic breccia, Paleocene stocks, and Eocene dikes at the close of Laramide tectonism, in the time period of about 75-50 million years. The concluding fourth event is the time of intrusion of mid-Tertiary stocks and dikes in the interval 35-29 million years.

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GEOLOGY AND GEOCHRONOLOGY OF THE DEL BAC HILLS, PIMA COUNTY, ARIZONA[1]

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INTRODUCTION

The Del Bac Hills, located on the San Xavier Indian Reservation approximately 10 miles southwest of Tucson, are of interest as an example of mid-Tertiary volcanic rocks common in southeastern Arizona. These hills are regarded geologically as the southernmost extension of the Tucson Mountains but structurally appear to form a portion of a northeast trend segmenting the Tucson Basin and separating the Tucson and Sierrita Mountains. Lithologies of the area are similar to those in the upper part of the Tertiary sequence exposed in the "A" Mountain-Tumamoc Hill area.

Acknowledgements

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REGIONAL SETTING

The Del Bac Hills form a physiographic unit approximately 7 miles long and trending N 60° E, recognized by Ganus (1965) as part of a regional structural trend, based on the interpretation of water table contour maps and on the structurally high occurrence of sediments of probable Pantano age in deep wells south of Tucson along the belt formed by the Del Bac Hills, Twin Hills, and Redington Pass between the Santa Catalina and Rincon Mountains. Turkey Track porphyry is exposed both in the Del Bac and Twin Hills. Gravity and magnetic surveys (Sumner, 1965; Davis, 1967) have revealed that this trend marks a probable basement scarp extending from the Avra Valley to Twin Hills and segmenting the Tucson Basin. North of this trend alluvial deposits are approximately 3,000 feet thick and south of it the same deposits exceed 5,000 feet in thickness. Basin sediments encountered in wells of the central basin south of the trend are much finer than similar sediments north of the trend (Davis, 1967).

Sherman and Hatheway (1964) observed "linears", trending N 50° W and N 10° W, on aerial photographs of the Tucson Basin and suggested that these features were caused by faulting or differential compaction of upper aquifer sediments. Davis (1967) pointed out that the linears overlie the basement scarp as defined by geophysical investigation. Similar prominent features trending N 45-60° W are seen on aerial photographs of the area immediately southeast of Black Mountain in the Del Bac Hills, crosscutting primary northeast drainage, and can be correlated with structural features in the area (Figure 1).

ROCK UNITS

Rocks outcropping in the Del Bac Hills were described by Heindl (1959) as consisting of basalt and andesite, andesite porphyry, speckled rhyolite, and conglomerate, probably a Pantano equivalent, which he termed the San Xavier conglomerate. The latter unit will not be described here. Volcanic rocks of the Del Bac Hills are of two principal types, Turkey Track porphyry and potassic basaltic andesites, both chemically unusual rocks which are widespread in southeastern Arizona. The limits of the area in which rocks of this age and type are found have not been established and they may prove to be quite extensive. On a regional scale, Turkey Track porphyry forms the base of a sequence of basaltic andesites when the two rock types are found in juxtaposition, leading Mielke (1964) to postulate that the two rock types may be products of gravitational differentiation within a magmatic source.

The units mapped in this investigation are shown in Figure 1.

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1. Contribution No. 161, Program in Geochronology, University of Arizona.

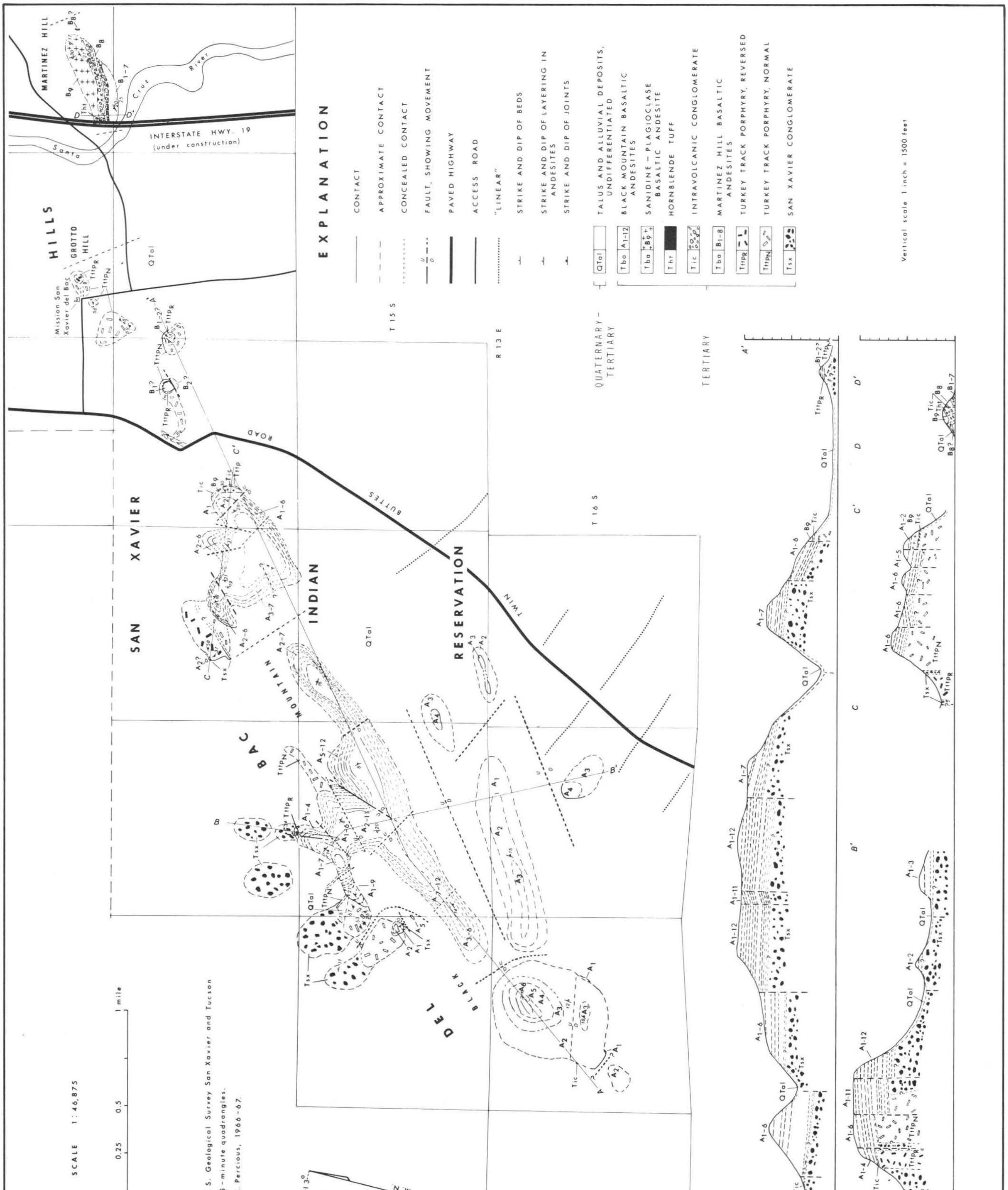

Figure 1 – Geologic map of the Del Bac Hills area, Pima County, Arizona

Turkey Track Porphyry

At least two approximately parallel dikes of Turkey Track porphyry are present in the Del Bac Hills. These features probably were continuous but now appear as scattered outcrops. The south dike seems to be the older of the two and has normal magnetic orientation. Its outcrop is approximately 1/3 mile wide and 4 miles long. The north dike has reversed magnetic orientation and is approximately 400 feet wide and 1½ miles long. A Turkey Track flow of reversed magnetic orientation overlies the porphyry of normal magnetic orientation. Both dikes entered along strike of the San Xavier conglomerate, which dips 15-35° NW. The south dike is highly weathered and iron-stained, giving it a characteristic yellow to red-brown appearance. The north dike is in general a much fresher appearing rock but also contains strongly weathered areas. Phenocrysts of plagioclase up to 1½ inches in length and of pyroxene ¼ inch in length are typical of both intrusive and extrusive phases. Joints trending parallel to the lengths of the dikes, roughly N 65° E, and dipping predominantly 60-70° SE are well developed in both dikes; joints of this strike dipping 50-60° NW are less well developed. Northwest trending joints dipping steeply to the northeast and southeast are also common. Joints trending north-south and approximately east-west are present. Fine quartz crystals commonly coat joints of the porphyry.

Structural adjustment along the south contact of the north dike is suggested by the stressed nature of a 2- to 8-inch wide zone of brown glass rimmed by calcite crystals, exposed in the NE¼, SW¼ of Sec. 29, T. 15 S, R. 13 E. The south dike also shows evidence of deformation in its southeastern half. Strongly sheared feldspars and needles of ferruginous material forming irregularly shaped zones several feet in diameter are interspersed in the dike with pods of normally porphyritic Turkey Track of similar dimensions. In some exposures the sheared material forms the matrix of the porphyry. The shearing is tentatively considered to be autoclastic in origin because well-defined zones of movement are absent.

Petrographically the dikes and associated flows vary somewhat in mineralogy but considerably in texture. Phenocrysts of plagioclase, orthopyroxene, and clinopyroxene occur in a groundmass of plagioclase and pyroxene; olivine is major to accessory; small crystals of magnetite are abundant; quartz is minor. A vesicular, strongly oxidized flow associated with the south dike, exposed on the two small hills southwest of San Xavier Mission in Sec. 27 and 28 of T. 15 S, R. 13 E, exhibits unzoned plagioclase phenocrysts ¼ to ¾ inches in length in a matrix of fine pyroxene and plagioclase needles. Phenocrysts and prismatic minerals of the groundmass are strongly oriented N 10-20° W, perpendicularly to the dike trend. The south dike contains up to 90 percent zoned plagioclase phenocrysts fairly well oriented parallel to the trend of the dike. The orientation suggests that the fissure along which the dike was emplaced was not opened by NW-SE tensional forces but by movement along the N 60-70° E trend, as indicated by Heindl (1959). The lower unit of Grotto Hill is not clearly extrusive, but is gradational with the south dike; its phenocrysts are oriented both parallel to the dike walls and N 30-40° W. The groundmass of this unit consists largely of small untwinned subhedral equigranular plagioclase with some laths.

The north dike contains a lower percentage of modal phenocrysts than the south dike, approximately 50 percent, and in it plagioclase phenocrysts are oriented N 30° E and N 10° E, oblique to the dike walls. The upper porphyry unit of Grotto Hill contains phenocrysts of plagioclase with preferred orientation in the N 30° E and N 10° W directions. A flow which is continuous with the north dike and caps the San Xavier conglomerate on the north end of Black Mountain contains phenocrysts oriented principally N 40-50° W, roughly perpendicular to the N 30° E trend of plagioclase phenocrysts in the dike. This flow and the upper unit of Grotto Hill both contain phenocrysts showing reaction with the groundmass; the phenocrysts occur in a matrix of predominantly subhedral equigranular plagioclase grains but with some laths. The deviation from parallelism of prismatic grains with the dike walls may have been the result of shearing stresses operating at the time of emplacement. Planar orientation of mineral grains is not well developed in the porphyry.

There is good correlation of the degree of preferential orientation of plagioclase phenocrysts with the apparent fluidity of the magma as determined petrographically. Slow cooling and minimal departure from equilibrium with the magma during formation are implied by the size and homogeneity of phenocrysts in the extrusive phases of the porphyry. The flow associated with the north dike was probably rather viscous, whereas the flow associated with the south dike seems to have been quite fluid. The small outcrop of Turkey Track porphyry in Sec. 2, T. 16 S, R. 12 E appears to be very shallow or extrusive and associated with the south dike.

As first suggested by Tolman (1909) there is cogent evidence that the Turkey Track porphyry formed in two stages, first developing large plagioclase crystals in a closed reservoir and later extruding as a porphyritic lava. The most compelling support for this premise is the occurrence of plagioclase phenocrysts ¼ inch or more in length at the contacts of the dikes with the San Xavier conglomerate. Fractured plagioclase phenocrysts with groundmass present in the fractures also support the theory. Ferromagnesian minerals rarely show this relationship to the groundmass. Olivine is generally more abundant in the extrusive phases than in the dikes; a comparison of the proportions of ortho- and clino-pyroxenes in the various bodies will require additional investigation.

The apparent ages of rocks dated by the potassium-argon method in this study are shown in Table 1. JKP-1-67 is a sample of the north dike taken approximately 30 feet from the south dike wall. It is not possible to specify the depth in the dike at which this sample was taken but it is reasonable to assume that it represents a depth of approximately 200 feet. JKP-9-67 is a sample of the most typical extrusive phase of the porphyry associated with the south dike. The nature of the contact between older and younger porphyry units suggests that little time elapsed between their extrusion. Assuming that the two units were extruded approximately contemporaneously, the anomalous date of JKPI-67 could be explained if the plagioclase of the north dike sample contains about 2.9×10^{-11} moles per gram of excess Ar^{40}, a value not inconsistent with results of similar determinations obtained in this laboratory (Damon et al., 1967; Livingston et al., 1967). No Ar^{40} excess was detected in plagioclase phenocrysts of the extrusive phase if the groundmass age is taken as a minimum, i.e., the Ar^{40} excess is less than 0.21×10^{-11} moles per gram, based on the error in determination of 0.8 m.y. and a 2-sigma criterion.

Tolman (1909) suggested that the source of the Turkey Track porphyry flow at "A" Mountain, dated at 28.0 ± 2.6 m.y. (Bikerman and Damon, 1966), appeared to be to the south. As the upper Turkey Track porphyry flow and north dike at San Xavier have the same magnetic orientation as the flow at "A" Mountain, and statistically the potassium-argon dates permit the correlation, the possibility that the "A" Mountain Turkey Track porphyry originated as far as 7 miles south cannot be excluded. The upper porphyry flow at San Xavier thins southward, implying a source north of the mission and Grotto Hill, which would be fulfilled by the northeast extension of the north dike at Black Mountain.

Table 1 – Potassium-Argon Ages of Volcanic Rocks of the Del Bac Hills

Sample No.	Mineral or Rock	Radiogenic Ar^{40} $\times 10^{-10}$ m/g	Atmospheric Ar^{40}, %	K, %	Apparent Age, m.y.
JKP-1-67	Turkey Track, north dike, plagioclase	0.669	47.7	0.802	46.4±1.4
JKP-9-67	Turkey Track, flow, plagioclase	0.360	33.8	0.765	26.3±0.8
JKP-9-67	Turkey Track, HF leached and insonated	0.374	33.5	0.765	27.3±0.8
JKP-9-67	Groundmass, magnetic fraction removed	1.60	26.8	3.86	26.9±0.8
JKP-10-67	Basaltic andesite (B_6), Martinez Hill, whole rock	0.837	39.2	1.99	23.5±0.7
JKP-68-66	Sanidine-plagioclase basaltic andesite (B_9) whole rock, no phenocrysts	0.876	38.7	1.99	24.7±0.7
JKP-49-66	Basaltic andesite, speckled (A_2), whole rock	0.892	32.8	2.01	24.8±0.7
JKP-50-66	Basaltic andesite (A_{12}), whole rock	1.05	58.6	2.48	23.7±1.0

Basaltic Andesites

Rocks which have the general appearance of basalts but which have relatively high alkali metal and silica contents were described by Halva (1961) as occurring in many localities in southeastern Arizona, including the Del Bac Hills. These rocks cap the upper flow of Turkey Track porphyry near San Xavier Mission; at Black Mountain they overlie a thin colluvial deposit formed on top of the Turkey Track porphyry; at Martinez Hill they are intercalated with similar colluvium containing abundant Turkey Track porphyry fragments, some units having flowed into channels of the conglomerate. The stratigraphic sections of these areas and of the "A" Mountain-Tumamoc Hill area are shown schematically in northwest-southeast section in Figure 2.

The petrologic and chemical anonymity of these basaltic andesite flows hinders correlation and mapping of individual flows. Halva (1961) noted the chemical variability within a single flow of basaltic andesite from Tumamoc Hill; in view of the chemical similarity of different flows within a series, a geochemical "fingerprinting" of individual flows may not be possible.

In general, flows of basaltic andesite outcropping in the Del Bac Hills are thin, less than 20 feet thick, but locally thicknesses of 75 to 100 feet are encountered. Three units, A_2, A_5, and B_9, have distinctive appearances in the hand specimen. Flows A_2 and A_5 are lighter colored than the average basaltic andesite and have a speckled appearance produced by small dots of opaque minerals in a matrix of feldspar laths. The lighter color owes its origin to the fact that the average size of feldspar laths is two to three times that of the typical basaltic andesite. Flow A_5 is in general somewhat lighter in color than A_2. Flow B_9 is a porphyritic basaltic andesite with sanidine and plagioclase phenocrysts which outcrops both at the top of Martinez Hill and at the northeast end of Black Mountain. The plagioclase phenocrysts are deeply corroded and rimmed by pyroxene; sanidine phenocrysts are strongly resorbed and may have rounded, rectangular, or pseudohexagonal outlines as well as the normal crystal morphology. Phenocryst abundance increases upward in the Martinez Hill outcrop. Chemically, the rock is indistinguishable from other basaltic andesites of the Martinez Hill (B) series. Flows A_3 and A_4 appear minutely porphyritic in the hand specimen and are useful in correlation when exposed in contact with either of the speckled basaltic andesites.

Age relations deduced from field relations have in general been borne out by radiometric dating (Table 1). Extrusion of these flows was essentially isochronous, and the standard deviation of the basaltic andesite dates in Table 1 is approximately equivalent to the analytical error.

The older basaltic andesites (B series) are characterized by K/Rb values of approximately 350, while flows of the Black Mountain (A) series have typical K/Rb values of about 260 (Table 2). This chemical grouping as well as geologic evidence implies separate sources for the two series. Based on their K/Rb values, the two basaltic andesite flows exposed on the small hills southwest of San Xavier Mission belong to the B series. These two flows are similar in texture to the two stratigraphically lowest flows (B_1 and B_2) exposed at Martinez Hill and are tentatively correlated with them.

No evidence was obtained for vents under the present outcrops. Gradations in thickness suggest a source south or southeast of Black Mountain and one south or east of Martinez Hill. A very small outcrop of hornblende tuff within the sediments at Martinez Hill thins and disappears northward; clearly its source was southward.

Flows of the Black Mountain series strike northwest and dip 5-20° NE. At San Xavier, the two basaltic andesite flows strike northeast and dip 13° northward. At Martinez Hill apparently untilted sediments dip 12° N, while tilted and faulted sediments and flows strike N 50-60° E and dip 20-25° NW. Very similar sediments intercalated with basaltic andesites at "A" Mountain are flat-lying or dip gently northward.

PETROGENESIS

The theory of Mielke (1964) that the Turkey Track porphyry and basaltic andesites may be genetically related, i. e., may have formed within a single magma chamber by means of gravitational separation is at least not disproved by several sources of information. First, all determinations to date in this laboratory of initial Sr^{87}/Sr^{86} for the two rock types have yielded values near 0.710 (Bikerman, 1965; Damon *et al.*, 1965). Also, the results of a number of specific gravity determinations on samples of these rocks from the Del Bac Hills suggests that the specific gravity of the Turkey Track porphyry is generally less than or approximately equal to that of the basaltic andesites (Table 3). The density of a molten rock is severely dependent upon its gas content, however, invoking a gravity separation mechanism implicitly excludes strong turbulence and convection, in which case the most highly gas-charged portion of the magma would be located at the top of the magma chamber. Plagioclase phenocrysts formed within such a gas-charged phase would very likely sink. The K/Rb date of Table 2 can also be interpreted to support a differentiation hypothesis.

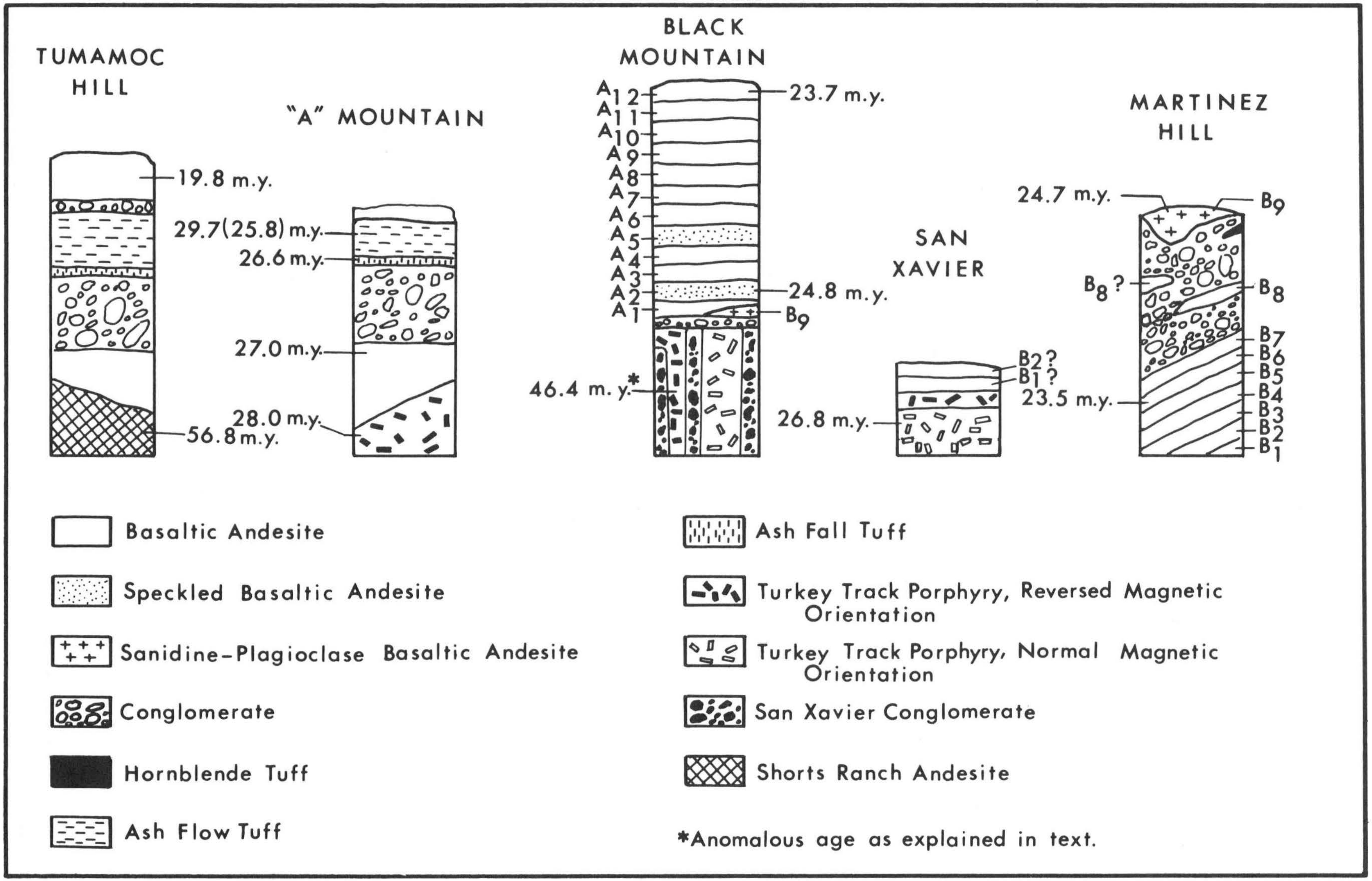

Figure 2 – Schematic northwest – southwest stratigraphic sections of the Del Bac Hills and "A" Mountain – Tumamoc Hill area, with apparent ages as determined by potassium – argon dating.

Table 2 – Potassium-Rubidium Ratios of Del Bac Hills Volcanics

Sample No.	Rock	K, %	Rb, PPM	K/Rb
JKP-1-67	Turkey Track dike, whole rock	2.57	148.1	174
JKP-74-66	Basaltic Andesite B_1 (?)	2.00	62.0	323
JKP-5-67	B_7	2.18	59.1	369
JKP-68-66	B_9, no phenocrysts	1.99	53.3	373
JKP-65-66	B_9, porphyritic	2.35	66.1	356
JKP-49-66	A_2	2.01	71.8	284
JKP-26-66	A_6	2.32	99.1	234
JKP-50-67	A_{12}	2.48	92.7	268

Table 3 – Specific Gravity Determinations for Del Bac Hills Volcanics

Sample No.	Rock or Mineral	Sp. G., 22°C	Mean Sp. G.
JKP-1-67	Turkey Track dike, whole rock	2.705	–
JKP-9-67	Turkey Track flow, whole rock	2.706	
		2.709	
		2.719	
		2.715	
		2.714	2.713 ± 0.002
JKP-1-67	Turkey Track dike, plagioclase	2.669	
JKP-9-67	Turkey Track flow, plagioclase	2.661	2.665
JKP-9-67	Turkey Track flow, groundmass, magnetic fraction removed	2.688	
		2.698	2.693
JKP-74-66	Basaltic Andesite, B_1 (?)	2.702	
		2.683	
		2.666	
		2.698	
		2.689	2.688 ± 0.005
JKP-5-67	B_7	2.766	
JKP-68-66	B_9	2.750	
JKP-49-66	A_2	2.772	
JKP-26-66	A_6	2.698	
JKP-50-66	A_{12}	2.699	
JKP-74-66	B_1 (?)	2.688	2.729 ± .014

It is curious that we have found no record of extrusives texturally and chronologically intermediate between the porphyry and basaltic andesites, though Halva (1961) demonstrated that the basaltic andesites are composed of low-potassium feldspars in a highly potassic matrix, analogous to the porphyry. If the two rock types formed from a single magma, conditions within the chamber must have been altered following the extrusion of the porphyry, or else the texture of the porphyry was developed during its migration to the surface, as suggested by Tolman (1909). Possible heating of the upper crustal rocks as the porphyry crystallized prevented the formation of additional porphyry from the remaining magma, which was then extruded as basaltic andesite, as suggested by Damon (1967, personal communication).

Whatever the genetic relationship between the porphyry and basaltic andesites, the two are closely associated in time and space and are unequivocally synorogenic, though their geotectonic significance is not yet clear. Their emplacement would appear to accompany the development of major Basin and Range features in southeastern Arizona. Radiometric dating of these rocks is hampered by the tendency of large phenocrysts to retain excess Ar^{40} and by the tendency of the basaltic andesites to lose Ar^{40} through devitrification and weathering. It is possible that when these problems are completely resolved and more data are available we may find the two rock types more restricted in time than we now consider them to be.

GEOLOGIC HISTORY AND STRUCTURE

Volcanism in the Del Bac Hills commenced approximately 27 million years ago as dikes of Turkey Track porphyry broke through the San Xavier conglomerate and spread both as relatively fluid and viscous flows. These flows were soon capped by a sequence of basaltic andesite flows in the area near the present channel of the Santa Cruz River. The Turkey Track porphyry in the west was topographically high and became deeply eroded. A thin conglomerate was deposited on top of the western portion of the porphyry, while a much greater thickness of the same deposit accumulated above the basaltic andesites in the east. Additional volcanism took place in the east during deposition of the conglomerate, culminating in a thick flow of sanidine-plagioclase basaltic andesite deposited in a stream channel of the conglomerate. This distinctive flow also extended to the extreme northern end of Black Mountain. No record of further volcanism remains in the eastern part of the area. Black Mountain volcanism ensued with the extrusion of cindery material soon after extrusion of the porphyritic basaltic andesite, incorporating fragments of it at the contact at the northeast end of Black Mountain. The composite thickness of basaltic andesites and intercalated sediments in the Del Bac Hills probably exceeds 1,000 feet.

The structural complexity produced by post-extrusive faulting in the Del Bac Hills may be appreciated from a view of the roadcut at the west end of Martinez Hill. No evidence was found for faulting during the emplacement of the volcanic rocks. Following emplacement, faulting occurred along the N 50-60° E, N 35-55° W, and N 10° W – N 10° E directions. The N 60° E trend which established the present configuration of the hills as a narrow chain was probably active first. Faults along this trend have the greatest throw, about 350 feet, and are high-angle normal faults generally downthrown to the south within the outcrops of volcanic rocks. Data from water wells drilled in alluvium adjacent to the hills indicate that the volcanics are present at depths of 200-500 feet. Heindl (1962) discussed ground-water shadows caused by the presence of buried ridges parallel to the trend of the Del Bac Hills and located approximately 2, 5, and 9 miles southeast of the hills. Transverse faults of north trend are approximately vertical and usually have less than 100 feet of throw. Transverse faults in the northwest direction have intermediate throw but appear to have significant heave in some cases. Northwest faults seem to be the most recent, though this was not demonstrated unequivocally. Transverse faults probably defined the structure upon which the Santa Cruz River is superimposed; the bedrock block present less than 100 feet below the river channel between Grotto Hill and Martinez Hill has been termed the Allison Barrier. Heindl (1962) also described ground-water shadows produced by buried topography near Martinez Hill which can be ascribed to the presence of transverse faults.

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TERTIARY VOLCANISM IN THE NORTHERN CHIRICAHUA MOUNTAINS COCHISE COUNTY, ARIZONA

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INTRODUCTION

The Chiricahua Mountains are geologically similar to neighboring ranges to the east in New Mexico. These ranges are largely made up of Tertiary volcanics, including acidic ash-flow deposits, acidic to basic flows, and associated breccias. The volcanic deposits are part of a large volcanic field which includes the Chiricahua Mountains, central and southern Peloncillo Mountains, and Animas Mountains, and extends into Mexico. The northern Chiricahua Mountains lie at the northwestern edge of this field.

The Tertiary volcanic formations of the northern Chiricahua Mountains have been described by Enlows (1955), Sabins (1957), and Fernandez and Enlows (1966) (Table 1). Their work is the basis for descriptions of the formations summarized in the present paper. The writer has obtained potassium-argon ages for the Rhyolite Canyon and Faraway Ranch Formations, and has studied the distribution of the Rhyolite Canyon ash flows and related volcanics in southeastern Arizona and southwestern New Mexico.

NIPPER FORMATION

The lower half of the Nipper Formation is made up of a conglomerate consisting of well-rounded cobbles and boulders of altered andesite up to several feet across cemented in a matrix of graywacke sandstone. In the upper half, light-weathering andesite

Table 1 – Volcanic formations of the Northern Chiricahua Mountains

Age	Formation	Thickness in feet		References
Miocene	Rhyolite Canyon	1927	silicic ash flows; capped by rhyodacite flow	Enlows, 1955
		angular unconformity		
Oligocene	Faraway Ranch	1375-2000	silicic to mafic volcanics and volcanic-derived sediments	Fernandez and Enlows, 1966; Sabins, 1957
Lower Tertiary to Upper Cretaceous	Nipper	2500±	mafic volcanic conglomerates and associated sediments	Sabins, 1957
		angular unconformity		
Lower Cretaceous	Bisbee Group		quartzite, limestone, siltstone, and conglomerate	

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flows predominate while conglomerates similar to ones found in the lower half are interstratified with basalt flows and graywacke sandstone.

The Nipper Formation is easily distinguished from the Faraway Ranch Formation since its mafic volcanics and conglomerates form dark ridges and hills in contrast to the light-colored cliffs and peaks formed by the overlying rhyodacite.

FARAWAY RANCH FORMATION

The thickest member of the Faraway Ranch Formation is the rhyodacite flow (Fig. 1). According to Sabins (1957) this member is approximately 2000 feet thick at Cochise Head. The remainder of the formation is made up of basalt flows and breccia, rhyolitic pyroclastic rocks, and fluviatile sediments. The pyroclastic rocks are the most extensive and probably correlative with similar rocks found throughout the Chiricahua Mountains and the nearby Peloncillo Mountains. A general thickening to the southeast, reaching thousands of feet in the southern Peloncillo Mountains, suggests that the source of these rocks is in southwestern New Mexico.

RHYOLITE CANYON FORMATION

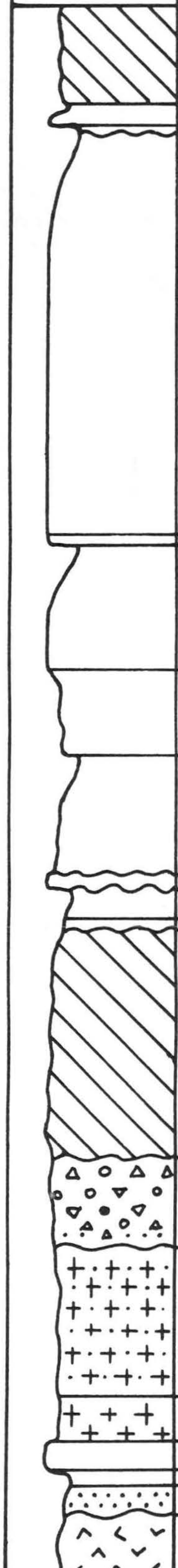
Six major ash flows and a capping rhyodacite flow make up the Rhyolite Canyon Formation. The ash flows are distinguished from each other by their lithology, color, jointing, and weathering characteristics (Fig. 1, 3, and 4; Table 2). Member 8 is distinguished by its high percentage of phenocrysts and pale-brown color. Members 6 and 4 are the only ones forming prominent columns in the Monument. Member 3 is dusky-red, similar in color to member 8 but easily distinguished by its high percentage of foreign rock fragments.

The size and percentage of phenocrysts generally increases in the progressively later ash flows (Table 2). This suggests that ash flows of the Rhyolite Canyon Formation may be characterized by compositional zonation such as has been described for ash flows from various parts of the world (see for example: Lipman et al, 1966). The progressive petrographic variations of successive ash flows and their overall petrographic homogeneity suggest a common source.

Thick sequences of ash-flow deposits are widespread in the Chiricahua, Peloncillo, and Animas Mountains, and adjoining smaller ranges. These deposits are predominantly rhyolitic or rhyodacitic in composition.

Table 2 – Phenocryst content of welded phases, Rhyolite Canyon Formation (after Enlows, 1955)

Member No.	Phenocrysts	Abundance in volume percent	Maximum size (mm)
8	quartz and sanidine magnetite	35 less than 1	4 2
6	quartz and sanidine magnetite	20-30 less than 1	3 0.5
4	quartz and sanidine magnetite	10-15 sparse	3
3	quartz and sanidine magnetite	15 sparse	2-3 1
2	quartz and sanidine magnetite biotite	5 occasional rare	1.5 0.5
1	quartz and sanidine magnetite hornblende	10 occasional rare	2



THICK.	MEMBER, DESCRIPTION	FM.
220'	9. Rhyodacite flow (?); black to medium dark gray, vesicular	Rhyolite Canyon
50'	8. Welded rhyolite tuff; soft, light-gray grading down into brittle, pale-brown	Rhyolite Canyon
10'	7. Rhyolite tuff; fairly coherent, light-gray	Rhyolite Canyon
880'	6. Welded rhyolite tuff; rather coherent light-gray tuff, grading down into poorly welded light-gray tuff, which grades into coherent, brittle, light-brownish-gray rock	Rhyolite Canyon
3'	5. Welded rhyolite tuff; glassy, lt. brownish-gray	Rhyolite Canyon
270'	4. Welded rhyolite tuff; soft, light-gray top, containing strongly welded grayish-red seams, grading down into coherent, brittle, pinkish-gray	Rhyolite Canyon
190'	3. Welded rhyolite tuff; firmly welded, dusky-red, with many prominent inclusions	Rhyolite Canyon
270'	2. Welded rhyolite tuff; soft, light gray at top grading into brittle grayish-red	Rhyolite Canyon
30'	1. Welded rhyolite tuff; brittle, dark gray, very firmly welded	Rhyolite Canyon
55'	9. Rhyolite sillar; very light gray, porous	Faraway Ranch
25'	8. Rhyolite sillar; moderate reddish-orange, porous, poorly consolidated; many inclusions	Faraway Ranch
500'	7. Rhyodacite flow; pinkish-gray to pale reddish-brown, hard, marked by prominent flow structure; grades from dense glassy, dark-gray base to grayish-pink scoriaceous top	Faraway Ranch
200'	6. Volcanic fanglomerate; coarse volcanic breccia and conglomerate overlying volcanic sandstones and breccias	Faraway Ranch
330'	5. Basalt breccia; medium gray to dusky-red basalt clasts in a grayish-orange matrix	Faraway Ranch
110'	4. Basalt flow and flow breccia; porphyritic	Faraway Ranch
65'	3. Welded rhyolite tuff; grayish-pink, porphyritic	Faraway Ranch
40'	2. Air fall tuff; pinkish-gray, fine-grained	Faraway Ranch
50'	1. Lithic graywacke; grayish-pink, coarse grained sandstone	Faraway Ranch
	Andesite	

Figure 1 – Composite section of Tertiary rocks in the Chiricahua National Monument (after Enlows, 1955, and Fernandez and Enlows, 1966)

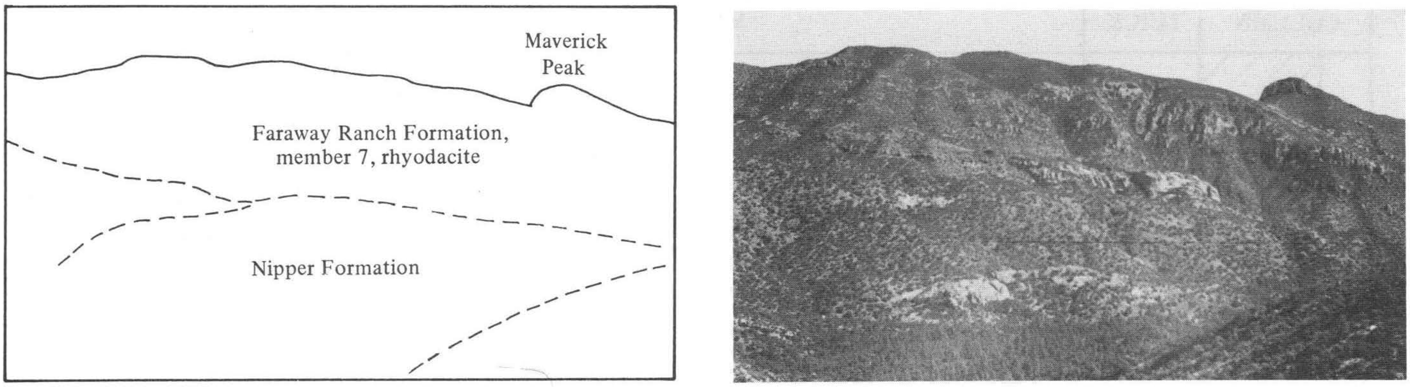


Figure 2 – View looking northeast across Whitetail and Indian Creeks showing Nipper Formation and member 7, rhyodacite of Faraway Ranch Formation.

The Rhyolite Canyon ash flows are distinguished from other such deposits by their unique textural and lithologic characteristics. These characteristics include: (1) microcrystalline groundmass, (2) generally small percentage of phenocrysts, (3) with the exception of member 3, containing only sparse foreign rock fragments, (4) generally no mafic minerals, and (5) no plagioclase.

The Rhyolite Canyon ash flows are mainly limited in distribution to the Chiricahua Mountains. They are probably correlative with similar deposits found in the neighboring ranges such as the Swisshelm Mountains to the west, Pedrogosa Mountains to the south, and central Peloncillo Mountains to the east. Locally in the Chiricahua Mountains this formation is underlain by much thicker and older ash-flow deposits.

Table 3 – Potassium–argon ages of volcanic rocks from the Chiricahua National Monument

Formation, Member*, Mineral, Sample No., Analysis	K % by weight	Ar^{40} radiogenic $x10^{-10}$m/g	Ar^{40} % atmospheric	K-Ar Age x 10^6 years
Rhyolite Canyon, member 8, sanidine (DM-3-67)	6.31	2.80	1.5	24.9±0.7
Rhyolite Canyon, member 6, sanidine (PED-12-62)				
20 to 35 mesh (note 1)	5.75	1.66	40.8	16.2±1.6
65 to 100 mesh (note 2)	5.90	2.55	2.2	24.1±0.7
Rhyolite Canyon, member 2, sanidine (DM-2-67)	6.75	3.02	14.2	25.0±0.8
Faraway Ranch, member 7, biotite (DM-1-67)				
first analysis	6.82	3.41	73.6	27.9±2.0
second analysis (note 3)	6.82	3.37	30.8	27.6±0.8

*Enlows, 1955, and Fernandez and Enlows, 1966

notes:
1 Reported by Damon et al, 1962
2 Treated in sonic tank and placed in vacuum oven before fusion
3 Same separate as for first analysis but placed in vacuum oven before fusion

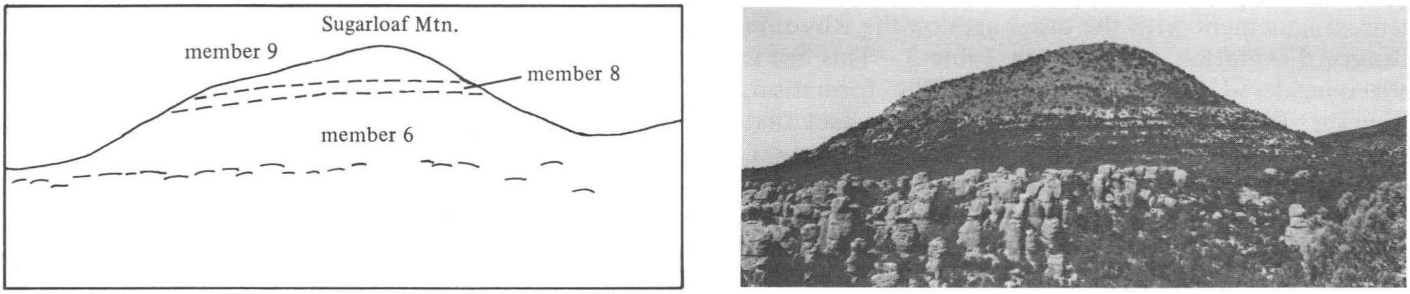


Figure 3 – View of Sugarloaf Mountain from Massai Point showing members 6, 8, and 9 of Rhyolite Canyon Formation.

POTASSIUM-ARGON AGES

Potassium-argon ages and analytical data obtained in this laboratory are presented in Table 3. The only age previously published is that of 16.2 million years for member 6 of the Rhyolite Canyon Formation (Damon et al, 1962). It is noted that this age is not in agreement with the new results. The reason for the discordant age is considered in Table 3.

The discordant 16.2 million year age is explained by alteration of the sanidine and incorporation of the alteration products in crystal fragments of the 20 to 35 mesh size on which the potassium and argon determinations were made. Extensive internal fracturing and alteration along these fractures within the sanidine phenocrysts is seen in the thin section. Since the sample was collected from the upper part of the ash flow, the alteration could have been caused by gases rising during cooling. For the second analysis of this sample, a much smaller mesh size, 65 to 100 mesh, was selected. It was assumed that, at this mesh size, the phenocrysts would be pulverized small enough to expose most of the alteration products. Sonification was used to help remove the alteration

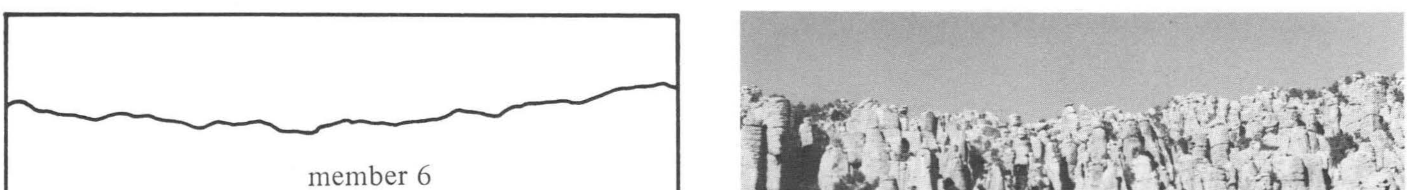


Figure 4 – View in Rhyolite Canyon just east of Ranger Station showing members 3, 4, and 6 of Rhyolite Formation.

products. The 24.1 million year age obtained is in general agreement with the other ages on the Rhyolite Canyon Formation presented in Table 3. This age is not considered an accurate age for the formation, however, in view of the alteration and the fact that even the 65 to 100 mesh size is not free of alteration.

In summary, the potassium-argon age of the Rhyolite Canyon ash flows may be taken as 24.9±0.6 million years. The period of eruption was probably short relative to the analytical error. The age of the rhyodacite flow, member 7 of the Faraway Ranch Formation, may be taken as 27.7±0.7 million years. No age is yet available on a lower member of this formation.

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ZONED ASH–FLOW SHEET IN THE REGION AROUND SUPERIOR, ARIZONA[1]

By

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INTRODUCTION

Remnants of a thick Tertiary ash-flow sheet cover large areas in parts of Gila, Pinal, and Maricopa Counties, Arizona (Fig. 1). The ash-flow sheet is of particular local interest because it covers potential mineral exploration targets in a region that has many ore deposits. This report briefly describes the physical features of the ash-flow sheet and explains how internal zoning can help interpret its structure.

Previous Work

The ash-flow sheet was first studied in the Globe 15-minute quadrangle by Ransome (1903, p. 88-95), who described the basal tuff correctly but considered the vitrophyre and the rest of the unit to be thick, massive lava flows of dacitic composition. Short and others (1943, p. 45-49) described the sheet near Superior as alternating dacitic lava flows and tuff deposits. N. P. Peterson carefully described the deposit in the vicinity of Globe and Miami (1962, p. 38-41). He realized that lava flows of this composition would be erupted as relatively short, viscous flows with contorted flow structures. This deposit, however, actually covers hundreds of square miles and contains uncontorted, flat to moderately tilted structures, so he concluded that it was probably laid down by several ash flows or incandescent clouds (N. P. Peterson, 1962, p. 40-41).

I have made additional studies of the deposit and have concluded that it is composed of a number of ash flows erupted in rapid enough succession to form an ash-flow sheet that is, in general, a simple cooling unit. The present report, outlining this thesis, is chiefly a condensation of an earlier open-file report (D. W. Peterson, 1961a).

Terminology

The terms used in this report follow the terminology proposed by Smith (1960a, p. 800-801). Abbreviated versions of several of Smith's definitions are repeated here.

Ash flow: The basic unit of ash-flow deposits; the deposit resulting from the passage of one nuée ardente.

Ash-flow sheet: Any unspecified sheetlike unit or group of units considered to be of ash-flow origin.

Welded tuff: A rock or rock body in which vitric particles have some degree of cohesion by reason of having been hot and viscous at the time of their emplacement.

Cooling unit: A single or multiple ash-flow deposit that can be shown to have undergone continuous cooling.

Simple cooling unit: An ash flow or sequence of ash flows that has had an essentially uninterrupted cooling history.

Compound cooling unit: One that shows departures in expectable zonation and other properties which result from simple cooling, because the intervals between ash flows were too great for readjustment to a single-unit cooling gradient.

To understand the definition of " ash flow" it may be helpful to review Smith's concept of "nuée ardente". He emphasized the original observation that a nuee ardente is composed of two parts, a basal avalanche that contains the bulk of the erupted material, and an overriding cloud of expanding gas and dust (Smith, 1960a, p. 802-804). Although a nuée ardente is both a type of eruption and an agent of transport, Smith emphasized its role as an agent of transport of material from the vent to its final resting place.

The deposit in the vicinity of Superior, Miami, and Globe is an "ash-flow sheet" made up of an undetermined number of separate "ash flows" that in most places cannot be individually recognized. Part of the deposit is composed of "welded tuff," and part is non-welded. In most places the ash-flow sheet constitutes a "simple cooling unit," but locally it grades laterally into a "compound cooling unit."

In most of the literature describing the area, "dacite" has been used to designate the rock type (Ransome, 1903, 1919, 1923; Short and others, 1943; Peterson and others, 1951; N.P. Peterson, 1962, 1963), and the name is firmly established in current local usage. Dacite is defined as a volcanic rock with

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1. Publication authorized by the Director, U.S. Geological Survey

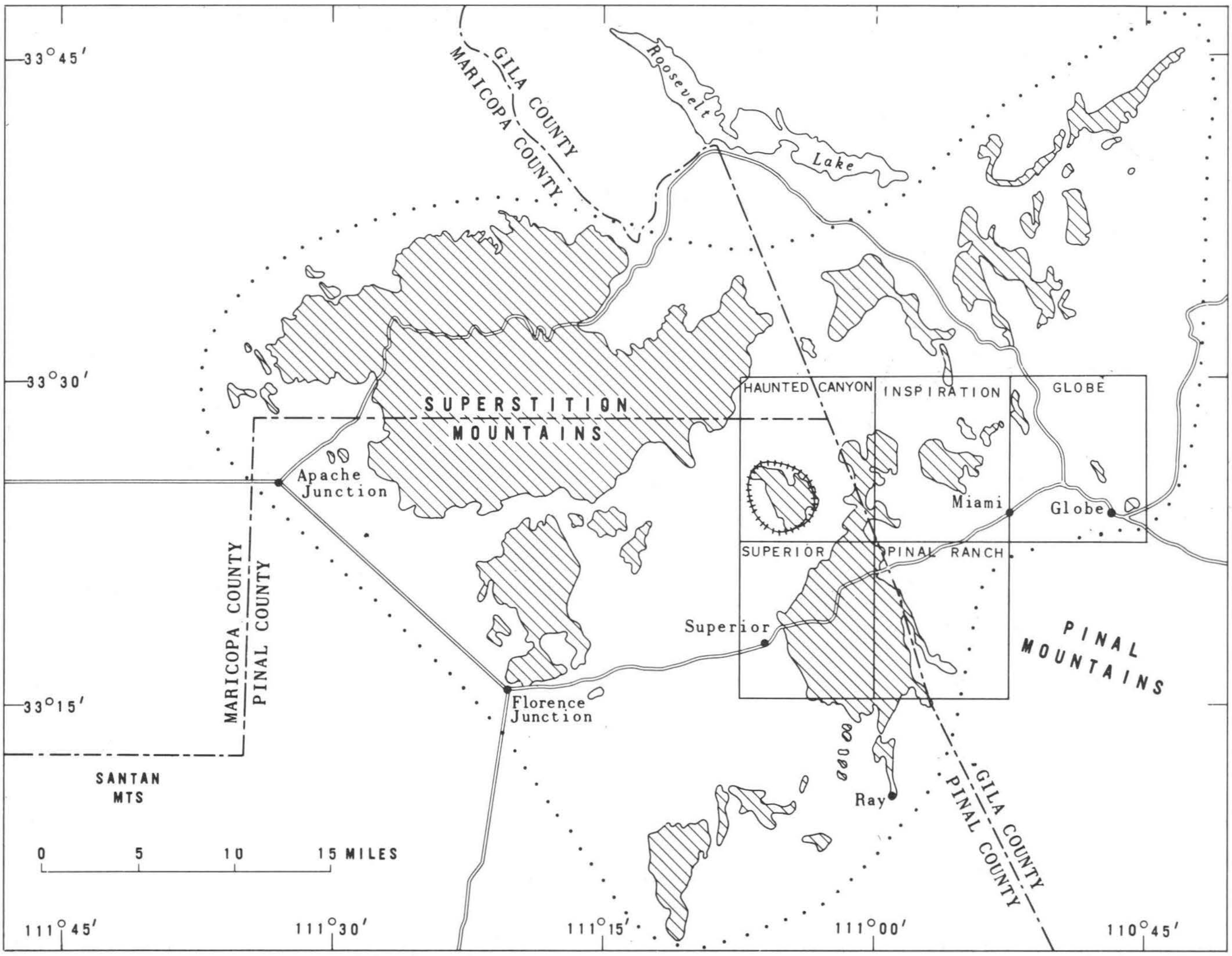

Figure 1 – Location Map of the Superior, Arizona Region

numerous quartz and feldspar phenocrysts, the feldspar phenocrysts being mostly plagioclase; on this basis dacite is a valid name for the rock. It should be recognized, however, that on the basis of its chemical composition, the rock is a quartz latite (Peterson, 1961a, p. 111).

ORIGINAL EXTENT, VOLUME, AND AGE

The area in which the ash-flow sheet crops out is shown in Figure 1. The deposit has been recognized from 10 miles west of the Superstition Mountains to the Salt River near Cherry Creek, and from a mile east of Globe to the vicinity of Ray. Outcrops of ash-flow rocks in the Santan Mountains may be part of the same sheet, but the correlation is not yet certain. The possible original extent of the sheet is indicated in Figure 1; this area is about 1500 square miles, but it may exceed 2000 square miles.

The maximum exposed thickness of the sheet is 2000 feet just east of Superior. Thicknesses of over 1000 feet are common in the central part of the area shown in Figure 1, and the sheet gradually thins toward its margin. The original thickness of the sheet is difficult to determine because of dissection by erosion and the irregular pre-eruption topography. However, 500 feet seems to be a reasonable estimate for the average thickness. This leads to an estimated volume for the sheet of about 150 cubic miles.

Ransome (1903, p. 94-95) assigned a Tertiary (?) age to the deposit, and this age is confirmed by isotope age dating techniques. Creasey and Kistler (1962, p. 1) determined an apparent absolute age of 20 million years on K-Ar ratios in biotite obtained from vitrophyre at the base of the deposit east of Superior. Damon and Bikerman (1964, p. 72) obtained an age of 19.9±0.9 million years on biotite from dacite about 2 miles east of Superior. (They used a slightly different decay constant and recalculated the age obtained by Creasey and Kistler to 19.4 million years.) These dates all indicate a middle Miocene age.

FIELD DESCRIPTION

Zoning

All of the zones of welded ash flows defined and described by Smith (1960b) are present in this ash-flow sheet, and they are diagrammatically represented in Figure 2. The three fundamental zones that depend

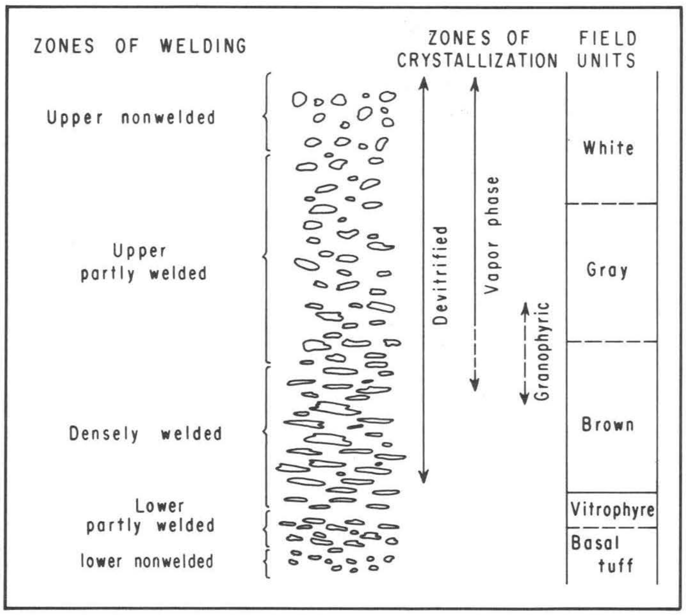

Figure 2 – Physical characteristics of the ash flow sheet

on the degree of welding include (1) upper and lower zones of no welding, (2) upper and lower zones of partial welding, and (3) the zone of dense welding. Superimposed on all but the lower part of the sheet are three zones representing the different types of crystallization that took place during the cooling of the sheet: (1) devitrification, (2) vapor-phase crystallization, and (3) granophyric crystallization. The zones of crystallization are superimposed upon the three fundamental zones of welding. In addition, the zones of crystallization overlap one another. In most vertical sections through the sheet, the successive zones in part follow the same pattern as indicated in Figure 2, without repetition or regression. This pattern indicates that, despite its great thickness, the sheet consists of a single cooling unit in most places.

The rocks of all the zones have certain features in common. Throughout the entire sheet the rocks are porphyritic with a similar phenocryst assemblage; in hand specimen phenocrysts can be identified as feldspar, quartz, biotite, accessory iron oxide, and lesser variable amounts of hornblende and sphene. Phenocrysts constitute from one-fourth to nearly one-half the volume of the rock; they range in size from barely discernible with the hand lens to 3 mm, and most are ½ to 1 mm in diameter.

Lithic inclusions are common throughout the ash-flow sheet, and generally make up 1 or 2 per cent of the rock. In the lower part of the sheet, however, they become much more abundant, generally making up about 10 per cent and locally as much as 25 per cent of the rock. All the older rocks of the district occur as inclusions. Most are angular chips a fraction of an inch in diameter, some are several inches across, and a few scattered boulders several feet in diameter have been observed.

In the field it has been convenient to map the following five units rather than the zones of crystallization or welding: (1) basal tuff, (2) vitrophyre, (3) brown unit, (4) gray unit, and (5) white unit. Some of these units have been mapped in part of the Superior quadrangle; Figure 3 shows their generalized distribution.

(1) The basal tuff includes the lower zone of no welding and part of the lower zone of partial welding. The glass shows no appreciable crystallization. The base of the ash-flow sheet consists of nonwelded crystal tuff wherever observed. The basal tuff is poorly to moderately indurated and weathers to gentle, subdued slopes. It is generally light gray to white but locally grades to shades of yellowish gray and moderate red. The basal tuff ranges in thickness from 2 to 100 feet or more, averaging about 10 to 20 feet.

The matrix of the nonwelded tuff is powdery and generally uniform; in addition to phenocrysts and lithic inclusions, it locally contains pumice lapilli and blocks. In the nonwelded tuff, orientation of constituents is random. Upward into the zone of partial welding, however, the pumice fragments and glass shards become flattened and uniformly oriented; as the tuff becomes more firmly consolidated, its specific gravity increases, and discs of black glass appear and become progressively more abundant upward. These changes all result from a progressive upward increase in the degree of welding. The zone of partial welding (the upper part of the basal tuff) ranges in thickness from a few inches to about 40 feet, averaging from 1 to 6 feet.

(2) The vitrophyre includes the lower part of the zone of dense welding that lacks superimposed crystallization. The lower part of the vitrophyre may also include the upper part of the lower zone of partial welding (Fig. 2). Most of the vitrophyre is a densely welded tuff composed of a matrix of black glass containing the normal assemblage of phenocrysts and sparse to abundant lithic inclusions. It is generally

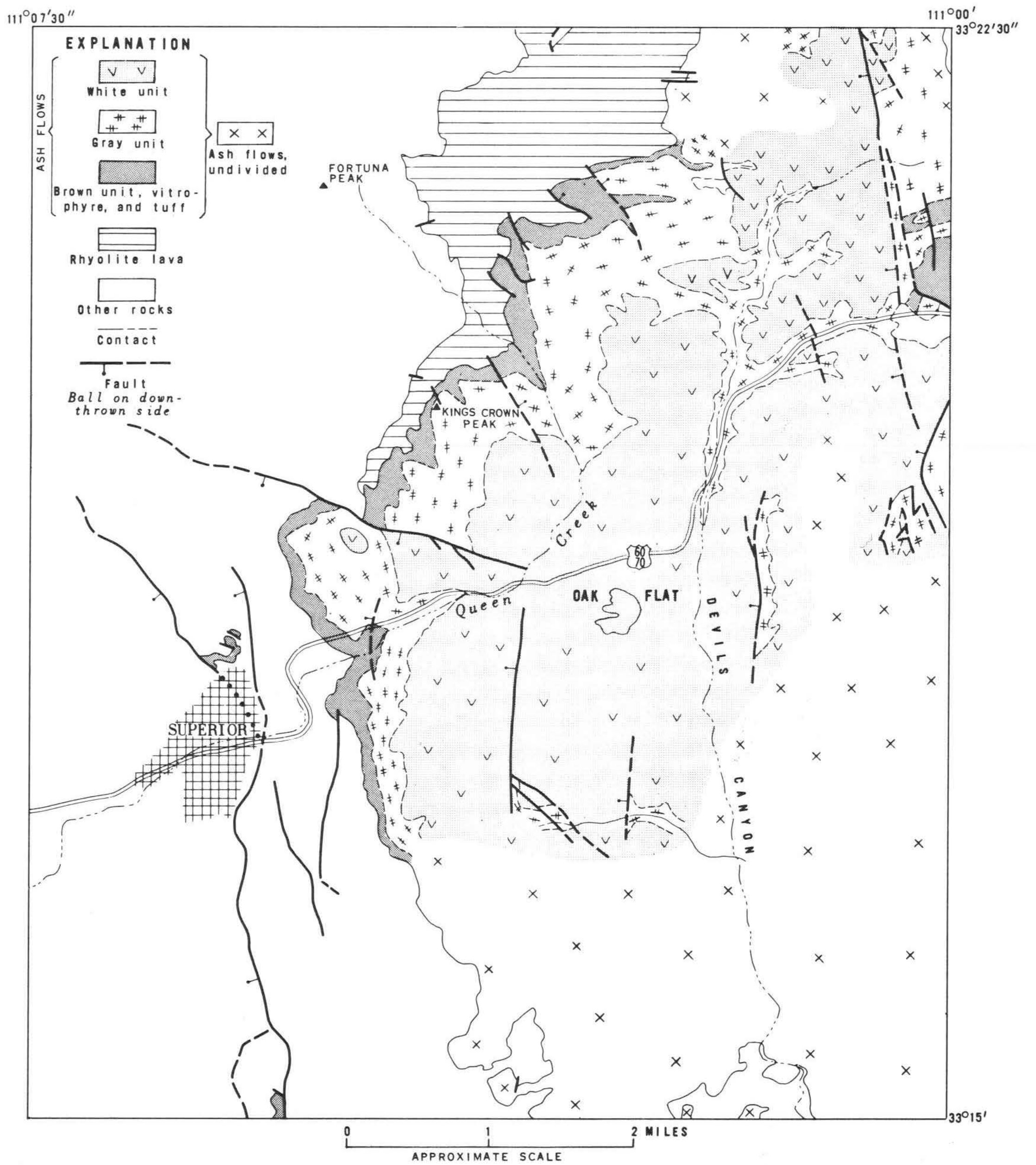

Figure 3 – Generalized geologic map of the Superior quadrangle, showing the distribution of recognized field units within the ash flow sheet. Recognition of the units has permitted identification of several faults within the sheet.

firm and resistant to weathering and stands out as a ledge above the softer basal tuff. The vitrophyre weathers to a dark gray or dark brown color that contrasts with the lighter colors of overlying and underlying rocks. It ranges in thickness from 2 to 80 feet and averages from 5 to 25 feet.

(3) The brown unit consists of the part of the zone of dense welding upon which has been superimposed the zone of devitrification. It also may include the lower part of the upper zone of partial welding, in which thin scattered lenticles that underwent vapor-phase crystallization are present. The dominant characteristic of the brown unit is a devitrification of the original glass of the groundmass to a dense, hard, flinty rock that is light brown to reddish brown in color. Careful scrutiny of the groundmass with a hand lens reveals eutaxitic structures characteristic of densely welded tuff; these structures show clearly under the microscope. The intensity of devitrification crystallization increases upward. This is expressed megascopically by a gradual change in color from brown to brownish gray to reddish gray. The thin,

light-colored lenticles in the upper part of the brown unit are flattened pumice fragments that have retained enough porosity to allow slight vapor phase crystallization; they gradually become more abundant upward into the upper zone of partial welding. The thickness of the brown unit cannot be given precisely, because of its gradational upper boundary, but it generally ranges from 20 to 200 feet. In Queen Creek Canyon the brown unit reaches its maximum thickness of about 450 feet.

(4) The gray unit lies entirely within the upper zone of partial welding, upon which the zone of devitrification crystallization has been strongly superimposed. This crystallization reaches the maximum coarseness in the gray unit, and in many places the original "welded-tuff texture" is obscured by the superimposed crystallization. The color of the rock ranges from reddish gray to medium and light gray. Pumice fragments are strongly flattened in the lower part of the unit and partly flattened in the upper part; as their flattening decreases, the amount of vapor-phase crystallization increases. However, welding of the groundmass throughout the gray unit was strong enough to confine vapor-phase crystallization chiefly to the pumice fragments. Both the lower and upper contacts of the gray unit are gradational. The unit ranges from a few feet to over a thousand feet in thickness.

(5) The white unit includes the upper part of the upper zone of partial welding and the entire upper zone of no welding. Its main characteristic is that vapor-phase crystallization not only occupies the pumice fragments but also permeates the groundmass and is there superimposed upon the devitrification crystallization. Crystallization is so intense that generally the original vitroclastic textures have been completely obliterated. The rock has an aphanitic groundmass that generally lacks planar or oriented structures. The color on the fresh surface is light gray to white; it weathers brownish gray to reddish gray, nearly the same as the gray unit. Pumice fragments range from partly flattened to nearly equidimensional in shape. On unweathered surfaces they are difficult to distinguish from the enclosing rock, but as the rock weathers to a darker color, the pumice fragments become more discernible. In most places erosion has removed a substantial part of the white unit, and only in the vicinity of Oak Flat, 4 miles east of Superior, has the original upper surface of the unit been recognized. The white unit has a maximum thickness of about 800 feet and averages perhaps 200 to 300 feet, but thicknesses are uncertain because of the gradational lower contact and the eroded upper surface.

Granophyric Crystallization

Smith (1960b, p. 152) defines granophyric crystallization as follows:

> "In silicic welded tuffs granophyric crystallization is characterized by groundmass quartz intergrown with, or as blebs associated with, alkalic feldspar and minor accessory minerals. The aggregate shows granophyric or micrographic textures similar to those shown by many slowly cooled rhyolitic flows, domes, and shallow intrusive rocks."

Granophyric textures are identified in thin section in specimens from the central part of the very thick section east of Superior. These textures occur chiefly in the centers of flattened pumice fragments in the lower part of the gray unit. The granophyric crystallization evidently took place where cooling was slowest and was promoted by the presence of residual vapors in the pumice fragments. The position of the granophyric crystallization zone illustrates well how the various zones of crystallization are superimposed on one another. This zone is thin, poorly defined, and discontinuous, and it is superimposed upon the zone of devitrification at a horizon where the zone of vapor-phase crystallization is also present.

Pumice Fragments

Light-colored cognate inclusions that are locally abundant in some parts of the ash-flow sheet have been identified as pumice fragments. They are lenticular to ovoid in shape; toward the top they are equidimensional, but downward they become progressively more flattened. Most of the inclusions range from 1 to 4 inches in their longest dimension, but both larger and smaller sizes are common. In general their light color contrasts with the slightly darker enclosing rock. Most of them carry approximately the same assemblage of phenocrysts in about the same proportions as the matrix and, except for their lighter color, appear to be practically the same rock. An important difference is that many of the phenocrysts in the enclosing rock are broken, whereas they are generally unbroken in the pumice fragments. The original pumiceous texture of the fragments has been largely obscured or obliterated by devitrification and vapor-phase crystallization, so that the fragments are now essentially a porphyritic rock with a uniform aphanitic groundmass.

The flattening of pumice fragments has been given considerable study (Peterson, 1961b). The apparent flatness of a fragment is defined as the ratio of its length to its height–a ratio which has a rather wide range of values at any given outcrop. The flattening ratio is defined as the mean value of the apparent flatnesses of a representative number (generally 30 or 40) of fragments. This ratio can be calculated either as an arithmetical average or as the mean of the logarithms of the apparent flatnesses. These two methods yield slightly different values; the logarithmic flattening ratio is more rigorous, but the arithmetical flattening ratio is easier to calculate in the field. Figure 4

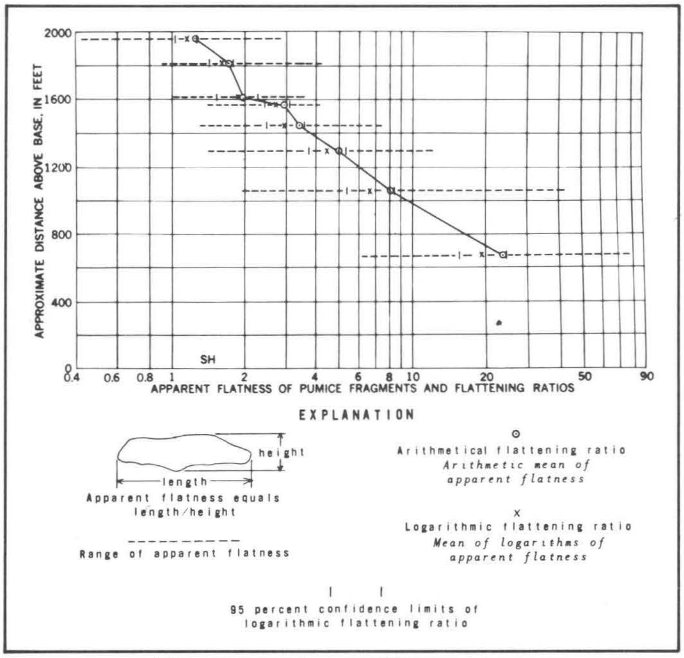

Figure 4 – Flatness Characteristics

shows the relation of the flattening ratio to the stratigraphic position in the ash-flow sheet; the flattening ratio increases as the depth of burial increases. This curve was obtained from fragments in the section of rocks exposed in roadcuts along U.S. Highway 60-70 between Superior and Oak Flat. Curves from other localities show similar relations.

Studies of flattening ratios have made it possible to estimate the amount of throw on faults in the ash-flow sheet. The flattening ratio also is a tool for estimating the distance of an outcrop below the original top of the sheet. Such applications are somewhat limited, however, because outcrops suitable for measurement of fragments are not numerous.

STRUCTURE OF THE ASH-FLOW SHEET

The term "sheet" appropriately describes the gross structure of the ash flows, inasmuch as the horizontal dimensions are many times greater than the thickness and the deposit extends over a wide area. The sheet was deposited on a surface of moderate to locally steep relief.

The attitude of most layering ranges from horizontal to dips of about 30°, but in a few places the dips are as much as 60°. The planar structure on which attitudes are measured is generally a joint system, distinct to indistinct, that lies parallel to the plane of flattening of the pumice fragments. It seems likely that the structures originally were nearly horizontal, and that the higher dips are due to post-solidification tilting. If the still-plastic rock had been deposited with an appreciable angle of dip, the rock would probably have flowed laterally, yet no evidence for such flowage has been recognized.

In earlier maps and reports, few faults were noted within the ash flows because of the uniform appearance of weathered surfaces from near the base to the top of the sheet. However, the distinct changes in lithology due to zoning and the systematic changes in the flattening ratio of pumice fragments provide the criteria that permit faults within the sheet to be recognized and mapped. A fresh surface must be obtained to identify the zone, so the work is rather slow and tedious; therefore, zones have been mapped and faults studied in detail in only a part of the Superior quadrangle (Fig. 3).

Several faults cutting the ash-flow sheet have been recognized, most of which probably belong to a single set. Most of the faults trend north to northwest, and the west or southwest side is dropped down, although a few have the opposite sense of displacement. Hammer and Peterson (in press) describe two principal sets of faults that cut the rocks of the Superior area. The older set trends principally eastward, and many of the faults are mineralized. Most of these faults are pre-Tertiary in age. The younger set trends north to northwest; its faults displace faults of the older set and offset Tertiary as well as older rocks. In general these faults are not mineralized. Most of the faults illustrated in Figure 3 belong to this second set.

Nearly everywhere the ash-flow sheet is cut by a system of vertical or nearly-vertical joints. The joints vary from clearly defined to indistinct, and from widely to closely spaced; most are from 5 to 15 feet apart. The joints commonly form distinct systems, in which parallel joints extend continuously for several hundred feet to more than a mile. In many places two joint systems intersect each other at angles from 60° to 90°. The continuity of the joints suggests that they are of tectonic origin, and are not simple cooling cracks. However, polygonal cooling joints are found in a few places, mostly in the vitrophyre.

SOURCE

The major source or sources of the ash flows have not yet been identified. Further study in areas west of the Haunted Canyon and Superior quadrangles may ultimately reveal the major eruptive center. However, a small caldera, about 3 miles in diameter, has been recognized in the southwestern part of the Haunted

Canyon quadrangle (Peterson, 1961a); its position is outlined in Figure 1. This caldera was probably the source for part of the deposit. At most, however, it could have supplied about 10 cubic miles of material –only a fraction of the total volume of the sheet (Peterson, 1961a, p. 71-72).

The caldera is a crudely circular structure in which ash flows and underlying rhyolite are downdropped and are surrounded by rocks of Paleozoic and Precambrian age (Peterson, 1960). The relations between the volcanic rocks and the older rocks around the border of the structure are complex and chaotic, and the older rocks are locally intruded by dikes of vitroclastic material similar to that in the ash-flow sheet. Local zones of alteration are common in the ash flows and rhyolite within the caldera. Erosion has removed all traces of any original topographic expression of a collapse feature, but the foregoing evidence is considered sufficient to identify the caldera (Peterson, 1961a, p. 66-72). Similar structures, perhaps larger, may lie farther west. M. F. Sheridan has tentatively recognized caldera-like structures in the western part of the Superstition Mountains (oral communication, 1967), which may provide additional sources for the ash flows.

PETROGRAPHY AND MINERALOGY

The nature, distribution, and appearance of phenocrysts throughout most of the ash-flow sheet are remarkably constant. They are nearly uniformly distributed, and constitute from 35 to 45 per cent of the rock. Plagioclase is the most abundant phenocryst mineral, followed by lesser amounts of quartz, biotite, sanidine, and opaque oxides. Hornblende is present in some specimens and absent in others. Sphene, apatite, and zircon are common accessory minerals, and a few specimens contain a little tourmaline. Over a hundred modal analyses show that the relative proportions of the different phenocryst minerals show a slight but systematic change from the bottom to the top of the sheet. Plagioclase decreases slightly, and quartz and sanidine increase.

The major phenocrysts average between ½ and 1 mm in diameter, but a few are as large as 3 mm. Except for the phenocrysts in pumice fragments, a high proportion of phenocrysts throughout the sheet are broken, and tiny angular crystal fragments are scattered through the matrix.

The plagioclase crystals, constituting from 55 to 80 per cent of all phenocrysts, are generally subhedral, rarely anhedral, and are commonly twinned after one or more twin laws. Most are distinctly zoned, showing either normal or oscillatory-normal patterns. Optical and X-ray diffraction studies of the plagioclase have not shown a unique composition, but they indicate that it lies in the range from oligoclase to andesine and probably has an intermediate structural state.

The ash-flow sheet generally contains only a small number of sanidine phenocrysts, about 1/2 to 5 per cent of the phenocrysts. In the white unit, however, sanidine makes up from 6 to 15 per cent of the phenocrysts. In all units the sanidine is subhedral or euhedral, and some crystals show slight to moderate corrosion and embayment of their borders. Most are untwinned, but a few are twinned on the Carlsbad law. X-ray diffraction study indicates an approximate composition of Or_{85}-Ab_{15}.

Quartz phenocrysts are anhedral and approximately equant, and they generally have deeply embayed borders. Quartz constitutes from 5 to 14 per cent of the phenocrysts in most of the ash-flow sheet, but from 11 to 25 per cent in the white unit. Grains are clear and unaltered, and some contain liquid inclusions. The quartz in most specimens shows slightly undulatory extinction.

In all parts of the sheet biotite makes up from 5 to 13 per cent of the phenocrysts and averages about 8 per cent. Biotite phenocrysts are generally euhedral or subhedral and form tabular books and flakes; many grains are distorted and bent. "Bird's-eye" structure is common, and pleochroism is pronounced with X = yellow, Y = Z = dark brown. Biotite in the lower part of the sheet is fresh, but in the upper part of the brown unit it is slightly altered, and farther upward the alteration becomes progressively more intense. Alteration begins as bleaching at the crystal boundaries and development of small clots of opaque oxides in the bleached areas. The bleaching progresses inward with further alteration, particularly along cleavage planes, and the opaque clots enlarge. Alteration is most intense in the white unit, where biotite is either replaced by chlorite or is completely bleached and accompanied by large concentrations of opaque oxide clots.

HISTORY OF THE ASH-FLOW SHEET

The magma, with a chemical composition of quartz latite, probably originated by selective melting of sialic material at a depth of several kilometers (Peterson, 1961a, p. 113-115). As it migrated upward it cooled, and plagioclase, sanidine, quartz, biotite, and other minerals crystallized. As crystallization continued, gas pressure rose; when about 40 per cent of the magma had crystallized, it found its way explosively to the surface. The properties of the magma–such as temperature, viscosity, and gas content–were such that it erupted as nueés ardentes. Gas escaped with enough violence to disrupt the magma into ash-sized particles, and the explosively vesiculating magma rapidly spread laterally in all directions as a gas-charged avalanche.

Mobility was aided by air engulfed by the incandescent mass; the suddenly heated air expanded violently, speeding the avalanche forward along its path and creating a constant turbulence within it (McTaggart, 1960). Billowing clouds of dust undoubtedly rose to great heights, but the bulk of the material was carried by the basal avalanche.

Successive eruptions rapidly followed one another; each eruption was an individual pulse separated from the next pulse by hours or days, but each successive layer was added before the next underlying layer had cooled appreciably. Each eruptive pulse added from a few tens to several hundred feet of material to the deposit. The erupted material had sufficient energy and mobility to travel distances of as much as 20 miles. The original relief was moderate to steep, perhaps on the order of 1000 feet; the deposits filled in valleys and ultimately covered hills under depths of several hundred feet.

The first material that came to rest on the cool prevolcanic surface was quickly chilled, and the glass particles became rigid enough to resist deformation. This material (the lower nonwelded zone) formed an insulating blanket causing material above it to cool more slowly, so that shards and pumice fragments retained their plasticity long enough to be deformed and flattened by the weight of the overlying material, thereby giving rise to the lower partly welded zone. The vitrophyre represents a layer in which the particles were plastic enough to become greatly flattened and thoroughly welded together, yet were chilled quickly enough to form a glass.

In a thick layer above the vitrophyre the still-plastic particles were deformed by the overlying load and thoroughly welded. Cooling, however, was slower, and the originally glassy constituents devitrified to form the cryptocrystalline, aphanitic groundmass characteristic of the brown unit. Higher in the sheet the overlying load was smaller and the degree of welding gradually decreased, so that some porosity was retained. Escaping gases collected in these pore spaces to promote additional crystallization. The intensity of vapor-phase crystallization increased upward as the degree of welding decreased and became still more intense through the gray unit. Finally the upward-streaming gases permeated all the spaces between particles to cause vapor-phase crystallization through the entire white unit. As crystallization became more complete, the outlines of particles became more diffuse because crystals grew across shard boundaries. Near the top of the sheet the particles were essentially undeformed and nonwelded, but their original outlines were ultimately obliterated by crystallization, owing to long contact with upward-rising hot gases.

The region was either standing high or was uplifted soon after the ash-flow eruptions, for erosion deeply dissected the sheet and locally cut entirely through it. Fluvial deposition followed, and the Gila Conglomerate was deposited in local basins. In some areas air-fall tuffs and lava flows, ranging in composition from basalt to rhyolite, were erupted and locally interfinger with the Gila Conglomerate. Abundant faults cut both the ash-flow sheet and the younger rocks.

Renewed uplift halted deposition of the Gila, erosion continued to dissect the ash-flow sheet and to cut into the younger rocks, and gradually the present-day topography developed.

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WEATHERBY CANYON IGNIMBRITE

By

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The Weatherby Canyon ignimbrite crops out over an area of more than 15 square miles in the Peloncillo Mountains in the area between Cowboy Pass (3 miles south of where Highway 80 crosses the mountains at Granite Gap) and the Southern Pacific Railroad. Tuffs and ignimbrites of rhyolitic and trachytic composition are present, although the rhyolitic rocks greatly predominate. The two types are interbedded in the upper part of the sequence, but the lower part consists only of rhyolite. The ignimbrite is particularly well exposed on 1117 Peak, south of Weatherby Canyon (Figure 1) No measurements of thickness of the sequence, or of individual deposits or members, have been made; but unless there is repetition of beds, at least 3,000 feet of ignimbrite is present on 1117 Peak and the ridges to the west. In this area the rocks dip uniformly to the east at an angle of about 15 degrees for a horizontal distance of 3 miles normal to the strike of the beds, with no apparent break in continuity.

The most prominent and abundant unit of ignimbrite is a light-gray to grayish-pink and rose-red hard compact aphanitic-porphyritic rhyolitic rock containing phenocrysts of quartz, clear sanidine, and a cloudy alkali feldspar in a devitrified matrix of shards, glass shreds, and hematite and magnetite particles. The phenocrysts constitute 15-25 percent of the rock and are mostly 1-2 mm in diameter. Numerous fragments of pumice are included in the ignimbrite, and cavities and vesicles, many of which are wholly or partly filled with quartz and alkali feldspar are abundant. The completely filled cavities are commonly the smaller ones, whereas the larger cavities are mostly lined with the later minerals. Most of the cavities, fillings, and pumiceous inclusions are flattened, lenticular, and elongated parallel to the bedding, and impart a eutaxitic structure of pseudobedding to the rock. Microscopic studies show that the finer fragments of the rock are also flattened and aligned parallel to the bedding, producing a microeutaxitic structure which bends around the phenocrysts, inclusions, fillings, and voids.

Quartz constitutes about 50 percent of the phenocrysts, and occurs as embayed and corroded euhedral crystals which characterize the rock and stand out as round glassy dots or blebs. Most of the remaining phenocrysts are clear square glassy light-gray to pinkish crystals of sanidine, some of which are slightly

Figure 1a

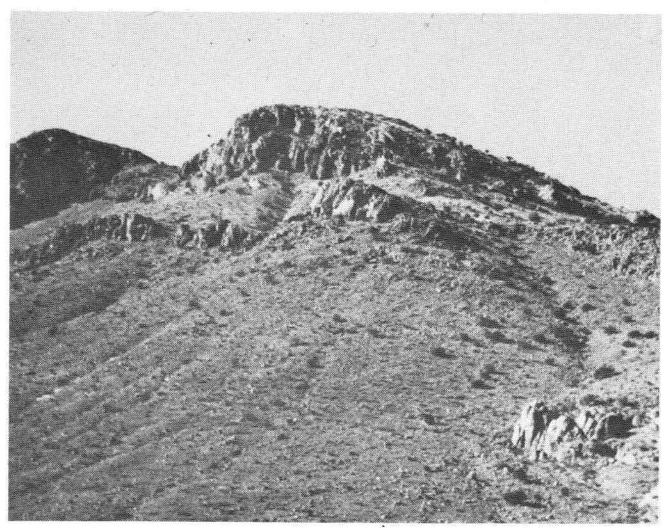

Figure 1b

Weatherby Canyon ignimbrite on the northeast side of 1117 Peak.

embayed. Cloudy alkali feldspar, most of which is almost completely kaolinized, shows in the hand specimen as dull, milky-white crystals, distinct from the glassy sanidine. Biotite is rare, but may be present. Magnetite grains, partly altered to hematite are abundant.

The matrix of the rock, which megascopically is aphanitic or microcrystalline in structure, is resolved microscopically into a groundmass of devitrified and recrystallized shards and glass shreds, with abundant hematite. A eutaxitic structure caused by the parallelism of the flattened and collapsed shards and the hematite streaks is pronounced in many sections, and is particularly well developed between closely spaced phenocrysts, inclusions, or void fillings (Figure 2) The original glassy character of the fragments has been lost, but the form of the shards has been preserved, although they are flattened and distorted because of collapse. Spherulitic and axiolitic structures are present. Westerveld (1943, p. 211; 1947, p. 34) stated that most ignimbrites show a recrystallization of the glassy groundmass, and that the spherulitic and axiolitic structures developed are composed of orthoclase or albite, and tridymite. He hypothesized that rising gases from the still-hot particles at lower levels within the deposit carry silica and alkalies upward, mineralizing the interstices between the glass and mineral particles as well as replacing the glass metasomatically. This is a pneumatolytic process and occurs immediately after emplacement of the deposit. According to this concept the welding of the shards is aided by cementation. In support Westerveld stated that in New Zealand and in eastern California pneumatolytic alteration of the tuffs is more pronounced in the upper layers.

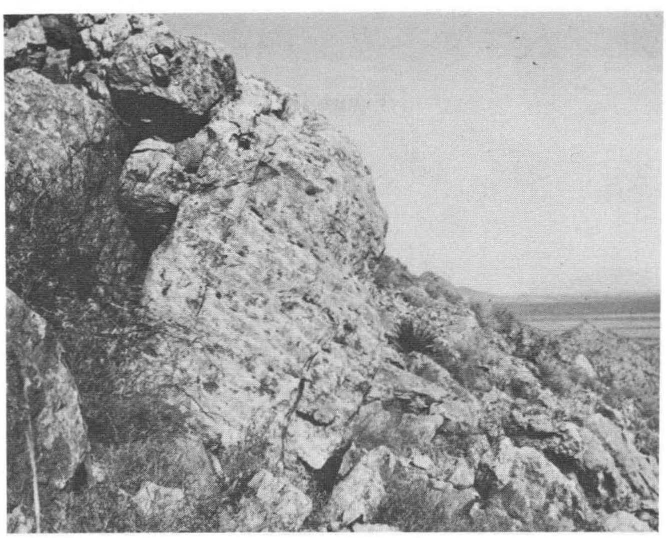

Figure 2 – Eutaxitic structure of the Weatherby Canyon ignimbrite at an exposure on the northeast side of 1117 Peak. The structure is due to elongation and flattening of rock fragments, volcanic ejecta, and voids, because of compaction while the rock was still hot and the fragmental material plastic. Some of the cavities are partly filled with secondary minerals.

In the ignimbrites of the Peloncillo Mountains the minerals composing the spherulites and axiolites are quartz and potassium feldspar. Many of the particles are so fine that the determination of whether they are sanidine or orthoclase was difficult, but some of the larger ones appear to be orthoclase and show evidence of alteration to kaolinite. No tridymite was identified.

In those rocks in which the eutaxitic structure is well developed, the shards are flattened and deformed and have molded themselves one to the other, and streaks of hematite are aligned parallel to the shards. In some rocks, however, only traces of a eutaxitic structure are present. The shards are collapsed and flattened, but they are not aligned; hematite and magnetite grains are scattered throughout the matrix and do not appear to be abundant. Spherulites and axiolites are not prominently developed, and the matrix is microgranular. Megascopically these rocks are not so compact as those with the microeutaxitic structure. Although they contain fewer voids and cavity fillings, they do not exhibit megaeutaxitic structure.

Enlow (1955, p. 1231) stated that in the Chiricahua Mountains some of the members of the Rhyolite Canyon formation show a progressive orientation and flattening of fragments and of vitric material from top to bottom of the beds. With an increase of pressure caused by the greater overburden, loose vitric material is compacted and welded together; the shards and glass shreds are flattened and molded one to the other and around phenocrysts and included fragments; and the iron oxide dust, originally scattered uniformly throughout the mass, is concentrated as the mass collapses with an increase of pigment per unit volume. The iron oxide aligns itself parallel to the shards and produces the typical eutaxitic structure. Gilbert (1938, p. 183) also states that the lower parts of the deposits show a more pronounced orientation of fragments and also more vitrification.

A very informative exposure is present in a gulch on the eastern side of the ridge about a mile south of Cowboy Pass in the NW¼ sec. 18, T. 26 S., R. 21 W. Hard, compact rhyolite ignimbrite showing eutaxitic structure grades upward into a less coherent porous ashy-gray tuff containing pumice fragments, lapilli, and a few quartz and sanidine crystals. The tuff shows no eutaxitic structure. The matrix of the tuff is an extremely fine-grained microgranular mixture of what is probably quartz and feldspar, but no definite determinations of the minerals could be made because of the small size of the individual particles. No indications of welding are present, and any shards or glass shreds that may have once been present have been completely destroyed, and no trace is left of their former presence. The matrix is the result of complete recrystallization and devitrification of a very fine deposit of volcanic ash and dust. It was not subjected to compaction as was the underlying material and so shows no eutaxitic structure. Undoubtedly the ashy-gray nonwelded porous tuff is merely the uppermost part of the deposit produced by the nuee ardente. Overlying the porous tuff with a very sharp contact is hard compact trachyte ignimbrite representing a distinctly separate nuee ardente eruption.

On the eastern side of 1117 Peak, and extending northward almost to Cowboy Pass, is a band of trachyte ignimbrite. In general the rock is redder than the rhyolite ignimbrite; it exhibits various shades of red, reddish-gray, and reddish-brown. Phenocrysts are mostly orthoclase and sanidine, but a few flakes of biotite are present. Quartz is rare or absent, in contrast to its abundance in the rhyolite ignimbrite. The phenocrysts are smaller and less abundant, and less prominent than in the rhyolite ignimbrite, but lithic fragments are more prominent. Pumiceous fragments and hollow lapilli are common. In most exposures cavities and cavity fillings are less frequent, and the rock is less porous than the rhyolite. .Elsewhere cavities are abundant, but they are not flattened nor elongated as much as in the rhyolite. In places the feldspar phenocrysts are indistinctly aligned parallel to the bedding. Megascopically the eutaxitic structure is not very prominent, but microscopically the collapsed shards and glass shreds are parallel in alignment, although hematite is scattered throughout the matrix rather than concentrated in streaks.

The trachyte ignimbrite appears to lie both above and below beds of rhyolite ignimbrite. A fault may form its eastern boundary, however, and thus it may represent the basal part rather than an intermediate part of the rhyolite ignimbrite sequence.

Smaller and less continuous exposures of trachyte ignimbrite are present near the head of Weatherby Canyon and also east of the main zone of trachyte ignimbrite described above. Actual contacts with the rhyolite ignimbrite could not be observed, and whether these boundaries are normal depositional contacts or fault contacts is not known. The former are inferred. This inference necessitates depositing an interbedding of rhyolite and trachyte ignimbrite and tuff, and might occur if the different rock types originated from separate vents, or if there were an alternation in mineral composition of the pyroclastic ejecta from a single parent magma. It might also occur if a number of vents had existed in the area during the eruption of the pyroclastic material, and each, during its initial or during its final stages of eruption, ejected trachytic material. Rhyolite material was ejected during the remainder of its period of activity. The various vents became active or dormant at different times over a long period. The bodies of trachyte rock would thus be interbedded with rhyolitic material from other vents, and this process might readily account for the lenslike shape of the trachytic rocks. This hypothesis offers an explanation of the distribution in time and space of these two rock types.

A fourth possibility is that the actual chemical composition of the trachyte and the rhyolite are identical or nearly so. Excess silica appearing as quartz in the rhyolite may be locked up in the glassy material in the trachyte. Different physical conditions of eruptions may have governed the type of rock produced. No chemical analyses of the rocks were made.

Lying above the trachyte ignimbrite on the east and south sides of 1117 Peak, and also on the eastern side of the ridge north of Weatherby Canyon is a well-bedded fine-grained light-gray to white crystal tuff. Embayed and corroded subhedral crystals of quartz and sanidine constitute about 60-70 percent of the rock. Magnetite altered to hematite is common, and a few euhedral crystals of green hornblende and of brown biotite are present. The microcrystalline matrix is a brown clay, possibly limonite stained montmorillonite resulting from the alteration of the original volcanic ash. A few angular fragments of foreign material are present. The rock is porous and semifriable in contrast to the hard compact ignimbrites. The mineral composition of the tuff is so distinct from the underlying trachyte that the tuff is believed to be unrelated to this rock and to represent a separate ash fall, perhaps related to rhyolite ignimbrite deposited at the same time elsewhere in the area. No gradation between the trachyte ignimbrite and the tuff was observed.

Near the head of Weatherby Canyon occurs a less granular and more tuffaceous-appearing rock which contains considerable fragmental material, including pumice, lapilli, and foreign rock fragments. Most of the crystals are sanidine and quartz, but kaolinized alkali feldspar is common and a few biotite flakes occur. This rock is intermediate in porosity and compactness between the tuff described above and the rhyolite ignimbrites. Microscopic examination shows it to be partly welded and recrystallized with replacement of much of the glass by quartz and orthoclase. An indistinct eutaxitic structure is present. The tuff at this locality is 30-50 feet thick, exhibits excellent bedding, and crops out immediately below trachyte ignimbrite. It is undoubtedly the upper part of a deposit of rhyolite ignimbrite.

Many of the features described by Enlow (1955) as characteristic of some of the members of the Rhyolite Canyon formation in the Chiricahua Mountains, 20 miles west and across the gravel-filled San Simon Valley from the exposures of ignimbrite in the Peloncillo Mountains, can be duplicated in the Weatherby Canyon Ignimbrite. Differences, of course, are present. A greater thickness of deposits appears to be present in the Peloncillo Mountains, and no trachyte is recorded by Enlow. The major features, however, warrant a correlation between the Rhyolite Canyon formation and the Weatherby Canyon Ignimbrite, and they are undoubtedly closely related in time, genesis, and method of formation. A late Tertiary age is postulated.

The Weatherby Canyon Ignimbrite may also correspond closely in origin and time of formation to the dominantly tuffaceous and pyroclastic Steins Mountain quartz latite porphyry north of Steins, or perhaps to the earlier Quarry Peak rhyolite, also largely fragmented in composition. Both of these formations reflect deposition of tuffaceous material from explosive igneous activity of a dominantly acidic magma, with the production of abundant ash, breccia fragments, glass shareds, shards, and other pyroclastic debris. Apparently, violent volcanic eruptions of dominantly rhyolitic magmas dominated geologic events in this and nearby areas in the latter part of the Tertiary.

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VOLCANIC GEOLOGY ALONG THE WESTERN PART OF THE APACHE TRAIL, ARIZONA

By

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The field trip route along the Apache Trail to Canyon Lake penetrates the western margin of a large volcanic field which extends eastward from the Goldfield Mountains to Globe, Arizona. (Fig. 1) This area includes approximately 450 square miles of predominantly silicic pyroclastic rock exposure. In the Goldfield and Superstition Mountains there is a wide range in rock composition from basalt and andesite to dacite and rhyolite. Although ash-flow tuffs make up a large percentage of the volume, lavas and epiclastic volcanic breccias constitute about 50 percent of the total. No specific volcanic centers have previously been demonstrated for this area. However, field evidence now suggests that volcano-tectonic subsidence is closely tied in with the evolution of these rocks.

Two moderate-sized calderas located within a central graben are the source for the most recent lavas and ash-flow tuffs in the vicinity of the Apache Trail: (1) the Black Mesa caldera, a 7 by 5 mile structure north of First Water Ranch on the east side of the highway, and (2) the Willow Springs caldera, a 4 by 3 mile structure northwest of Government Wells on the west side of the highway. Topography, structural motif, and distribution of rock units permit the region surrounding these calderas to be divided into three significant zones: (1) volcanic plateau, (2) collapse collar, and (3) caldera core.

The volcanic plateau is generally at a higher eleva- than the collapse collar, which in turn occupies a higher position than the caldera core. For example, the Superstition Mountains at 5,000 feet form the volcanic plateau for the Black Mesa caldera. The collapse collar is at 3,000 to 3,500 feet and the caldera core is at 2,000 to 2,500 feet. The original topographic relief is partially modified within the Willow Springs caldera by the resurgence of the caldera core and protrusion of post-collapse marginal domes.

A basic structural motif is well displayed by both calderas. The volcanic plateau is relatively flat-lying and unfaulted as in the Superstition front. The collapse collar, on the other hand, is broken by many faults and the bedding dips from 30° to 60°. The faults generally strike to the northwest, but some are peripheral to the caldera. Domes and dikes protrude along faults in this zone. The central core is only weakly faulted and the dips are nearly horizontal.

Distribution of rock units is also consistent with the caldera pattern. Ash-flow tuffs predominate in the volcanic plateau and extend the greatest distance from the caldera centers. The ash flows thicken and increase in number as they approach the collapse collar. Glassy dikes and rhyolite domes are notable features of the collar zone. Most dikes parallel caldera margin fractures. Epiclastic volcanic breccia in the collar dips inward and thickens toward the caldera center. Particle size and dips in the breccia decrease inward from the rim. The caldera core is covered with flat-lying breccia overlain by a thin capping of basalt.

Rock units show a wide range in composition and mode of emplacement. Table 1 gives the stratigraphic sequence of rocks and relates each unit to the stage of caldera development. From the distribution of the rocks and their structural relationships a volcanic history of the area may be constructed.

Prior to volcanism a gentle northeast dipping erosion surface existed on the granite basement. A violent pryoclastic eruption to the east provided ash for the older epiclastic breccia which filled a northwest trending trough north of the Goldfield Mountain front. The main graben faulting was followed by the outpouring of basalt which was overlapped by andesite lavas and breccias along the southern margin of the graben. Rhyolite ash flows and lavas were erupted from vents along the caldera margins due to the local insurgence of magma into the graben zone. Two calderas collapsed in stages following rhyolite ash extrusion. Each ash eruption stage was followed by the extrusion of a glassy rhyolite lava suggesting a resurgence of magma after each collapse. That the caldera core was a topographic low after final ash-flow eruption is attested to by the later infilling of the calderas with epiclastic volcanic breccia composed of rhyolite lava and ash particles as well as andesite boulders. A final resurgence uplifted the central core, introduced marginal ring dikes, and emplaced rhyolite domes on the caldera margin in the collapse collar. The central cores were then flooded with a thin capping of basalt, bringing the cycle to an end (Figure 2).

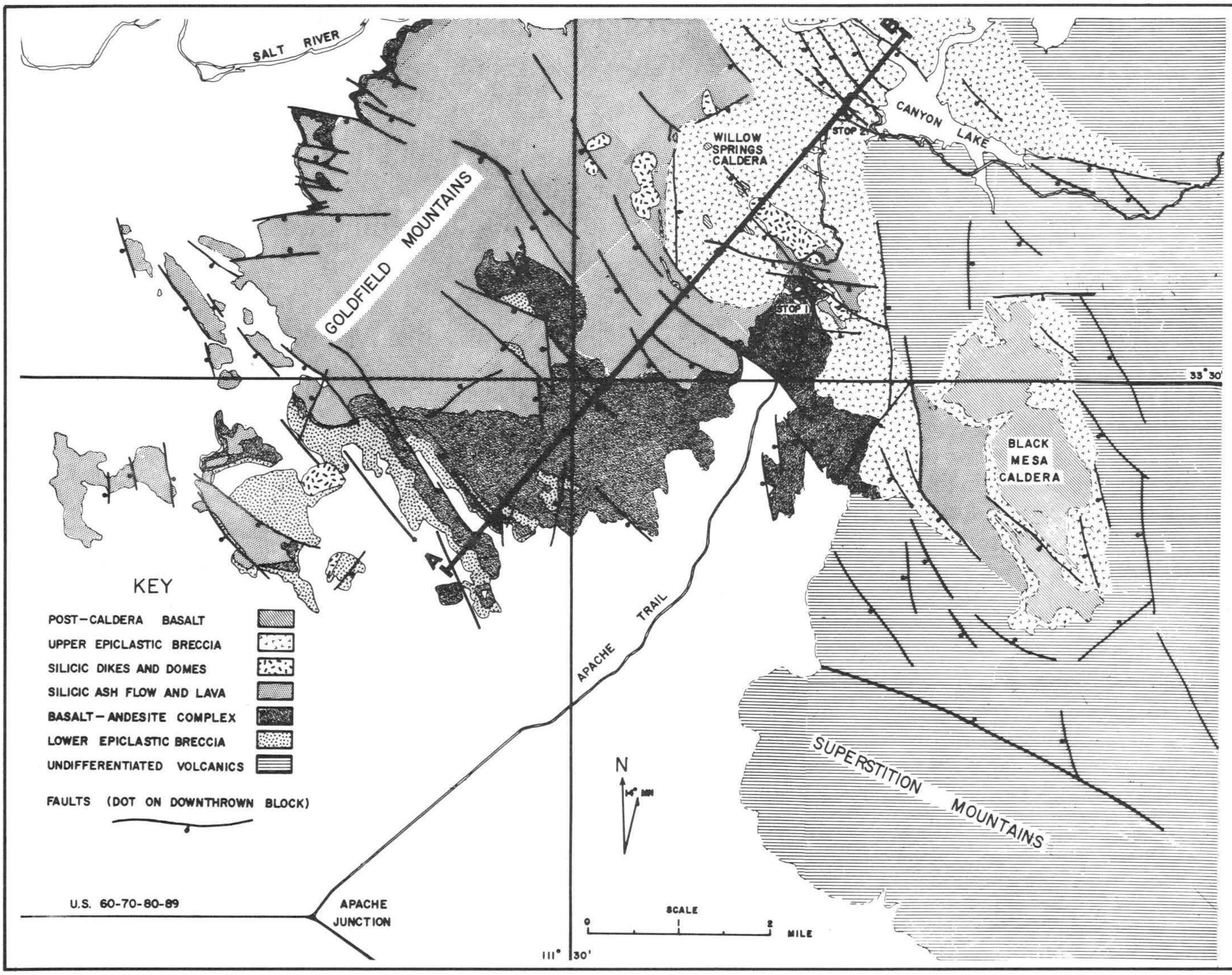

Figure 1 – Surficial geology of a portion of the Goldfield and Superstition Mountains

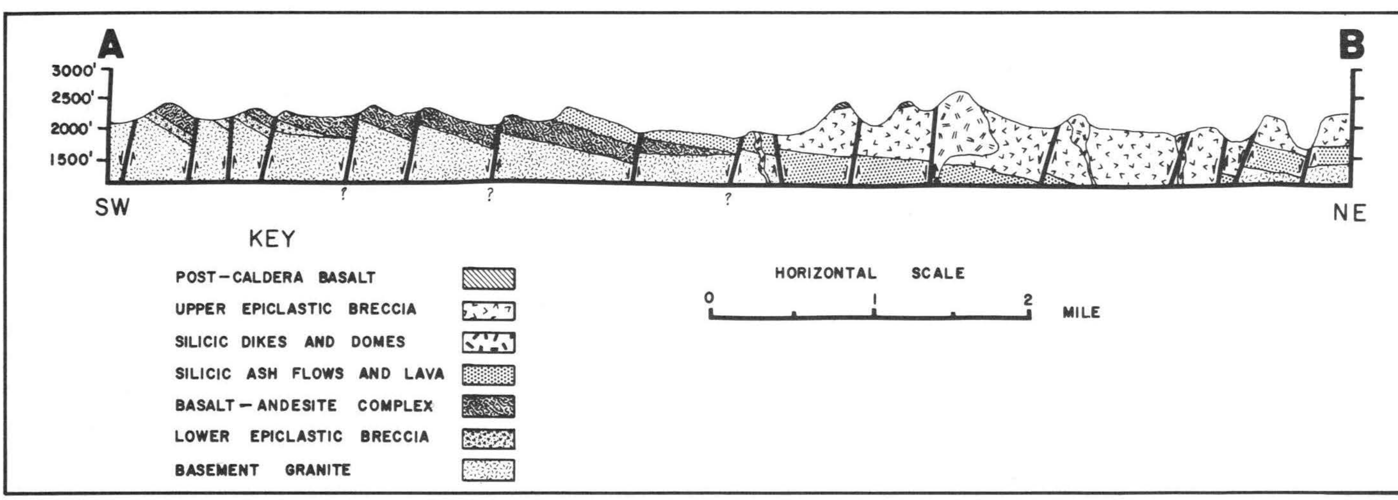

Figure 2 – Cross Section A–B Showing the Willow Springs Caldera

Table 1 – Rock Units in the Goldfield Mountains

UNIT	LITHOLOGY	STRUCTURAL ZONE	ERUPTIVE CYCLE
Late lavas	thin porphyritic basalts	caldera core	post resurgent dome, central core capping
Marginal dikes and domes	glassy dikes, lithoidal domes; mainly rhyolite, some dacite	collapse collar	weak resurgence of central dome
Epiclastic tuff and breccia	volcanic pebbles and boulders in an ash matrix; mudflows and waterlaid tuff	collapse collar and central core	post collapse, caldera filling
Ashflow tuff and lava complex	non-welded rhyolite tuff, glassy rhyolite lava, less than 10% phenocrysts	volcanic plateau, collapse collar, and central core	pre-collapse, insurgence of rhyolite magma
Older basic complex	basalt lavas, andesite lavas and breccias, 30% phenocrysts	southern margin of graben zone	pre-insurgence of rhyolite magma, postgraben faulting
Older epiclastic volcanic breccia	granitic pebbles and boulders in volcanic ash matrix	related to pre-graben topography	related to an older pyroclastic cycle

TERMINOLOGY AND DISTRIBUTION OF ASH FLOWS OF THE MOGOLLON – SILVER CITY – LORDSBURG REGION NEW MEXICO[1]

By

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University of New Mexico

INTRODUCTION

The New Mexico part of Field Trip No. 1 of the 1968 meeting of the Cordilleran Section, Geological Society of America, will traverse at least three distinct ash-flow provinces: (1) The western part of the Mogollon Plateau, seen late on the first day and on the morning of the second day in the Mogollon and Pinos Altos Mountains and around the Gila Cliff Dwellings National Monument, Stops 9-14; (2) the Mimbres province, seen on the afternoon of the second day, Stops 15-18, and (3) the southwestern corner of New Mexico, seen on the morning of the third day, Stop 19 (Fig. 1).

All three provinces have been studied in piecemeal fashion, resulting in confused terminology and correlation. This article will attempt to clarify old stratigraphic terms, define new ones not previously published, and suggest correlations. It is a progress report and an expression of one man's opinions. The only point on which all workers agree is that a great deal more needs to be done.

In preparing this summary, I have benefitted greatly from discussion with my co-workers, especially Dr. Peter J. Coney, Middlebury College, and Mr. Rodney C. Rhodes, University of New Mexico. They have permitted me to draw freely from their field observations, but I take sole responsibility for interpretations.

HISTORICAL BACKGROUND

G. K. Gilbert (1875) first described the great quantities of rhyolites among the Tertiary volcanic rocks of southeastern Arizona and southwestern New Mexico, and Lindgren (*in* Lindgren, Graton and Gordon, 1910) first recognized a prevailing sequence of andesite-rhyolite-basalt. He explained it by invoking fractionation of andesite magma into rhyolitic and basaltic fractions by liquid immiscibility, a process popular in his native Sweden in pre-Bowen days. Andesites tend to fill deep basins between major Laramide porphyry centers such as Morenci and Santa Rita. Because the pioneer geologists were mainly concerned with mining camps they failed to see the thickest andesite sections, leading to the myth of a bimodal rhyolite-basalt province that has lingered into our day.

Most of the older geologists regarded Tertiary volcanic rocks as overburden of Laramide metal deposits and wall rock of Tertiary ones. None were volcanologists and none recognized ash flows, although some, like Paige (1933) wondered how supposedly viscous rhyolite "lavas" could travel tens of miles down gradients of less than 100 feet per mile.

In 1950 the New Mexico Bureau of Mines and Mineral Resources began a systematic program of detailed mapping of selected areas of volcanic rocks and reconnaissance mapping of wider area. This work involved not only permanent members of its staff but graduate students and their professors. The then Director of the Bureau, Eugene Callaghan, had previously become familiar with "welded tuffs," as ash-flow tuffs were generally called between the publication of Iddings (1899) and Smith (1960), in the Great Basin. He introduced a great many geologists (myself included) to their existence and problems. His own concepts were summarized in 1953. Simultaneously with work by members of the State Bureau of Mines, the U.S. Geological Survey undertook detailed geologic mapping in the Santa Rita – Silver City mining area under the late Robert M. Hernon and William R. Jones. After a promising start, most of this work, both state and federal, was not completed and had ceased by the late 1950's. My current program began in 1964 and is oriented

1. Research supported by NASA grant NGR-32-004-011.

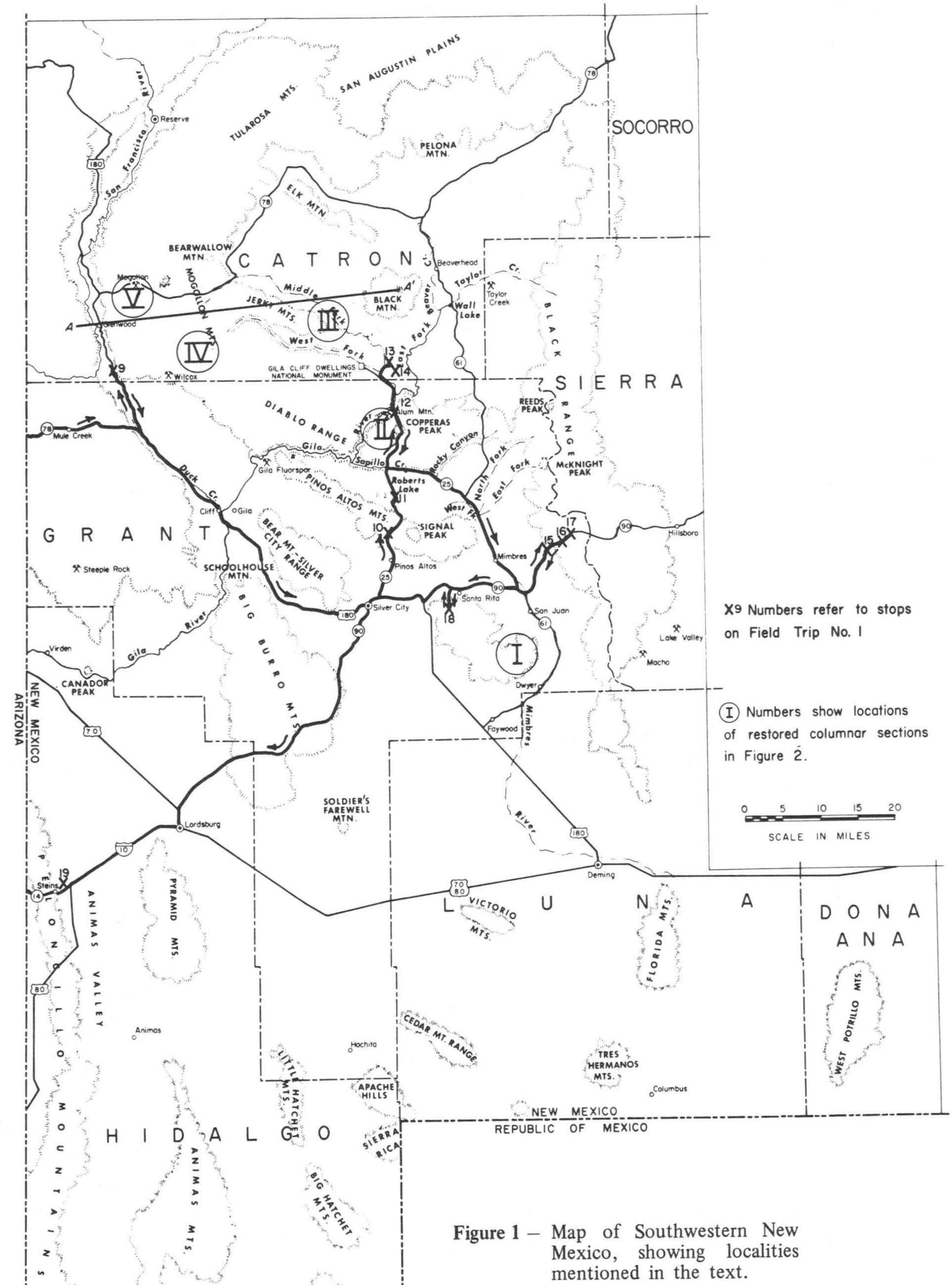

Figure 1 – Map of Southwestern New Mexico, showing localities mentioned in the text.

toward the role of large-scale volcanism in the evolution of crusts of this and other planetary bodies. Its purpose has been explained elsewhere (Elston, 1964, 1965).

The Mogollon Plateau and Mimbres Provinces

Work prior to 1960 is summarized on the Geologic Map of New Mexico (Dane and Bachman, 1965). The discussion which follows relates to symbols on this map, because it is the basic reference work which most geologists would use. Eight volcanic rock units are shown in the Mogollon Plateau and Mimbres Provinces, and all can be seriously questioned. This criticism is not directed against the persons who compiled the map, but against the circumstances under which it was done. Actual field work was either detailed mapping by graduate students, who commonly lacked the necessary experience, or reconnaissance mapping by professionals who had insufficient time to cover the vast and difficult terrain assigned to them. As a participant in both programs, I can attest to the shortcoming of the material handed to the compilers, who were themselves unfamiliar with the region.

Another factor was the lack of K-Ar dates; long-range correlations were largely a matter of guesswork. In general, the compilers correlated rock types, keeping close to the well-known sequence of andesite-rhyolite-basalt. Exceptions were recognized but could not be evaluated. As a result the map units are compromises, rationalized on the explanation sheet by disclaimers.

The first K-Ar dates from southwestern New Mexico were published in 1964 (Weber and Bassett, 1964, Burke and others, 1964). Thirteen additional dates, obtained during the past two years at the Geochronology Laboratory, University of Arizona, are so important that it will take an entire article to explain them (Bikerman, Damon, and Elston, in preparation). However, the raw data were made available by Damon and others (1966) and are used here.

The symbols used on the Geologic Map of New Mexico (Dane and Bachman, 1965) for the Mogollon Plateau and Mimbres Provinces are, in order of age:

(1) Kv: This symbol is correctly applied to Cretaceous andesite breccias around Pinos Altos, which are intruded by mineralized porphyries of Laramide age, confirmed by a K-Ar date (McDowell, 1966). Southeast of Morenci, Arizona, boulders of andesite and dacite in sediments containing plant fossils of latest Cretaceous age (Erling Dorf, personal communication, Pradhan and Singh, 1960) shows that the assignment of Cretaceous age to a broad belt of apparently older volcanics is not without grounds. However, a K-Ar age of 34.7 ± 1.0 m.y. was obtained from this region (Damon and others, 1966). It is not yet known whether the discrepancy is due to a mid-Tertiary period of hydrothermal alteration associated with mineralization in the Steeple Rock mining district or, more likely, to an error in reconnaissance mapping by Elston (1960). The rocks in question contain only a few thin ash flows.

(2) Ta: This symbol is locally used for Tertiary "andesite, basalt, and latite flows and pyroclastic rocks." The intention seems to have been to separate the andesites below thick rhyolitic sections, known since the days of Lindgren. Unfortunately, the map explanation goes on to state that "the unit includes the Rubio Peak Formation of Hernon and others (1953) and generally equivalent beds." Now, in its type area, the Rubio Peak Formation intertongues with the overlying Sugarlump Rhyolite Tuff (Fig. 2, column I), assigned to the Datil Formation by Dane and Bachman (1965). It is therefore not clear how rocks designated as Ta should be distinguished from the andesite and latite facies of the Datil Formation (Tdl and Tda of Dane and Bachman (1965).[1] Further, some rocks designated as Ta and, especially, Tdl may well be Cretaceous, but evidence is lacking.

(3) Td – Datil Formation. Since the bulk of known ash flows are designated as part of the Datil Formation, this term requires special consideration. The term itself is unfortunate because it refers to the Datil Mountains, in Socorro County, but the type section of 1,824 feet of sediments and volcanics measured by Winchester (1920) is 30 miles to the east, in the Bear Mountains (about 30 miles northeast of the northeast corner of Figure 1). Since then, the type section has been redefined three times: By Wilpolt and others (1946), who removed the basal 685 feet of sedimentary rocks, mainly reddish sandstone, and placed them in a separate formation, the Baca; by Tonking (1957), who extended the Datil upward to include additional units, especially rhyolite ash flows, but also a capping basalt; and by Willard (1959) who removed the basalt. A full account of these transactions is given by Weber (1964). Willard and others (1961) extended the term Datil southward from the type locality for 100 miles, to the Pinos Altos Mountains. Dane and Bachman (1965) extended it southward another 40 miles, to just north of

1. Author's personal note: I originally named the Rubio Peak Formation and mapped its type locality (Elston, 1953). The subsequent history of the name is explained in a generous footnote in Hernon and others (1964).

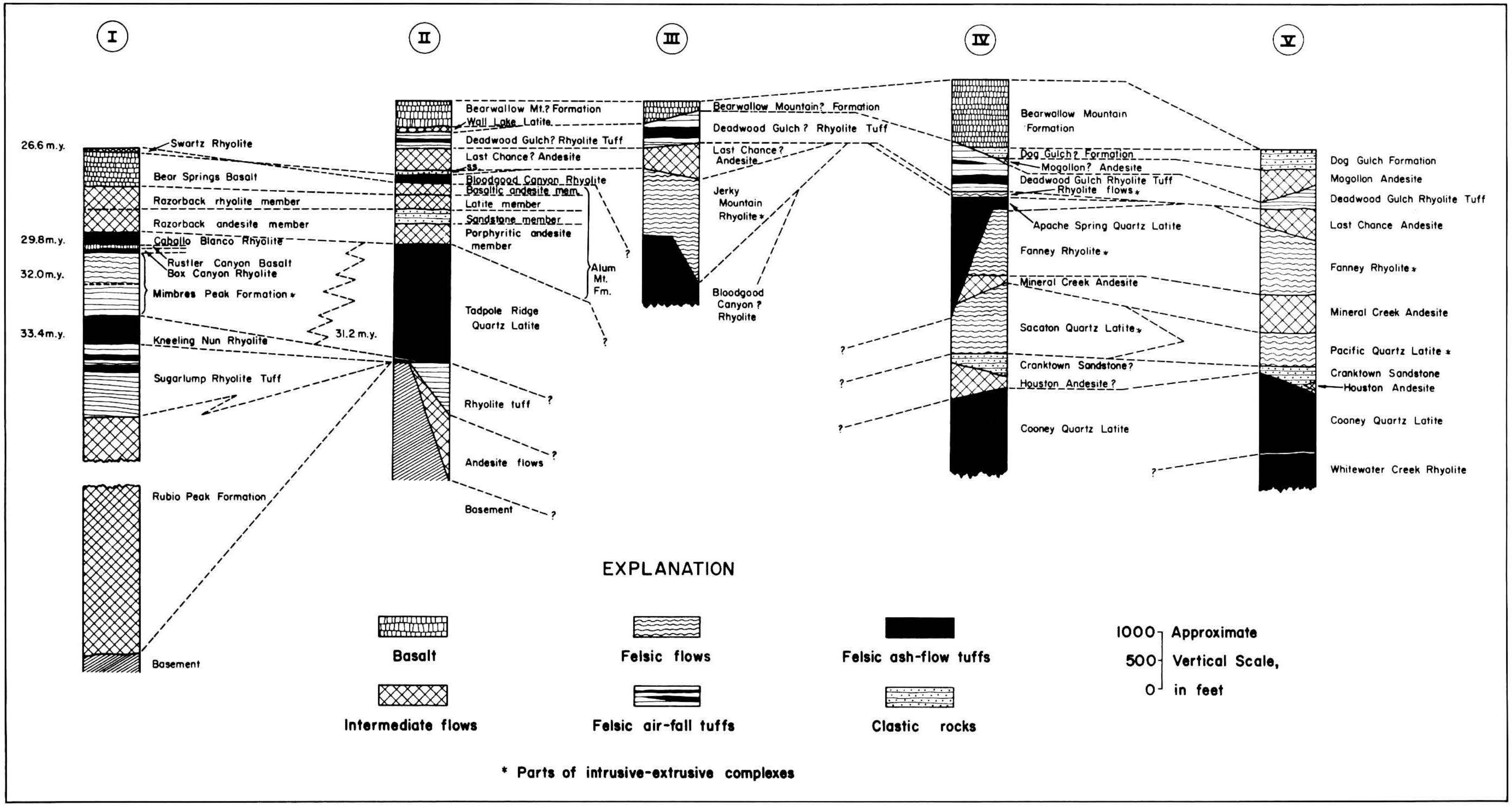

Figure 2 – Tentative correlation chart of Tertiary volcanic rocks of Mogollon Plateau and Mimbres Provinces, New Mexico. Section I is in Mimbres Province, Sections II to V are in Mogollon Plateau Province. See Figure 1 for locations. Sources of data: Section I – Elston (1957); Section II – W.E. Elston, unpublished field work; Section III – P.J. Coney and W.E. Elston, unpublished field work; Section IV – R.C. Rhodes, unpublished field work; Section V – Ferguson (1927).

Deming. It has also been carried eastward across the Rio Grande and westward to the Arizona line.

The intention of the compilers is clear: The term Datil Formation was to designate the rhyolites and quartz latites, characterized by thick ash-flow cooling units, that separated older andesite from younger basalt. It was generally believed that the rhyolitic rocks were roughly contemporaneous and probably Miocene. The age was based on flimsy structural and paleontological evidence: The Datil is profoundly unconformable with rocks deformed during the Laramide orogeny, yet it is cut by Basin-and-Range faults. No identifiable fossils have yet been extracted from the Datil, but the jaw bone of a *Brontotherium* found in gravels associated with possibly pre-Datil andesite in the northern Black Range was tentatively dated as Oligocene by J. F. Lance (personal communication). Unfortunately, the discoverer, Mr. Charles B. Hutchins, died shortly after his discovery, and the site of his find cannot be located. The specimen is at the University of New Mexico. A lower limit was determined by post-Datil fossil conifers in the Black Range near Kingston, said to be early Miocene to early Pliocene (Kuellmer, 1954, p. 29).

Like everybody else, I used the term Datil for the major ash flows and associated rocks in 1964 and 1965. By that time, K-Ar dates had shown the bulk of the Datil to be Oligocene. Field work on the Mogollon Plateau had revealed stratigraphic complexities and I concurred in a suggestion by R. H. Weber to raise the Datil from formation to group status (Elston, 1965, p. 170-171).

Since 1965, additional field work and new K-Ar dates have thrown an entirely new light on the Datil. It represents not one but at least three cycles of rhyolitic eruptions. The age of the type section was bracketed between approximately 38 and 29 m.y., well within the Oligocene. Rocks of about the same age range will be referred to as *Datil (restricted sense)* in the rest of this article. Rocks that are clearly younger, or which have not yet been dated, will be referred to as *Datil (broad sense).*

Recent K-Ar dates have shown that the ash flows of the Mimbres province (Figure 2, column I) are Datil (restricted sense) in age. On the other hand, great sections from the interior of the Mogollon Plateau province (Figure 2, sections III, IV, and V) are distinctly younger.

Within the Datil (restricted sense) several distinct ash-flow provinces can be recognized, presumably from different sources. In the Mimbres province (Figure 2, column I), the Kneeling Nun Quartz Latite has its source in a megabreccia zone on the west flank of the Black Range, described in the road log of Field Trip No. 1 for the afternoon of the second day. Its age was determined by McDowell (personal communication). The Caballo Blanco Rhyolite also thickens toward the Black Range, but its source is unknown. It can be traced southwestward for 50 miles, to the Knight Peak graben separating the Gold Hills from the Big Burro Mountains (Figure 1). Both are differentiated compound cooling units that become more calcic and less quartzose toward the top. North of Santa Rita, a north-trending Laramide structural high that controls (or is caused by) the mineralized Santa Rita and Hanover-Fierro stocks existed as a physical topographic barrier in Oligocene time. The Kneeling Nun and Caballo Blanco Formations butt up against it and abruptly pinch out; west of the high an entirely different section takes their place. This is the Tadpole Ridge Formation (new name), roughly contemporaneous with the Kneeling Nun – Caballo Blanco section (Figure 2, column II). Its name is derived from Tadpole Ridge on the western end of the Pinos Altos Mountains; its source is unknown, and what little is known about its lithology is described in the road log of Field Trip No. 1, Stop 10. Farther north, ash flows of great thickness but unknown source or age occur along the western foot of the Mogollon Mountains. The best-known section consists of the Whitewater Creek Rhyolite and Cooney Quartz Latite, at least 2,000 feet thick, of the Mogollon mining district (Ferguson, 1927). Attempts at K-Ar dating have failed so far, because of regional chloritization. They may well be Datil (restricted sense), but this cannot be proved at present. Farther north yet, the older of two rhyolite ash-flow sequences mapped within the Datil (broad sense) at the western end of the San Augustin Plains by Stearns (1962) and shown on his map as $Tdrp_1$ probably ties in with the Datil (restricted sense).

In Figure 2, section I is locally capped by a thin rhyolite flow breccia, the Swartz Rhyolite. K-Ar dating has shown that this insignificant unit is roughly equivalent in age to massive ash flows originating in local cauldrons within the Mogollon Plateau. They are the Apache Spring Quartz Latite (new name), and Bloodgood Canyon Rhyolite (new name). Stratigraphic relationships and ages are shown in Figure 2, structural relationships in Figure 3.

The Apache Spring Quartz Latite is a massive cooling unit, at least 2500 feet thick within its source, the Bursum cauldron (new name, after Bursum road, New Mexico Highway 78), currently being studied by R. C. Rhodes. The cauldron is 12-15 miles in diameter; the Apache Spring Quartz Latite is largely confined to the cauldron and is differentiated, becoming more mafic toward the top. Outliers of

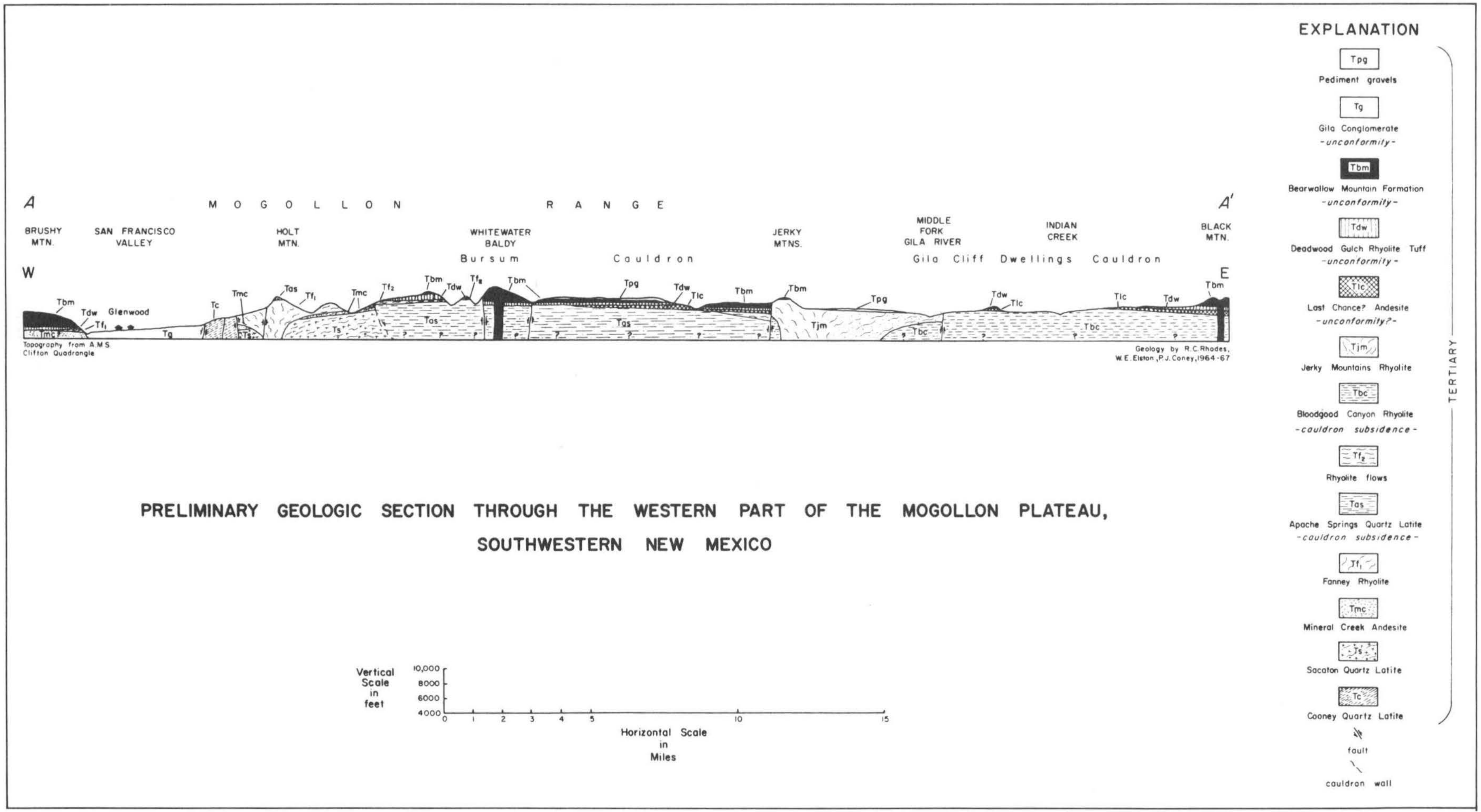

Figure 3 – Geologic section across western part of Mogollon Plateau province, along line AA', Figure 1.

Apache Spring locally crop out on the western crest of the Mogollon Range and form the basal part of the upper of the two ash-flow units mapped by Stearns (1962) to the north and designated $Tdrp_2$. In an earlier publication (Elston, 1965), written before K-Ar dates had become available, I incorrectly correlated the Apache Spring Quartz Latite with the Kneeling Nun and Tadpole Ridge Quartz Latites, referring to them collectively as "biotite-rich two-feldspar rhyolites and quartz latites." The name Apache Spring is derived from a locality in sec. 36, T. 11 S., R. 18 W.

The new term *Bloodgood Canyon Rhyolite* replaces the term *Moonstone Tuff* coined by Wargo (1959), and used by Elston (1965) and Elston and Coney (1967). The unit is at least 2,000 feet thick in its poorly delineated source cauldron, of which the Diablo Range and Jerky Mountains seem to form the western rim. The canyon for which it is named is a tributary of Little Creek, and drains the northeastern flank of the Diablo Range in secs. 5 and 6, T. 13 S., R. 14 W. Gila Cliff Dwellings National Monument is near the edge of the suspected source cauldron, which is hereby called the Gila Cliff Dwellings cauldron (new name). The relatively unwelded top of the Bloodgood Canyon Rhyolite is exposed in the parking area on the east side of the Gila River, near the Cliff Dwelling.

The Bloodgood Canyon Rhyolite is a massive ash-flow compound cooling unit characterized by conspicuous phenocrysts of rounded quartz and sanidine cryptoperthite ("moonstone"). Biotite is scarce and plagioclase absent. Pumice fragments, nearly spherical in shape, are conspicuous at the top and grade into flattened and somewhat elongated streaks near the base. In this respect, the Bloodgood Canyon Rhyolite resembles the Superior Dacite, seen on the first day of Field Trip No. 1.

Unlike the Apache Spring Quartz Latite, the Bloodgood Canyon Rhyolite spilled copiously out of its source cauldron. To the southwest, its distal edge has been located in the Pinos Altos and Silver City ranges, in the northern end of the Big Burro Mountains, and west of Cliff. To the north, its ultimate extent is unknown, but it forms the upper part of the $Tdrp_2$ unit of Stearns (1962). To the northwest, it forms cliffs several hundred feet high around Reserve, where it clearly breaks down into several individual ash-flow units. West of Reserve, rocks resembling Bloodgood Canyon Rhyolite occur in the Blue Mountain Primitive Area (P. E. Damon and J. C. Ratte, personal communication). Thus the entire sheet seems to have a minimum diameter of 85 miles, with the northern end yet to be discovered. However, there are unresolved problems in tracing its extent to the east, and in slightly conflicting age dates from widely separated localities (26.3±0.8 and 23.2±0.7 m.y., Bikerman, Damon, and Elston, in preparation). It is therefore not yet clear whether all rocks tentatively included in the formation did, in fact, originate from a common source and in a single eruptive cycle spanning several million years.

Wherever the margins of the Bursum and Gila Cliff Dwelling cauldrons were seen, the outcrops of the contained ash-flow tuff end abruptly, usually in fault contacts against great elongated protrusive domes of quartz latite or flow-banded rhyolite. The Apache Spring Quartz Latite abuts against the Sacaton Quartz Latite (new term, in part equivalent to the Pacific Quartz Latite of Ferguson, 1927, type locality Sacaton Mountain in Wilcox Mining District) Locally, outliers of Apache Spring lie on the post-Sacaton Fanney Rhyolite of Ferguson (1927) (Fig. 3). In many places an unnamed Fanney-like rhyolite overlies the Apache Spring.

In the Middle Fork of the Gila River, west of Black Mountain, Bloodgood Canyon Rhyolite plunges beneath a single-feldspar flow-banded rhyolite, the Jerky Mountains Rhyolite (new name, after the Jerky Mountains which are largely made up of this formation). In the Diablo Range the flow-banded rhyolite bordering the Gila Cliff Dwelling cauldron may be post-Bloodgood Canyon, but this is still uncertain because no unfaulted contact has yet been found.

Only the western margins of the Bursum and Gila Cliff Dwellings cauldrons are known. Eastward, the contained ash flows (Apache Spring and Bloodgood Canyon, respectively) dip underneath younger rocks in the inner basin of the larger Mogollon Plateau volcano-tectonic structure (see discussion by R. C. Rhodes at Stop No. 5, Field Trip No. 1, and preceding notations in road log). Masses of flow-banded rhyolite, resembling the Fanney and Jerky Mountain formation, are known from Elk Mountain, the country east and west of Pelona Mountain, and the western flank of the Black Range. Their relation to ash flows and cauldron structures is not yet known.

The break between the Datil (restricted sense) and the Apache Spring-Bloodgood Canyon ash flows of the Mogollon Plateau probably involved a series of geologic events including eruption of basaltic and andesitic rocks in the Mimbres Province (Figure 2, column I) and intrusion of mineralized porphyry bodies at Magdalena, dated at about 28 m.y. (Weber and Bassett, 1964). The dual nature of the rhyolites in the Datil (broad sense) west of the type locality was clearly recognized by Stearns (1962), who mapped several sedimentary and volcanic units of intermediate composition between his two rhyolite ash-flow units ($Tdrp_1$ and $Tdrp_2$). One of the intervening andesites (Tda_2) strongly resembles the "Turkeytrack Porphyry" of southeastern Arizona.

After the eruption of the Bloodgood Canyon Rhyolite and associated rocks, the Mogollon Plateau province was bevelled to low relief, and unconformably covered by relatively thin but persistent beds of sand and gravel, interlayered with a third "Datil" sequence of rhyolite tuff. It consists of airfall tuff, and sandy tuff as well as poorly-welded ash flows. The unit has tentatively been traced into the Deadwood Gulch Rhyolite of the Mogollon mining district (Ferguson, 1927), and is shown as Deadwood Gulch(?) Rhyolite in Figure 2. Its pyroclastic parts are highly felsic, rich in pumiceous glass but poor in phenocrysts. Neither the age nor source of the formation are known. In the higher parts of the Mogollon Range the Deadwood Gulch(?) reaches a maximum thickness of about 1,000 feet; thicknesses from a feather edge to 400 feet are more usual. The fine-grained sandy beds are its most persistent constituents. The units can be traced over an area from the Gila Cliff Dwellings to Beaverhead, Glenwood, and further west. Its ultimate limits are unknown.

At least one flow-banded dome-forming rhyolite is known to be younger than the Deadwood Gulch(?) Rhyolite: The highly porphyritic (quartz and sanidine phenocrysts) flow-banded Taylor Creek Rhyolite (new name), well known for its association with cassiterite deposits in the Taylor Creek tin mining district after which it was named. It forms an arcuate outcrop belt from the vicinity of Pelona Mountain, along the western side of the Black Range, as far south as South Diamond Creek. Locally, flows and flow breccias issuing from the domes are interbedded with moonstone-bearing rhyolite ash flows. The belt of Taylor Creek Rhyolite forms the youngest and innermost known member of the roughly concentric arcuate protrusive bodies interpreted as the surface expression of a ring-dike complex 75 miles (125 km) in diameter (Elston, 1964). The world over, ring-dike complexes with associated rhyolite ash flows, usually preserved in the central volcano-tectonic depression, are commonly associated with tin mineralization. Examples occur in Australia, Southwest Africa, Nigeria, the Sudan, the Iberian Peninsula, Brazil, and elsewhere.

To summarize: The Datil (broad sense) can be subdivided into at least three major ash-flow sequences in the Mogollon Plateau province. (1) The Datil (restricted sense), (2) the Apache Spring – Bloodgood Canyon sequence, and (3) the Deadwood Gulch(?) – Taylor Creek sequence. Each sequence is associated with arcuate elongated belts of intrusive-extrusive ("protrusive") composed of flow-banded rhyolite or quartz latite which tend to become progressively younger toward the center of the Mogollon Plateau. If seen at a deeper erosion level, they would constitute a ring-dike complex. Andesite and latite flows and pyroclastics occur at various horizons.

On the Geologic Map of New Mexico the Datil (broad sense) outcrop area on the Mogollon Plateau Province is enlivened by a complex color scheme, representing numerous facies. On the other hand, equivalent rocks in the Mimbres Province are shown as undivided Datil Formation, Td. The uninitiated might suppose that the compilers had much information on the Mogollon Plateau Province and little on the Mimbres Province. The exact reverse is true: The Mogollon Plateau had, at the time of compilation, been covered by only the most rapid reconnaissance mapping, and there had been virtually no petrographic work. Several bulletins of detailed geology had been published on the Mimbres Province (Kuellmer, 1954, Jicha, 1954, Elston 1957) and they contain petrographic descriptions based on hundreds of thin sections, supplemented by a number of superior chemical analyses.

(4) QTb: The unit shown on the Geologic Map of New Mexico as QTb is now known to consist of numerous rock types of varying ages. None are Quaternary and few are true basalt. The andesite-rhyolite-basalt cycle has already been mentioned several times, and it now appears that the capping basaltic sequence of one rhyolite can be time-equivalent to the basal andesite of another. Each of the three rhyolite sequences that make up the Datil (broad sense) is indeed capped by dark-colored rocks that range in composition from rhyolite to basalt. The Datil (restricted sense) section of the Mimbres province is capped by the Razorback - Bear Springs section (Fig. 2, column I), approximately equivalent in age (and partly in lithology) to the Alum Mountain Formation (new name, after Alum Mountain, Stop 12 on Field Trip No. 1) of the Pinos Altos - Gila Cliff Dwellings area (Fig. 2, column II). The Apache Spring - Bloodgood Canyon rhyolite ash-flow sequence of the Mogollon Plateau Province is capped by a basaltic andesite tentatively correlated with the Last Chance Andesite at Mogollon (Ferguson, 1927), but possibly younger. It is shown as Last Chance(?) Basaltic Andesite in Fig. 2, columns II and III. The Deadwood Gulch - Taylor Creek sequence is locally capped by the Wall Lake Latite (new name; the dam of Wall Lake south of Beaverhead is anchored on this rock) and, more generally, by the Bearwallow Mountain Formation (new name, after a prominent peak north of Mogollon which is littered with basaltic bombs).

In addition, isolated basalts, not related to rhyolite sequences in any systematic manner, occur in various places (e.g., Rustler Canyon Basalt in Fig. 2, column I). The younger basalts intertongue with the base of the Gila Conglomerate.

(5) QTr: The symbol QTr is used for rhyolites younger than the most prominent basalt sequence in any particular area. No ash flows are included under the symbol. It includes the post-Bear Springs Swartz Rhyolite of the Mimbres Province (Fig. 2, column I), of late Oligocene or early Miocene age (26.6±0.8 m.y., Damon and others, 1966), and a group of northwest-trending post-Bearwallow Mountain rhyolite domes, flows, glassy rocks, and non-welded pyro clastics near Mule Creek dated at 18.6 m.y. (Weber and Bassett, 1964). Not shown on the Geologic map of New Mexico are domes of latite that appear to be younger than the Bearwallow Formation. The upper part of Eagle Peak, east of Reserve, is an example. The latite is given the new name of Pelona Latite. Pelona Mountain (see Fig. 1 for location) is an eruptive center of a basalt tentatively assigned to the Bearwallow Mountain Formation. A dome of latite partly fills a circular valley that still retains characteristics of a crater or caldera of Bearwallow Mountain age.

(6) Qb: All rocks discussed so far are older than the main stage of Basin-and-Range faulting and the main mass of Gila Conglomerate. The only Qb in the Mogollon and Mimbres Provinces is a nearly flat-lying olivine basalt flow near Mimbres, just below the top of the Gila Conglomerate, seen on the afternoon of the second day of Field Trip No. 1. It has recently been dated as 6.3±0.4 m.y., or Pliocene (Damon, personal communication). No true Quaternary volcanic rock, has yet been identified in the Mimbres or Mogollon provinces, although virtually undissected basalt cinder cones, maars and lava fields are common on both sides of the Mexican border.

(7) Qvr: Supposedly post-Gila rhyolite flows at the southern end of the Knight Peak graben are based on a mapping error. A graduate student mistook terrace gravels derived from Datil (restricted sense) rocks for bedrock.

(8) Tv: This symbol is used to indicate "extrusive rocks of varied composition and age." It should clearly have been used more freely.

A Note on the Southwestern Province

On the Geologic Map of New Mexico (Dane and Bachman, 1965) certain symbols change along a line roughly following U. S. 70 west of Deming. This division is not as arbitrary as might seem at first glance. South of U. S. 70 lies the Basin-and-Range province, the Sonoran and Mexican geosynclines, and the highway roughly follows the postulated Texas lineament. The Pennsylvanian Florida archipelago of Kottlowski (1960) and the Cretaceous Burro uplift of Elston (1958) are just north of the highway.

A complicated debate concerning the existence and identification of early Cretaceous rocks (Kv) in the southwestern province need not concern us here, since the rocks in question contain no ash flows.

Ash flows are widespread in the southwestern province, and many local names have been assigned. The Geologic Map of New Mexico has divided them into a lower and an upper unit, Tvl and Tvu, respectively. The dividing marker is a massive and widespread quartz latite cooling unit, called Gillespie Quartz Latite by Zeller and Alper (1965) and Steins Mountain Quartz Latite by Gillerman (1958). Where identifiable it forms the base of Tvu. On Field Trip No. 1, the Steins Mountain Quartz Latite can be seen from Stop 19. Tvl includes not only rocks that would be included in the lower part of the Datil (broad sense) farther north, but possibly also late Cretaceous andesites like those around Pinos Altos and andesites designated elsewhere as Ta. Tvu includes rocks that are probably equivalent to the upper part of the Datil (broad sense) and, possibly, younger yet.

Since the Steins Mountain Gillespie Quartz Latite is not everywhere present, the Tvl - Tvu boundary cannot be drawn consistently. In the absence of even a single K-Ar date, correlation with eruptive phases in the Mimbres and Mogollon province is impossible. Alper and Poldervaart (1957) presented evidence, from similarity in chemical composition and zircon populations, that the Animas Quartz Monzonite stock in the Animas Mountains is the unroofed source of the pre-Gillespie Oak Creek Quartz Latite ash-flow tuff. Aside from this, little is known about the volcano-tectonic history of the area. The scarcity of post-ash flow basalts (QTb) is noteworthy but remains unexplained. Quaternary(?) basalt flows occur near Hachita and Animas.

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