ARIZONA GEOLOGICAL SOCIETY

SOUTHERN ARIZONA GUIDEBOOK III

1968

EDITED BY

SPENCER R. TITLEY

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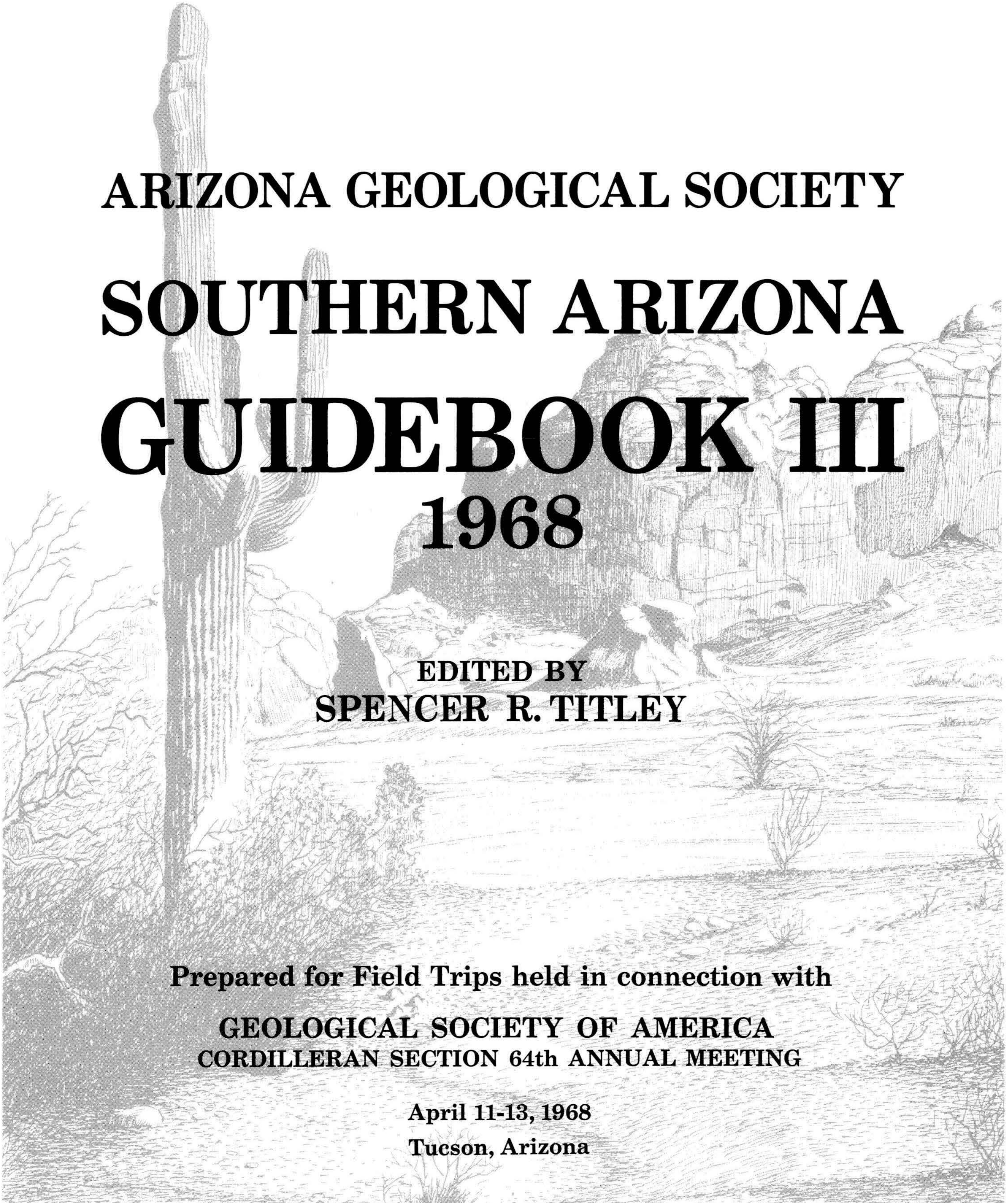


ARIZONA GEOLOGICAL SOCIETY

SOUTHERN ARIZONA
GUIDEBOOK III
1968

EDITED BY
SPENCER R. TITLEY

Prepared for Field Trips held in connection with
GEOLOGICAL SOCIETY OF AMERICA
CORDILLERAN SECTION 64th ANNUAL MEETING

April 11-13, 1968
Tucson, Arizona

THIS GUIDEBOOK IS RESPECTFULLY DEDICATED TO THE

MEMORY OF

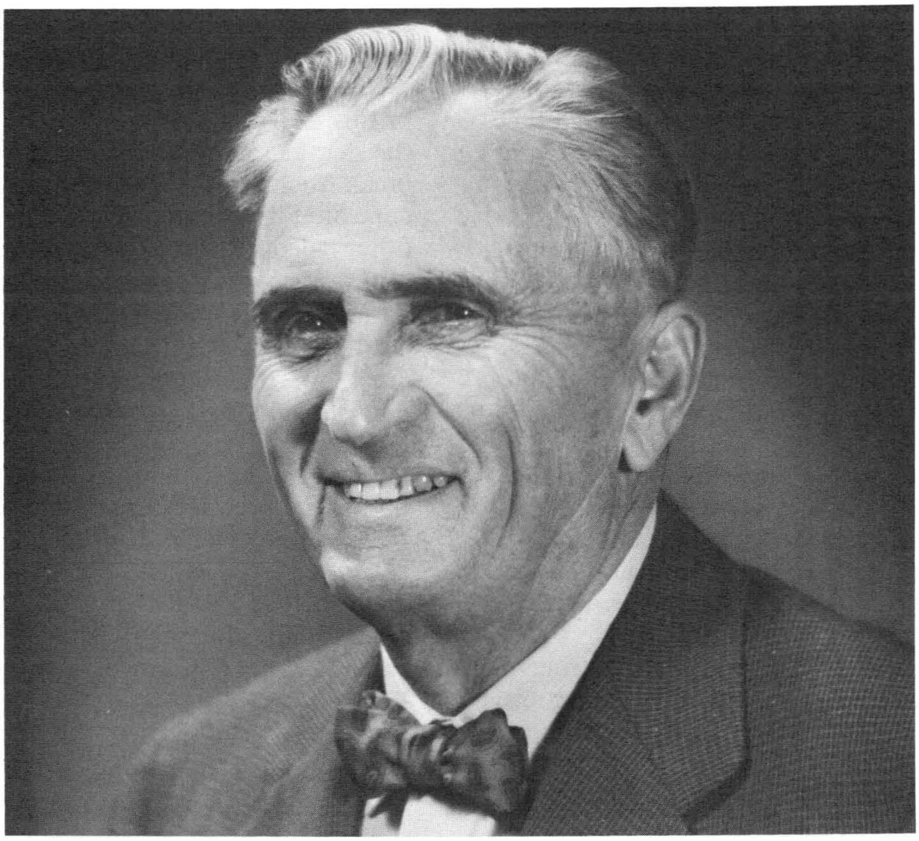
HARRISON ASHLEY SCHMITT

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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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.

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[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.

I have received technical assistance from Mr. Douglas Peck of the University of Arizona Press. Mr. Robert Mills of Publication Services Inc. and his staff, particularly Miss Susan E. Klemt, have carried out spartan work against unbending deadlines to prepare the manuscript and their extremely competent assistance, and patience, is appreciated. Mr. Tad Nichols has contributed much of the aerial photography and Dr. John Sumner has contributed his aircraft and flight time. Mr. John Fitzgerald has kindly granted the permission for use of his art. Finally, I wish to thank the many members of the Society, particularly Professor Terah Smiley, its president, and my colleagues in the Department of Geology for their assistance and counsel in many matters related to preparation of the Guidebook.

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

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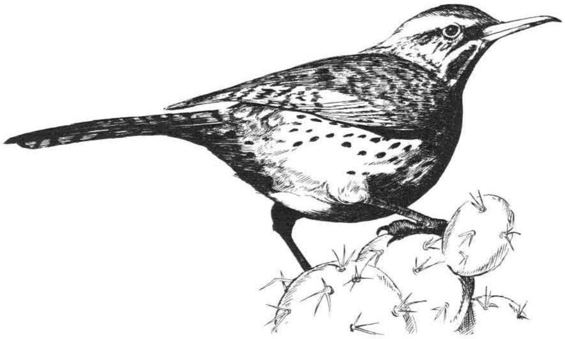
TABLE OF CONTENTS

GENERAL ARTICLES

ROAD LOGS

GENERAL ARTICLES



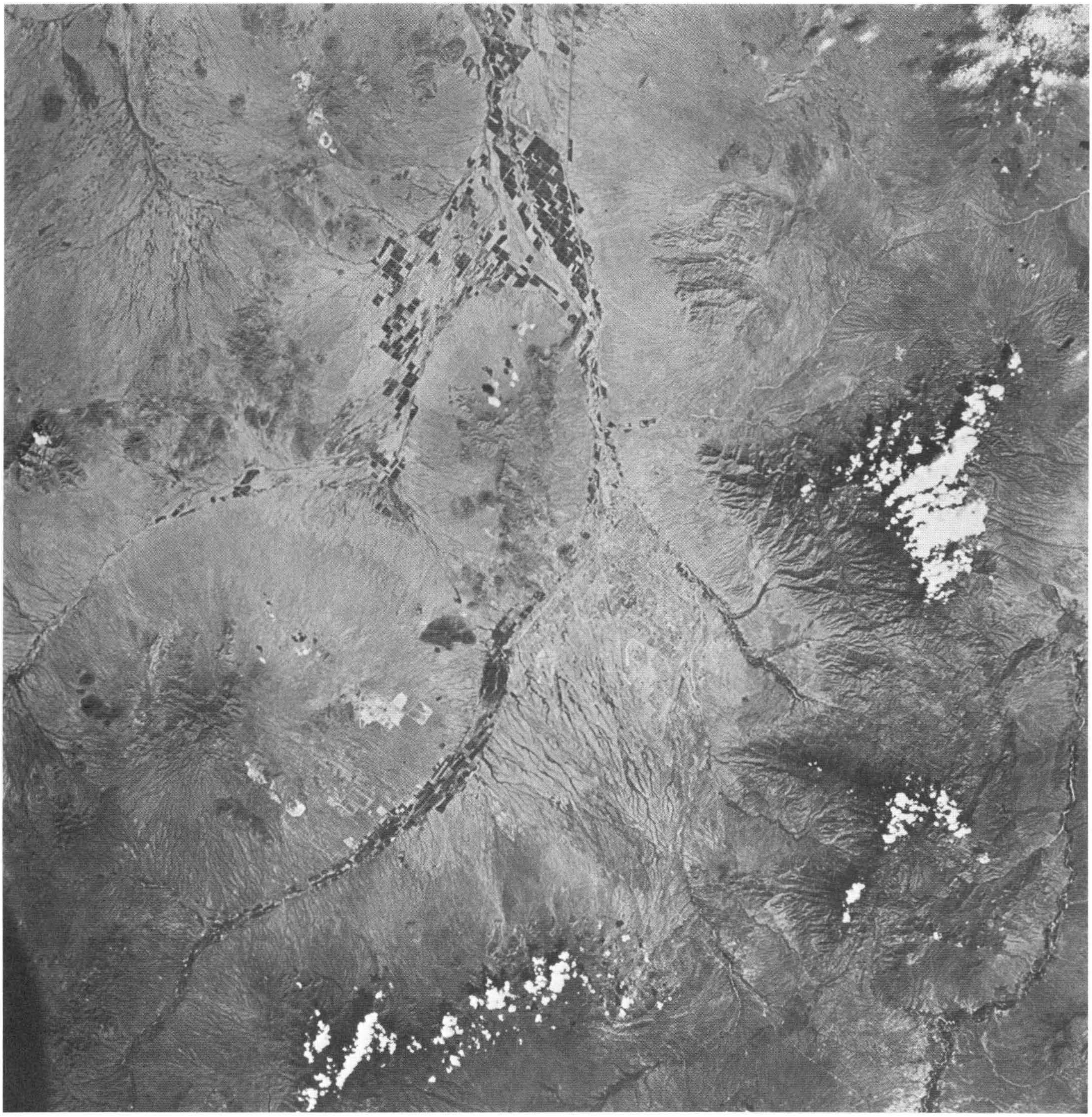


Figure 1 – Photograph from Gemini V Mission centered on Tucson, Arizona. North is oriented along the northeast diagonal of the picture. Catalina and Tortolita Mountains in upper-right quadrant, Sierrita Mountains and the Pima mining district in the lower left quadrant. Additional explanation in text. NASA Photograph

SOUTHERN ARIZONA – THE VIEW FROM GEMINI

By

Spencer R. Titley
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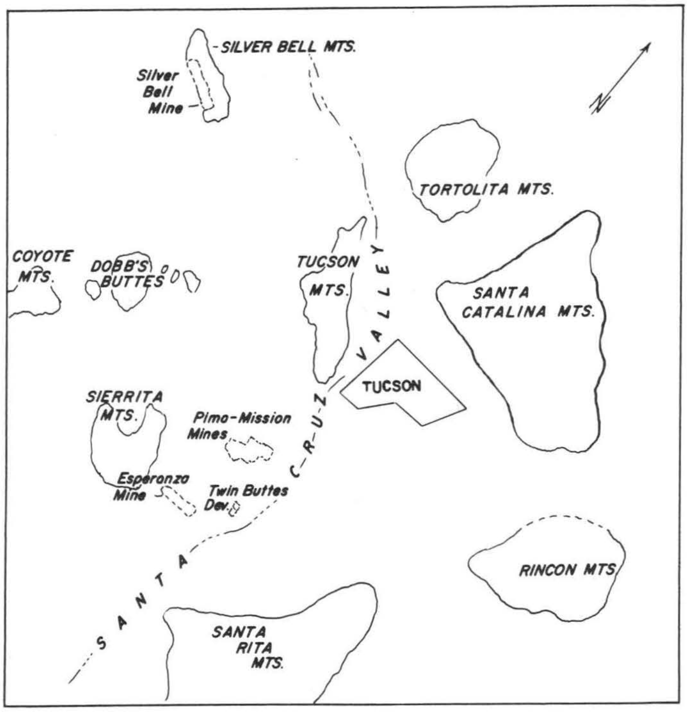
Photographs of the earth taken during the Gemini Manned Space Flight Program have provided much new and significant geological information about the southern part of the United States. Because of the nature of rock exposures and the absence of abundant vegetation those photographs which cover the arid southwest show major geological features in revealing and spectacular fashion.

As part of a continuing program in the Department of Geology at the University of Arizona hyperaltitude photography is being evaluated together with data derived from other methods of remote sensing with a view toward establishing the value of the data in terms of solving geologic problems. The basic effort of this program has been centered upon study and interpretation of a group of photographs taken on the Gemini IV Mission in June 1965. The group comprises several overlapping photographs of southern Arizona that extend from the Baboquivari Mountains on the west to the Chiricahua Mountains on the east. Although the strip of coverage by photography exceeds these boundaries, intensive study has been restricted to only these few photographs of southeastern Arizona where rock exposures are prominent and there exists extensive coverage of good geological mapping of at least reconnaissance scale.



Index map to Figure 1

The photography used has been supplied by the National Aeronautics and Space Administration and consists of 70mm copy transparencies. Original photographs were taken with a hand-held Hasselblad 500C camera with f/2.8 lens on 70mm Ektachrome MS (SO-217) film of ASA 64 rating (Lowman, McDivitt, and White, 1966). In the present study, the transparencies have been used to prepare black and white prints at varying contrasts and, for slight enhancement of color, they have been copied on Kodachrome.

The basic technique of study of detail has been that of examination of the 70mm transparencies through the binocular microscope. Low to moderate powers used with the 70mm transparencies have aided in discovering some detail. The use of broad-band red, yellow, blue and green filtered light has been used to enhance color contrasts on the transparencies and filtered light has been used with both the projection of of slides and microscopic studies. On the Gemini IV photographs studied, useful detail down to about 30 meters across, if linear, can be observed, but point objects are difficult to resolve and work with at sizes much below 75 meters. These numbers, however, are subject to some variation that is influenced by degree of albedo or color contrast.

As a general evaluation of the Gemini IV photographs of this portion of Arizona, little detail of bedrock composition has been discerned beyond gross delineation of mountains or hills of limestone, of characteristic grey color, and usually of Paleozoic age. Dark, flat-lying volcanic rocks are distinctive as are certain well exposed intrusive or extrusive igneous rock masses which are bright or light colored in contrast to enclosing rocks. Further complicating the problem of study of rock exposure is the extensive, by contrast, vegetation on north-facing mountain slopes, a problem which exists in the interpretation of aerial photographs at any scale.

The colored photographs reveal the broad range of red colors that are typical of soils of this desert province. The lack of uniformity of color is potentially significant. Study of the colors and their significance has been carried out by both light-filtering processes with the transparencies and ground and low-level aerial inspection. A variety of factors appear to contribute to the coloration. In a study of the origin of color on Mars, Binder and Cruikshank (1963, 1964) found that varying proportions of hematite and goethite in surface stains produce differences in visible color and their comparisons have been carried out in southern Arizona.

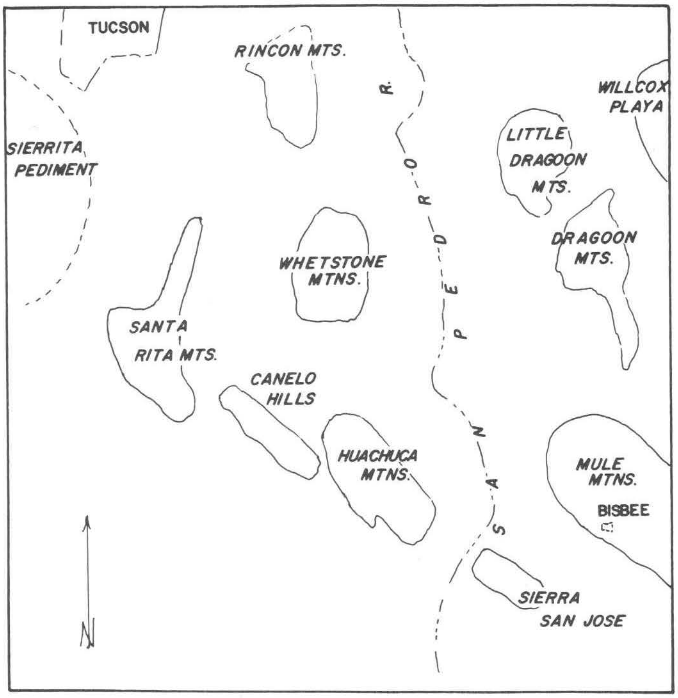
For the most part, soils of the pediments or bajadas are transported and it is only near the valley centers where significant maturing of soils and development of good profiles develops. It is on the pediments and bajadas where the colors are most pronounced and variable. The one major factor that appears to influence soil color is the nature of parent rock material. Rocks which are high in iron, particularly basalts and andesites, produce intense colors close to outcrop and in the regolith. Movement of the weathered material down the pediment appears to dissipate the color and the color ultimately vanishes with consequent maturing or rapid erosion of soils at the valley centers.

In the area of study, soils derived from limestone units do not show the red coloration on the Gemini IV photographs although there is local coloration that is visible at altitudes up to 5000 feet above ground. The dominant host rocks of the red soils of the region appear to be volcanic rocks of composition latite through basalt and the thick stacks of clastic rocks of the Cretaceous section. Granitic rocks, unless mafic- or sulfide-rich do not appear to be important.

Of potential economic significance is the discernment of those patches of coloration that may reflect the oxidation products of a weathered mineral deposit. Such coloration at Bisbee can be observed on the ground and from aircraft. The color at Bisbee shows on the photographs but the spot is so small as to be unworkable with the techniques presently employed. It would have shown, prior to mining, on the Gemini pictures and its isolation and contrast with surrounding rocks would have been sufficient to demand attention. From the standpoint of a ground- or aerial-observer the coloration at the south end of the Dragoon Mountains in the Courtland-Gleeson district is one of the most spectacular in southern Arizona. Yet, this coloration is virtually lost in the broader patterns of pediment color that extends the length of the Sulfur Springs Valley. Nonetheless, soil coloration is an aid in interpretation of parent rock composition. Where isolated spots of color contrast occur they would appear to require examination. Haynes (1968) has used the color photography as an aid to interpretation of Pleistocene and Recent history along the San Pedro River.

Along with color or albedo, the other most striking aspect of hyperaltitude photography is the portrayal of the nature of land forms. The pronounced structural grain of this part of the Basin and Range Province is obvious as is the nature of the forms developed on the structures. Various stages of pediment evolution and the drainage patterns are clearly shown. Although much of the relief information is present on existing topographic maps the shadowing on the photographs enhances relief and thus, combined with color contributes to interpretation of subtle features.

A few major structural features are visible and are noteworthy. Figure 1, taken on the Gemini V Mission is centered on Tucson, Arizona and shows the Catalina and Tortolita Mountains north of the city. Similar K-Ar dates for the Oracle Granite in the Tortolita and Catalina Mountains (Damon, 1968) suggest similar cooling histories of these mountain masses. On the photograph, there is strong suggestion that the two ranges are a geological entity and that the gap between them represents a down-dropped block. McCullough (1963) has noted the tensional



Index map to Figure 2

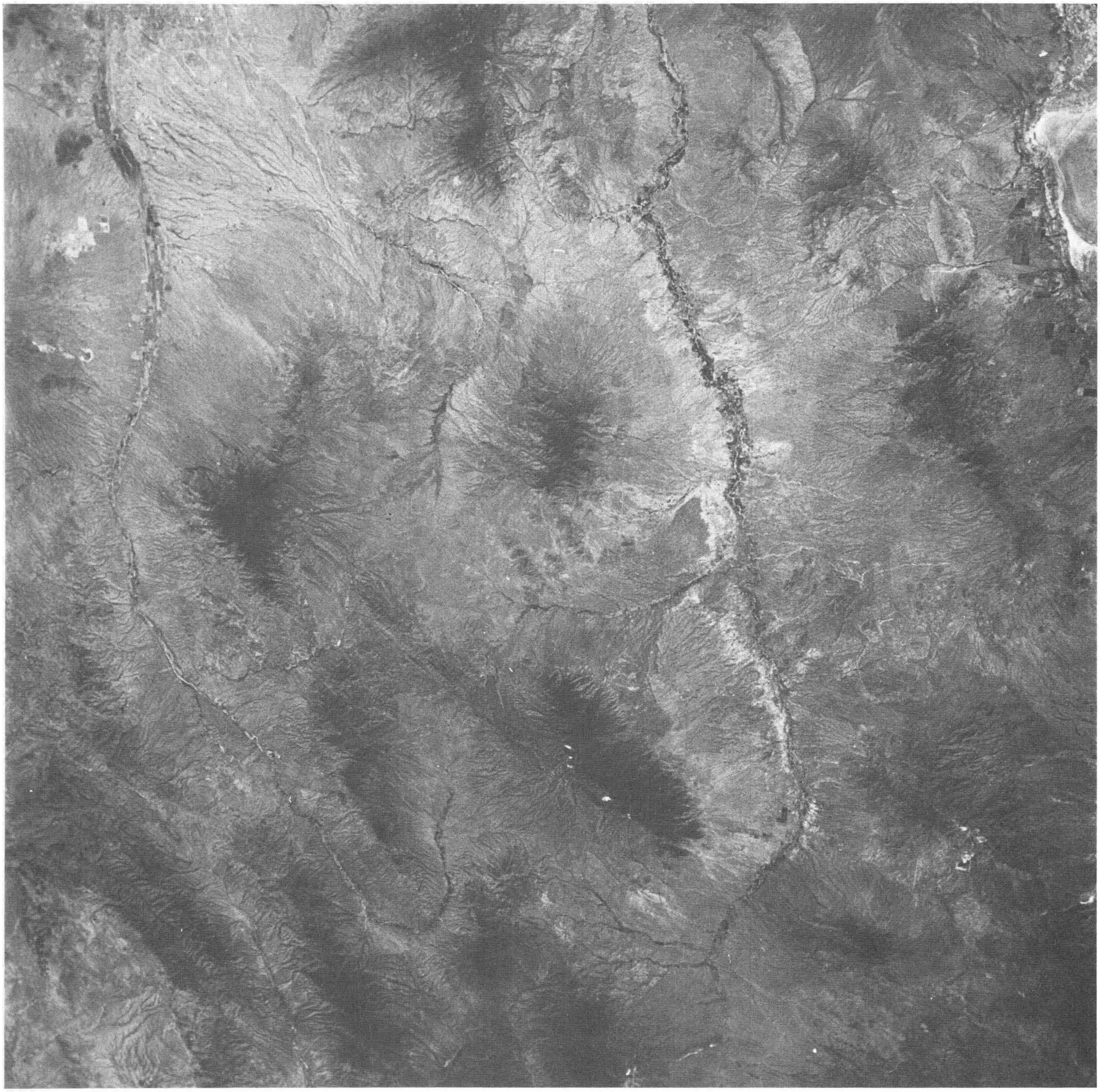


Figure 2 – Photograph from Gemini IV Mission centered approximately on the Whetstone Mountains in Cochise County, Arizona. North is uppermost. Bisbee is shown in the southeast quadrant, the Pima mining district in the northwest quadrant and the Santa Cruz Valley lies on the western edge and the San Pedro Valley lies near the center. Additional explanation in text. NASA Photograph

nature of north-trending structures across the central portion of the Catalinas of which the Pirate Fault may be an example. The continuity of the faulted, elongate, dome-like exposure of the Tortolita-Catalina mass is apparent. Also noteworthy is the albedo change along a line which is the projection of the outcrop of a domal form and which represents a topographic break in the overburden. The line of the Santa Cruz River projects through the Catalina-Tortolita gap. Other alignments can be observed on Figure 1, and the arcuate trace of the Dobb's Buttes-Coyote Mountains, concentric to the Sierrita uplift and pediment, is conspicuous. Also conspicuous are marked northwest- and north-trending structures in the Tucson Mountains.

Figure 2, overlapping but lying east and south of Figure 1, was taken on the Gemini IV flight. Other structural information is present on it. A pronounced alignment, at least 150 km in length, extends northwestward from the southwest face of the Sierra San Jose south of Bisbee in Sonora, along the southwest face of the Huachuca Mountains, through the Canelo Hills and the central part of the Santa Rita Mountains, and into the region of the Esperanza Mine on the Sierrita pediment. Its trace is lost as a topographic form beyond the Sierrita Mountains but on its northwesterly projection lie numerous volcanic hills such as the Dobb's Buttes and the Vaca Hills. Northwest structures, transverse to the orientation of the range cross the Santa Rosa Mountains on the projection of the alignment. Structures lying north and south of this line and paralleling it are numerous and have been long known and the line is a pronounced feature on the geologic maps. Its most consistent lithologic association is with volcanic rocks although these rocks lie in contact along the line with a variety of other lithologies which include intrusive igneous rocks.

Insofar as the landforms may represent structure they can be studied to gain some idea of possible regional stresses and, coupled with accurate chronologic data, can be used to assist in interpretation of the structural history of this portion of the Basin and Range Province. Orientation-frequency plots can be prepared from accurate azimuth information derived by microscopic study. The major advantage offered by the photographs when compared with topographic maps is the relatively sharper detail of form and the occasional possibility of precisely locating structural or stratigraphic information. In addition to the obvious form and structural information contained on the photographs, preliminary work indicates that study of the colors may provide further useful information that can be related to parent rock type, to history of landform development, and to processes of soil formation or modification.

ACKNOWLEDGEMENTS

The photographs used in this study have been provided through the courtesy of the National Aeronautics and Space Administration. Dr. Paul Lowman and Mr. Herbert Tiedemann of that organization have been most helpful in making the information available.

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APPLICATION OF THE POTASSIUM–ARGON METHOD TO THE DATING OF IGNEOUS AND METAMORPHIC ROCK WITHIN THE BASIN RANGES OF THE SOUTHWEST*[1]

By

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THE PRECAMBRIAN OF ARIZONA AND SONORA

On the basis of field observations, the Precambrian rocks of Arizona have for many years been divided into the 'younger Precambrian' (Apache group, Grand Canyon Series) and the 'older Precambrian' (Vishnu, Yavapai and Pinal Series) which include all more intensely metamorphosed and deformed Precambrian rocks whether or not they are overlain by younger Precambrian rocks (Butler and Wilson, 1938; Anderson, 1951). In some areas, e.g. the Santa Catalina Mountains of Pima County, the younger Precambrian Apache group of rocks have been metamorphosed but may still be recognized by their characteristic lithological sequence and by the fact that they overlie the older Precambrian with a marked structural and metamorphic unconformity. In many localities the younger Precambrian rocks are intruded by vast diabase sills and dikes. Basalt flows are also present and some of the sedimentary formations are tuffaceous.

The older Precambrian consists of a great thickness of sedimentary and volcanic rocks. The oldest rocks consist predominantly of slates, thin limestones, tuffs and cherts intercalated with basaltic to rhyolitic volcanics (Yeager greenstone, Ash Creek group). These are overlain by the shales, greywackes, sandstones and conglomerates of the Alder group that are also intercalated with lavas of variable but predominantly rhyolitic composition. The youngest extensive formation of the older Precambrian is the Mazatzal quartzite which has been recognized over a wide area from northeastern through central to southeastern Arizona (Wilson, 1962).

The older Precambrian rocks were laid down in extensive geosynclinal troughs that were not confined to Arizona but extended in a northeasterly direction across the North American continent (for review see Damon and Giletti, 1961; Wilson, 1962). These troughs were folded into northeast-trending mountain systems that were probably comparable in extent and duration with the Appalachian system of the eastern United States but, until recently, evidence existed for only one orogeny, the Mazatzal Revolution (Wilson, 1936, 1939). According to Wilson (1939), this orogeny took place 'after deposition of the Mazatzal quartzite and long before Apache sedimentation' (p. 1160). Hinds (1935, 1936, 1938) had postulated a pre-Mazatzal Revolution (Arizona Revolution) but on the basis of insufficient evidence (Wilson, 1939). Stratigraphic evidence for an earlier orogeny has now been described by Philip M. Blacet of the U. S. Geological Survey (Anderson, 1963) who mapped a granodiorite gneiss basement (Brady Butte granodiorite) which unconformably underlies the Alder group of the Yavapai Series south of Prescott, Arizona. This granodiorite has been dated at approximately 1,700 m.y. by E. J. Catanzaro of the U. S. Geological Survey (Anderson, 1963). Thus, stratigraphic evidence now exists for two distinct orogenic episodes during the older Precambrian. Rhyolitic volcanic rocks and granitoid intrusions also demonstrate the existence of episodic magmatism.

Sufficient isotopic dating data are now available to define distinct episodes of Precambrian magmatism and thermal metamorphism. Only data obtained by other than the potassium–argon method will now be discussed because our purpose is to evaluate the K-Ar method relative to independent age criteria. Professor L. T. Silver and his associates at California Institute of

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*This paper represents a portion of a chapter written for the book Radiometric Dating for Geologists. Permission to publish the paper has been granted by John Wiley and Sons.

[1] Contribution No. 140 of the Program in Geochronology, University of Arizona.

Table 1 – Comparison between K-Ar dates for biotite and muscovite from the Precambrian of Arizona and Sonora

Rock unit and location	K–Ar date for igneous or metamorphic rock (m.y.)		K–Ar date for pegmatite (m.y.)	Com-parison date (m.y.)	
	Biotite	Muscovite	Muscovite		
Metamorphic terrain, Bamori District, Sonora	—	1680(1)	1680(1)	1650 1690	K-Ar on hornblende from metamorphic rock(2) Rb-Sr on muscovite from pegmatite(3)
Pinal schist, Gila County, Arizona	—	1385(2)	1610(2)	1630	Rb-Sr isochron for Madera quartz diorite(4)
Yavapai schist, Yavapai County, Arizona	1156(2)	1440(2)	1555(2)	1740	Uranium–isotopic lead on gneissoid rhyolite and granodiorite(5)
Chino Creek granite, Yavapai County, Arizona	1330(6)	1460(2)	—		
Pinacate gneiss, Sonoyta District, Sonora	1170(2)	—	1440(2)		
Oracle granite, Pinal County, Arizona	1420(6)	—	1420(6)	1420	Rb-Sr mineral isochron(7)
Brahma schist, Coconino County, Arizona	1240(6)	—	1410(6)	1695	Uranium–isotopic lead(8)

(1) Damon and others (1962a); (2) Unpublished data, this laboratory; (3) Livingston and Damon (1965); (4) Livingston (1966, unpublished data); (5) Silver (1966); (6) Damon & others (1962b); (7) Livingston and others (1967); (8) Pasteels and Silver (1965).

Technology have obtained U-Pb isotopic ages of between 1,660 and 1,760 m.y. on suites of zircons from rhyolites and granitic intrusives from the Dragoon quadrangle in Cochise County (Silver, 1963; Silver and Deutsch, 1963), from the northern Mazatzal Mountains in east central Arizona (Silver, 1964), from the Bagdad region in west central Arizona (Silver, 1966), and from the Grand Canyon of the Colorado River (Pasteels and Silver, 1965). Wasserburg and Lanphere (1965) have reported ages of about 1,660 m.y. for both pegmatites and a quartz monzonite pluton from the Grand Wash cliffs region of northwestern Arizona by the mineral and whole rock mineral rubidium–strontium isochron methods, respectively. In this laboratory (see Table 1), Livingston has obtained a whole rock mineral Rb-Sr isochron age of 1,630 m.y. on the Madera quartz diorite which is intrusive into the Pinal schist of the Pinal Mountains in Gila County, Arizona. Concordant Rb-Sr and K-Ar mineral dates indicate that the Precambrian terrain of the Bámori district (southeast of Caborca) of Sonora was subjected to intense thermal metamorphism 1,680 m.y. ago and has remained refrigerated since that time (Table 6).

Rubidium–strontium whole rock or mineral isochron ages of from 1,400 to 1,450 m.y. have been obtained for granitoid batholiths such as the Ruin granite of the Salt River Canyon, Gila County (Livingston, 1962a, 1962b; Livingston and others, 1967) and the Oracle granite from the northern Santa Catalina Mountains in Pinal County (Livingston and others, 1967). Erickson and Livingston (Damon and associates, 1966) have obtained a 1,440 m.y. isochron on the Eaton gneissic granodiorite in the Dos Cabezas Mountains of Cochise County. A Rb-Sr whole rock mineral isochron age of 1,450 m.y. was obtained by Wasserburg and Lanphere (1965) for a gneissose complex from the northern Virgin Mountains near the Arizona border in Nevada. Recently, Silver (1966) reported a uranium–isotopic lead age of 1,375 m.y. for a cogenetic zircon suite from the Lawler Peak granite of the Bagdad region in Yavapai County.

Thus, there is abundant evidence for a series of magmatic–thermal and metamorphic events for the older Precambrian of Arizona and Sonora concentrated between 1,630 and 1,760 m.y. ago which we will tentatively refer to as the Arizonan Revolution* to distinguish it from the later Mazatzal Revolution that occurred between about 1,370 and 1,450 m.y. ago. There is abundant isotopic dating evidence for both of these complex events in the Precambrian of neighboring states (for review see Wasserburg and Lanphere, 1965).

The vast diabase sheet in the Sierra Ancha Mountains of east central Arizona has been dated by the uranium–isotopic lead method on cogenetic zircon suites (Silver, 1963) and by the K-Ar method on biotite (Damon and others, 1962b) at 1,150 m.y. Wasserburg and Lanphere (1965) have also published Rb-Sr data for both minerals and whole rock which indicate that some of the plutonic activity in southeastern Nevada and northwestern Arizona took place about 1,060 m.y. ago during the younger Precambrian.

The Grand Canyon disturbance has been associated with the intrusion of the diabase sills (e.g. see Wilson, 1962, p. 17-20). Thus the isotopic data indicate that this occurred 1,150 m.y. ago. The existence of ca. 1,060 m.y. plutonism suggests that later plutonism may also have been involved. As previously mentioned, there is as yet no definitive stratigraphic or isotopic evidence for Paleozoic plutonism in Arizona or Sonora.

POTASSIUM–ARGON DATING OF THE PRECAMBRIAN ROCKS OF ARIZONA AND SONORA

A histogram of K-Ar dates on mica minerals from rocks classified stratigraphically as Precambrian or for other reasons considered to be Precambrian is shown in figure 1. It is evident that all three Precambrian magmatic–thermal and metamorphic events are clearly represented by K-Ar radioactive clocks that have begun reading time or have been reset during one of these events. There is also abundant evidence of clock resetting during the intense late Cretaceous–Cenozoic magmatic–thermal and metamorphic events. However, the interpretations of the clock settings during post-Grand Canyon disturbance time are not sufficient without reference to other dating methods or field and petrographic investigations. For example, we are investigating the possibility that the peak at 300 to 400 m.y. in figure 1 may represent a real and hitherto undetected geologic event rather than merely partial clock resetting. We know that the clock reading 760 m.y. was partially reset by a basic dike that was found upon reinvestigation in the field. We have investigated a large number of cases in the field where the cause of resetting was clearly determinate. An example is given in figure 2 from the Precambrian of Sonora. A K-Ar date for the Granito Aibó of 150 m.y. was clearly the result of nearly complete resetting owing to a 105 m.y. quartz monzonite intrusion. A Rb-Sr date on feldspar yielded 700 m.y., whereas in a neighboring area the metamorphic terrain gave concordant K-Ar and Rb-Sr dates of 1,680 m.y. for several different minerals (see Table 1). On the other hand, in the southern

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*The designation of this geologic event as the Arizonan Revolution is not generally accepted by other geologists.

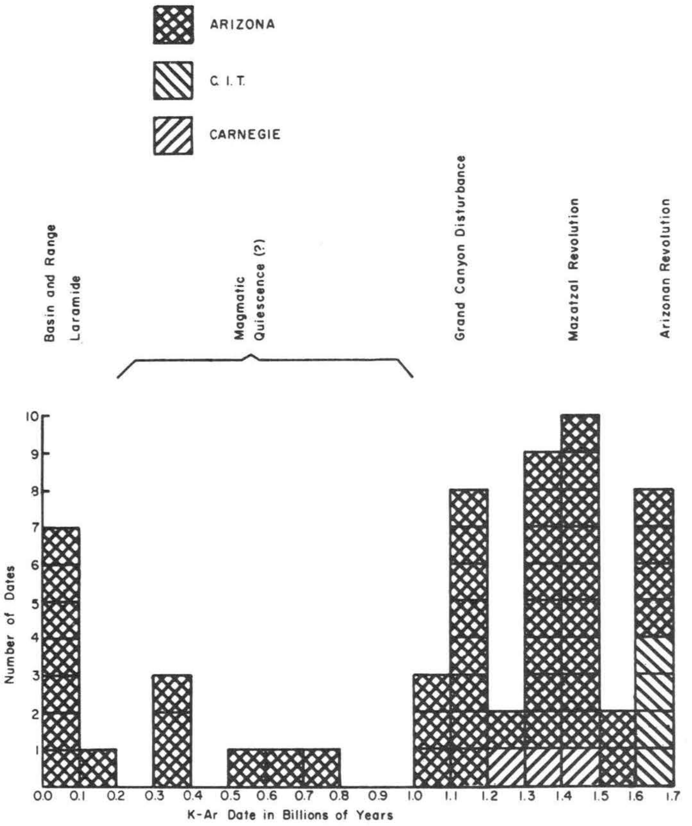

Figure 1 – Potassium-argon dates for mica minerals extracted from rocks assumed by geologists to have originated during Precambrian time. Mineral dates within labeled peaks are believed to represent emplacement time or time of episodic response to thermal events associated with known orogenies. Mineral dates falling within the quiescent period are believed to represent partial argon loss as a result of late Mesozoic and Cenozoic thermal events although the possibility remains that some thermal events are as yet unrecognized (see text). See Wasserburg and Lanphere (1965) for California Institute of Technology dates and Aldrich and others (1957) for Carnegie Institution of Washington dates.

Sierra Ancha Mountains of Gila County, Arizona where there is no evidence for postintrusion regional metamorphism of the Ruin granite (figure 3) or Apache group (contact thermal effects are observable near the contacts of the diabase sill), K-Ar dates on biotite from the Ruin granite yield the same age as obtained by whole rock or mineral Rb-Sr isochrons (Damon and others, 1962b; Livingston, 1962a, 1962b; Livingston and others, 1967). As previously mentioned, similar ages are also obtained on the diabase sill by both the uranium–isotopic lead method on a cogenetic zircon suite and by K-Ar on biotite.

The resetting of clocks is evident by the characteristic inverted dates for coarse mica from pegmatite versus fine-grained mica from schistose country rock (see figure 4 and Table 1). It is interesting that the retentivity of strontium in the micas seems to be only slightly greater than that for argon. This has also been observed by Gast and Hanson (1963) and Hart (1964). The characteristic order of argon retention seems invariably to be coarse-grained muscovite > fine-grained muscovite > fine-grained biotite. The coarse-grained muscovites are only completely reset by an intense thermal event, whereas the fine-grained biotites respond even to the mild thermal event associated with the Grand Canyon disturbance. With reference to figure 5, fine-grained biotite seems to be responding roughly as our 10 μ reference phlogopite, whereas fine and coarse muscovite correspond roughly to the 100 and 1,000 μ phlogopites, respectively. Thus, concordant K-Ar dates on minerals having widely different diffusion properties indicate clock setting followed by refrigeration, whereas each discordant K-Ar radioactive clock reading may or may not correspond to a distinct event. During periods of normal crustal temperature gradient, rocks within one mile of the surface are essentially refrigerated and negligible argon

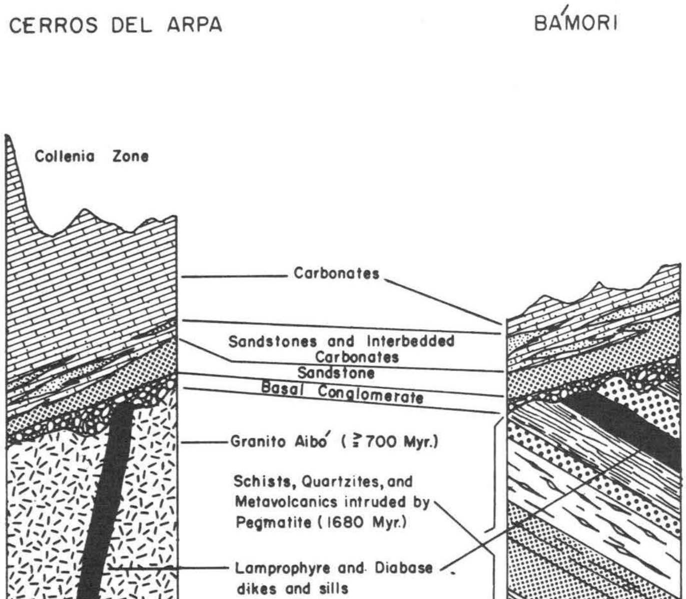

Figure 2 – Correlation of Cerros del Arpa Precambrian strata with Precambrian strata of Bamori in Sonora, Mexico. Intrusion of a mid-Cretaceous quartz monzonite pluton has caused uncertainty as to the original age of the Granito Aibo (Damon and others, 1962).

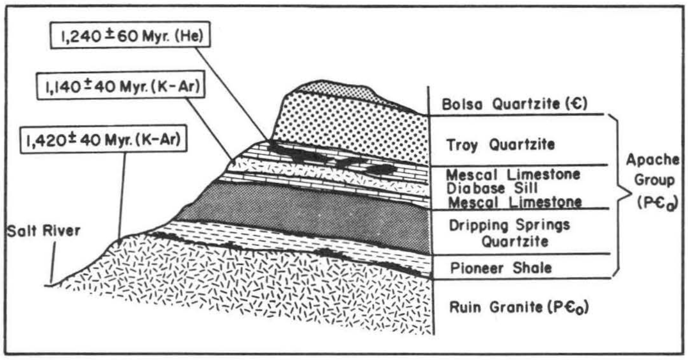

Figure 3 – Younger Precambrian Apache group overlying older Precambrian Ruin granite in the Sierra Ancha Mountains north of the canyon of the Salt River. See text for discussion of conformable dating results by different methods on different mineral and rock samples which demonstrate that this terrain has remained refrigerated since emplacement of the Ruin granite except for local effects due to the diabase sill. The helium date on magnetite in the Mescal limestone is less accurate than the potassium-argon dates (Damon and others, 1962b; Livingston, 1962a, 1962b; Silver, 1963).

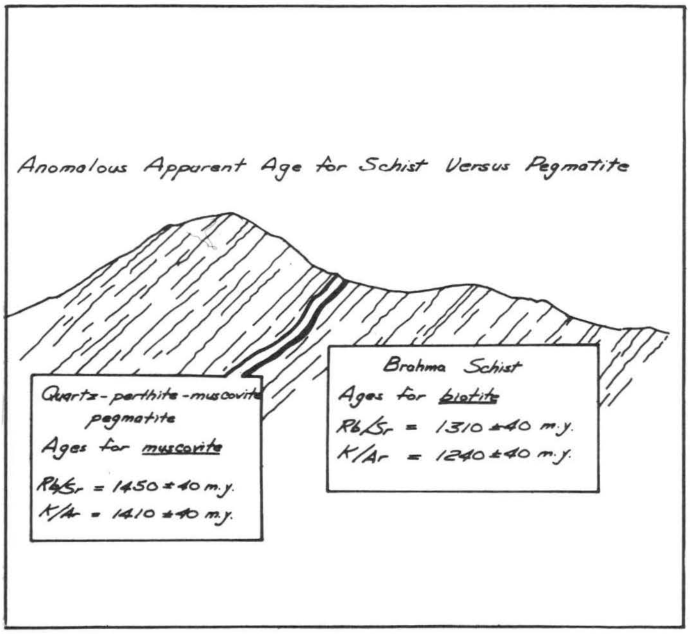

Figure 4 – Pegmatite vein intruded into Brahma schist on Kaibab Trail, Grand Canyon, National Park. The dates show the typical inversion which is a result of the greater retentivity of pegmatitic muscovite relative to fine-grained biotite. Mineral genesis occurred about 1700 Myr ago (Pasteels and Silver, 1965). The muscovite mineral has responded to elevated temperatures during the Mazatzal orogeny but has not responded significantly to the Grand Canyon disturbance as has the biotite.

loss occurs. When the temperature rises during periods of abnormal thermal activity, there will be a more or less distinct threshold temperature for significant argon loss. For complete resetting of the K-Ar clocks during a thermal event of 100 m.y. duration, roughly 155°c is required for the fine-grained biotite, 230°c for the fine-grained muscovite, and 325°c for the coarse-grained muscovite. The temperature thresholds are far enough apart so that one may be completely reset, whereas the others are only slightly perturbed. Thus, a single K-Ar date for a mineral that has had a long and complex history yields little definite information. However, a number of K-Ar dates on different minerals provides valuable information concerning the genesis and thermal history of the mineral, and because of the episodic response of K-Ar clocks, a statistical analysis of K-Ar dates allows for a rather precise dating of thermal events.

PHANEROZOIC HISTORY OF THE BASIN RANGES

There have been a number of excellent reviews of the geology of the western United States. For this resumé, the author has relied heavily on Eardley (1951), Gilluly (1963, 1965), Kay (1951), McKee (1951) and Osmond (1960).

During the Paleozoic era the Basin and Range Province north of about latitude 36° N was miogeosynclinal in the eastern part and eugeosynclinal to the west. The first well-documented orogeny took place in early to middle Mississippian time. As a result, a welt, known as the Manhattan geanticline or Antler orogenic belt, developed in the central part of what is now the Basin and Range Province (north of 36° N lat). Thereafter the welt extended until it included during Cretaceous time all of the northern Basin and Range Province.

During Phanerozoic time the southern part of the Basin and Range Province in Arizona, New Mexico and Sonora was essentially part of the hedreocraton, and from time to time the area was submerged by epicontinental seas. For most of this time western Arizona and northwestern Sonora were shelf and continental margin of the hedreocraton. A profound unconformity exists at the base of the lower and middle(?) Triassic Moenkopi Formation (Wilson, 1962). At the beginning of the Mesozoic era, all of the area now included in the Basin and Range Province below latitude 35° N was uplifted to form an extensive highlands area. To the north the sea regressed from the area east of the welt during the Triassic Meso–Cordilleran geanticline phase of the Manhattan geanticline. As a result of this extensive uplift of the southern province, a broad sheet of gravel, the Shinarump conglomerate, which was derived from the south, was deposited over most of northeastern Arizona and adjoining area.

The Nevadan orogeny, which resulted in the main folding of the Sierra Nevada in late Jurassic time, was also active in Arizona. According to Wilson (1962, p. 48), 'from northeastern Arizona to the southwestward, an erosion surface at the base of the Cretaceous cuts progressively across older rocks that had been uplifted and deformed during the Nevadan Revolution.' The Nevadan uplift gave rise to the Glance conglomerate of southeastern Arizona.

As mentioned previously, during Cretaceous time the welt in the northern area spread out to include all of the Basin and Range Province. On the other hand, the Mexican (or Sonoran) geosyncline developing in southwestern Arizona invaded the southern hedreocratonic area during early Cretaceous time and spread in a west-northwesterly direction across the southern part of Arizona and Sonora. During late Cretaceous time the Sonoran geosyncline continued as a deep embayment but, in the larger perspective, it formed only a small part of the Rocky Mountain geosyncline. The great late Cretaceous sea spread until in Turonian time it not only united the Gulf of Mexico with the Arctic Ocean but its width extended from central Utah to western Iowa (Cobban, 1960). Following a maximum transgression in Turonian time, the epicontinental seas retreated until by late Maestrichtian time all of the western interior of the United States had reemerged.

The retreat of the epicontinental seas occurred during the Laramide orogeny. In the northern Basin and Range Province, the welt attained its maximum development. Throughout the entire province, deformation resulted in the uplift of mountains and the crust was invaded by synorogenic granitic intrusions.

In mid-Tertiary time the tilted fault block ranges and broad basins were formed during and following extensive outpourings of andesitic to rhyolitic volcanic rocks. It was at this time that the Basin and Range Province came into existence as a physiographic province.

Recently, Gilluly (1965) has reviewed the evidence for Phanerozoic magmatism in the western United States. In Arizona the first clearcut evidence for Phanerozoic magmatism is the occurrence of siliceous ash beds in the Triassic Chinle Formation on the Colorado Plateau. Elsewhere in the Basin and Range Province there is considerable evidence for andesitic-rhyolitic (and basaltic) volcanism during Triassic time and, apparently, the oldest Phanerozoic plutons were emplaced during this period. Plutonism and volcanism are recurrent in late Jurassic time penecontemporaneously with the Nevadan orogeny. Thereafter there is abundant evidence for periodic magmatism during the Cretaceous and Cenozoic. The vast floods of siliceous ash flows during the mid-Tertiary orogeny are of particular importance. Basin and Range volcanism during middle to late Pliocene and Pleistocene time is primarily basaltic in composition.

Earlier workers considered the Mesozoic Nevadan, Santa Lucian, Laramide, and Basin and Range orogenies to be separate and discrete geologic events. Because of a lack of definitive stratigraphic evidence, distinctions have gradually blurred until the following point of view expressed by Wilson has become quite common: 'Laramide igneous activity is marked by batholiths, stocks, dikes, plugs and volcanic rocks, especially within the Basin and Range Province. For this latter region, the orogeny is not clearly separable from the Triassic-Jurassic Nevadan Revolution; furthermore, it appears to blend with the crustal unrest and igneous activity of middle to late Cenozoic time' (Wilson, 1962, p. 58). In the following section, the chronological evidence of K-Ar dating will be used to evaluate this problem. Are these orogenies discrete events? Does magmatism within this Province during Mesozoic time occur quasi-continuously or in discrete pulses?

POTASSIUM–ARGON DATING OF LATE MESOZOIC–CENOZOIC EVENTS

The University of Arizona in Tucson is located in the heart of the southern part of the Basin and Range Province (figure 5) within a broad basin surrounded by mountains which form a typical Basin and Range topographic setting (figure 5). These nearby mountain ranges have been the subject of intensive K-Ar dating studies by members of this laboratory (Bikerman, 1965; Bikerman and Damon, 1966; Damon and Bikerman, 1964; Damon and others, 1963; Damon and others, 1964; Livingston and others, 1967; Mauger, 1966; Mauger and others, 1965). The approximately 2,000 square mile area in figure 5 is probably the most thoroughly dated area of this size in the United States and it serves as a convenient prototype for the chronology of magmatic events within the Basin and Range Province.

A summary of dating results in the northern Tucson Mountains around Safford Peak is given in figure 6. In that area the Cretaceous(?) volcanic rocks have been too disturbed by subsequent geologic events to warrant attempts at K-Ar dating. However, fresh unaltered samples have been obtained from the Cenozoic section above the Cretaceous(?) volcanic rocks.

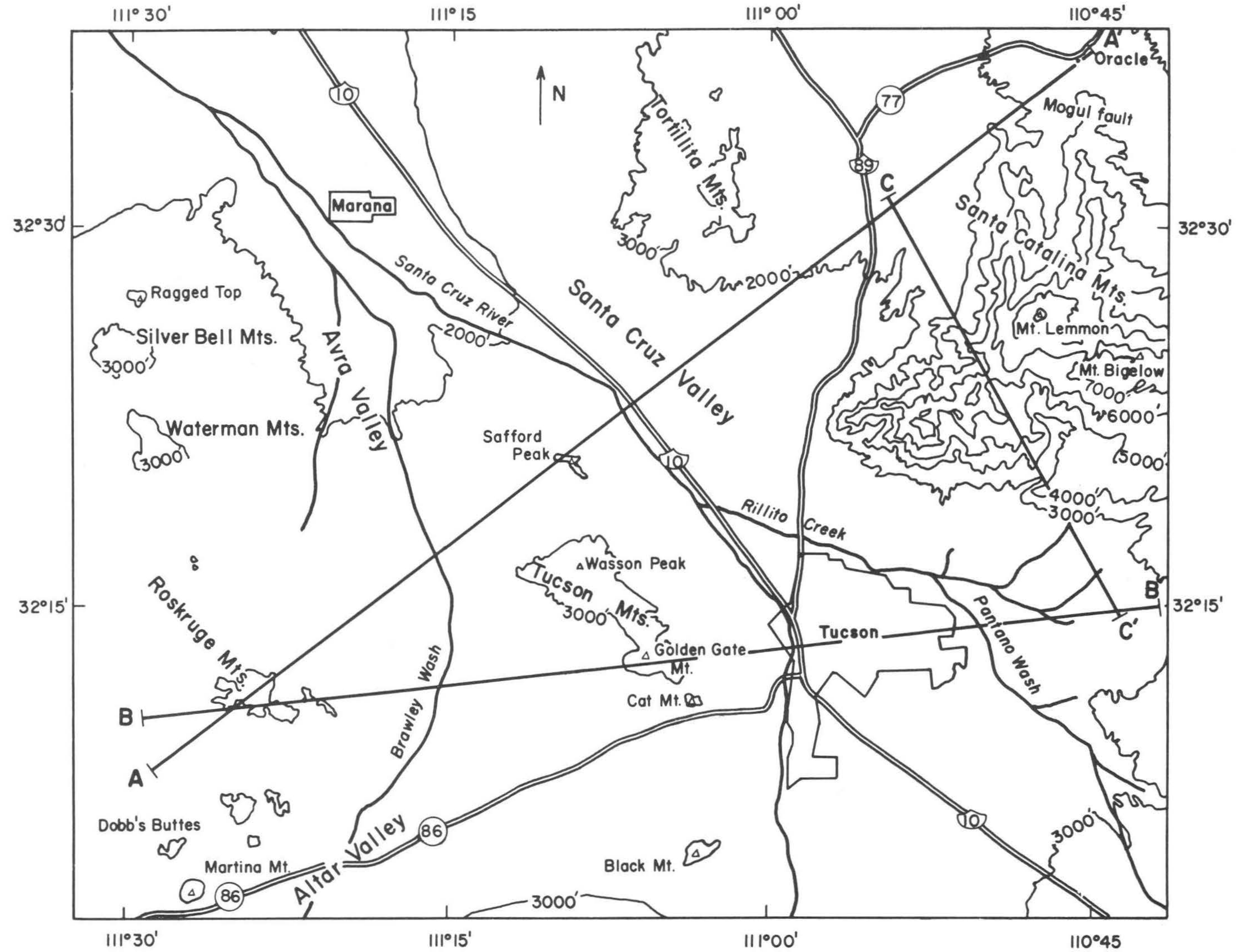

Figure 5 – Location map and lines of section for the typical Basin and Range area around Tucson, Arizona (1,000-foot contour interval, scale 1:250,000).

Biotite separates from the volcanic units yield a consistent chronology beginning with the 38.5 ±1.2 m.y. Rillito Andesite which floors the Cenozoic volcanic sequence and terminating with the intrusion of the Safford Dacite Neck at 24.5 ±0.8 m.y. The three intervening volcanic rock units average 26.3 ±1.3 m.y. and considering the precision of individual K-Ar dates are, therefore, penecontemporaneous. The entire section is tilted about 20° to the northeast which demonstrates that major Basin and Range faulting occurred during post-early-Miocene time.

An idealized section through the southern Tucson Mountains is shown in figure 7. Cretaceous sedimentary rocks have been intruded by Laramide granite and quartz monzonite plutons (71-75 m.y.) and are overlain by a chaotic breccia and ash flow sequence which appear from field and dating evidence to be younger than the plutons. The last event of the Laramide sequence is the extrusion of the Shorts Ranch Andesite which has been dated at 56.8 m.y. on biotite. Unconformably overlying the Shorts Ranch Andesite there is a sequence of basaltic andesites flooring and capping a sequence composed of a colluvial gravel deposit, an air-fall tuff and two ash flows representing distinct cooling units. The youngest unit, a basaltic andesite, has been dated at 19.8 m.y. on fresh whole rock. Several important generalizations appear to be warranted for the Tucson Mountains. First, magmatism appears to have occurred in two pulses, one in late Mesozoic–early Cenozoic time and the other during mid-Tertiary time. Second, Basin and Range faulting has affected the entire volcanic sequence during

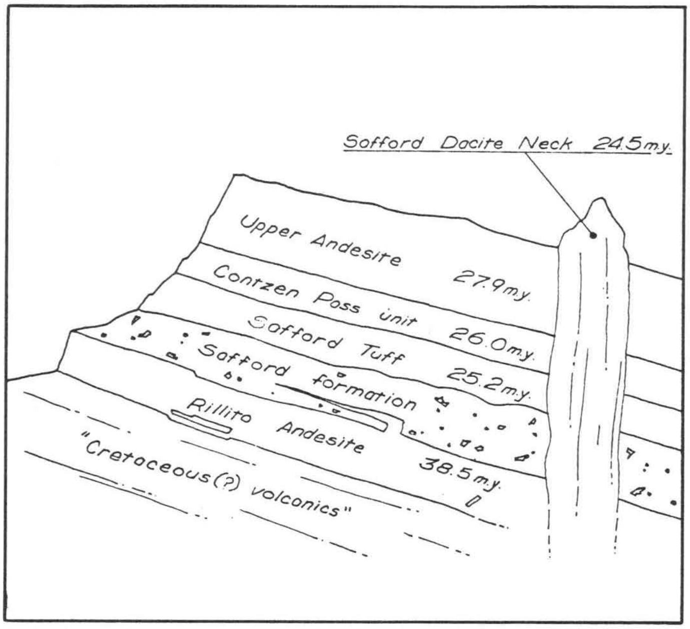

Figure 6 – Idealized section of volcanic rocks from northern Tucson Mountains around Safford Peak (from Bikerman and Damon, 1966).

post-early-Miocene time. A similar sequence has been observed in the Silver Bell mining district to the northwest, in the Roskruge Range to the west and in the Sierrita Range to the south. Idealized cross-sections across the region (figure 5) are shown in figure 8.

With reference to the line of section AA′ which extends from the Roskruge Range in Pima County to Oracle in Pinal County, the section in the Roskruge Range is floored by andesitic volcanics and sediments, one andesitic unit of which has been dated at 108 m.y. on whole rock. Resting on the Cretaceous sedimentary–volcanic terrain are two felsic ash flow sequences separated by a thin sedimentary bed. The K-Ar dates indicate a significant lapse of time between deposition of the two ignimbritic sequences. The older sequence appears to be penecontemporaneous with the granitoid plutons in the neighboring Tucson Mountains to the east, whereas the younger sequence is penecontemporaneous with the pluton in the Roskruge Range at Cocoraque Butte (ca. 69 m.y.) and with a similar ignimbritic sequence, the Cat Mountain Rhyolite, in the Tucson Mountains. The mid-Tertiary volcanic pulse, which begins in the Roskruge Range with a granodioritic plug at La Tortuga Butte, includes a basaltic andesite sequence ranging in age from 15 to 24 m.y. and terminates with the extrusion of a small ash flow with well-developed eutaxitic texture (the Recortado ash flow dated at 13 m.y. on sanidine: section BB′). According to Bikerman (1965), there may have been some uplift of the Recortado ash flow above the present valley floor during the past 13 m.y. i.e. during post-late-Miocene time, but it is essentially flat lying and has not been noticeably affected by Basin and Range faulting. Following the mid-Tertiary pulse of silicic magmatism, minor amounts of postorogenic basalt were extruded.

The section going from A to A′ (figure 8) continues across the Tucson Mountains, which have already been discussed, to the low-lying Tortillita Mountains. In that range a granodiorite gneiss, which appears identical in lithology to the Precambrian Oracle granite in the northern Santa Catalina Mountains around Oracle, has been dated at 26 m.y. indicating intensive heating during mid-Tertiary time. The section then crosses the Pirate fault which flanks the northern Santa Catalina Mountains. All rock units between the Pirate fault and the Mogul fault, which strikes NW–SE across the Santa Catalina Mountains, have been intensely

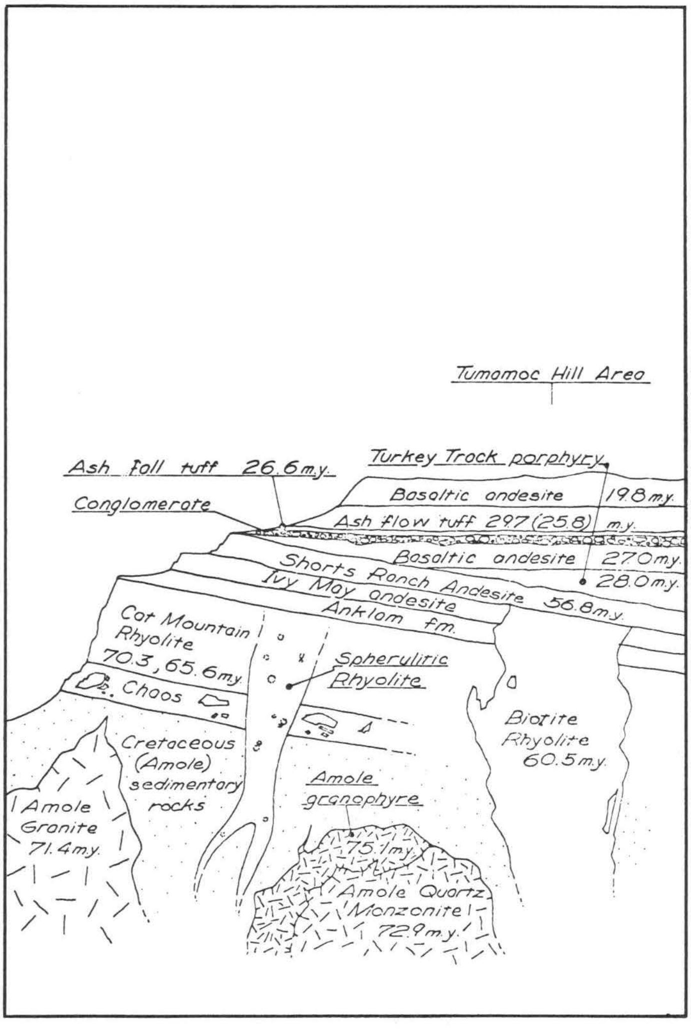

Figure 7 – Idealized section through the southern Tucson Mountains (from Bikerman and Damon, 1966).

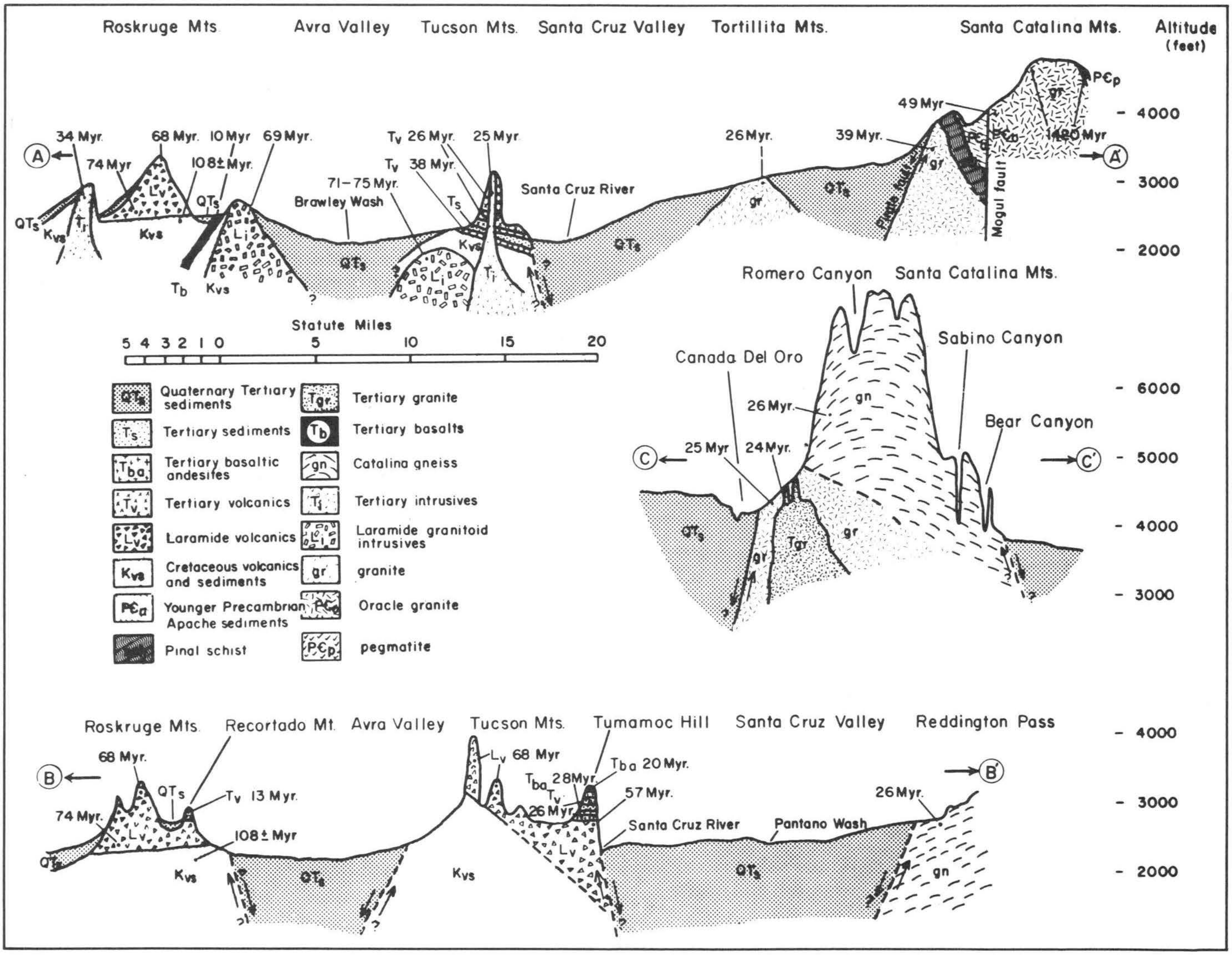

Figure 8 – Idealized cross sections with great vertical exaggeration along lines of section given in location map (Fig. 5).

heated during Tertiary time. Thus, Oracle granite in the shear zone immediately northeast of the fault yielded a 49 m.y. date on biotite, whereas outside of the shear zone northeast of the fault K-Ar and Rb-Sr results for muscovite, biotite and plagioclase minerals yield concordant 1,420 m.y. dates.

In the southern Santa Catalina Mountains and Rincon Mountains, there is further evidence of an extensive episode of Cenozoic metamorphism (figure 8, line of section CC′). Potassium–argon dates on biotite, muscovite, plagioclase and orthoclase from the gneiss and plutonic intrusions into the gneiss are all approximately concordant at about 27 m.y. even though Catanzaro and Kulp (1964) have demonstrated a Precambrian age by the uranium–isotopic lead for zircons extracted from the gneiss. However, a detailed analysis of the data for these samples indicates real differences in the apparent age of the different minerals as shown in Table 2. The samples were collected from different localities as much as 20 miles apart.

The approximately concordant age on the lowest potassium phase, plagioclase, suggests that excess environmental ^{40}Ar is very low and thus the built-in age for the pegmatitic muscovite minerals is a result of inherited ^{40}Ar in the most retentive phase. Damon and Bikerman (1964) have shown that the cooling of the Catalina and Rincon gneiss is closely correlative with intense magmatism from 25 to 28 m.y. ago within the area shown in figure 5. Hedge (1960), on the basis of sodium–potassium ratios in muscovite minerals coexistent with orthoclase and plagioclase, has estimated a 400°c to 500°c temperature for alkali metal equilibration within the gneiss. If the cooling of the Santa Catalina–Rincon block began about 28 m.y. ago with the temperature equal to 400°c at that time, the built-in age of the pegmatitic muscovite is equivalent to that expected for a 1,000 μ 'standard' phlogopite at that temperature. If we assume that the biotite minerals in the gneiss are equivalent to 10 μ 'standard' phlogopite, then a sharp limit can be set on the duration of elevated temperatures. Thus, the array of argon dates for different minerals in Table 2 is quite consistent with an exponential cooling rate from 400°c at 28 m.y. ago to 100°c at 23 m.y. ago.

Table 2 – Average apparent age of different minerals from the Santa Catalina and Rincons gneissic complex.

Mineral	Number of different samples	Average K-Ar date for samples (m.y.)
Biotite	5	25.2 ± 0.5[a]
Orthoclase	1	26.8 ± 0.8[b]
Muscovite (fine-grained from gneiss)	4	27.0 ± 0.9[a]
Plagioclase	1	29.3 ± 0.9[b]
Muscovite (large books from pegmatites)	3	31.7 ± 0.5[a]

[a] Standard deviation of mean.

[b] Standard deviation for precision of single analysis.

Data from Damon and others (1963); Livingston and others (1967);
Mauger and others (1966).

About 15 miles east of point C′ (figure 5), a middle Tertiary unit, the Mineta Formation, crops out at Mineta Ridge on the east flank of the Rincon Mountains (Chew, 1962). A black, fetid freshwater limestone unit of these beds, subunit 12 of the upper unit, contains identifiable remains of a young rhinoceros (*Diceratherium*). According to Lance (1960, p. 156), this fossil is 'certainly no older than upper Oligocene or younger than middle Miocene.' Above sub-unit 12, according to Chew (1962), the arkosic sandstones, siltstones and fine-grained conglomerate commonly contain muscovite. According to Hedge (1960, p. 18), the sodium–potassium ratios of this muscovite are what 'one would expect if the muscovites were merely detrital remnants derived from exposure of gneiss in the Santa Catalina and Rincon Mountains which are only a few miles away.' The Mineta beds have been faulted and tilted during Basin and Range uplift in contrast to relatively undisturbed late Miocene and Pliocene beds. Thus the stratigraphic relationships are consistent with uplift and cooling of the Catalina–Rincon block during early Miocene time, followed by erosion of some gneiss before late Miocene time. Large areas of gneiss are exposed and being eroded at the present time.

Returning to the line of section AA′ (figure 8), the Tortillita Mountains appear to have participated in the thermal metamorphic event along with the Santa Catalina–Rincon Mountains. However, the region near the Mogul fault was either not heated to as high a temperature or it cooled earlier than the areas to the south and southwest. Furthermore, the area around Oracle north of the fault has remained at low temperatures since Precambrian time. Obviously, these K-Ar results will provide important boundary conditions for the solution of the structural problems related to the Basin and Range orogeny. The Catalina–Rincon block is typical of many ranges containing metamorphic rocks throughout the Basin and Range Province (Armstrong and Hansen, 1966; Mauger and others, 1966). According to Mauger and others, 'the concordant argon results from individual mountain ranges fall into the 20-30 m.y. time interval and are essentially compatible with geologic estimates of a late Oligocene–early Miocene beginning for rift faulting in the Basin and Range Province' (p. A-I-5).

Turning now to the Basin and Range Province as a whole, including southern Oregon but excluding Idaho, southwestern Texas and the state of Chihauhua in Mexico, we have found K-Ar histograms to provide a useful frame of reference. The histogram in figure 9 was prepared essentially according to the criteria used by Damon and Mauger (1966, p. 100). These criteria for selecting K-Ar dates are as follows:

(1) Only hypabyssal plutons and volcanic rocks are included because these rocks have cooled relatively rapidly and accordingly the mineral dates most closely represent the time of emplacement. Andesitic (including potassic basaltic-andesites) to rhyolitic volcanics are plotted with the hypabyssal plutons. Basalts (excluding potassic basaltic-andesites) are plotted separately. Metamorphic rocks are excluded although their distribution would not be dissimilar.

(2) Only one date is presented for a single mappable rock unit. When several dates for a rock unit were available, the average age was considered as 'one' date.

(3) All rock units were located within the Basin and Range Province.

(4) Only dates falling within the time encompassed by the period from 5 to 90 m.y. are included. This period of time encompasses early Turonian (late mid-Cretaceous) through late Hemphillian (late Pliocene) time.

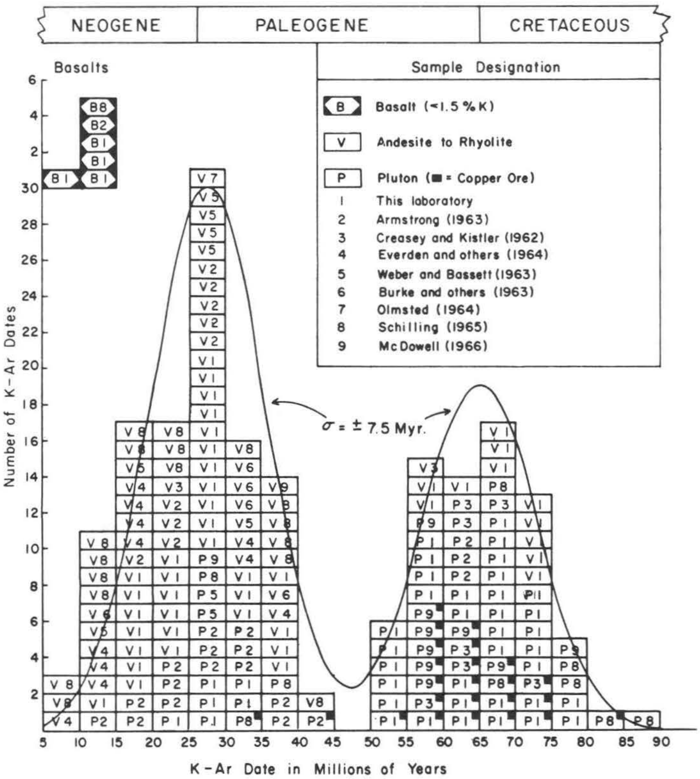

Figure 9 – Histogram of late Cretaceous–Cenozoic potassium–argon data for hypabyssal plutonic and volcanic rocks of the Basin and Range Province (after Damon and Mauger, 1966).

(5) Plutons associated with copper ore are distinguished by a darkened square in the upper right-hand corner of the unit box to indicate the temporal relationship between copper mineralization and plutonism.

As pointed out by Damon and Mauger (1966, p. 100), 'the resulting histogram provides a striking demonstration of the occurrence of two distinct episodes of magmatism during this time within the Basin and Range Province.' The pertinent characteristics of the histogram, with one exception, have not changed with the accumulation of more dates. They listed these characteristics as follows (p. 100):

(1) The data may be resolved, as a first approximation for reference, into two normal (Gaussian) distributions, each with a standard deviation (σ) of ±7.5 m.y.

(2) The distributions peak at the Paleogene–Neogene boundary and in late Cretaceous (Maestrichtian)–early Cenozoic (Paleocene) time.

(3) Over 90% of the dates comprising the earlier magmatic pulse fall within the limits of the classical Laramide, i.e. the time encompassed by the Laramie, Fort Union and Wasatch formations. The close time correlation between Laramide magmatism and the Laramide as defined stratigraphically is quite impressive. At least some of the spread in ages is due to precision limits for the analyses, about ±2.5 m.y. on the average, or one-half class interval of the histogram. All but a few of the K-Ar dates for magmatic rocks comprising the later pulse fall within the time encompassed by the Oligocene and Miocene epochs.

(4) There is magmatic quiescence during earliest Turonian through mid-Campanian time and again during middle to late Eocene time.

(5) There is a striking excess of dates over those of a simple normal distribution at the Paleogene–Neogene boundary. Furthermore, this is not the result of excessive sampling in one area. This excess seems to be indicative of prolific extrusion of magmas at this time throughout the Basin and Range Province.

(6) Basalts show up dominantly as Pliocene in age. Although the number of dates are few, field evidence points toward their extrusion as being a real and significant event which continued into Plio–Pleistocene time. Many mid-Tertiary rocks, which have been classified as basalts in the field, are actually alkali-andesites with a remarkably high potassium content (Halva, 1961; Mielke, 1965; Taylor, 1959).

(7) The Laramide is represented by more hypabyssal plutons than volcanics, whereas the opposite is true for the mid-Tertiary magmatic pulse. This may be due to two factors: stratigraphic elevation and subsequent depth of erosion.

(8) As a second approximation, the ages comprising the pulses are not perfectly normally distributed. The normal distribution, which serves as a reference for discussion, obviously obscures real and significant complexities. The histogram for each pulse is skewed towards younger ages. There seems to be a relatively quick onset of magmatism and a relatively slow relaxation.

With the accumulation of new data, point (8) no longer seems to be valid because the Laramide magmatic pulse has tended to more closely fit a Gaussian distribution. There still remains a tendency for an excess of magmatic events relative to a simple Gaussian distribution in late Miocene and early Pliocene time. Separate histograms are presented in figure 10 for the southern and northern Basin and Range Province and that part of the entire province which is at a distance greater than 160 miles from the margin of the Colorado Plateau. These histograms suggest that the departures from Gaussian symmetry are the result of more intense magmatism in the southern province between 25-30 m.y. and more prolific magmatism in the northern province during late Miocene–early Pliocene time. There are also fewer Laramide magmatic events dated within the northern province (see also Armstrong, 1966, p. 584) and at a great distance

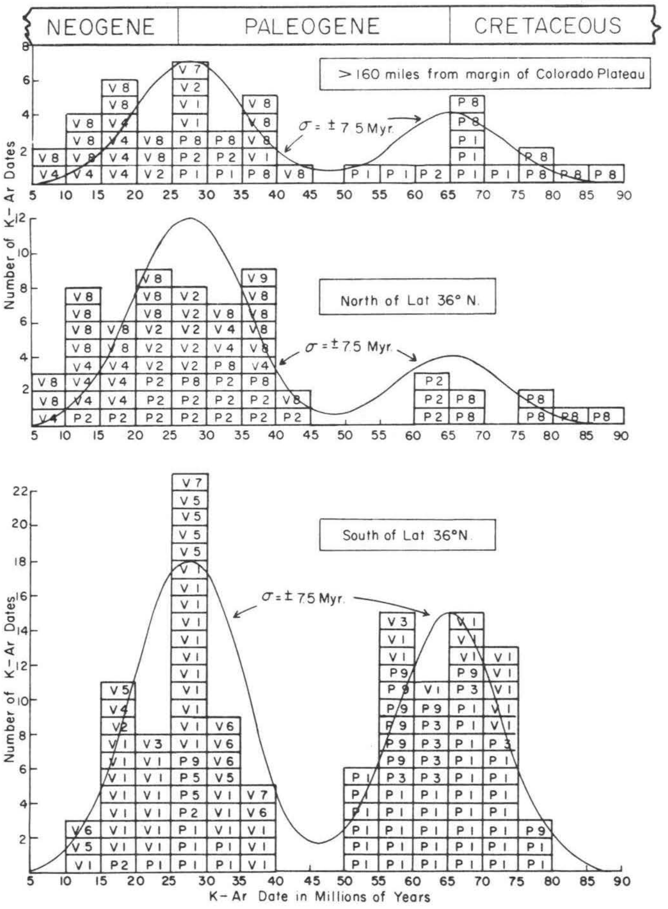

Figure 10 – Histograms of late Cretaceous–Cenozoic potassium–argon data for hypabyssal plutonic and volcanic rocks separately plotted for different regions within the Basin and Range Province.

from the Colorado Plateau. There remains the possibility that many Laramide magmatic rocks remain covered by the more recent flood of lava in the northern province.

Considering again the Basin and Range Province as a whole, in the words of Damon and Mauger, (1966, p. 100-101):

> 'there is a striking time relationship between magmatism and orogeny as evidenced by the stratigraphic record. Laramide magmatism is essentially confined within the classical Laramide as stratigraphically defined. During the Eocene, erosion and basin filling is correlative with the waning of magmatism and finally with magmatic quiescence during middle to late Eocene time. The mid-Tertiary magmatism was accompanied by Basin and Range tectonism (Gilluly, 1963; Osmond, 1960). Finally, Plio–Pleistocene basaltic volcanism postdates the major uplift of the ranges (e.g. see Osmond, 1960; Taylor, 1959).'

The postorogenic extrusion of basaltic lava may be the result of the cooling and rigidifying of the crust allowing the propagation of faults into the source region of the lava beneath the Mohorovicic boundary.

The relationship between Laramide magmatism and copper mineralization has also been discussed by Damon and Mauger (1966, p. 102-106). All of the dated late Mesozoic–Cenozoic copper porphyry deposits of the Basin and Range Province are Laramide with the possible exception of the Bingham, Utah deposit. The other mid-Tertiary pluton associated with a copper ore deposit, shown in figure 9, is the Railroad Mining District stock in the Piñon Range of Nevada dated by Armstrong (1966) at 33 m.y. on biotite. The Railroad Mining District ore deposit is a silver–lead–copper limestone-replacement body. Thus, with the exceptions noted, the late Mesozoic–Cenozoic copper porphyry deposits of the Province are concurrent with Laramide magmatism and there appears to be a genetic relationship between ore and igneous rock. According to Damon and Mauger (1966), K-Ar dating results indicate that 'whatever

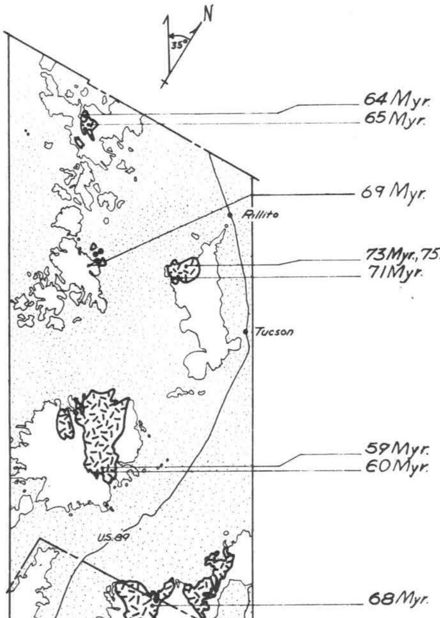

Figure 11 – Potassium–argon data for Laramide plutons along a 100-mile portion of Mayo's (1958) southwestern Arizona belt (scale = 1:735,000).

processes the genetic tie may involve, the age data require that these processes are restricted in time to the cooling history of the host porphyry' (p. 106).

Mayo (1958) has pointed out that the ore districts of the Southwest tend to occur along or at the intersection of structural lineaments. Using the K-Ar method we have dated plutons which are located along one of Mayo's lineaments, the southwestern Arizona belt. A 100-mile portion of this belt is shown in figure 11. The belt contains many Laramide plutons and ore districts that are from southeast to northwest: Cananea (20 miles south of the Arizona–Sonora border, 59 m.y. pluton), Patagonia–Duquesne, Helvetia, Pima, Amole, Silver Bell, Bagdad (170 miles NW, 71 m.y. pluton), and Mineral Park (250 miles NW, 72 m.y. pluton). The fact that the copper porphyry plutons were not randomly distributed in space and time is of considerable interest to geologists responsible for the designing of exploration programs.

Acknowledgments

This research was supported by the United States Atomic Energy Commission, Contract AT(11-1)-689, United States National Science Foundation Grant GP-3738, and the State of Arizona.

The author wishes to thank The Geological Society of America for permission to reprint Figures 14 and 15 from the *G.S.A. Bulletin,* Vol. 77, November 1966 (copyright 1966); and the Society of Mining Engineers of American Institute of Mining Engineers for permission to reprint Figures 21 and 22 from *Transactions AIME,* Vol. 235, March 1966 (copyright 1966).

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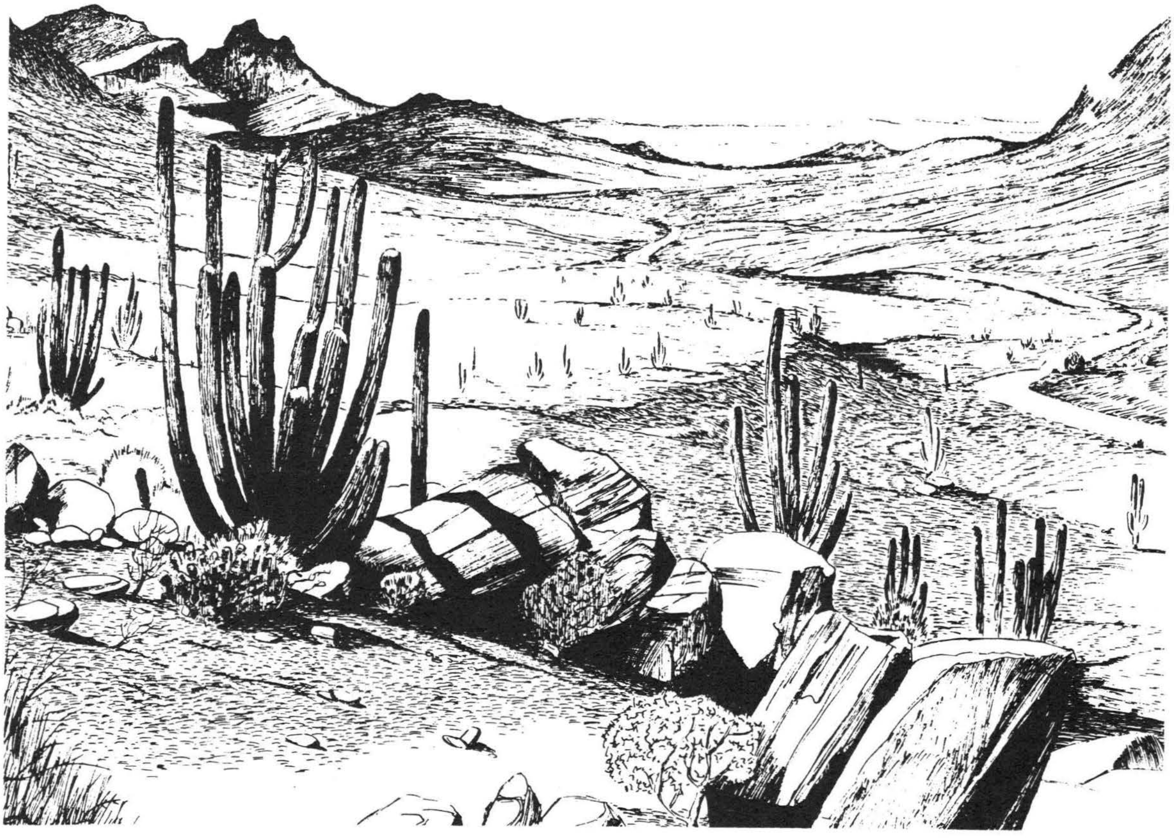

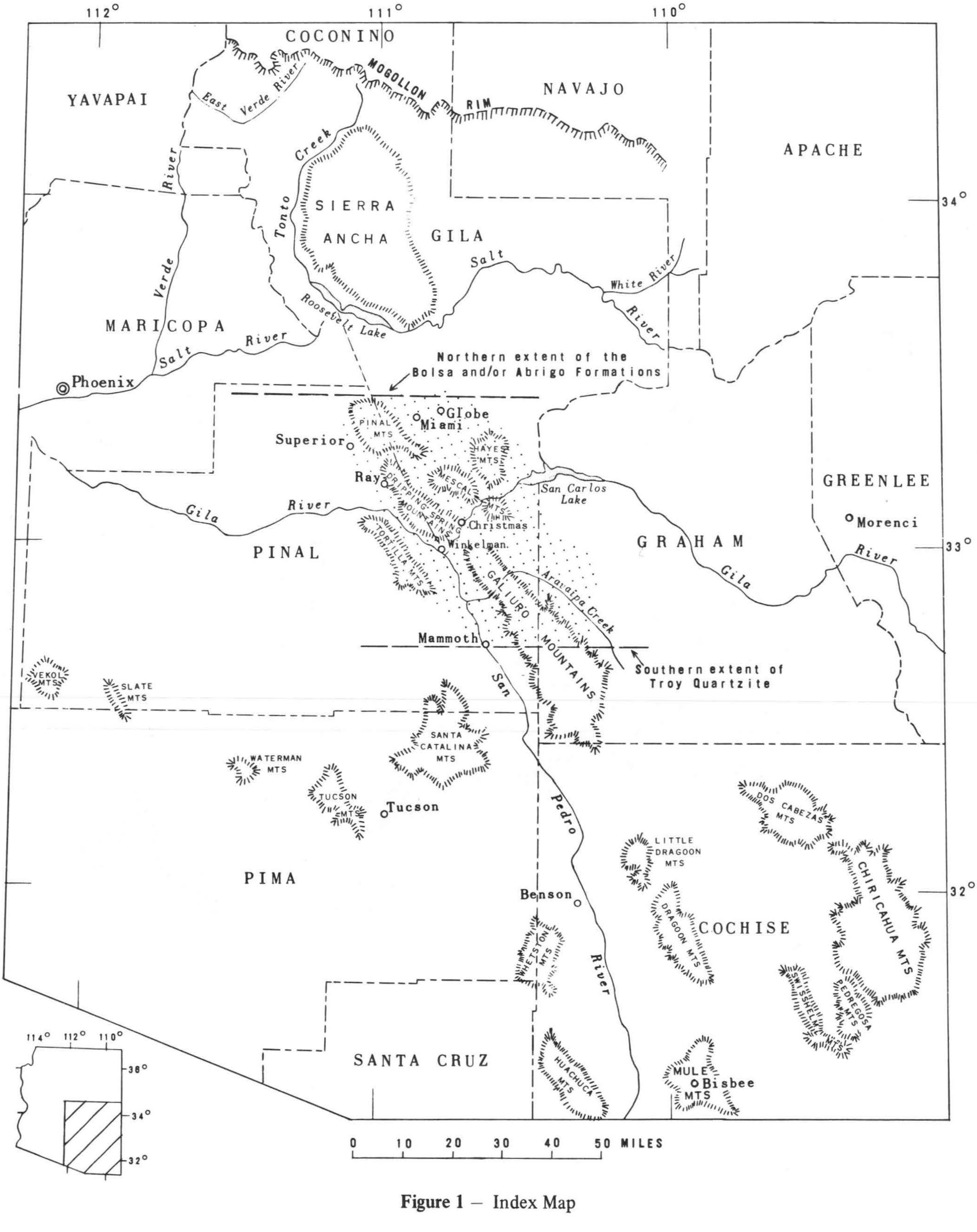

Figure 1 – Index Map

STRATIGRAPHIC RELATIONS OF THE TROY QUARTZITE (YOUNGER PRECAMBRIAN) AND THE CAMBRIAN FORMATIONS IN SOUTHEASTERN ARIZONA[1]

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TROY QUARTZITE

The Troy Quartzite was named by Ransome (1915) for exposures on Troy Mountain in the Dripping Spring Mountains near Ray (fig. 1). The thickest and most widespread exposures of the Troy, however, are between the Salt River and the Mogollon Rim, where it has been subdivided into three members (Shride, 1967).

The lower member is fine- to medium-grained pale-red firmly cemented arkose. It is present only in a local basin in the Sierra Ancha, where it is as much as 450 feet thick. The middle member is massive to thin-bedded, mostly medium- to coarse-grained white sandstone with a sericite-clay matrix. Many beds contain granules and small pebbles, mostly of quartz, that thickly coat or sparsely litter bedding surfaces. The character and distribution of pebbles and granules is one of the distinctive features of the member. Convolute laminations are also common. The middle member has a maximum thickness of about 250 feet north of the Salt River, but it thickens to at least 750 feet in the area south of Globe, where it comprises almost the entire thickness of the Troy (fig. 3). Between Superior and Mammoth the middle member contains less sericite-clay and is more quartzitic than it is to the north. The basal 50-100 feet is largely dark-colored coarse conglomerate. The upper member is light-gray medium-grained well-sorted, predominantly thin-bedded, crossbedded quartzite. It has a maximum thickness of about 500 feet in the Sierra Ancha, but becomes much thinner southward and is largely absent south of Globe because of erosion prior to deposition of the Middle Cambrian Bolsa Quartzite.

STRATIGRAPHIC RELATIONS OF THE TROY QUARTZITE, BOLSA QUARTZITE, AND ABRIGO FORMATION

The upper part of the Troy Quartzite of Ransome (1915, 1916) was regarded by Darton (1925) as equivalent to the Bolsa Quartzite and Abrigo Formation (Ransome, 1904), both of Cambrian age. Stoyanow (1936) erroneously referred to the Bolsa Quartzite in the northern Santa Catalina Mountains as the Troy Quartzite. As a result, until recently in the area north of the latitude of Mammoth, all strata between the younger Precambrian Apache Group and the Devonian Martin Formation (fig. 2) have been called Troy and considered to be equivalent to the Bolsa and Cambrian in age. In the area south of Globe, studies by Krieger (1961, 1968a-d), D. W. Peterson (1962), and Willden (1964) demonstrated that the Troy, as formerly mapped, consists of both a younger Precambrian part and the Bolsa and(or) Abrigo Formations. A. F. Shride (oral commun., 1960; see also Shride, 1967) has shown that most of what Ransome called Troy in the Dripping Spring Mountains, as well as almost all of it north of Globe, is Precambrian in age. The name Troy, therefore, is now restricted to the Precambrian part (Krieger, 1961). These studies have also shown that after deposition of the Troy (restricted), the younger Precambrian sedimentary rocks were intruded by large sills of diabase and extensively eroded prior to deposition of the Bolsa Quartzite.

Between Globe and Mammoth (fig. 1, stippled area; fig. 3) both the Precambrian Troy Quartzite and the Cambrian Bolsa and Abrigo Formations are present. South of Mammoth no Troy remains. North of Globe neither the Bolsa nor the Abrigo have been recognized. However, some of the basal Paleozoic sandstones have been tentatively correlated with the Cambrian Tapeats Sandstone of the Grand Canyon area (Finnell, 1966, and written commun., 1967). Other unfossiliferous sandstones underlying the Devonian Martin Formation in the area north of Globe are considered basal Martin (Shride, 1967; Teichert, 1965). In the area of overlap (fig. 1, stippled area) erosional remnants of the Troy are overlain in some places by the Bolsa Quartzite; in others, by one of the members of the Abrigo Formation (fig. 5) or by the Martin Formation (figs. 3, 4). Local absence of the Cambrian formations in this area and their complete absence north of Globe is due partly to nondeposition and partly to pre-Martin erosion. Local absence of the Troy in the area of overlap, and its complete absence

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

Devonian		Martin Formation
		UNCONFORMITY
Cambrian		Abrigo Formation
		Bolsa Quartzite
		MAJOR UNCONFORMITY
Younger Precambrian		Diabase
		Troy Quartzite
		UNCONFORMITY
	Apache Group	Mescal Limestone (basalt flows at and near top)
		Dripping Spring Quartzite Barnes Conglomerate Member
		Pioneer Formation Scanlan Conglomerate Member
		ANGULAR UNCONFORMITY
Older Precambrian		Granitic to dioritic rocks
		Pinal Schist

Figure 2 – Stratigraphic nomenclature of Precambrian and lower Paleozoic rocks in southeastern Arizona

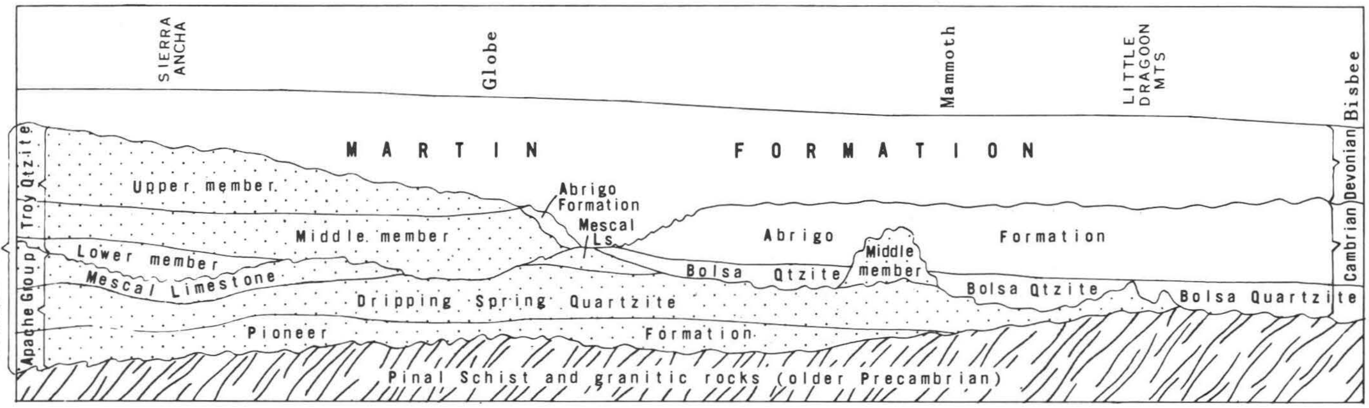


Figure 3 – Stratigraphic relations between the Sierra Ancha and Bisbee, Arizona

for some distance, at least, south of Mammoth, is due to pre-Bolsa erosion.

The distribution of younger Precambrian strata (Troy Quartzite and Apache Group) at the time of deposition of the lower Paleozoic formations was caused by (1) variable inflation of the strata by intrusion of sills of Precambrian diabase, (2) pre-Bolsa erosion, and (3) in northern outcrops, post-Abrigo pre-Martin erosion (fig. 4). The younger Precambrian rocks were not measurably tilted either by the intrusion of diabase, or by the faults that were largely induced by the intrusion of diabase (Shride, 1967). Thus the Cambrian or Devonian rocks in most places paraconformably overlie the younger Precambrian strata. As a result of the concordant attitudes, the hiatus between the younger Precambrian and Cambrian rocks in many places is not easily recognized, in spite of the fact that it represents a significant interval in time. Also, the large sills of diabase were for many years believed by most workers (except Darton, 1925, p. 254, 257) to be related to dark dikes that cut the Paleozoic rocks (Peterson, N. P., 1962; Ransome, 1903, 1919).

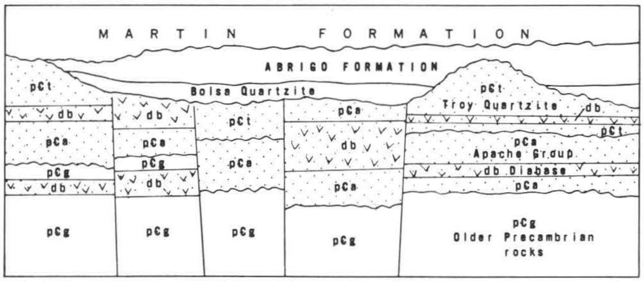


Figure 4 – Diagrammatic sketch

Isotopic and field data are now at hand to prove that the large diabase sills are Precambrian in age. A diabase sill intruded into the Troy Quartzite has yielded lead-isotope ratios in zircon and uraninite (Silver, 1960) and potassium-argon ratios in biotite (Damon and others, 1962; S. C. Creasey, oral commun., 1966), which indicate ages of 1,200 million years and 1,140 million years, respectively.

Shride (1958, 1967) recognized that a zone of regolithic material was found wherever the Martin rests on diabase, proving that the diabase is pre-Martin in age. Similar zones of regolith or of transported regolith have since been found beneath Cambrian strata farther south (Creasey, 1967a; Krieger, 1961, 1968a-d; Peterson, D. W., 1962). Thus the Troy Quartzite is at least half a billion years older than the Cambrian rocks.

The prolonged erosion that followed intrusion of the diabase resulted in a surface largely of low relief, so that in the area of overlap the Bolsa Quartzite was laid down in some places on deeply weathered diabase and in others on Troy Quartzite or on rocks of the Apache Group. Here and there isolated monadnocks stood above the general surface and the Abrigo Formation was deposited on younger Precambrian rocks (fig. 5). North of Mammoth, the Martin Formation rests locally on younger Precambrian rocks because of nondeposition of Cambrian rocks combined with extensive erosion of post-Abrigo age.

CAMBRIAN STRATIGRAPHY

The Bolsa Quartzite is the basal Cambrian unit in most of southeastern Arizona (fig. 3) and is conformably overlain by the Abrigo Formation. Both were named by Ransome (1904) for exposures in the Bisbee area. South of the Little Dragoon Mountains the Bolsa rests on older Precambrian crystalline rocks on a surface of low relief (Gilluly, 1956; Hayes and Landis,

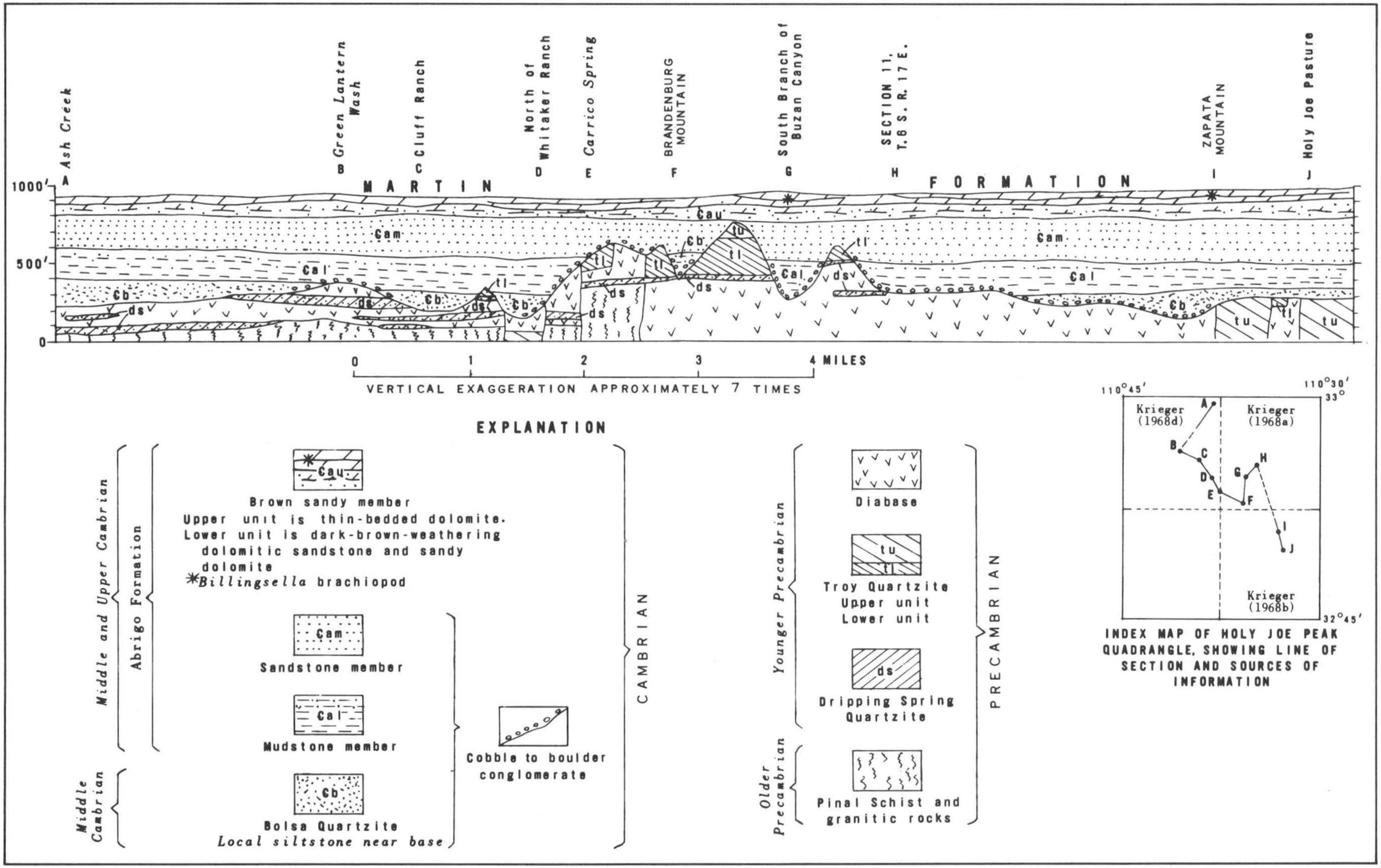


Figure 5 — Stratigraphic relations between Ash Creek and Holy Joe Pasture, Arizona

1965). In and northwest of the Little Dragoon Mountains it rests on younger Precambrian rocks on a surface that has considerable local relief (Cooper and Silver, 1964; Creasey, 1967a). Between Mammoth and Globe it is absent in places, owing to nondeposition (fig. 4). The Abrigo was deposited at these localities on younger Precambrian rocks (Krieger, 1968a-d). North of Winkelman, pre-Martin erosion locally removed part or all of the Cambrian rocks that had been deposited (figs. 3 and 4). In this area the Martin rests on the lower part of the Abrigo, on the Bolsa, or on younger Precambrian rocks (Shride and Krieger, unpublished data; Willden, 1964; Peterson, D. W., 1962 and oral commun., 1967).

BOLSA QUARTZITE

The Bolsa Quartzite consists of yellowish- and pinkish-gray to pale- and grayish-red, brown-weathering quartzite or firmly cemented sandstone. The tabular beds, separated by shaly or silty partings, range in thickness from 1 inch to about 5 feet and average about 2 feet. Much of the formation is crossbedded. The texture and composition of the Bolsa change rather systematically from coarse grained and feldspathic in the lower part to fine grained and nonfeldspathic in the upper part.

In most areas the lower third of the formation is medium to coarse grained with local concentrations of granules. The middle part of the formation is mostly medium to fine grained. The upper part is mostly fine to very fine grained with increasing amounts of siltstone upward. In and north of the Little Dragoon Mountains, where the lower coarse-grained beds are locally missing because of onlap, the fine-grained upper beds of the Bolsa rest on younger Precambrian rocks or are separated from them by a few feet of red siltstone or pebble to boulder conglomerate.

A conglomerate (0-50 feet thick) forms the basal part of the Bolsa in many places. It contains pebbles of quartz and quartzite, and locally of schist and granite. In and north of the Little Dragoon Mountains the basal conglomerate, where it rests on diabase, is red and contains cobbles and boulders of quartzite. The red color is due largely to abundant regolithic material derived from diabase. Associated with this conglomerate are local areas of red siltstone and fine-grained silty sandstone. Local accumulations of red siltstone as much as 100 feet thick have been reported in the Santa Catalina Mountains and near Superior (Creasey, 1967a; Peterson, D. W., 1962 and oral commun., 1967). Similar siltstone and conglomerate are common where the Abrigo overlies the diabase (Krieger, 1968a, d).

ABRIGO FORMATION

The Abrigo Formation gradationally overlies the Bolsa Quartzite. Three members, all of regional extent, are recognized by the author (figs. 6 and 7). The lower member is mostly mudstone. The middle member is largely limestone in Cochise County. It grades laterally into sandy dolomite in the northern Santa Catalina Mountains, and into sandstone north of Mammoth. The upper member is divided into a lower unit of dolomitic sandstone and sandy dolomite and an upper unit of dolomite or limestone that is absent in many places because of pre-Martin erosion. Intraformational conglomerates are characteristic of most of the Abrigo Formation, especially south of the latitude of Mammoth. Although the lower member contains more sand and less carbonate in northern outcrops, it can easily be recognized regionally. The upper member, especially the lower unit, is essentially the same wherever present. Recognition of the sandstone facies of the middle member in northern outcrops has been helpful in unraveling regional stratigraphic relations of the Abrigo.

Some authors have subdivided the Abrigo into three or four members and given the members lithologic or locality names. The terminologies used by various authors are shown in figure 6. Because of facies changes, particularly in the middle member, general terms such as lower, middle, and upper are preferred in discussing regional relations.

Lower Member

The lower member is dominantly pale-yellowish-brown to olive-gray, brown-weathering sandy mudstone, claystone, and siltstone with some beds of carbonate and sandstone. Beds are characteristically thin; bedding surfaces are very irregular. The carbonate in the member in much of Cochise County is very fine grained gray limestone interlaminated and interbedded with mudstone. Limestone is more abundant in the upper part of the member. In the Little Dragoon Mountains the carbonate beds in the basal 100 feet of the member consist of brown dolomite. All the carbonate in and north of the northern Santa Catalina Mountains is dolomite. North of Mammoth, dolomite is inconspicuous in most of the member. The amount and coarseness of sand, especially in the upper part of the member, increases from south to north.

Middle Member

The middle member of the Abrigo Formation consists of two distinct facies: (1) limestone in Cochise County west of the Dos Cabezas and Chiricahua Mountains; and (2) sandstone north of Mammoth, with a transitional zone of sandy dolomite and dolomitic sandstone north of the latitude of Tucson.

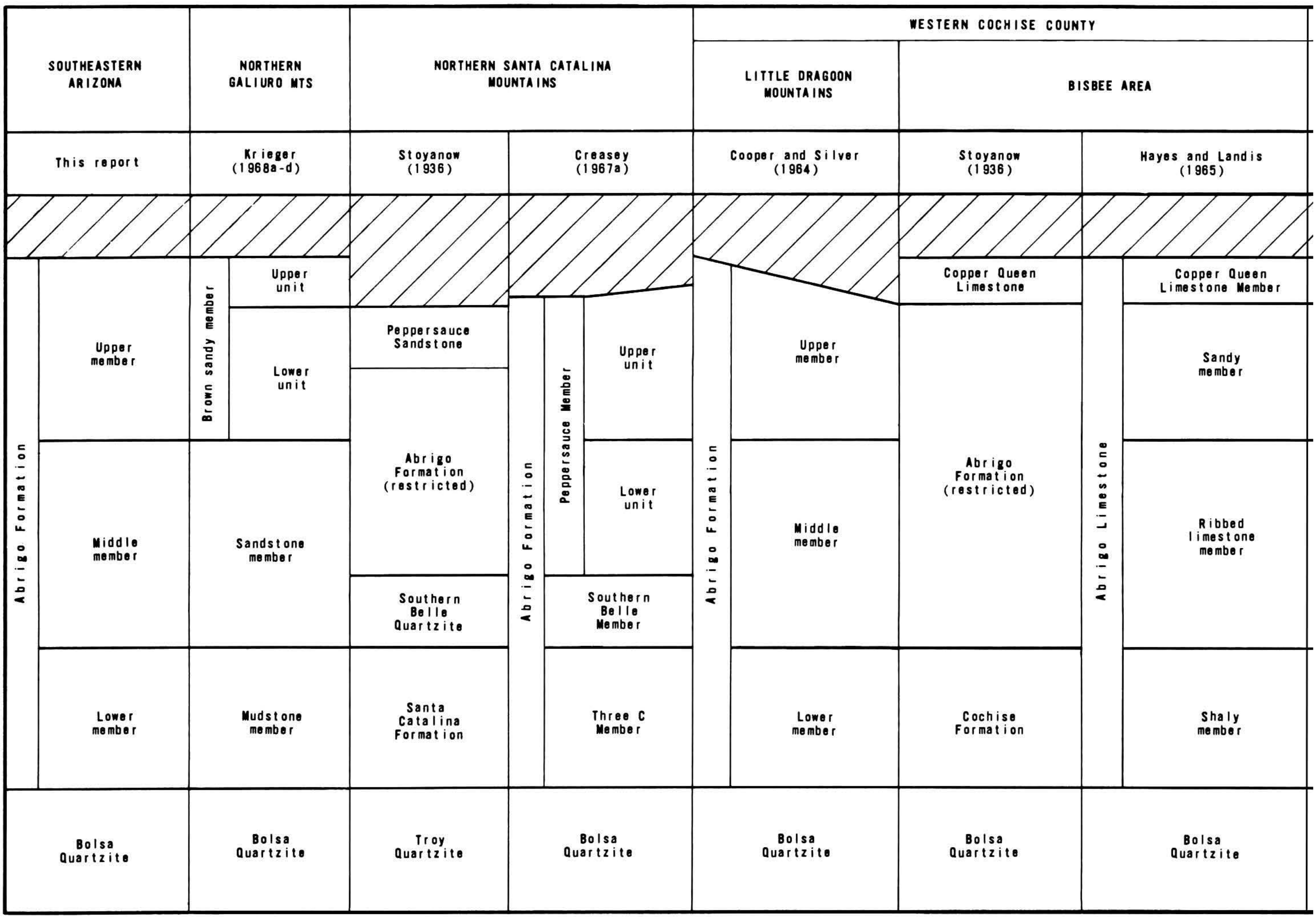


Figure 6 — Correlation chart of Cambrian and Ordovician Stata in southern Arizona and southwestern New Mexico

Limestone Facies.—The middle member in most of Cochise County is thin-bedded, very fine-grained, light-gray limestone. It has a ribbed appearance caused by differential weathering of the abundant, irregular, anastomosing layers or wispy laminae of light-brown-weathering, more resistant mudstone or silty limestone. In the area between the latitudes of Tucson and Mammoth the member is very thin-bedded, very fine-grained, brown dolomitic sandstone and sandy dolomite.

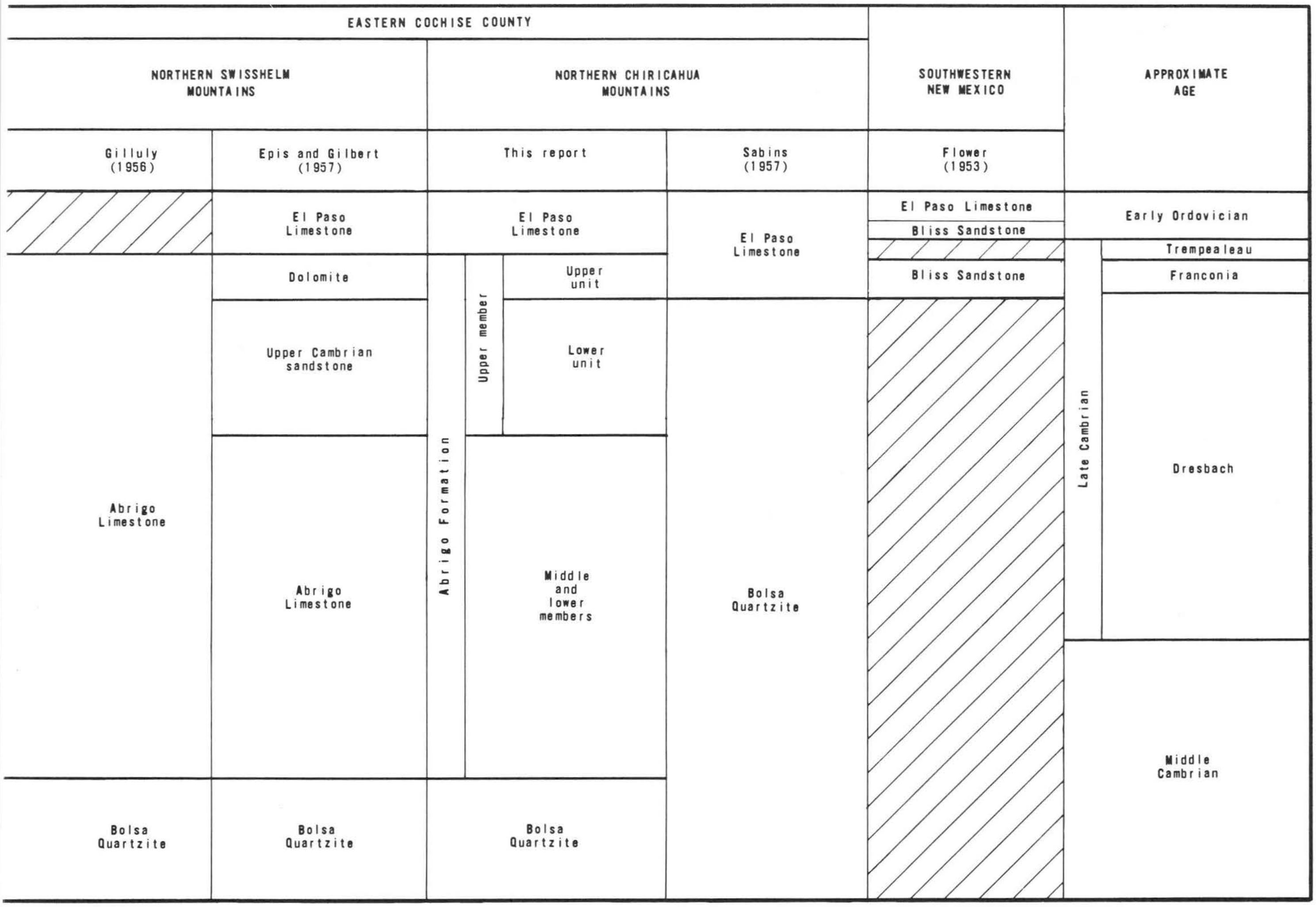
Sandstone Facies.—North of Mammoth the middle member consists entirely of thin-bedded light-colored sandstone with partings of sandy siltstone and shale. The southern margin of this sandstone crops out a short distance northwest of the Little Dragoon Mountains (fig. 7), where it is placed at the top of the lower member (Cooper and Silver, 1964). It is correlated with the 65-foot Southern Belle Member (fig. 6) of Creasey (1967a) in the northern Santa Catalina Mountains.

Upper Member

The upper member consists of two units, but as a result of pre-Martin erosion, the upper unit is thin or absent in many places between Bisbee and the Santa Catalina Mountains. North of the latitude of Winkelman and in the Tortilla Mountains (Krieger, unpublished data), no remnants of the upper member have yet been reported.

Lower Unit.—The lithology of the lower unit is recognizable regionally in southeastern Arizona. The unit consists largely of coarse-grained crossbedded glauconitic dark-brown-weathering dolomitic sandstone and sandy dolomite. Beds are mostly a foot or more thick, in contrast to the generally thinner beds of the strata above and below the unit.

Upper Unit.—In most places the upper unit consists of brown, buff- to gray-weathering, mostly thin-bedded, medium-grained dolomite and some sandy dolomite and glauconitic beds. At Bisbee (fig. 5) the



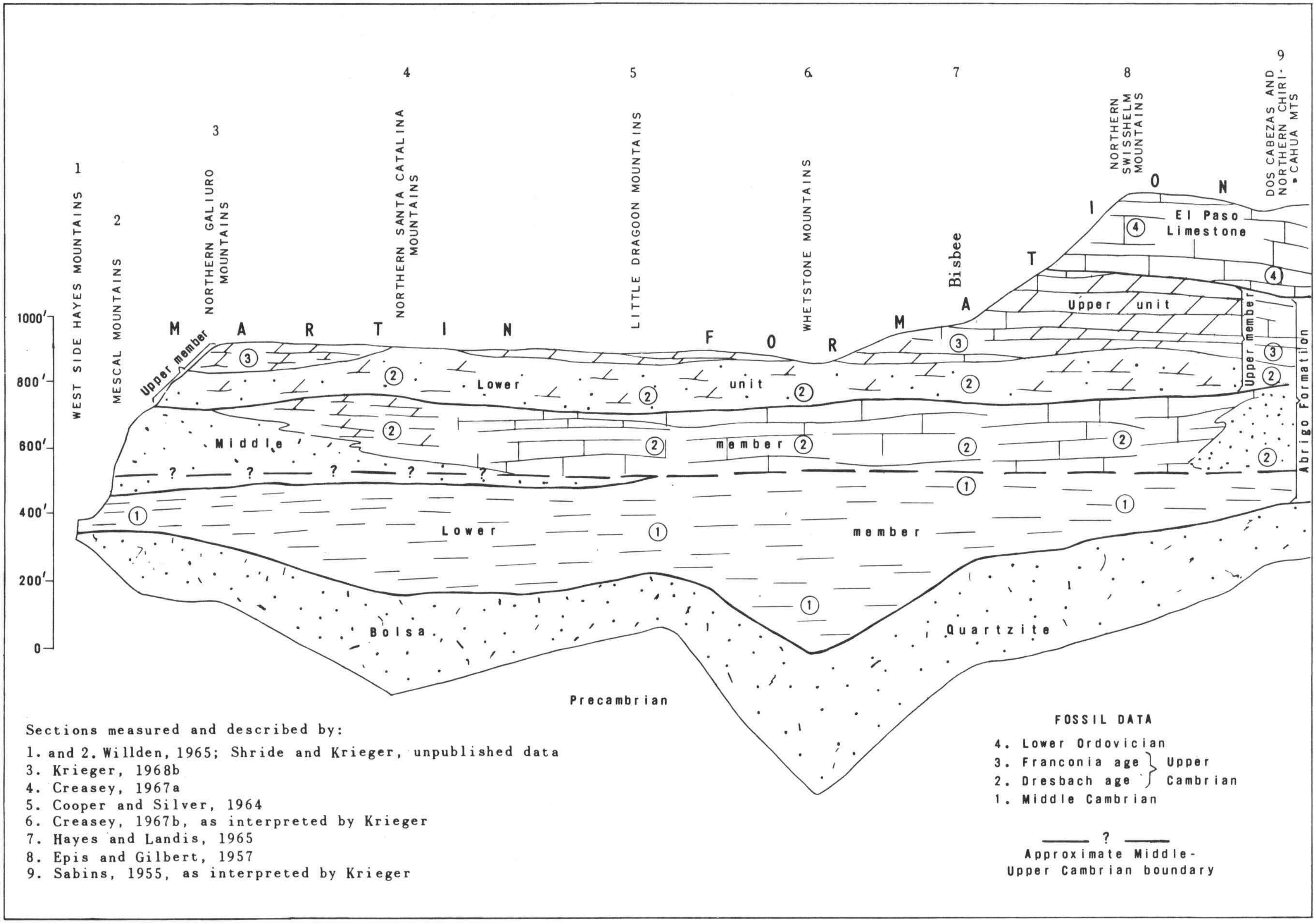
unit is called the Copper Queen Limestone Member (Hayes and Landis, 1965) and consists mostly of thin-bedded medium-grained limestone. In the Little Dragoon Mountains the unit, where present, is limestone in some places and dolomite in others (Cooper and Silver, 1964). In the northern Galiuro Mountains (fig. 5) and in eastern Cochise County (fig. 7), all the carbonate is dolomite.

Biologic Features

Features largely, if not wholly, of biologic origin are abundant in the Abrigo Formation. They consist of swish marks, fucoids, *Scolithus*, and tracks, some made by trilobites, and others of unknown origin. Most of the Bolsa Quartzite is devoid of these features, but fucoids and *Scolithus* occur locally and are common in the transitional zone at the top. Phosphatic brachiopods, recognizable in many places only as white crescents in hand specimen, are common in much of the Abrigo Formation. They are especially abundant and characteristic of the lower member and the lower unit of the upper member in northern outcrops. They also occur sporadically at the top of the Bolsa in beds transitional to the Abrigo. The trace fossils are helpful in distinguishing isolated outcrops of Cambrian sandstone from those of the Troy Quartzite. The phosphatic brachiopods aid in distinguishing the Abrigo Formation from all except the transitional beds at the top of the Bolsa. Index fossils, such as trilobites and the brachiopod *Billingsella,* have been found only in the Abrigo Formation.

AGE AND CORRELATION OF CAMBRIAN STRATA

The Abrigo Formation ranges in age from late Middle Cambrian through the early two-thirds of the Late Cambrian (Stoyanow, 1936; Palmer, A. R., in Gilluly, 1956 and in Cooper and Silver, 1964; Hayes and Landis, 1965). The Bolsa is inferred to be Middle



Sections measured and described by:

1. and 2. Willden, 1965; Shride and Krieger, unpublished data
3. Krieger, 1968b
4. Creasey, 1967a
5. Cooper and Silver, 1964
6. Creasey, 1967b, as interpreted by Krieger
7. Hayes and Landis, 1965
8. Epis and Gilbert, 1957
9. Sabins, 1955, as interpreted by Krieger

Figure 7 – Cambrian–Ordovician relations between Hayes Mountains and Dos Cabezas Mountains, Arizona

Cambrian in age because it conformably and gradationally underlies the Abrigo. Middle Cambrian fossils have been found in the lower member of the Abrigo in Cochise County, northern Santa Catalina Mountains, Mescal Mountains, and on the west side of the Hayes Mountains. Early Late Cambrian (Dresbach age) fossils have been found in the middle member and lower unit of the upper member of the Abrigo in Cochise County and the northern Santa Catalina Mountains. The middle Late Cambrian (Franconia age) brachiopod *Billingsella* has been found near the base of the upper unit of the upper member in widely scattered localities in Cochise County and in the northern Galiuro Mountains. The fossil and lithologic evidence, summarized in figure 7, suggests that the Bolsa and lithologic units of the Abrigo are, for the most part, time-conformable, at least in the north-northwest-trending belt that extends from Bisbee and the Southern Pedregosa Mountains to the Globe-Superior area.

In southwestern New Mexico the Bliss Sandstone (fig. 6) of Late Cambrian and Early Ordovician age was deposited on Precambrian rocks and is overlain by the El Paso Limestone of Early Ordovician age. Carbonate rocks containing Lower Ordovician fossils have also been found overlying the Abrigo in a few places in eastern Cochise County. Because of the stratigraphic relations and general lithologic similarities of the Bolsa to the Bliss and the Abrigo to the El Paso, the Bolsa and Abrigo have been considered time-transgressive units laterally continuous with the Bliss and El Paso (Sabins, 1957; Lochman-Balk, 1956; Kelley and Silver, 1952). However, Epis and Gilbert (1957) pointed out that the Bolsa in the northern Swisshelm Mountains is separated from the Cambrian and Ordovician strata by the Abrigo Limestone (fig. 6). They also showed that the Abrigo Limestone (lower and middle members of this report) is separated from the El Paso Limestone by their Upper Cambrian sandstone and the overlying dolomite that contains *Billingsella.* These two units make up the upper member of the Abrigo Formation of this report. In the southern Pedregosa Mountains, Epis (1958) describes a sequence of Cambrian strata that is similar to that in the northern Swisshelm Mountains. However, he reported considerably more sand and less carbonate in the part of the section that I am calling the middle member of the Abrigo. In the Dos Cabezas and northern Chiricahua Mountains, a thick section (465-600 feet) of largely sandy strata was called the Bolsa Quartzite, and the overlying carbonate strata (340-445 feet thick) were called the El Paso Formation by Sabins (1957). The sections as described in his unpublished thesis (F. F. Sabins, 1955) may be interpreted as shown in figure 6 (left-hand column, Chiricahua Mountains) and figure 7. Sabins described the lower 200 feet of the section in the Chiricahua Mountains as massive, thick-bedded, coarse- to medium-grained quartzite that is commonly arkosic in the basal 100 feet and conspicuously crossbedded at some horizons. This description fits in a general way the Bolsa as known throughout most of southeastern Arizona. Above the cliff-forming quartzite are about 100 feet of slope-forming thin-bedded brown to green siltstone and shaly sandstone. Beds of this sort have not been assigned to the Bolsa in the rest of southeastern Arizona. They appear to be similar to much of the lower member of the Abrigo north of Mammoth. The rest of Sabin's "Bolsa" section is largely sandstone, most of which can perhaps be correlated with the sandstone facies of the middle member of the Abrigo in northern outcrops. The top of his "Bolsa" is dark-brown-weathering glauconitic sandstone that is typical of the lower unit of the upper member of the Abrigo throughout southeastern Arizona. The base of the overlying carbonate beds contains the brachiopod *Billingsella.* Epis and Gilbert (1957) correlated these beds with the dolomite at the top of the Cambrian section in the northern Swisshelms. The greater amount of sand in what I interpret to be the middle member of the Abrigo in the Dos Cabezas and Chiricahua Mountains is probably due to proximity to the eastern margin of the Cambrian basin of deposition. The situation appears to be quite similar to that north of the Santa Catalina Mountains, where the middle member is sandstone.

The Bliss Sandstone in southwestern New Mexico (Flower, 1953, 1955; Kottlowski and others, 1956) is lithologically very similar to the lower unit of the upper member of the Abrigo in southeastern Arizona. However, the Bliss is Franconia (middle Late Cambrian) and Lower Ordovician in age, whereas the lithologically similar part of the Abrigo is upper Dresbach (early Late Cambrian) in age.

Thus, although the Bolsa and Abrigo are essentially time-stratigraphic units in a belt trending north-northwestward from southern Cochise County to the Globe-Superior area, the preliminary data indicate that the upper part of the Abrigo may be slightly time-transgressive east of this belt. The Bolsa Quartzite and Abrigo Formation crop out in mountain ranges west of Tucson (McClymonds, 1959). Fossil and lithologic data, however, are insufficient to determine whether the Bolsa and Abrigo are time-stratigraphic or time-transgressive from west to east.

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DIAGNOSTIC CHARACTERISTICS OF THE PALEOZOIC FORMATIONS OF SOUTHEASTERN ARIZONA

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INTRODUCTION

In southeastern Arizona a major portion of the Paleozoic sequence is dominantly limestone. The limestones composing the middle and upper part of this sequence are mostly various shades of gray, and in many localities are so similar that it is sometimes difficult, without detailed examination, to differentiate them. The purpose of this paper is to outline those distinguishing lithologic and faunal aspects of the Paleozoic formations that will permit their identification in the field, particularly in isolated outcrops. For each of the formations, readily accessible localities of outcrop and selected references are listed. One general and indispensable paper which includes names and thicknesses of formations, very brief descriptions of some, and an extensive bibliography is "A résumé of the geology of Arizona," by E. D. Wilson.

West of Sulphur Spring Valley (Fig. 1) the various formations are relatively uniform in thickness and lithology. East of Sulphur Spring Valley, however, many of the formations change markedly, and numerous formations or notable facies changes appear that are distinct from those to the west. For simplicity, therefore, the areas to the west of Sulphur Spring Valley are designated the *western area*; the areas to the east are designated the *eastern area* in which are the Dos Cabezas, Chiricahua, Pedregosa, Peloncillo, Swisshelm and southwestern Guadalupe Mountains, and the Clifton-Morenci district.

CAMBRIAN SYSTEM

Bolsa Quartzite

The basal formation of the Paleozoic sequence is the Bolsa Quartzite of presumed Middle and, in the eastern area, Late Cambrian Age from which Sabins (1957a, p. 471) reported trilobites and brachiopods from the Chiricahua and Dos Cabezas Mountains of southeastern Arizona. North of the Gila River lingulid brachiopods of Middle Cambrian Age have been collected from what was previously described as Troy Quartzite (Stoyanow, 1936, p. 475), but is now considered Bolsa. The Troy-Bolsa problem is discussed in detail by Krieger (1961), Shride (1961), and Krieger, (this guidebook). In the Clifton-Morenci district the Coronado Quartzite of Lindgren (1905, p. 59) is without doubt equivalent to the Bolsa Quartzite and is so designated today.

The Bolsa is typically brown to reddish brown but in many localities parts of the formation are nearly white. The formation is generally a resistant quartzite, mostly evenly bedded but locally notably crossbedded. The thickness ranges from about 400 to 700 feet (130-300 m). In the lower part it is more feldspathic and coarser grained than in the more quartzitic, finer grained upper part. Conglomerate beds are abundant, more so in the lower part, and in some localities there are cobbles up to several inches in diameter.

The Bolsa tends to form cliffs or steep rubbly slopes which are covered in many places with *Agave schottii*, the "shin-stabber". This little agave is widespread but prefers siliceous rocks where it thrives particularly well.

References—Cooper & Silver, 1964; Creasey, 1967a & 1967b; Epis & Gilbert, 1957; Gilluly, 1956; Hayes & Landis, 1965; Krieger, 1961; McClymonds, 1959a & 1959b; Sabins, 1957a; Stoyanow, 1936.

Accessible localities—Readily accessible localities in southeastern Arizona in which the Bolsa can be examined are the following:

Twin Buttes area, Mineral Hill just north of the entrance to the Banner Mining Company office on Twin Buttes Road (Fig. 2). (SE¼ SW¼ sec. 35, T. 16 S., R. 12 E., Twin Buttes 15′ quadrangle).

Colossal Cave area, at the entrance to the Posta Quemada (or Day) ranch, just north of where the road from Vail to Colossal Cave swings north at the southeast end of Pistol (or Beacon) Hill (Fig. 3). (NE¼ SE¼ sec. 7, T. 16 S., R. 17 E., Rincon Valley 15′ quadrangle).

Mule Mountains, on US 80 about 1 mile north of junction with State 90, east of the highway and across the wash (Fig. 4). (SE¼ SW¼ sec. 16, T. 22 S., R. 23 E., Tombstone 15′ quadrangle).

Helvetia, western slopes of hills north of the old

ghost town. (C S½ sec. 15, T. 18 S., R. 15 E., Sahuarita 15′ quadrangle).
Courtland, on the road to Pearce just north of Courtland on both sides of the road. (So. cen. SW¼ sec. 16, T. 19 S., R. 25 E., Pearce 15′ quadrangle).
Dragoon Mountains, low hills east of the mouth of Stronghold Canyon (Fig. 6). (NE¼ sec. 24, T. 17 S., R. 23 E., Pearce 15′ quadrangle).
Sulphur Spring Valley, about a mile on the dirt road off of the Rucker Canyon Road about 4 miles east of the turnoff from US 666. (SW¼ sec. 6, T. 19 S., R. 27 E., Squaretop Hills 15′ quadrangle).
Dos Cabezas Mountains, Bolsa extends all along the southwest side of State 186 from about 2 miles west and 2 miles east of the town of Dos Cabezas, and crosses the outcrop about 4 miles southeast of town. (Fig. 12).
Chiricahua Mountains, north end of Blue Mountain about 10 miles north of Portal on the road to San Simon, about ½ mile west of road (Fig. 5). (C W½ sec. 20, T. 26 S., R. 31 E., Vanar 15′ quadrangle).

Abrigo Formation

The Abrigo Formation includes several units that were proposed as formations by Stoyanow (1936, p. 466) which are now considered as members or facies of the Abrigo. These are the Pima Sandstone, Cochise Formation, Copper Queen Limestone, Rincon Limestone, Southern Belle Quartzite, and Peppersauce Canyon Sandstone.

The Abrigo is of Middle and Late Cambrian Age, lying conformably on the Bolsa. Lithologically the Abrigo contains a heterogeneous assemblage of limestone, dolomite, sandstone, siltstone, and shale, typically thin to medium bedded. Colors are bluish, greenish or yellowish gray, commonly weathering rather dark. Numerous fossils, especially trilobites and brachiopods, have been collected from the various units of the Abrigo, but in most localities fossils are rather scarce. Where completely developed, the Abrigo ranges from about 600 to 800 feet (200-270 m) thick.

The most prominent features of the Abrigo that permit its ready identification are the alternation of relatively thin beds of clastic and carbonate rocks in which the bedding is wavy or gnarly, and intraformational flat-pebble or edgewise conglomerates, common throughout the formation. The alternation of less resistant clastic rocks and more resistant carbonate rocks commonly results in a ribbed weathered surface, quite distinct from that yielded by any other formation in the Paleozoic sequence. The Abrigo is a relatively non-resistant formation, and with the overlying Martin Formation, forms topographic lows or saddles between the resistant Bolsa and Escabrosa.

References–Cooper & Silver, 1964; Creasey, 1967a & 1967b; Epis & Gilbert, 1957; Gilluly, 1956; Hayes & Landis, 1965; Krieger, 1961; McClymonds, 1959a & 1959b; Stoyanow, 1936.

Accessible localities:
Colossal Cave area, in the flats a few hundred yards north of the Bolsa outcrops (Fig. 3).
Twin Buttes area, east of the Bolsa in the low saddle between the hills (Fig. 2).
Dragoon Mountains, at the entrance to Stronghold Canyon, overlying the Bolsa to the northeast (Fig. 6). (NW¼ NW¼ sec. 19, T. 17 S., R. 24 E., Pearce 15′ quadrangle).
Mule Mountains, along the east side of US 80 for about a mile north of the junction with State 90 (Fig. 4).
Bisbee area, in Black Gap just south of Warren on the road to Bisbee Junction (Fig. 7). (NW¼ sec. 26, T. 23 S., R. 24 E., Bisbee 15′quadrangle).
Santa Catalina Mountains, Peppersauce Wash, a few hundred yards up the wash to the west from the Mt. Lemmon Road (Fig. 9). (NW¼ NW¼ sec. 28 (unsurv), T. 10 S., R. 16 E., Mammoth 15′ quadrangle.)

CAMBRIAN-ORDOVICIAN SYSTEMS (EASTERN AREA)

Ordovician fossils were recognized many years ago in the Clifton-Morenci district in the "Longfellow limestones" of Lindgren (1905, p. 62; Stoyanow, 1936, p. 484). Much of the Longfellow resembles the Abrigo in color, bedding and composition.

In the western foothills of the Dos Cabezas Mountains west of the village of Dos Cabezas there is a long ridge of lower and middle Paleozoic rocks. At this locality the lowest formation of the Paleozoic sequence is the Bolsa Quartzite and overlying the Bolsa are about 350 feet (110 m) of limestone, dolomite, and siltstone. Darton (1925, p. 296) wrote, "The limestone beds under the Martin had all the characteristics of the Abrigo beds at Bisbee, but Ordovician fossils were found in the upper beds. Most of the limestone of the formation has slabby bedding, weathers to a light blue gray color and has brown reticulating stems of a supposed seaweed on many of the bedding planes. In these peculiarities it resembles the El Paso limestone of southwestern New Mexico, as well as the Abrigo, Longfellow and Muav limestones."

In the Chiricahua Mountains the formation between the Bolsa Quartzite and the overlying Devonian beds was assigned to the El Paso Limestone by Sabins (1957a, p. 472). He stated (p. 475), "The El Paso and the Abrigo formations are lithologically similar and occupy identical stratigraphic intervals and are probably laterally continuous. The Abrigo is older than the El Paso. . .the name El Paso is here extended into Arizona for the rocks of the same age and lithofacies, in preference to using Abrigo limestone which is the same lithofacies, but is older." At Blue Mountain the El Paso is about 450 feet (150 m) and near Portal about 715 feet (235 m) thick.

In the Swisshelm and Pedregosa Mountains a somewhat different sequence of rocks occurs between the Bolsa and the overlying Devonian beds. Epis and Gilbert (1957, p. 2233) described a measured section in the northern Swisshelm Mountains and above the Bolsa assigned 390 feet (130 m) of dominantly thin bedded gray limestone and 195 feet (65 m) of dolomitic sandstone and sandy dolomite to the Abrigo and 460 feet (150 m) of dolomite below and limestone above to the El Paso Limestone.

Accessible localities:

Chiricahua Mountains, Blue Mountain, in the saddle south of the Bolsa Hill (Fig. 5).

Dos Cabezas Mountains, south of State 186, just west of Dos Cabezas, above the Bolsa to the west (Fig. 12). (SE¼ SE¼ sec. 31, T. 14 S., R. 27 E., Dos Cabezas 15′ quadrangle).

DEVONIAN SYSTEM

General

The Devonian rocks of southeastern Arizona are among the most varied lithologically of any in the Paleozoic sequence. In the western area the Devonian rocks are assigned to the Martin Formation (Martin limestone of Ransome, 1904, p. 22). In the eastern area the Devonian rocks are assigned to several formations, discussed below.

Wright (1964, p. 12) discussed briefly the areal distribution and nomenclature of the Devonian of southeastern Arizona. His stratigraphic cross sections (Wright, 1964, Figs. 19 and 20) show clearly the lithologic content and diversity, and regional variation of these Devonian rocks.

Martin Formation

The Martin Formation is essentially of Late Devonian Age and overlies the Abrigo disconformably. In most places this contact is apparently conformable but the time represented by the hiatus extends at least from mid-Ordovician to mid-Devonian.

The Martin is typically about 300 to 450 feet (100-150 m) thick. In areas of low or gentle dip where the lower part of the Paleozoic sequence is reasonably complete the Martin tends to form ledgy slopes below the cliff-forming Escabrosa Limestone.

Much of the Martin is gray limestone, but dolomites and dolomitic limestones are more prevalent in it than in the Abrigo below or the Escabrosa above. Toward the north it becomes more sandy and dolomitic. One of the features that distinguishes the Martin is the weathering color of many of the beds, a distinctive yellowish brown tint that once seen and recognized is a diagnostic characteristic.

The Martin is not generally very fossiliferous but usually a few fossils may be found in it. The brachiopod *Atrypa* is one genus commonly seen. Small branching corals, *Coenites* (or *Cladopora*) are not uncommon in some areas. More rarely the compact colonial corals *Pachyphyllum* and *Hexagonaria* are found.

References–Cooper & Silver, 1964; Creasey, 1967a & 1967b; Gilluly, 1956; Hayes & Landis, 1965; McClymonds, 1959a & 1959b; Stoyanow, 1936; Wright, 1964.

Accessible localities:

Twin Buttes area, Mineral Hill, east of the saddle above the Abrigo (Fig. 2).

Dragoon Mountains, entrance to Stronghold Canyon, above the Abrigo to the northeast (Fig. 6). (SW¼ sec. 18, T. 17 S., R. 24 E., Pearce 15′ quadrangle).

Mule Mountains, west of US 80, below the Escabrosa in the ridges north of State 90 (Fig. 4).

Bisbee area, above the Abrigo in Black Gap (Fig. 7).

Santa Catalina Mountains, Peppersauce Wash, north of the wash where Mt. Lemmon Road crosses it (Fig. 9). (NW¼ sec. 28 (unsurv), T. 10 S., R. 16 E., Mammoth 15′ quadrangle).

Dos Cabezas Mountains, south of State 186, just west of Dos Cabezas (Fig. 12). (SE¼ SE¼ sec. 31, T. 14 S., R. 27 E., Dos Cabezas quadrangle).

Eastern Area Formations

In the extreme southeastern part of Arizona the lithology of the Devonian rocks is not typical of the Martin as it is exposed to the west. Several names have been given to rocks of equivalent age in the eastern area. These include Percha Shale, Portal Formation, Swisshelm Formation, and Morenci Shale.

In the Chiricahua Mountains, a sequence of dark fine-grained clastic rocks with lesser amounts of thin-bedded limestones lies between the El Paso and Escabrosa Formations. In the past these dark, clastic Devonian beds have been assigned to the Percha Shale but Sabins (1957a, p. 475) noted the differences between these rocks and the type Percha in New Mexico and proposed for them a new name, the Portal Formation. At Blue Mountain, north of Portal, these Devonian rocks are about 320 feet (105 m) thick and form the intermediate slopes between the saddle cut on the weak El Paso Formation and the Escabrosa cliffs above.

Near Morenci, overlying the Longfellow Limestone are about 175 feet (60 m) of dominantly dark shales that Lindgren (1905, p. 66) called the "Morenci shales." These rocks are probably assignable to either the Portal Formation or to the Percha Shale of New Mexico.

Farther south in the Pedregosa and Swisshelm Mountains the Devonian rocks are of quite different lithologies from either the Portal or Martin Formations. Epis, Gilbert and Langenheim (1957, p. 2243) named these rocks the Swisshelm Formation. The Swisshelm formation is about 600 feet (200 m) thick in the type area near Leslie Pass in the southern Swisshelm Mountains. It is not notably different from the Martin in its upper part, but the lower part is markedly different, being composed of weak sandy, shaly and marly beds that are not conspicuous in the Martin Formation to the west.

References–Epis, Gilbert & Langenheim, 1957; Sabins, 1957a; Wright, 1964; Zeller, 1965.

Accessible localities:

Chiricahua Mountains, at Blue Mountain the Portal Formation lies above the El Paso on the slopes below the Escabrosa cliff (Fig. 5).

MISSISSIPPIAN SYSTEM

Escabrosa Limestone

The Escabrosa Limestone is of Early Mississippian Age (Kinderhook and Osage), probably somewhat younger (Meramec) in its upper part. The contact with the underlying Martin and the Devonian formations of the eastern area is apparently conformable. The lack of diagnostic fossils of known age range in the uppermost Devonian and lowermost Escabrosa forces one to consider the possibilities of gradation from one into the other, or of a hiatus representing latest Devonian time, or earliest Mississippian time, or both. The thickness of the Escabrosa ranges from about 600 to 750 feet (200-250 m).

In the eastern area, Armstrong (1962, p. 1) elevated the Escabrosa to group rank and described two new formations within it, Keating below and Hachita above, with type sections at Blue Mountain (p. 5) in the northern Chiricahua Mountains. He considered the age range of the Escabrosa Group to be from about the middle of Lower Mississippian (Kinderhook-Osage boundary) to middle Upper Mississippian (through upper Meramec but not into Chester).

The Keating Formation is a sequence of calcilutites and encrinites, thin to medium (bedium) bedded, 350 to 600 feet (110-200 m) thick. The Hachita Formation is a massive encrinite ranging from 250 to 350 feet (80-110 m) thick, the resistant cliff-forming unit. At present these formation names have not attained general usage in Arizona.

In the Clifton-Morenci district Lindgren (1905, p. 69) assigned 170 feet (55m) of blue and gray limestone to his new "Modoc limestone." In the northern part of the Clifton quadrangle he (p. 72) named "heavy-bedded bluish gray limestones with a characteristic upper Carboniferous or Pennsylvanian fauna" the Tule Spring Limestone. Stoyanow (1936, p. 511) discussed these limestones and considered that all of the Modoc and the lower 200 feet (65 m) of the Tule Spring was equivalent to the Escabrosa. The upper 300 feet (100 m) of the Tule Spring was designated Pennsylvanian.

The Escabrosa is typically a coarse-grained, light gray to white limestone, commonly containing a very high percentage of crinoidal debris. Bedding is thick to massive, clastic content is very low, and the formation tends to form high steep cliffs. Most of the limestone cliffs more than 100 feet high in the mountains of southeastern Arizona are of either the Escabrosa Limestone or the much younger Permian Concha Limestone. Where even mildly metamorphosed, the Escabrosa alters to a distinctive clean white marble.

Fossils in the Escabrosa are not very abundant except for the prevalent crinoidal debris. A few zones of horn corals may be found in some localities and the diagnostic colonial coral *Lithostrotionella* occurs in places, as do scattered assemblages of bryozoans and brachiopods, but in general the Escabrosa is less fosilliferous than most of the younger formations.

The Escabrosa may be overlain by either of three Paleozoic formations. Throughout most of southeastern Arizona it is overlain disconformably by the Horquilla Limestone or the equivalent Naco Limestone further north in Pinal and Gila Counties. In the eastern area, however, the younger Mississippian Paradise Formation rests on the Escabrosa, probably conformably. In central Cochise County the black Prince Limestone, originally designated Upper Mississippian? but now generally considered to be lowermost Pennsylvanian, overlies the Escabrosa without structural discordance.

References–Armstrong, 1962; Cooper & Silver, 1964; Creasey, 1967a & 1967b; Gilluly, 1956; Hayes & Landis, 1965; McClymonds, 1959a & 1959b; Sabins, 1957a; Stoyanow, 1936.

Accessible localities:

Colossal Cave, the cave is in the Escabrosa (Fig. 3).

Twin Buttes area, at Mineral Hill the Escabrosa rests on the Martin and makes up most of the eastern hill; and on the northeastern slope of the high hill northwest of San Xavier mine (Fig. 2). (SE¼ sec. 3, T. 17 S., R. 12 E., Twin Buttes 15′ quadrangle).

Dragoon Mountains, at the entrance to Stronghold Canyon the Escabrosa caps the small hills east of the Martin (Fig. 6). (Cen S½ sec. 18, T. 17 S., R. 24 E., Pearce 15′ quadrangle).

Mule Mountains, the Escabrosa caps the large hill and extends to north in the area west of US 80, north of State 90 (Fig. 4).

Bisbee area, the Escabrosa caps the hills on either side of Black Gap, south of Warren (Fig. 7).

Naco Hills, southernmost tip of the Naco Hills is Escabrosa (Fig. 8). (NE¼ sec. 2, T. 23 S., R. 23 E. Bisbee 15′ quadrangle).

Chiricahua Mountains, Blue Mountain, the high ridge above the Portal Formation is Escabrosa (Fig. 5).

Santa Catalina Mountains, Peppersauce Wash, north of Mt. Lemmon Road, west of 3 C ranch (Fig. 9).

Dos Cabezas Mountains, both sides of State 186 about 2 miles west of Dos Cabezas (Fig. 12). (SW¼ sec. 25, T. 14 S., R. 27 E., Dos Cabezas quadrangle).

Paradise Formation

The Paradise Formation of Upper Mississippian Age (Meramec-Chester) has its type locality north of Portal in the Chiricahua Mountains. At Blue Mountain the formation is about 150 (50 m) thick and consists mostly of alternating thin to medium beds of limestone and shale, quite varicolored but mostly dark. The weathering color, however, is dominantly yellowish brown, so that the formation shows as a topographically weak, yellow band between the dark gray cliffs of Escabrosa below and Horquilla above.

The Paradise is known with certainty in Arizona from the mountains of the eastern Area. In New Mexico, however, it crops out over a large part of the southwestern portion of the state.

Its yellow weathering color, weak topographic expression, thin-bedded alternations of limestone and shale, and abundant fossils, particularly the screw-shaped bryozoan *Archimedes*, make it one of the most readily recognizable formations in southeastern Arizona.

References–Armstrong, 1962; Hernon, 1935; Sabins, 1957a; Stoyanow, 1936; Zeller, 1965.

Accessible locality:

Chiricahua Mountains, at Blue Mountain where the Paradise occupies the sag between the higher Escabrosa hill to the north and lower Horquilla hill to the south (Fig. 5).

PENNSYLVANIAN SYSTEM

Black Prince Limestone

The Black Prince Limestone crops out in the Gunnison Hills (type section), Little Dragoon Mountains, Johnny Lyon Hills, and Whetstone Mountains. It has not been reported with certainty from any other localities. Originally the Black Prince was assigned a Mississippian Age (Gilluly, Cooper and Williams, 1954, p. 13) but with some consideration that it might be Pennsylvanian. Later work (Nations, 1963) seems to prove that it is Pennsylvanian and that the Mississippian fossils in it are reworked from the underlying Escabrosa and were incorporated in the formation when the Pennsylvanian seas transgressed the old Mississippian erosion surface.

The Black Prince varies in thickness from about 120 feet (40 m) in the type locality to as much as 280 feet (90 m) in the Whetstone Mountains (Creasey, 1967). The formation is dominantly light gray limestone, commonly with a pink tinge. The basal 20 to 30 feet (7-10 m) is red or maroon shale, mottled with green and containing fragmental chert. Above this, limestone is dominant but scattered green-mottled red shale interbeds occur throughout the section. These mottled maroon and green shale intercalations are probably the most distinctive feature of the Black Prince, as the limestones are not notably different from those of the adjacent Escabrosa and Horquilla Formations.

References–Cooper & Silver, 1964; Creasey, 1967b; Gilluly, 1956; Gilluly, Cooper & Williams, 1954; Hayes & Landis, 1965; Nations, 1963.

Accessible locality:

No localities of the Black Prince are readily accessible. One of the best exposures is on either side of the Cascabel-Willcox road where it crosses the Johnny Lyon Hills in the low saddle about 8 miles east of the Redington-Pomerene road (Fig. 16). (W½ sec. 22, T. 14 S., R. 21 E., Dragoon 15′ quadrangle).

Horquilla Limestone

Throughout southeastern Arizona except where the Black Prince occurs, the Horquilla Limestone is the basal Pennsylvanian formation. The Horquilla is the Naco Limestone as restricted by Stoyanow (1936, p. 522) and was used in this sense in southern Arizona for some 20 years before the Horquilla was defined. Just south of Winkelman and north of the Gila

River equivalent rocks are still assigned to the Naco Formation.

The Horquilla commonly rests disconformably on the Escabrosa, or the Black Prince where it occurs, or on the Paradise at some places in the eastern area. The Horquilla is a light to dark gray, cherty limestone, pinkish gray in many places, and unfortunately, like the Escabrosa, has many beds made up largely of crinoidal debris. The Horquilla contains more interbeds of red and green mudstone than the Escabrosa. The shales are not commonly exposed as they are nonresistant to erosion and are usually covered in the outcrops. Because of the greater amount of mudstone, the Horquilla tends to form steep, ledgy slopes above the more sheer Escabrosa cliffs. The Horquilla ranges in thickness from about 1000 feet (330 m) in the Tombstone area to as much as 1600 feet (520 m) in the Gunnison Hills and Chiricahua Mountains. To the west the Horquilla thins to less than 600 feet (200 m) in the Waterman Mountains (McClymonds, 1959a, p. 72), whereas to the east it thickens to 3600 feet (1200 m) in the Big Hatchet Mountains of southwestern New Mexico (Zeller, 1965, p. 37).

One of the definitive characteristics that distinguishes the Horquilla from the Escabrosa is the presence of medium to large fusulinids, which are completely lacking in the Escabrosa. Also the Horquilla is generally richer in megafossils than the Escabrosa and has a greater variety. The tiny-tubed colonial coral, *Chaetetes*, occurs only in the Horquilla and Black Prince where it forms rounded "cabbage-heads" a few inches to a foot or more in diameter.

References–Bryant, 1955; Cooper & Silver, 1964; Creasey, 1967b; Gilluly, 1956; Gilluly, Cooper & Williams, 1954; Hayes & Landis, 1965; McClymonds, 1959a & 1959b; Sabins, 1957a; Stoyanow, 1936.

Accessible localities:

Colossal Cave area, south of the Vail Road about 1.3 miles east of the Posta Quemada (Day) Ranch (Fig. 3). (SE¼ sec. 12, T. 16 S., R. 16 E., Rincon Valley 15′ quadrangle).

Twin Buttes area, southwestern slope of high hill northwest of the San Xavier mine (Fig. 2).

Mule Mountains, westernmost tip, just north of State 90, 1.2 miles west of the junction with US 80 (Fig. 4). (NE¼ NE¼ sec. 18, T. 22 S., R. 23 E., Tombstone 15′ quadrangle).

Bisbee area, at Black Gap, north of the Escabrosa outcrops just southeast of the city of Warren (Fig. 7). (SE¼ SE¼ sec. 23, T. 23 S., R. 24 E., Bisbee 15′ quadrangle).

Chiricahua Mountains, south ridge and slope of Blue Mountain above the Paradise (Fig. 5). (SE¼ sec. 20, T. 26 S., R. 26 E., Vanar quadrangle).

Dos Cabezas Mountains, both sides of State 186, about 2 miles west of Dos Cabezas (Fig. 12). (SE¼ sec. 26 and NW¼ sec. 36, T. 14 S., R. 27 E., Dos Cabezas 15′ quadrangle).

PENNSYLVANIAN-PERMIAN SYSTEMS

Earp Formation

The Earp Formation rests conformably on, and is gradational from, the underlying Horquilla. This boundary is difficult to establish firmly. In the original description Gilluly, Cooper and Williams (1954, p. 19) wrote, ". . .the base of the Earp is arbitrarily taken where the thin shaly limestones and reddish shales become dominant over the more massive limestones of the Horquilla." They had previously stated that the one good exposure of the basal part of the Earp in the type area was on the lower slopes of Earp Hill where there appeared to be no erosional or other discordance with the underlying Horquilla Limestone. Later, Gilluly (1956, p. 39) used the same measured sections as in the Gilluly, Cooper and Williams (1954) report and only paraphrased slightly parts of the descriptions of the formations. The quotation on p. 39 is exactly the same as cited above in the earlier paper. On his map (Pl. 1), however, Gilluly showed the Earp and Horquilla in fault contact. Later work has corroborated this interpretation as it appears that the much thicker sections of Earp in the Gunnison Hills and Whetstone Mountains contain a sequence of beds in the lower part that is missing at Earp Hill.

Thus the choice of the boundary between the Earp and Horquilla Formations involves local conditions of deposition and later structural events as well as interpretation as to where "the thin shaly limestones and reddish shales become dominant." In spite of the boundary problems, the formation is easy to recognize if the sequence is reasonably complete. Fusulinid evidence indicates that the Pennsylvanian-Permian boundary lies a few hundred feet above the base of the formation. Fusulinids in the lower part are of Upper Pennsylvanian (Virgil) Age whereas immediately above these Lower Permian (Wolfcamp) fusulinids occur.

The Earp is a formation of extremely varied lithology with more clastic beds than in the adjacent formations. Colors are also varied; the limestones are commonly pinkish, yellowish or greenish gray, the sandstone white to light gray or light brown, the siltstones and shales gray, green or red. The clastic rocks are usually calcareous and the limestones are silty or shaly. In the upper part are dolomitic or silty limestones that weather orange to reddish brown, in some areas conspicuously. Because of its diverse lithology and relatively thin bedding, it is one of the less competent units in the Paleozoic sequence and seems to have been more strongly sheared, faulted and deformed than the other more competent formations during post-Permian tectonic activity.

In the type area the Earp is about 600 feet (200 m) thick in contrast to the 1000 feet (320 m) or more in the Gunnison Hills and Whetstone Mountains. In the Chiricahua Mountains, however, Sabins (1957a, p. 489) assigned more than 2700 feet (900 m) to the Earp. In the Big Hatchet Mountains Zeller (1965, p. 48) measured about 1000 feet (320 m) of Earp. The excessive thickness of Earp in the Chiricahua Mountains is not yet adequately explained.

One of the unique features of the Earp is a red chert-pebble conglomerate in the middle part of the formation, commonly several feet thick, that occurs in many localities. This conglomerate is a certain marker for the Earp Formation as no similar unit is known in any other Paleozoic formation of southeastern Arizona. In areas where the red chert-pebble conglomerate has not been noted, gray chert- and limestone-pebble conglomerates have been recorded at about the same stratigraphic position. These may be equivalent to the red chert-pebble conglomerate.

Megafossils are not as common in the Earp as in the Horquilla below and are mostly similar to those in the Horquilla. In the lower Earp, however, large fusulinids are abundant; in few places are there more than 20 or 30 feet of beds without fusulinids, and generally the interval is even less. The combination of thin alternating clastic and calcareous beds occupying slopes or saddles between more resistant limestones, the red-chert-pebble conglomerate and the abundant large fusulinids leave no doubt as to recognition of the Earp.

References–Bryant, 1955; Cooper & Silver, 1964; Creasey, 1967b; Gilluly, 1956; Gilluly, Cooper & Williams, 1954; Hayes & Landis, 1965; McClymonds, 1959a & 1959b; Rea & Bryant (in press); Sabins, 1957a; Zeller, 1965.

Accessible localities:

Colossal Cave area, 0.5 miles east of Posta Quemada (Day) ranch south of the road from Vail (Fig. 3). (SE¼ SW¼ sec. 7, T. 16 S., R. 17 E., Rincon Valley 15′ quadrangle).

Tombstone Hills, type area on the south slopes of Earp Hill, north of the Government Draw road, about 3 miles east of US 80 (Fig. 11). (N½ S½ sec. 4, T. 21 S., R. 23 E., Tombstone 15′ quadrangle).

Dragoon Mountains, northeastern tip of the mountains, on the northwestern slopes, southwest of the Golden Rule mine, south of the road about 5 miles east of Dragoon. (NE¼ sec. 27, T. 16 S., R. 23 E., Cochise 15′ quadrangle).

Chiricahua Mountains, southeast tip of high ridge 0.5 miles north-northwest of Portal (Fig. 13). (NW¼ sec. 26, T. 26 S., R. 31 E., Portal 15′ quadrangle).

PERMIAN SYSTEM

Colina Limestone

The Colina Limestone lies conformably and gradationally on the Earp. The Colina is dominantly thick bedded to massive, dark gray to black limestone. Its age is Lower Permian with some uncertainty as to whether it should be assigned to Wolfcamp or Leonard. Some evidence supports the thesis that it may be of Wolfcamp Age in its lower part, Leonard in its upper.

The lower boundary of the Colina is usually distinct where the dark limestones supersede the clastic, varicolored beds of the Earp. The upper boundary is less secure, however, as the dolomitization that distinguishes the overlying Epitaph from the Colina does not maintain the same stratigraphic position. In a number of places limestones in the upper Colina grade laterally into dolomites which are indistinguishable from the Epitaph. Thus the choice of boundary and hence of thickness is largely dependent on the extent of dolomitization.

Approximate thicknesses reported for the Colina in various parts of southeastern Arizona are as follows: Tombstone type area, 600 feet (200 m); Gunnison Hills, 450 feet (150 m), top eroded; Chiricahua Mountains, 550 feet (180 m); Whetstone Mountains, 200 feet (65 m); Naco Hills, 495 feet (160 m), top eroded; Waterman Mountains, 200 feet (65 m); isolated hill northeast of Elfrida, 470 feet (155 m), top eroded; Big Hatchet Mountains, 500 feet (160 m). As mentioned, these variations in thickness may be in part choice of a boundary based upon the degree of dolomitization, but the thinning to the west represented by the 200 feet in the Waterman Mountains, and the thickening to the southeast, 1000 feet in the Guadalupe Mountains, may be valid depositional variations. If the thicknesses of the Colina and the Epitaph are combined, the variation is much more regular and uniform, ranging from 200 feet in the Waterman Mountains to the west where no Epitaph is recognized and faulting is severe, to about 1300 feet (420 m) through central Cochise County to about 2000 feet (650 m) in extreme southeastern Arizona and southwestern New Mexico.

One of the most diagnostic features of the Colina is the very dark gray to black color on a fresh surface and the tendency to be much lighter on a weathered surface. Another important characteristic is the presence of large gastropods of the genus *Omphalotrochus* which are almost wholly confined to the Colina in southeastern Arizona. These gastropods are commonly 2 to 4 inches (5-10 cm) in diameter and may reach 6 inches (15 cm). In isolated outcrops or severely faulted areas the Colina might be mistaken for some parts of the Concha or Rainvalley Formations (described below) but probably no others.

References–Bryant, 1955; Cooper & Silver, 1964; Creasey, 1967b; Gilluly, 1956; Gilluly, Cooper & Williams, 1954; Hayes & Landis, 1965; Sabins, 1957a; Zeller, 1965.

Accessible localities:

Tombstone Hills, above the Earp on Earp Hill; southwest of the old Tombstone-Bisbee road just west of the junction with US 80 about 1.6 miles south of Tombstone airfield (Fig. 11); southeast from above, east across US 80 with Epitaph above on the north slope of these low hills (Fig. 11). (NE¼ NE¼ sec. 6, and NW¼ NW¼ sec 5, T. 21 S., R. 23 E., Tombstone 15′ quadrangle).

Mule Mountains, west end of Government Butte, east of US 80, 1.5 miles south of Government Draw road (Fig. 10). (SW¼ sec. 18, T. 21 S., R 23 E., Tombstone 15′ quadrangle).

Whetstone Mountains, southeast tip of the range, just north of State 82, about 2.2 miles west of junction with State 92 (Fig. 14). (S½ NW¼ sec. 15, T. 20 S., R. 19 E., Fort Huachuca 15′ quadrangle).

Chiricahua Mountains, 2 miles west of Portal on the north side of the road to Paradise (Fig. 13). (NW¼ NW¼ sec. 27, T. 17 S., R. 31 E., Portal 15′ quadrangle).

Gunnison Hills, northwest tip of Scherrer Ridge south of US Interstate 10 about 3 miles east of Johnson Camp turnoff (Fig. 17). (SE¼ SW¼ sec. 20, T. 15 S., R. 23. E., Dragoon 15′ quadrangle).

Epitaph Formation

Overlying the Colina Limestone is the Epitaph Formation of probable lower Leonard Age. The Epitaph was originally defined as the Epitaph Dolomite in the Tombstone type area where the lower 250 feet (80 m) is dolomite and the upper 500 feet (160 m) is alternating limestone, mudstone and dolomite. In other parts of Arizona, the Epitaph is even more variable and includes much gypsum in the Empire and Whetstone Mountains and in the Twin Buttes area. The massive lower dolomite member, so prominent near Tombstone, thins to the west to only about 130 feet (40 m) in the eastern Whetstone Mountains (Creasey, 1967b) and is not recognized west of this locality. In contrast, to the east in the southeastern corner of the State, the Epitaph, more than 900 feet (300 m) thick, is dominantly dolomite (Dirks, 1966). In southwestern New Mexico where 1500 feet (500 m) are recognized, conditions of deposition changed radically as the lower 500 feet (160 m) are interbedded limestone, dolomite, sandstone and mudstone with much gypsum whereas the upper 1000 feet (320 m) are practically uninterrupted dolomite (Zeller, 1965).

The Epitaph is relatively unfossiliferous and the fossils found are usually similar to or identical with the Colina species. One of the most distinctive features of the Epitaph dolomites is the abundance of knots, blebs and geodes of quartz and calcite, ranging from a few millimeters to a few centimeters in diameter. No other formation in the Paleozoic in southeastern Arizona has these blebs and geodes in quantity except the Rainvalley Formation which is much higher in the section. Abundant gypsum in southeastern Arizona is known only from the Epitaph.

References–Bryant, 1955; Cooper & Silver, 1964; Creasey, 1967b; Dirks, 1966; Gilluly, 1956; Gilluly, Cooper & Williams, 1954; Kelly, 1966; Zeller, 1965.

Accessible localities:

Tombstone Hills, above the Colina on the east side of US 80 about 1.6 miles south of Tombstone airfield (Fig. 11).

Whetstone Mountains, southeast tip of the range, just north of State 82, about 2.2 miles west of junction with State 92 (Fig. 14). (S½ NW¼ sec. 15, T. 20 S., R. 19 E., Fort Huachuca 15′ quadrangle).

Scherrer Formation

The Permian Scherrer Formation is also of Leonard Age, probably Lower or Middle. In the type area in the Gunnison Hills it consists of 65 feet (20 m) of red siltstone at the base, 300 feet (100 m) of white to brown sandstone with a few limestone beds in the lower part, 160 feet (50 m) of limestone and dolomitic limestone, and the upper part of 160 feet (50 m) of light brown to pink sandstone. Although thicknesses may vary considerably, the sequence is persistent throughout western Cochise, Pima and Santa Cruz Counties. In the eastern area, however, the middle member pinches out and the formation thins. In the Chiricahua Mountains Sabins (1957a, p. 496) reported about 50 feet (15 m) of red siltstone and 100 feet (30 m) of quartzitic sandstone. In the Big Hatchet Mountains of southwestern New Mexico only about 20 feet (7 m) of sandstone above the Epitaph are assigned to the Scherrer.

The lower contact is gradational from the Epitaph below, chosen where the uppermost limestones or dolomitic limestones grade into the red siltstones of the Scherrer. The upper contact is also gradational, through a zone of calcareous sandstone and sandy limestone a few tens of feet thick, into the basal gray limestones of the Concha. Topographically the Scherrer tends to form slopes below the cliff-forming, very cherty lower part of the Concha.

The sandstones are mostly of fine to medium grain, well rounded and well sorted. Cross bedding is common. In many places it is an orthoquartzite but this seems to be a surface phenomenon, so-called "case-hardening." Small brown spots from the oxidation of an iron mineral, generally occurring as pits or nodes, are characteristic and seem to be diagnostic of the Scherrer throughout its area of outcrop.

The siltstone and sandstone members are unfossiliferous. A few fossils are found in the middle limestone member and these are mostly similar to Concha fossils except for the presence of distinctive echinoid spines shaped like a short thick baseball bat. Earlier these were assigned to the genus *Permocidaris* which is now considered synonymous with *Archaeocidaris*.

References–Bryant, 1955; Cooper & Silver, 1964; Creasey, 1967b; Gilluly, 1956; Gilluly, Cooper & Williams, 1954; Luepke, 1967; McClymonds, 1959a & 1959b; Sabins, 1957a; Zeller, 1965.

Accessible localities:

Twin Buttes area, saddle north of Helmet Peak, east of Twin Buttes Road (Fig. 2). (NE¼ NE¼ sec. 11, T. 17 S., R. 12 E., Twin Buttes 15′ quadrangle).

Gunnison Hills, northwest tip of Scherrer Ridge, south of US Interstate 10 about 3 miles east of Johnson Camp turnoff (Fig. 17). (SE¼ SW¼ sec. 20, T. 15 S., R. 23 E., Dragoon 15′ quadrangle).

Concha Limestone

The Concha Limestone is one of the most prominent cliff-formers in southeastern Arizona. It is a thick bedded to massive, very cherty, very fossiliferous, medium to dark gray limestone. The lower part is without doubt of Leonard Age, probably later Leonard, but the upper part may be of Guadalupe Age. Fusulinids of the genus *Parafusulina* occur about 350 feet (115 m) above the base and these have been variously considered as of latest Leonard or earliest Guadalupe Age.

Throughout southeastern Arizona the Concha has a thickness of about 500 feet (160 m). Where it is less, faulting is probably responsible or it has been eroded. Where it is greater, the measurements probably include beds now assigned to the overlying Rainvalley Formation. The lower contact is gradational from the Scherrer below. The upper contact is also gradational, chosen where the uniform thick bedded to massive gray limestones are superseded by thinner bedded, more varicolored limestones of the Rainvalley.

The Concha has fewer clastic rocks than any other Paleozoic formation of southeastern Arizona and is probably the most cherty and most fossiliferous. The chert is mostly light gray, but it ranges from white to black, not uncommonly red or brown. It occurs generally in zones of nodules which may be several inches thick and as much as two feet long. In places the nodules are so closely packed as to form pseudobeds.

One distinctive 30-foot (10 m) zone occurs above the middle of the Concha. In this zone light gray chert that weathers a notably lighter brown than the other chert in the Concha composes nearly 50 per cent of the interval and in the field was termed the "tan chert zone." It is less resistant to erosion than the adjacent rocks and in several areas marks a break in the cliffs or occurs in saddles or sags.

The most striking and readily recognizable fossils of the Concha are the large productid brachiopods, *"Dictyoclostus"* of authors, now assigned to several genera. The large *"Dictyoclostus" bassi* is particularly prevalent in the lower cherty cliff-forming part. Another widespread easily recognizable fossil in this part of the Concha is the sponge, *Actinocoelia*, which usually occurs in chert nodules up to several inches in diameter. Also abundant are numerous other brachiopods, bryozoa, corals, crinoid stems, echinoid plates and spines, gastropods and pelecypods, the latter two more abundant toward the top.

References–Bryant, 1955; Bryant & McClymonds, 1961; Cooper & Silver, 1964; Creasey, 1967b; Gilluly, 1956; Gilluly, Cooper & Williams, 1954; McClymonds, 1959a & 1959b; Sabins, 1957a; Zeller, 1965.

Accessible localities:

Snyder Hill, upper Concha on west side of hill below the Rainvalley, south of State 86 about 3 miles west of Kinney Road. (SW¼ NW¼ sec. 3, T. 15 S., R. 12 E., San Xavier Mission 15′ quadrangle).

Twin Buttes area, main peak of Helmet Peak, above the Scherrer (Fig. 2).

Mustang Mountains, northern tip of range, south of State 82, 11 miles east of Sonoita (Fig. 15). (S½ SW¼ sec. 3, T. 20 S., R. 18 E., Fort Huachuca 15′ quadrangle).

Rainvalley Formation

Above the Concha is the youngest Permian formation of southeastern Arizona, the Rainvalley. The top of the Rainvalley is at all places an erosion surface, overlain unconformably by Cretaceous beds or by alluvium. Thus the thickness varies greatly with a maximum of about 500 feet (160 m) in the southeastern Empire Mountains (Total Wreck Ridge). Most of the fossils are the same species that are in the Concha and no fusulinids have been found in the

Rainvalley. Thus the age of the Rainvalley may be late Leonard but is more probably early Guadalupe.

The limestones of the Rainvalley are more varicolored, thinner bedded, more dolomitic and more silty than in the Concha. Chert is less abundant, but shows a greater tendency to occur in beds, some as much as two feet thick. Most of the chert is gray but in some areas brown, red and purple chert nodules form pseudobeds in the lower part of the formation. Blebs and geodes of calcite and quartz that resemble those in the Epitaph are common, particularly in the more dolomitic beds. Some sandstone and siltstone beds also occur in the Rainvalley whereas none are known in the Concha.

The fossils, as mentioned above, belong to the same genera as those in the Concha. Not enough work has been done on these younger Permian fossils to establish faunal zones. The specific assignment of many of the forms is uncertain, probably a number are undescribed, and the exact ranges of the known species have not been accurately delimited.

References–Bryant, 1955; Bryant & McClymonds, 1961; Creasey, 1967b; McClymonds, 1959a & 1959b.

Accessible localities:

Snyder Hill, Rainvalley on the top and east slope above the Concha.

Twin Buttes area, south ridge of Helmet Peak (Fig. 2).

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Table 1 – SYMBOLS FOR MAPS

Tg	–	Tertiary granite	**Me**	–	Escabrosa & Paradise Fms.
Kg	–	Glance Cg.	**Ds**	–	Portal Fm.
Pr	–	Rainvalley Fm.	**Dm**	–	Martin Ls.
Pcn	–	Concha Ls.	**O-€e**	–	El Paso Ls.
Pcs	–	Concha & Scherrer Fms.	**€a**	–	Abrigo Fm.
Ps	–	Scherrer Fm.	**€b**	–	Bolsa Qtzte.
Ped	–	Epitaph Dol.	**p€r**	–	Rattlesnake Point Granite
Pepg	–	Gypsum in Epitaph Dol.	**d**	–	diabase
IPPe	–	Earp Fm.	**g**	–	granite
IPPeh	–	Earp & Horquilla Fms.	**qm**	–	quartz monzonite
IPh	–	Horquilla Ls.	**gd**	–	granodiorite

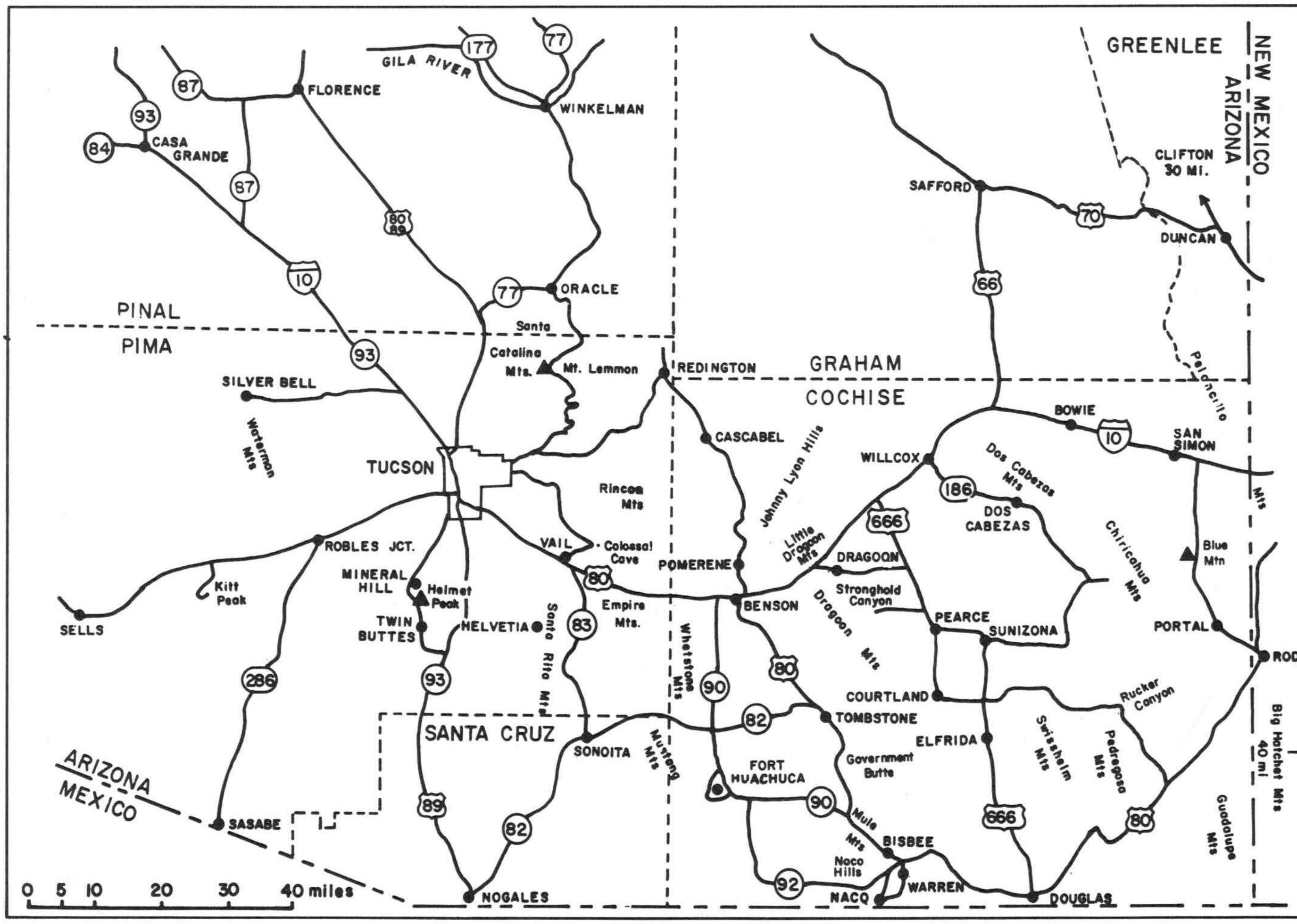


Figure 1 – Index Map of Southeastern Arizona

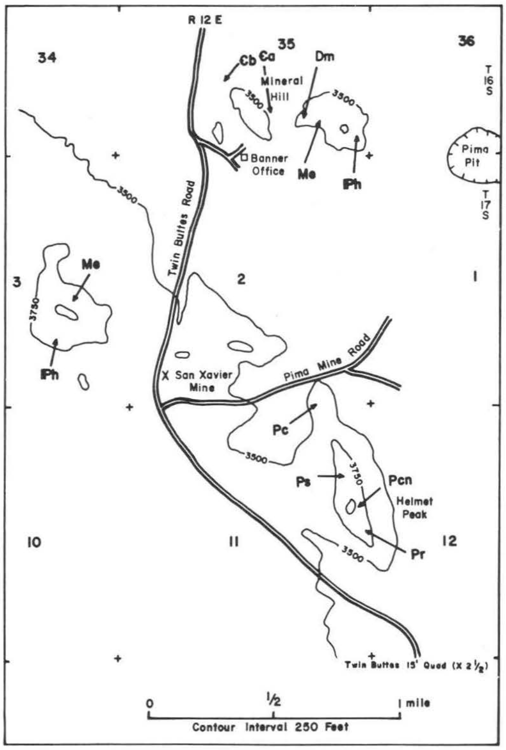


Figure 2 – Twin Buttes Area–Mineral Hill and Helmet Peak

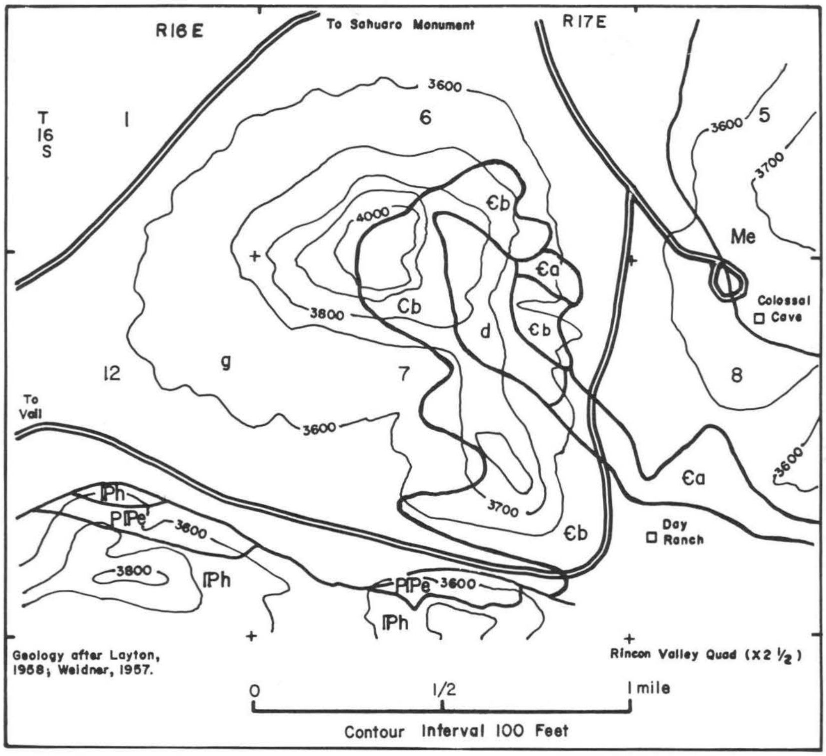


Figure 3 – Colossal Cave Area

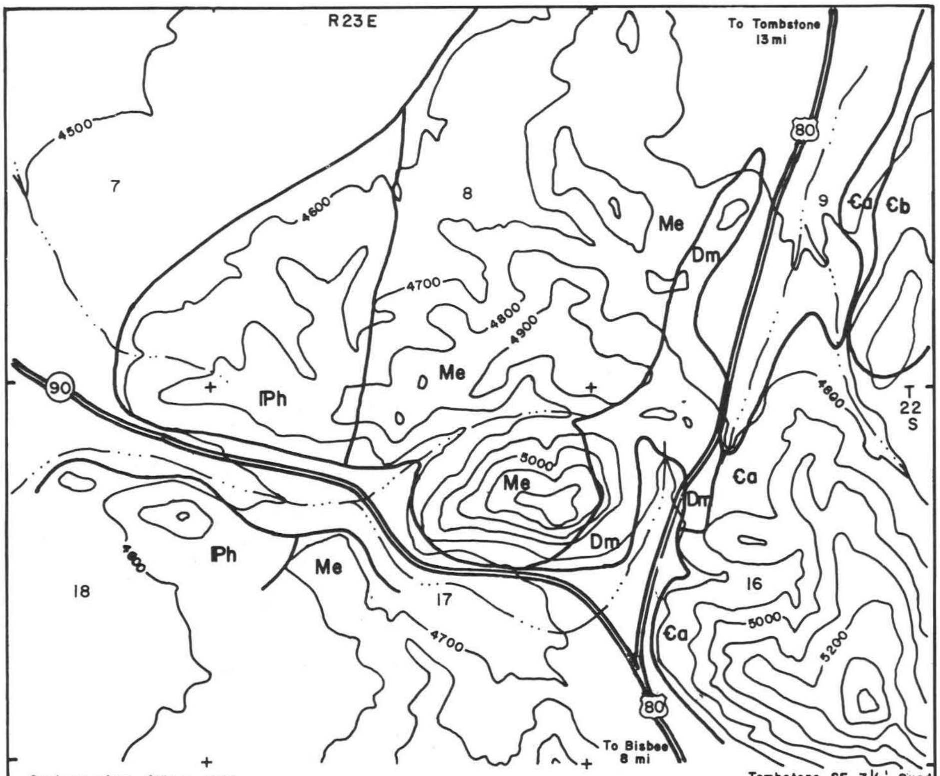


Figure 4 – Northwestern Mule Mountains

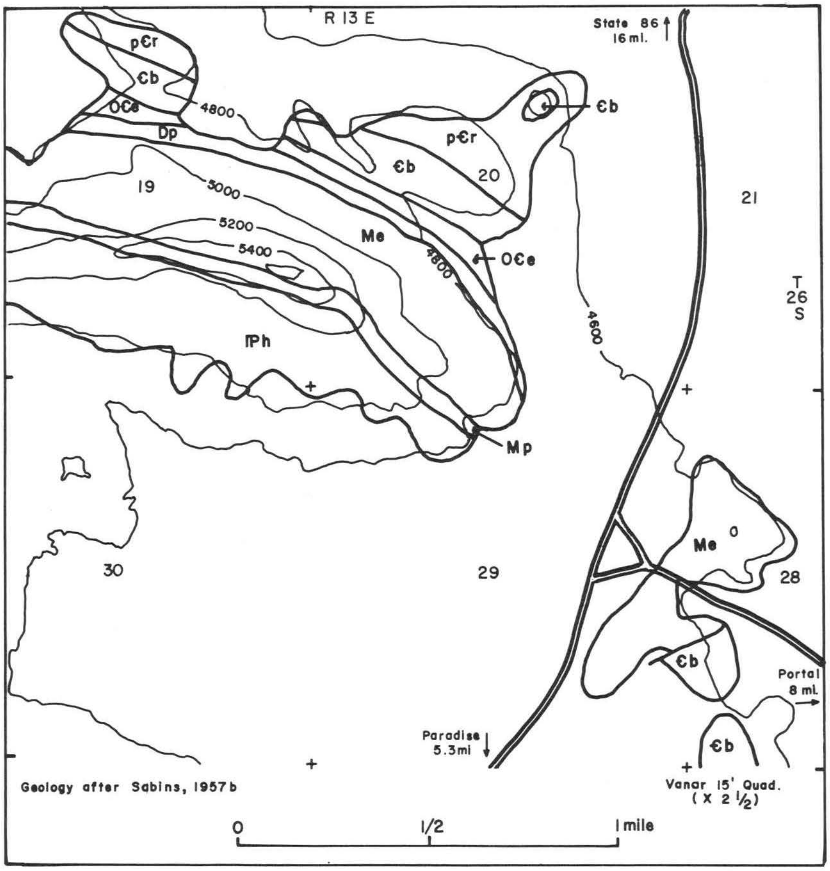


Figure 5 – Chiricahua Mountains–Blue Mountain

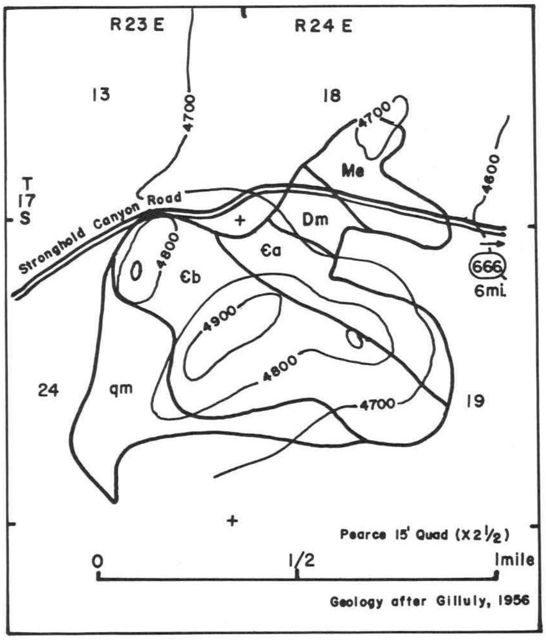


Figure 6 – Dragoon Mountains–Entrance to Stronghold Canyon

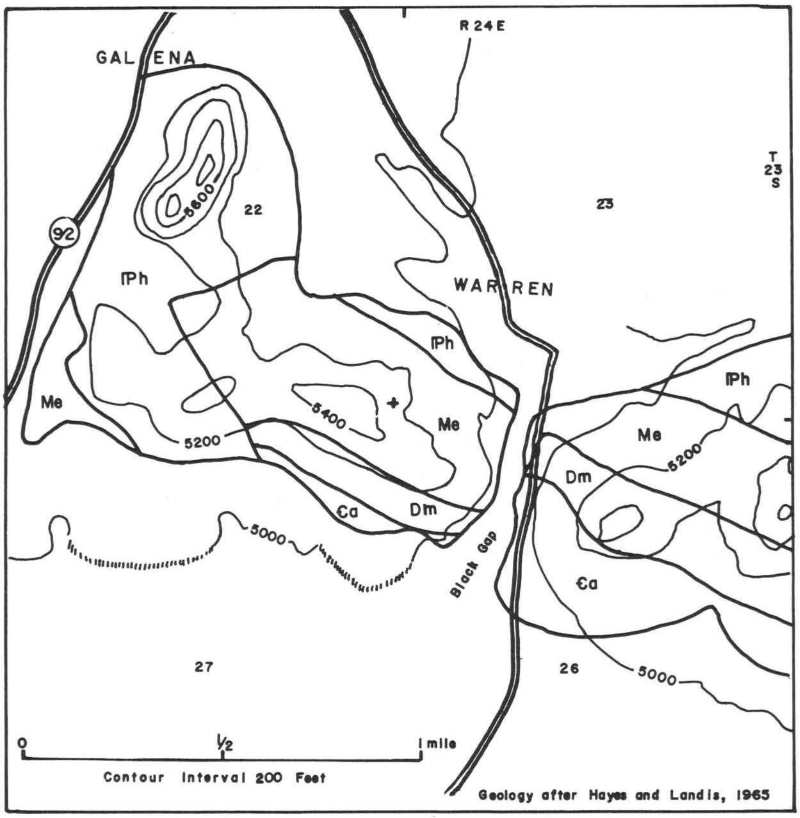


Figure 7 – Bisbee Area, Black Gap

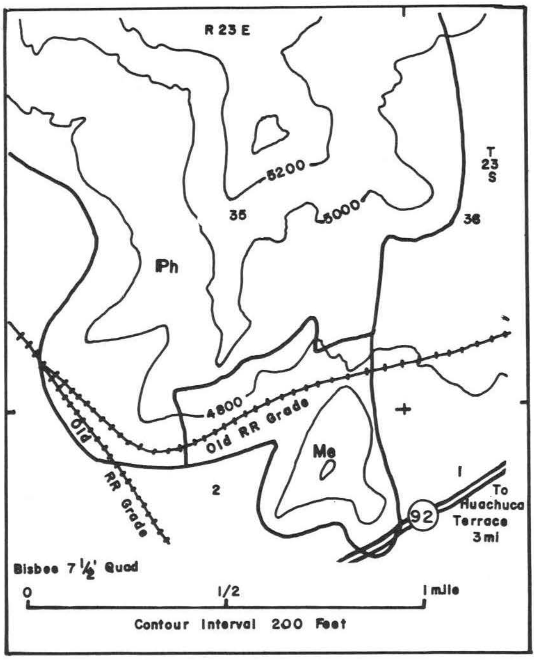


Figure 8 – Bisbee Area, Naco Hills

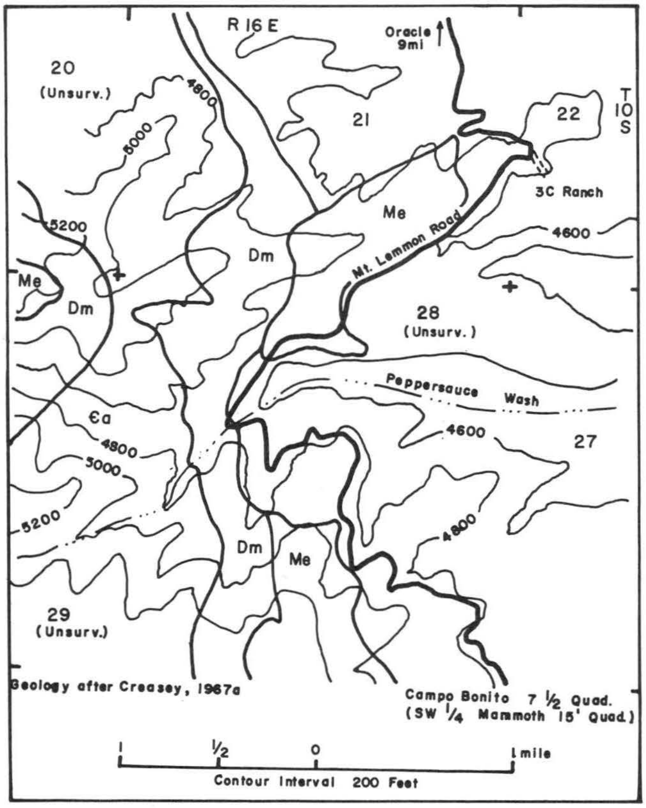


Figure 9 – Northern Catalina Mountains, Peppersauce Wash

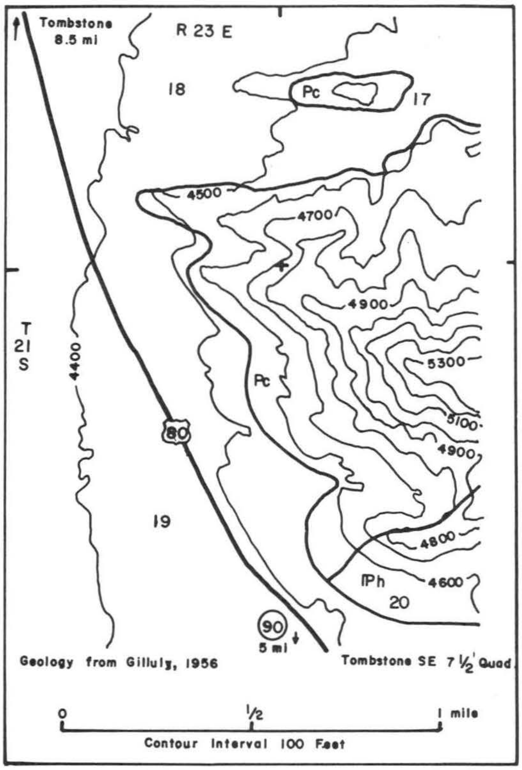


Figure 10 – Mule Mountains, West End of Government Butte

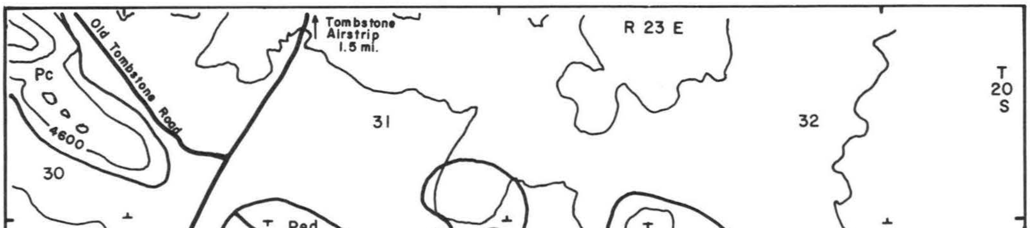


Figure 11 – Tombstone Area, Earp Hill

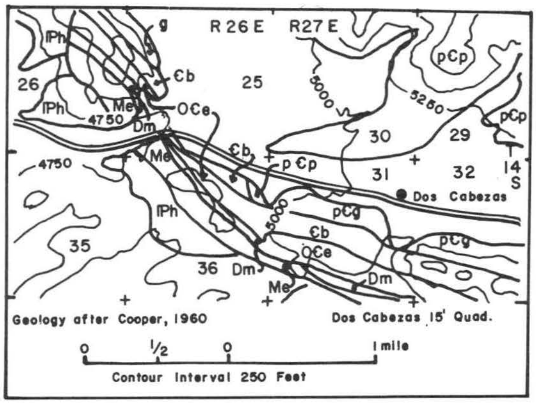


Figure 12 – Dos Cabezas Mountains, Near Dos Cabezas

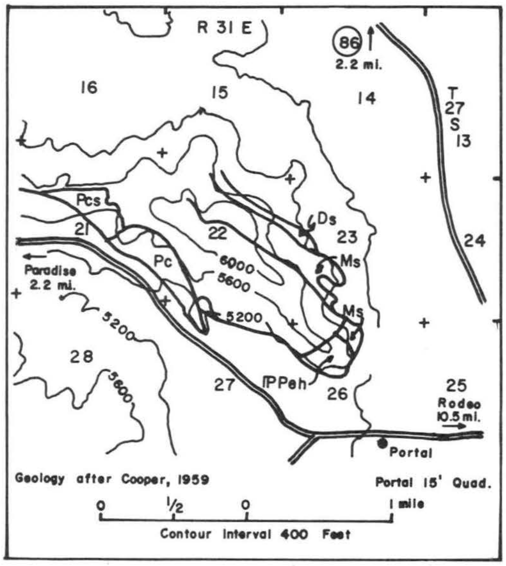


Figure 13 – Chiricahua Mountains, Ridge Northwest of Portal

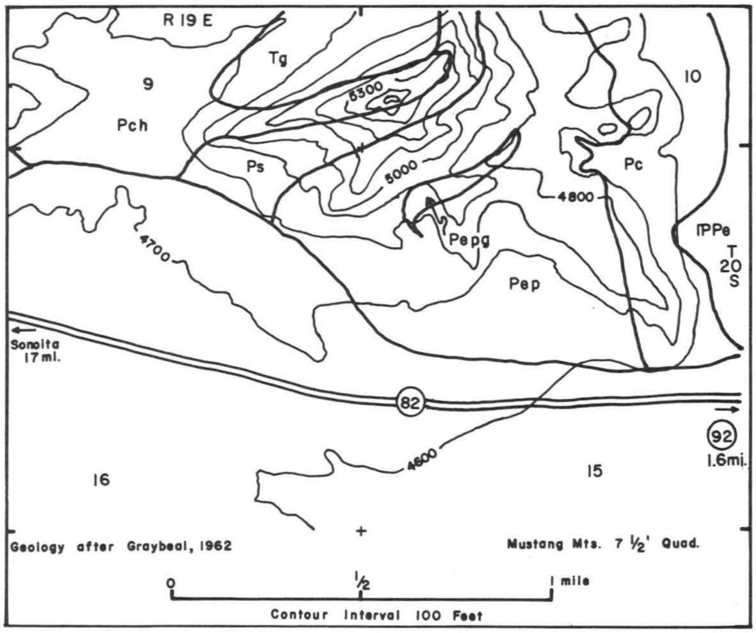


Figure 14 – Southeastern Tip of Whetstone Mountains

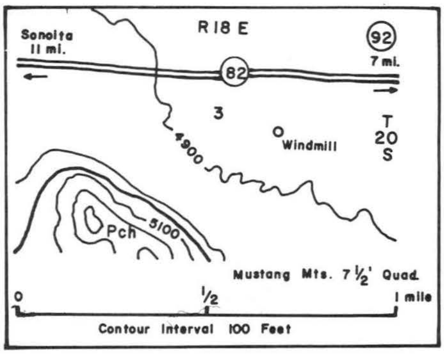


Figure 15 – North End, Mustang mountains

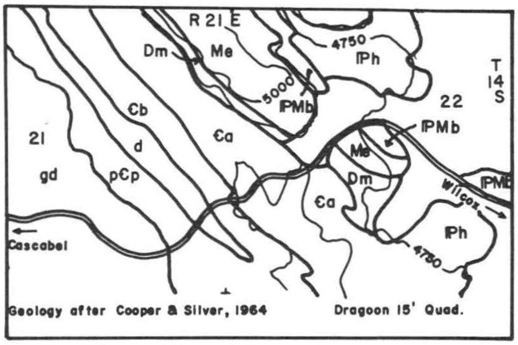


Figure 16 – Johnny Lyon Hills

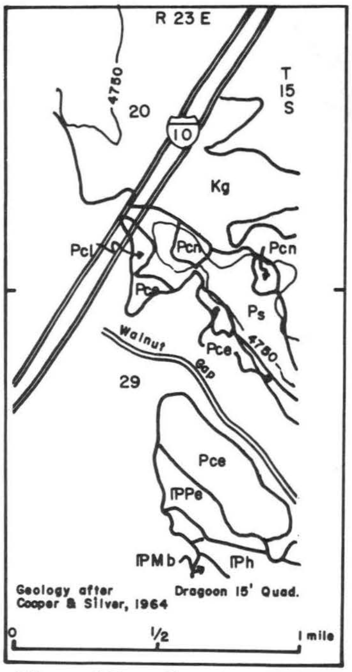
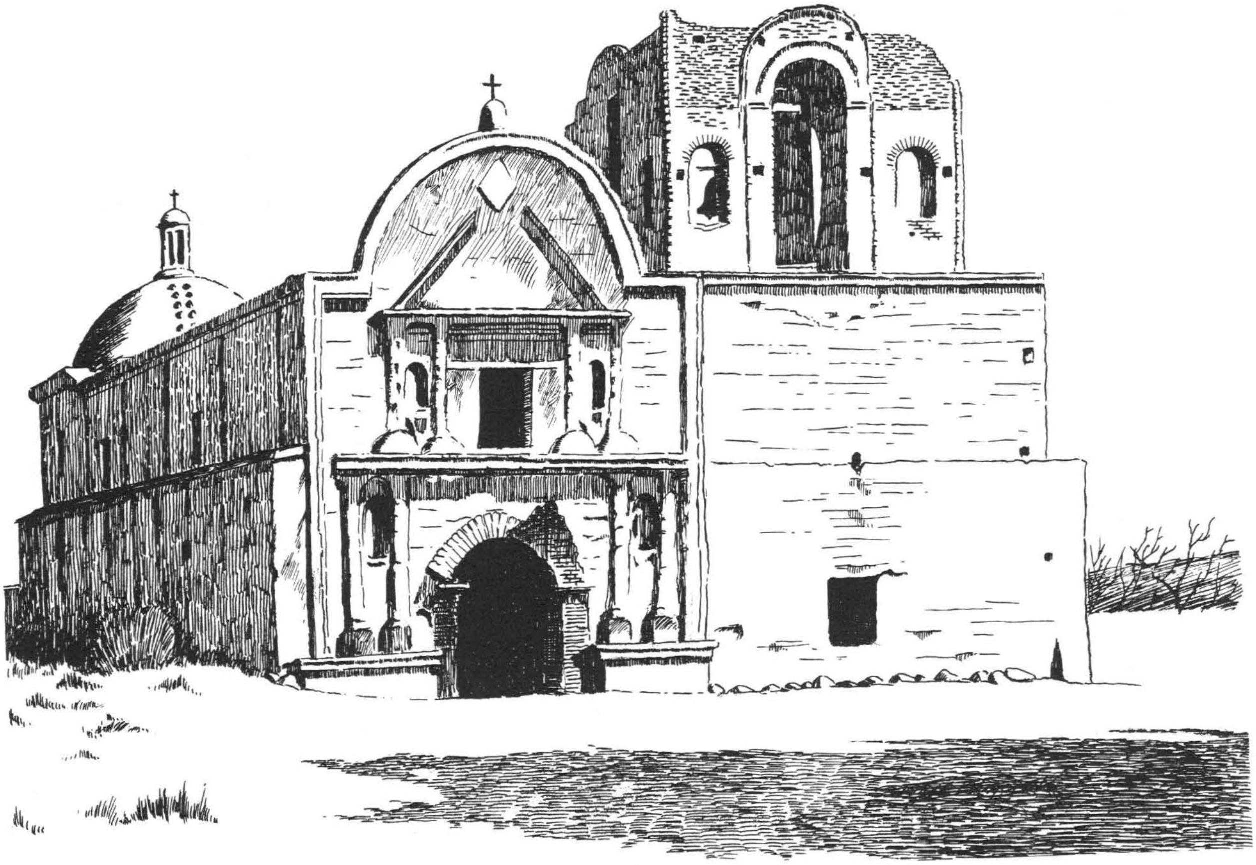


Figure 17 – Gunnison Hills, Scherrer Ridge



MESOZOIC SEDIMENTARY AND VOLCANIC ROCKS OF SOUTHEASTERN ARIZONA*

By

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SUMMARY

The Mesozoic history of southeastern Arizona was complex and varied. In Triassic and Early Jurassic time the region experienced at least two periods of volcanic activity, apparently separated by a period of plutonism. A more widespread period of plutonism and uplift ensued in Middle Jurassic time. During Late Jurassic and earliest Cretaceous time the region was being subjected to erosion. After a brief period of local volcanic activity, the late Early Cretaceous sea advanced from the south and southeast and the region received deposition of a thick deltaic sequence. In early Late Cretaceous time regional uplift and the first phases of the Laramide orogeny occurred. The resulting mountainous area was eroded and fluviatile sediments were deposited in valley areas tributary to the sea to the southeast. Widespread volcanic activity followed, and finally another episode of plutonism at the end of the Cretaceous.

INTRODUCTION

The area considered herein is restricted to a region roughly between Tucson and the southeastern corner of Arizona (fig. 1). Specifically, it lies between the Mexican border and latitude 32° 15' N., and between New Mexico and longitude 111° 15' W.

Interpretations of stratigraphic relations and regional correlations of Mesozoic rocks in the region are complicated by the lack of datable fossil material in most of the units and by structural complexities; since late Early Permian time various parts of the region apparently have been subjected to nearly a half dozen episodes of faulting and nearly as many episodes of plutonism. Recently, however, much has been learned about these Mesozoic rocks by professors and students from universities, geologists associated with the minerals industry, and U.S. Geological Survey geologists. Current and recently completed geologic mapping by the Survey includes: Sierrita Mountains by J. R. Cooper, Santa Rita Mountains by Harald Drewes (1966), Empire Mountains by T. L. Finnell, Patagonia Mountains by F. S. Simons, Canelo Hills by R. B. Raup, Huachuca and Mustang Mountains by Hayes and Raup (1967), Whetstone Mountains by Creasey (1967), Mule Mountains by Hayes and Landis (1964), Dragoon Mountains by Gilluly (1956), Little Dragoon Mountains by Cooper and Silver (1964), and some reconnaissance mapping by Cooper (1959 and 1960). Radiometric dates have been obtained by S. C. Creasey, R. W. Kistler (some are presented in Creasey and Kistler, 1962), T. W. Stern, R. F. Marvin, and others of the Geological Survey, and P. E. Damon and others of the University of Arizona. We are indebted to all the above-mentioned workers and to earlier workers, but we are responsible for the interpretations presented here.

Our correlations (fig. 2) are based on analysis of local geologic relations, on paleontologic data of variable usefulness, on radiometric age determinations of variable reliability, on some petrologic studies, and on the assumption that major geologic events must have some degree of regional continuity.

Radiometric age determinations of horizons in the upper half of the Mesozoic are assigned with confidence because replicate determinations or concordant determinations using different methods or minerals are available. Many of the horizons in the lower half of the Mesozoic are dated by single determinations using the lead-alpha method on zircons concentrated from volcanics; nevertheless, these ages inspire some confidence because most agree with the geologic field relations. A few radiometric dates, not shown on figure 2, do not fit field relations. They will be reviewed later in longer articles permitting more detailed description of the geology. These problem dates are not considered a serious handicap to the more than 40 useful dates because most of these samples were, by necessity, collected from equivocal sites. Some were from mildly metamorphosed rock, and some from strongly weathered rock or from rock that could be suspected of having a mixed origin.

We are following Holmes' (1965, p. 360) time scale for most of the Mesozoic but here use the more refined scale of Gill and Cobban (1966) for the Upper Cretaceous.

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

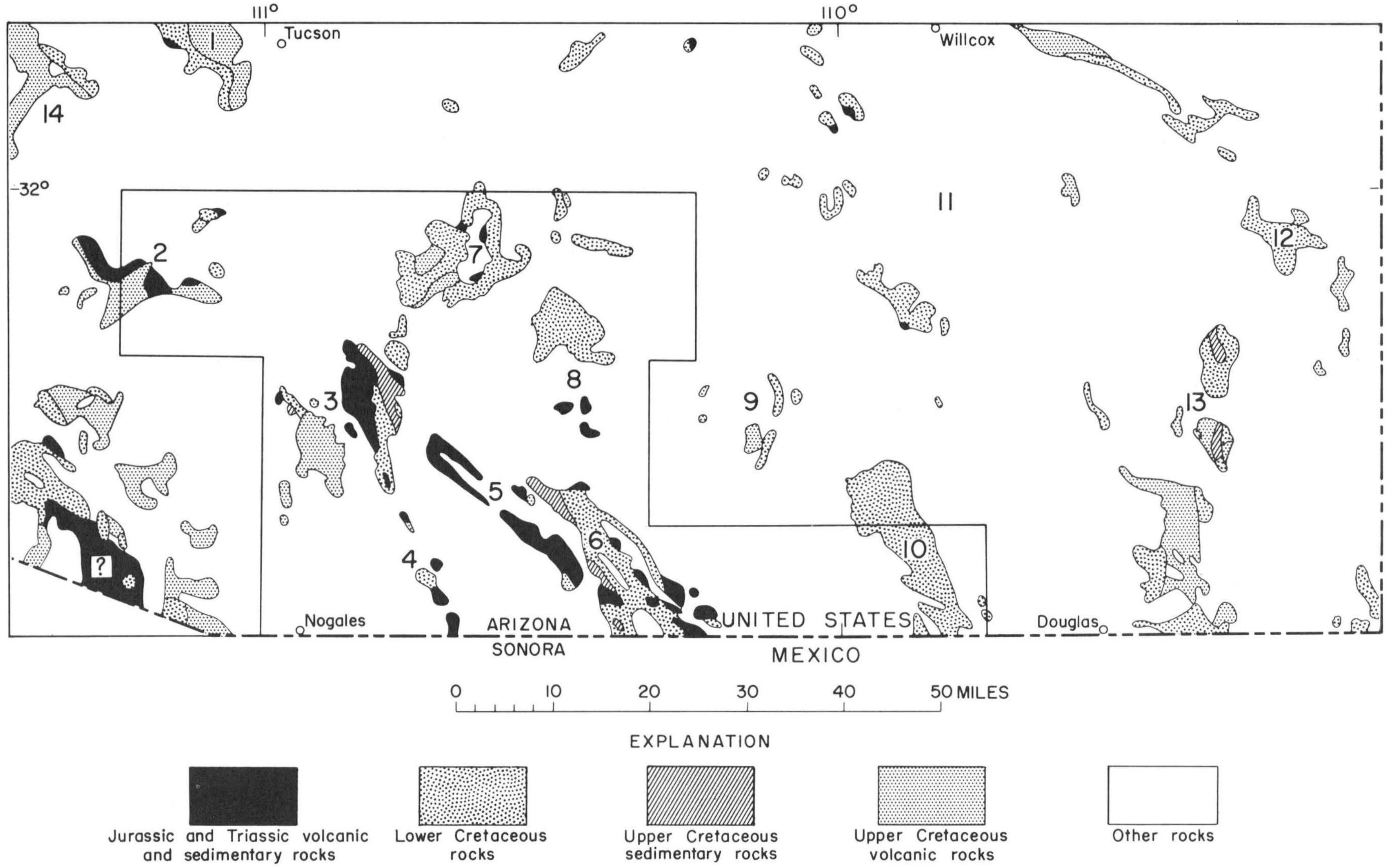


Figure 1 – Map showing distribution of Mesozoic volcanic and sedimentary rocks in southeastern Arizona. 1) Tucson Mts., 2) Sierrita Mts., 3) Santa Rita Mts., 4) Patagonia Mts., 5) Canelo Hills, 6) Huachuca Mts., 7) Empire Mts., 8) Whetstone and Mustang Mts., 9) Tombstone Hills, 10) Mule Mts., 11) Dragoon Mts. area, 12) Chiricahua Mts., 13 Pedregosa Mts., 14) Roskruge Mts. Outline shows areas of current mapping projects of U. S. Geological Survey.

REGIONAL SETTING

Sub-Mesozoic rocks of southeastern Arizona include Precambrian metamorphic, plutonic, and sedimentary rocks that are unconformably overlain by about 5,000 feet of Paleozoic marine sedimentary rocks ranging in age from Late Cambrian to late Early Permian. The Mesozoic sequence is unconformably overlain by volcanic and sedimentary rocks of Cenozoic age.

The Mesozoic rocks have a composite maximum thickness of about 40,000 feet. They include rhyolitic to andesitic volcanic rocks, sedimentary rocks largely of subaerial origin, and some marine beds. Plutonic rocks were intruded in Triassic, Jurassic, and Late Cretaceous time but are here considered only in connection with their age relation to sedimentary and volcanic rocks. The Mesozoic rocks are treated here in three major divisions separated from each other and from older and younger rocks by major unconformities: (1) Triassic and Jurassic rocks, (2) Lower Cretaceous rocks, and (3) Upper Cretaceous rocks.

PERMIAN-TRIASSIC UNCONFORMITY

Marine Paleozoic rocks are separated from subaerial Mesozoic rocks by a widespread unconformity. The youngest Paleozoic formation preserved anywhere beneath the unconformity is the Rainvalley Formation of Permian age, but in places much older rocks lie immediately beneath the unconformity. The oldest Mesozoic rocks inferred to overlie the Permian-Triassic unconformity are included in a volcanic sequence, at least the middle portion of which is of Triassic age. The basal contact of these volcanics has not been seen, but the local relief in the Santa Rita Mountains may have been great, for a lens of cobble conglomerate in the sequence contains some clasts of Precambrian granitic rock. The oldest Mesozoic rocks actually in depositional contact with Permian rocks in known exposures are red beds of presumed later Triassic age in the Canelo Hills. The local relief on the erosion surface there may not have been great, inasmuch as the contact irregularities are minor, no basal conglomerate is present, and the lowest chert-pebbles of Paleozoic origin in conglomerates intercalated in the red beds are well rounded. On the other hand, the red beds at several places in the Canelo Hills contain exotic blocks of Permian rock interpreted by Simons and others (1966) to be landslide debris from nearby hills. In the Huachuca Mountains, at least, Triassic and Jurassic volcanics overlie normally faulted Paleozoic rocks.

TRIASSIC AND JURASSIC ROCKS

Description

Three major units–two of them largely of volcanics and the third a medial red-bed unit–make up the oldest major division of Mesozoic rocks. These rocks are most abundant in the western part of the region, mainly in relatively small, faulted areas.

The older volcanics, about 10,000 feet thick, are typically represented by the formation of Mount Wrightson in the Santa Rita Mountains. Most of these volcanics are rhyodacite, but andesitic rocks are common in the lower and upper fourths of the formation. A little conglomerate is intercalated in the middle of the formation, and sandstone and quartzite lenses are scattered throughout and are abundant toward the top. The rhyodacite is intensely indurated and about half of it is finely flow laminated. The rhyodacite contains, in addition to thick lava flows, welded tuff and agglomeratic tuff facies. The andesitic rock includes some vesicular flows and local pillow lavas. The larger lenses of sandstone and quartzite have sweeping crossbedding of the eolian type; the grains are well sorted, are largely well rounded, and are mostly of foreign origin but are admixed with locally derived volcanic detritus.

Similar rocks in a slightly thinner sequence form the volcanics of Ox Frame Canyon in the Sierrita Mountains, and occur in a fault zone along Flux Canyon in the northern part of the Patagonia Mountains.

The medial red-bed unit is typified by the red beds of the lower part of the Canelo Hills Volcanics (Hayes, Simons, and Raup, 1965) in the Canelo Hills. A similar red-beds unit about 2,000 feet thick occurs in the Gardner Canyon area in the east-central part of the Santa Rita Mountains, and in the Rodolfo Wash area in the Sierrita Mountains. The red beds consist of thick-bedded to massive mudstone and siltstone in which some sandstone, conglomerate, and volcanics are intercalated. The pebbles of the conglomerate are chiefly chert (derived from Paleozoic formations) and volcanic material (presumably derived from the above-described formation of Mount Wrightson and similar rocks). The volcanics in the red-beds unit are generally pale reddish-purple, finely porphyritic latite, dacite, or andesite effusive tuffs, flows, and breccias.

Somewhat similar and possibly equivalent units occur in the Empire Mountains, in the northern end of the Santa Rita Mountains, and on the west and southwest flanks of the Sierrita Mountains. The Recreation Redbeds of Brown (1939) of the Tucson Mountains probably also represent the unit. The Walnut Gap Volcanics of the Little Dragoon Mountains area (Cooper and Silver, 1964) contain red beds and are provisionally correlated with these rocks.

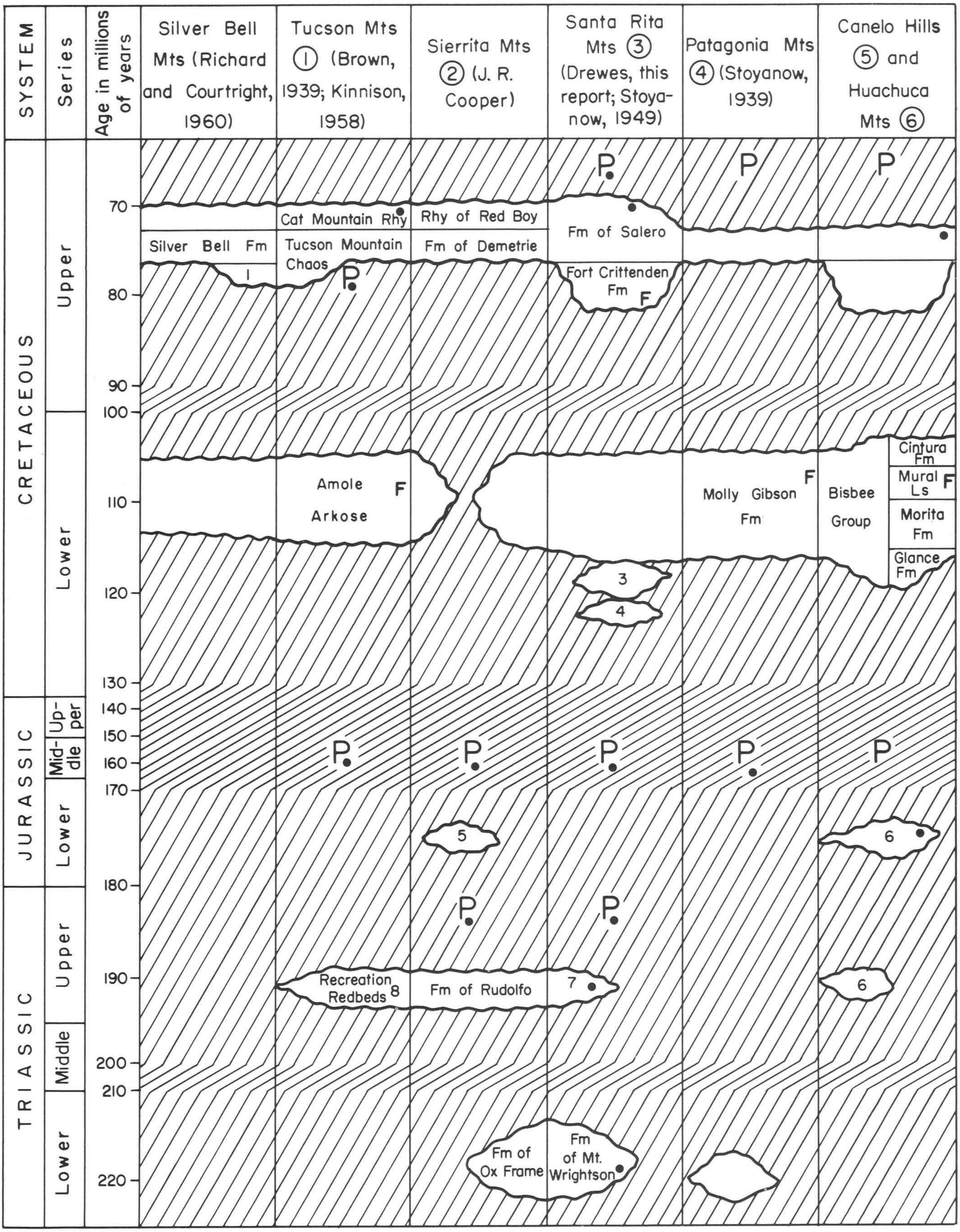
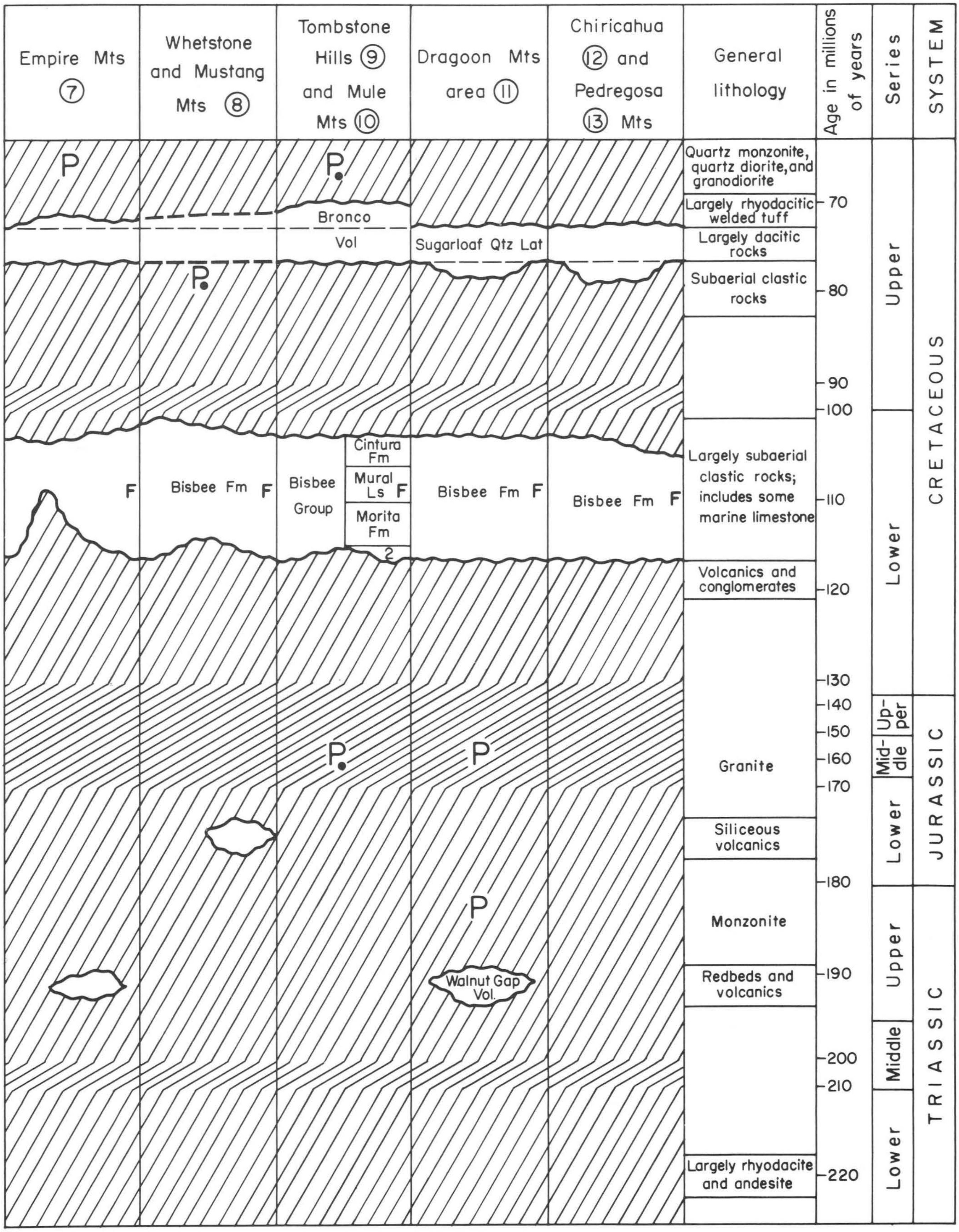


Figure 2 – Correlation chart of Mesozoic rocks in southeastern Arizona. **P**, plutonic and associated rocks; ●, radiometrically dated rocks; **F**, fossil-bearing rocks. Numbers in locality boxes refer to locality numbers on figure 1. Note different time scales.



Numbers within chart: 1, Claflin Ranch Fm.; 2, Glance Cgl.; 3, Fm. of Bathtub; 4, Fm. of Temporal Gulch; 5, Rhy. of Stevens Mountains; 6, Canelo Hills Vol. (part); 7, Redbeds of Gardner Canyon; 8, includes "Cretaceous" volcanic rocks.

These possibly correlative units vary in proportions of component lithologies. Red beds are a very minor constituent of the Walnut Gap Volcanics, whereas no true volcanics, only volcanic sediments, are present in the unit on the west side of the Sierritas. The rocks in the Empire and Tucson Mountains are less massive than those in the Canelo Hills and Gardner Canyon area of the Santa Rita Mountains. The rocks of the northern end of the Santa Rita Mountains contain more sandstone, grit, and conglomerate than siltstone.

The youngest of the major units of Triassic and Jurassic age, with a composite thickness in excess of 7,000 feet, is the upper part of the Canelo Hills Volcanics. These rocks have been recognized only in the Canelo Hills and the west flank of the Huachuca Mountains, but probable equivalents also occur in the Mustang Mountains and may be represented by the rhyolite of Stevens Mountain on the west side of the Sierrita Mountains (J. R. Cooper, oral commun., 1967). They consist of silicic flows, tuffs, and some clastic rocks. The rhyolitic lava resembles the flow-laminated volcanics of the formation of Mount Wrightson, but field relations in the Canelo Hills indicate that it is younger than red beds whose clasts include flow-laminated rhyolitic rock. Radiometric dates also indicate that the upper part of the Canelo Hills Volcanics is younger than the volcanics of the formation of Mount Wrightson.

Age

The formation of Mount Wrightson is considered to be older than the red-bed unit on the basis of a lead-alpha age determination of volcanic rock in the formation (fig. 2) and on the fact that the red-bed unit, which has yielded a considerably younger lead-alpha age (fig. 2), in places contains cobbles of flow-banded volcanic rock identical in appearance to that in the formation of Mount Wrightson. Furthermore, Thoms (1966) reports that beds on the west side of the Sierrita Mountains which we believe to be equivalent to the formation of Mount Wrightson, are in depositional contact with Paleozoic rocks and are overlain by beds tentatively correlated by J. R. Cooper (oral commun., 1967) with red beds of Rodolfo Wash. The relatively great age of the formation of Mount Wrightson is further supported by the fact that monzonite that is intrusive into the formation has yielded a lead-alpha age of 184± m.y. The monzonite, in turn, was intruded by a granite that has been dated by the potassium-argon and lead-alpha methods as of Middle Jurassic age (fig. 2).

The red-bed unit is considered to be older than the upper part of the Canelo Hills Volcanics on the basis of field relations (Hayes, Simons, and Raup, 1965) and on the basis of a still-younger radiometric date in the overlying volcanics; in this case a potassium-argon age determination of biotite from welded tuff (fig. 2). A minimum age for the Recreation Redbeds of Brown (1939), which we correlated with the red beds of the Canelo Hills Volcanics and of Gardner Canyon, is indicated by a potassium-argon date of 150 m.y. for an andesite porphyry that has intruded the formation (Damon and others, 1967). In several areas, geologic evidence alone dates many of these rocks as post-Early Permian and pre-late Early Cretaceous.

JURASSIC-CRETACEOUS UNCONFORMITY

Jurassic plutonic activity was followed by pronounced uplift and deep erosion, to produce the Jurassic-Cretaceous unconformity. This unconformity places Cretaceous rocks on Jurassic granite in the Santa Rita, Patagonia, Huachuca, Dragoon, and Mule Mountains, and on other Triassic and Jurassic rocks in the Sierrita, Huachuca, and Empire Mountains, in the Dragoon Mountains area, and possibly in the Tucson Mountains. Relief on the unconformity is considerable in many areas and amounts to hundreds of feet in the Mule Mountains and is at least 1,000 feet locally in the Santa Rita and Huachuca Mountains. Arkosic conglomerate filling old canyons in those ranges is at least as coarse as is the most recent piedmont gravel in the same areas.

LOWER CRETACEOUS ROCKS

During Early Cretaceous time two groups of rocks were deposited in the region: (1) an older relatively local group of volcanic and associated sedimentary rocks, and (2) a younger widespread thick group of sedimentary rocks, the Bisbee Group and its correlatives.

Volcanic and Associated Sedimentary Rocks

Volcanic and sedimentary rocks of the older group are the combined formations of Temporal Gulch and of Bathtub, each about 2,000 feet thick, of the southeastern flank of the Santa Rita Mountains. Rocks similar in lithology and comparable in age to at least the youngest part of the sequence in the Santa Ritas occur in the Huachuca Mountains in the basal part of the Bisbee Group (Hayes and Raup, 1967). In the Santa Rita Mountains these rocks consist of roughly equal amounts of epiclastic rock, rhyolitic tuffs and flows, and andesitic or dacitic volcanics. A minor unconformity separates the two formations there, and the basal part of each formation contains lenticular and locally very thick bodies of coarse conglomerate. Some of these conglomerates are arkoses derived wholly of detritus of the Jurassic granite; others contain abundant Precambrian granitic rocks. Such deposits indicate the large amounts of local uplifts and presumably faulting that occurred between Middle Jurassic and earliest Cretaceous time.

The volcanic rocks are also highly lenticular. Some groups of andesitic flows or volcanic breccia as much as 1,000 feet thick extend only 2 to 3 miles. The rhyolitic rock includes some welded tuff and lava, but most is tuff and tuff breccia. The volcanic rocks are everywhere so intensely altered that radiometrically datable minerals are destroyed, and zircon sufficiently abundant to provide material for dating was found only in a tuff immediately overlying the Jurassic granite. A Middle Jurassic date determined thereon, while not impossible considering the large range of possible error assigned the results, is suspect because of the likelihood that the tuff flow could have picked up its zircon from granite grus over which it flowed.

In the Huachucas, this sequence of volcanics and conglomerates rests unconformably on the Canelo Hills Volcanics and is apparently conformable with the overlying Bisbee and, thus, is dated geologically as of probable Early Cretaceous age.

Bisbee Group and Correlative Rocks

Sedimentary rocks of Early Cretaceous age are widely distributed in southeastern Arizona (fig. 1) and are 10,000 feet thick or more in some areas. Throughout the region they are made up largely of clastic sediments deposited in a subaerial environment, but rocks of marine origin make up a significant part of the sequence in the southeastern part of the region. These Lower Cretaceous strata are believed to represent part of a large delta complex on the margin of a sea that existed to the southeast, mostly in Mexico. In the northwest, marine rocks are supplanted by brackish-water facies and the continental rocks are more arkosic. For the purposes of this paper it is convenient to divide the region into southeastern, northeastern, southwestern, central, and northwestern areas.

Southeastern area. – In the Mule Mountains (Ransome, 1904; Hayes and Landis, 1964) and Huachuca Mountains (Hayes and Raup, 1967) all of the Lower Cretaceous strata are assigned to the Bisbee Group, which is made up of four formations: the Glance Conglomerate at the base (Glance Formation in the Huachucas where it locally contains abundant lava of intermediate composition, described above), the Morita Formation, the Mural Limestone, and the Cintura Formation. The Morita and Cintura Formations are made up mostly of repeated sequences of pinkish-gray arkosic cross-laminated sandstones that grade upward into massive grayish-red siltstones and mudstones. The Mural Limestone is a fossiliferous marine unit. The Bisbee Group is as much as 5,700 feet thick in the Mule Mountains and ranges from nearly 6,000 to about 10,000 feet thick in the Huachucas.

In the Pedregosa and southern Chiricahua Mountains the Bisbee Group is nearly 8,000 feet thick and is divisible into four formations that, except for the greater prevalence of marine rocks, are roughly comparable to those in the Mule Mountains (Epis, 1952).

Northeastern area. – In the Dragoon (Gilluly, 1956), Little Dragoon (Cooper and Silver, 1964), and Dos Cabezas (Sabins, 1957b) Mountains no significant marine units are present and the Bisbee can be treated as a formation similar in lithology to the Morita and Cintura Formations of the Mule Mountains; a distinct basal conglomerate member is generally present. The formation may be more than 15,000 feet thick at one locality in the Dragoon Mountains.

Southwestern area. – Rocks similar in aspect and probably equivalent to the Bisbee in the Patagonia Mountains were included by Stoyanow (1937) in his Patagonia Group. These rocks are roughly 5,000 feet thick. Bisbee-like rocks are also present in ranges to the west of the Patagonias.

Central area. – Rocks that are correlative in large part with the Bisbee Group of the Mule Mountains are present in the Whetstone Mountains and were called the Bisbee (?) Formation by Creasey (1967). The sequence there is at least 6,500 feet thick and may be several thousand feet thicker; it was divided into four stratigraphically distinct subunits by Tyrrell (1957). The rocks are generally similar to those in the Mule Mountains but apparently represent a more landward facies. Marine limestone is rare, but thin-bedded limestone of fresh- to brackish-water origin is relatively abundant in one member. Much of the sandstone in the Whetstones is more arkosic than to the southeast.

The Lower Cretaceous sequence in the Empire Mountains and in the northern part of the Santa Rita Mountains is similar to that in the Whetstones, and the same subunits are recognizable. In the northern part of the Empires the basal several thousand feet of the sequence is in apparent onlap relations with what T. L. Finnell (oral commun., 1967) believes was a rising highland of Precambrian rock.

Northwestern area. – Several thousand feet of strata in the Tucson Mountains in the Amole Arkose of Brown (1939) are very similar to Lower Cretaceous strata of the Whetstone, Empire, and northern Santa Rita Mountains and are undoubtedly general correlatives. Rocks similar to the Amole Arkose are present in the northeastern part of the Sierrita Mountains and in the Roskruge Mountains to the west of the Tucson Mountains where they are included in the Cocoraque

Formation (Heindl, 1965). The Cocoraque is about 2,000 feet thick.

Age. – Collections of marine invertebrates from the Mural Limestone in and near the Mule Mountains and reported on by T. W. Stanton (in Ransome, 1904), Stoyanow (1949), J. B. Reeside, Jr. (in Gilluly, 1956), and Douglass (1960) strongly indicate a correlation of the Mural with the Trinity Group of Texas. Fossils collected by Stoyanow (1949) and during our studies from the Mural in the Huachuca Mountains also indicate a Trinity age, as do fossils from limestones in the Bisbee Group in the Pedregosa Mountains. The entire Bisbee Group in those areas may represent much of Aptian and Albian time. Fossils reported by Tyrrell (1957) in the Whetstone Mountains and by Stoyanow (1949) in the Patagonia Mountains also suggest an Albian age. Fossils collected by Brown (1939) and Kinnison (1958) from the Amole Arkose of Brown (1939) in the Tucson Mountains are not as definitive; correlation of part, if not all, of that formation with the similar strata of the Whetstones is done on the basis of lithology.

MID- TO LATE CRETACEOUS UNCONFORMITY

Uplift and erosion again followed the deposition of the Bisbee Group and equivalent rocks. A mid- to Late Cretaceous unconformity has been described from southeastern Arizona by Darton (1925), Epis (1952), and Gilluly (1956). Such an unconformity is demonstrable in the Santa Rita, Huachuca, and Pedregosa Mountains, and in the Canelo Hills, where sedimentary rocks of Late Cretaceous age overlie the Bisbee and contain fragments of Bisbee, gently truncate some beds at the top of the Bisbee, or truncate faults in the Bisbee. In other areas, Upper Cretaceous volcanic rocks overlie gently to isoclinally folded Lower Cretaceous rocks.

In many areas the relief of the mid- to Late Cretaceous unconformity is not large, for little of the upper part of the Bisbee, as it is known in the type area, is missing. In other areas, however, as in the Sierrita Mountains, rocks of Jurassic and probably Triassic age underlie Upper Cretaceous volcanics (J. R. Cooper, oral commun., 1967). Similarly, at the north end of the Empire Mountains, Upper Cretaceous volcanics overlie rocks that may be as old as Precambrian (T. L. Finnell, oral commun., 1967). Inasmuch as basal Upper Cretaceous conglomerates in many places contain clasts identifiable as having been derived from Triassic and Jurassic and even Paleozoic rocks, there are probably other areas, that are either not exposed or not yet discovered, in which Lower Cretaceous rocks had been removed before Upper Cretaceous rocks were deposited.

UPPER CRETACEOUS ROCKS

Lower Sedimentary Sequence

Sedimentary rocks of Late Cretaceous age lie with probable conformity beneath latest Cretaceous volcanic rocks in a few ranges in the region. This sequence of rocks, though locally of great thickness, is not as widely distributed as are Lower Cretaceous rocks or the Upper Cretaceous volcanics.

The best known of these Upper Cretaceous sedimentary rocks are included in the Fort Crittenden Formation of Stoyanow (1949) in the Adobe Canyon area on the east side of the Santa Rita Mountains. At the base of the sequence there, in unconformable relations with the underlying Bisbee Formation, is a lenticular conglomerate made up dominantly of well-rounded cobbles of earlier Mesozoic volcanic and sedimentary rocks. Above this is a 525-foot-thick sequence of gray shale and subordinate siltstone in which are found a varied fauna including fresh-water mollusks, fish, turtle, and dinosaurs of Santonian to Maestrichtian age (Miller, 1964). Above this fossiliferous shale unit in the Adobe Canyon area is more than 6,000 feet of variable grayish-red and brown conglomerate and arkosic sandstone and subordinate shale. High in the unit are several thin rhyolitic tuff beds.

A similar sequence of strata unconformably overlies the Bisbee Group on the west side of the Huachuca Mountains. Locally there, conglomerates are dominant in the basal 600 feet of the unit. These are overlain by a sequence, at least 700 feet thick, of shale and graywacke that contains fresh-water mollusks similar to those in the shale and sandstone of the Santa Rita Mountains.

Discontinuous exposures of the same sequence as that of the Huachucas extend for several miles along the northeast side of the Canelo Hills. There, conglomerates similar to those in the upper part of Stoyanow's (1949) Fort Crittenden Formation in the Santa Ritas apparently overlie the shale and siltstone member. On the southwest side of the Canelo Hills, beds of sandstone, conglomerate, shale, and minor tuff are overlain by Upper Cretaceous andesite breccia. These may represent the top of the Fort Crittenden Formation.

In the Rucker Canyon area of the Pedregosa and Chiricahua Mountains, Epis (1952) described a sequence at least 4,000 feet thick, dominantly of well-rounded conglomerates that rest unconformably on the Bisbee Group and appear to grade up into andesites. Those conglomerates, which are derived from the Bisbee and from Paleozoic formations, are undoubtedly roughly equivalent to the Fort Crittenden Formation.

Local thin conglomerate units at the base of the Tucson Mountain chaos of Kinnison (1959) occur in a similar stratigraphic position in the Tucson Mountains, and are here considered as possible equivalents to beds high in the Fort Crittenden Formation. Richard and Courtright (1960) have previously correlated the Tucson Mountain chaos of Kinnison (1959) with thin conglomerate and breccia units that locally appear conformably beneath Upper Cretaceous andesites in the Empire Mountains and elsewhere in the region.

The thick sequences in the Huachuca and Santa Rita Mountains are similar to, and were probably once coextensive with, dated Upper Cretaceous strata described by Taliaferro (1933) in the Cabullona area in Mexico, a few miles southwest of Douglas, Arizona.

The presence of terrestrial vertebrates and freshwater invertebrates, together with the character and distribution of the conglomerates and other sediments, suggests that these Upper Cretaceous strata were deposited locally in subaerial valleys cut on the Bisbee Formation and older rocks after the earliest phases of the Laramide orogeny. The principal drainage direction was probably southeastward toward the Late Cretaceous Mexican geosyncline.

UPPER VOLCANIC SEQUENCE

The youngest of the major units of Mesozoic rocks consists of distinctive andesite to dacite breccia, rhyodacitic tuff and welded tuff, and a little sedimentary rock, having a combined thickness of as much as 4,500 feet. These rocks conformably overlie the Fort Crittenden Formation of Stoyanow (1949) in the Santa Rita Mountains, and units in the Pedregosa Mountains (Epis, 1952) correlative with the Fort Crittenden Formation and the overlying volcanics also are conformable. In other areas, presumably old high areas between the major valleys in which the Fort Crittenden Formation and correlatives were deposited, the volcanics unconformably overlie Lower Cretaceous or older rocks. Our regional correlations of these Upper Cretaceous volcanic units are basically similar to earlier correlations by Richard and Courtright (1960), although they considered the rocks to be of Tertiary age. Our chief contribution here is to briefly describe these rocks in areas not described by them (Richard and Courtright, 1960).

The sequence in the Salero area of the Santa Rita Mountains contains a basal member of dacitic flows and tuff and a capping unit of sedimentary and tuffaceous rock in addition to the characteristic dacite breccia and rhyodacite welded tuff. In ascending order, there is as much as 400 feet of flows, 1,000 feet of dacitic breccia, 1,200 feet of rhyodacite welded tuff, and at least 2,100 feet of sedimentary and tuffaceous rock. The dacitic breccia grades laterally into an arkose and arkosic conglomerate facies, where it overlies a rugged old erosion surface cut on granite. The fragments in the breccia are set in a matrix of pulverized dacitic material, and scattered throughout the dacitic debris are blocks of exotic material as much as 1,500 feet across. These are described in more detail by Simons and others (1966, p. D19-D21). Similar exotic blocks appear in a correlative andesitic or dacitic breccia in the Tucson Mountains, the Tucson Mountain chaos of Kinnison (1959). Similar breccias are characteristic of the formation of Demetrie Wash in the Sierrita Mountains, the volcanics in the formation of Jones Mesa in the Canelo Hills (Hayes and Raup, 1967), the lower parts of Sugarloaf Quartz Latite and Bronco Volcanics of the Dragoon Mountains region (Gilluly, 1956), the Nipper Formation of Sabins (1957a) in the Chiricahua Mountains, and andesites mapped by Epis (1952) in the Pedregosa Mountains. Such breccias are also present in the Empire Mountains and probably occur in the Flux Canyon area of the northern Patagonia Mountains.

The overlying rhyodacite welded tuff of the Salero area is a brownish-gray to greenish-gray massive unit in which separate cooling units have not been recognized. It is a crystal tuff with abundant biotite in well-developed, commonly chloritized, books. Similar welded tuff forms the Cat Mountain Rhyolite of Brown (1939) in the Tucson Mountains. Nonwelded rhyolite tuff of the Red Boy Peak area in the Sierrita Mountains and the upper parts of the Sugarloaf Quartz Latite and Bronco Volcanics of the Dragoon Mountains region are probably equivalent. Tuff in a similar stratigraphic position also occurs in the Empire Mountains.

The lowest and uppermost members of the formation of Salero seem to have no counterparts in the region. The uppermost member, however, underlies an area in the extreme southwest of the Santa Rita Mountains, and investigation of the unstudied area farther to the southwest might disclose its presence there. The uppermost member consists of alternating tuffaceous sandstone, volcanic conglomerate, tuff breccia, agglomerate, and some red beds, largely hornfelsed by intrusives of late Late Cretaceous age.

Samples of these Upper Cretaceous volcanic rocks from the Tucson and Santa Rita Mountains, Canelo Hills, and elsewhere have been dated by the potassium-argon method by Bikerman and Damon (1966) and by Geological Survey laboratories (fig. 2). The dates obtained verify the inferred Late Cretaceous age of at least the volcanics of the Salero area which conformably rest on Stoyanow's (1949) Fort Crittenden Formation of known Late Cretaceous age.

The youngest Mesozoic rocks of the region are plutonic rocks, commonly diorite or granodiorite but including some coarse-grained quartz monzonite. Their emplacement was followed in the Paleocene and Eocene by intrusion of more quartz monzonite, granodiorite, and, commonly, quartz latite porphyry, including many of the ore-associated bodies of the region.

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STRATIGRAPHY OF SOME CRETACEOUS FORMATIONS OF SOUTHEASTERN ARIZONA

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INTRODUCTION

Thick sequences of Cretaceous sedimentary rocks are exposed in and near many of the mountain ranges in southeastern Arizona. The Bisbee Group, type section for the lower Cretaceous, is located in the Mule Mountains and Ninety One Hills near Bisbee in southern Cochise County. These rocks were initially described by Dumble (1902), and later by Ransome (1904), and Hayes and Landis (1961).

Recent stratigraphic studies have been completed by Moran (1957), Tyrrell (1957) and Moore and Miller (1960).

Stoyanow (1936) designated a sequence of rocks in Adobe Canyon on the southeast flank of the Santa Rita Mountains as Upper Cretaceous (Fig. 2), and called them the Sonoita Group.

The stratigraphic position of thick sequences of rocks in and adjacent to the Empire Mountains has, for many years, been uncertain. These rocks have been tentatively correlated by most workers with the Lower Cretaceous Bisbee Group. Others have felt that these rocks were more closely related to the Upper Cretaceous Sonoita Group in the Santa Rita Mountains.

The stratigraphic and structural relationships between the known Cretaceous sections are not simple. Rapid lateral changes in lithology are common. Distinctive marker beds are thereby very rare, and even when present, are not consistent for any great distance.

The most recent regional deformation is of the Basin and Range type. As most of the present surface is that of basins, most of the Cretaceous rocks are covered, and relatively long-range correlations are necessary. In addition to these broad areas of recent sediment cover, local structural complications within the ranges make it necessary to piece the section together from a variety of separated exposures.

Tertiary deformation and intrusion, with attendant metamorphism, have also obscured many of the relationships of the Cretaceous rocks.

CRETACEOUS STRATIGRAPHY

Bisbee Group

In southern Cochise County the Bisbee Group of Early Cretaceous age (Aptian and Albian) is exposed in the Mule Mountains and the Ninety One Hills (Fig. 2). This area is approximately 50 miles southeast of the Empire Mountains. Ransome (1904) called this group of rocks the Bisbee Group. The Group consists of four separate formations which he called the Glance Formation, Morita Formation, Mural Limestone and Cintura Formation.

The most recent work on the Bisbee Group is by Hayes and Landis (1961). In this study, Stoyanow's (1949) Lowell Formation is shown to be lithologically similiar and slightly thicker than the equivalent parts of the Mule Mountains section. Hayes and Landis interpret the Lowell to be equivalent to the upper 375 feet of the Morita Formation and all of the Lower Mural Limestone.

The upper parts of the Morita Formation are replete with various representatives of *Acanthohoplites* and *Trigonia;* specimens of *Trigonia* are common in the lower Mural Limestone and those of *Douvilleiceras* in the Upper Mural Limestone.

The thicknesses and general lithologies of the four formations are shown in Section I, figure 3.

Unnamed Cretaceous Rocks of the Huachuca Mountains

The Huachuca Mountains are approximately 20 miles west of the Mule Mountains and 30 miles south-southwest of the Empire Mountains (Fig. 2). Cretaceous rocks in an 8,226 foot section in Parker Canyon on the southwest side of the range were described by Moran (1957). He considered these rocks to be Aptian and Albian in age and equivalent to the rocks of the Nuevo Leon, Trinity and Fredericksburg Stages of Texas. *Ostrea ragsdalei,* and *Trigonia maloneana* are found in the upper parts of Unit 2 and in Unit 3.

Six units are defined in the measured section, designated by number from bottom to top. Moran's descriptions are condensed and the sequence is represented in Section 2, figure 3.

Cretaceous Rocks of the Whetstone Mountains

In a study of the Whetstone Mountains (Fig. 2) Tyrrell (1957) measured and described numerous sections of Cretaceous rocks. Abundant faulting has broken, repeated, or eliminated many of the rocks of these sections, but in one locality, on the southwest flank of the range, a complete, unbroken sequence is present. At this locality 8,548 feet of section are exposed. The section certainly continues to the southwest under the alluvial cover of the basin fill. This sequence contains four readily definable formations which are part marine and part non-marine. Tyrrell reports specimens of *Trigonia maloneana, Ostrea franklini,* and *Gryphaea mucronata* from the Shelleburg Canyon formation. These rocks have been grossly correlated by Tyrrell with the Bisbee Group and are shown in Section 3, figure 2.

The informal nomenclature used by Tyrrell is used in this report in the description of the rocks in the vicinity of the Empire Mountains.

Cretaceous Rocks of the Santa Rita Mountains

Most of the formations described so far can be seen in various localities in the Santa Rita Mountains but the occurrences are so scattered and incomplete that little use can be made of them insofar as the purposes of this paper are concerned. There are, however, some exposures of recognizable Hilton Ranch conglomerate along the east front of the range.

Fort Buchanan and Fort Crittenden Formations

A thick sequence of Upper Cretaceous rocks on the east flank of the Santa Rita Mountains, approximately eight miles southwest of the town of Sonoita was named the Sonoita Group by Stoyanow (1936). This group was divided into two formations. The lower, containing 2,000 feet of conglomerate, sandstone and shale, was named the Fort Buchanan Formation, and the upper, named the Fort Crittenden Formation, consists of over 2,500 feet of conglomerate, sandstone and shale (Stoyanow, 1949). Remains of *Gorgosaurus libratus* are reported to be present in the lower sandstones and shales of the Fort Crittenden Formation. More recent work by Moran (1957) showed the total thickness of the Sonoita Group to be at least 2,500 feet greater than reported by Stoyanow (see Section 5, figure 3).

Cretaceous Rocks of the Empire Mountains

Parts of the Lower Cretaceous section are exposed on the flanks of the Empire Mountains (Fig. 2). Most of the area is structurally complex, being broken into separate blocks by normal faults. Distinctive marker beds are rare within the section, making it necessary to piece together fragmentary sections in order to construct the overall sequence.

Sections 3 and 4 in figure 2 illustrate the manner in which the informal nomenclature of Tyrrell (1957) has been applied to these rocks.

The thickest continuous section in this area was measured by Moore (1960, p. 1). This section extends from Total Wreck ridge on the east flank of the Empire Mountains to Cienega Wash (Fig. 1, C). The rocks in this section are correlative with Tyrrell's Willow Canyon and Apache Canyon formations. A small part of the lower portion of the Shelleburg Canyon formation is also present at the very top of the section. The total thickness is 8,100 feet.

The top of the lower formation, the Willow Canyon formation, is approximately 6,200 feet above the Paleozoic-Cretaceous unconformity, the unconformity being the position in the section below which limestone beds become a significant part of the section. As a consequence of the establishment of this boundary, a few thin limestone beds are included in the topmost portion of the Willow Canyon formation.

Willow Canyon Formation

The Willow Canyon formation is 6,200 feet thick in Cienega Wash as compared to the 433-foot thickness of the same formation at its type locality in the Whetstone Mountains. The basal conglomerate member averages approximately 50 feet in thickness, but it ranges up to 100 feet in some places and in others it is absent. This formation lies with angular unconformity on upper Paleozoic rocks, and the cobbles and boulders in the conglomerate were derived primarily from the underlying Concha and Rainvalley Formations. The conglomerate is distinctive in its physical appearance, having a moderate reddish brown (10 R 4/6) calcareous matrix surrounding the subrounded to sub-angular limestone pebbles and cobbles. This unit grades upward into the olive gray (5 Y 3/2) and moderate brown (5 YR 3/4) sandstone and siltstone of the upper member.

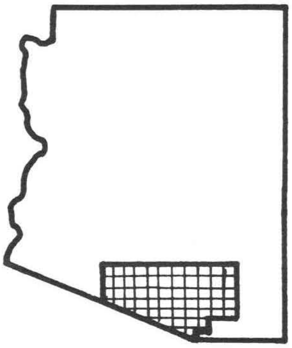

Figure 1a – Index Map of Arizona Showing Pima County

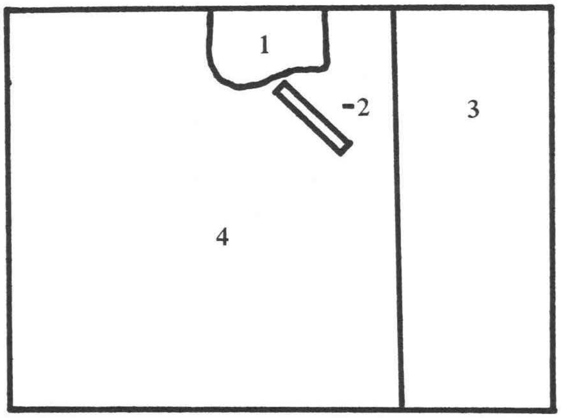

Figure 1c – Index Map of Mapped Area Showing Sources of Geologic Data.

1. Galbraith, 1958
2. Moore, measured section, 1960
3. Tyrrell, 1957
4. This report

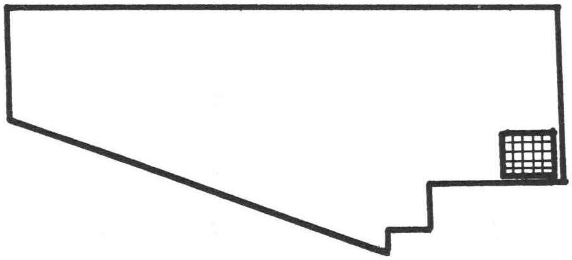

Figure 1b – Index Map of Pima County Showing Area Mapped in this Report

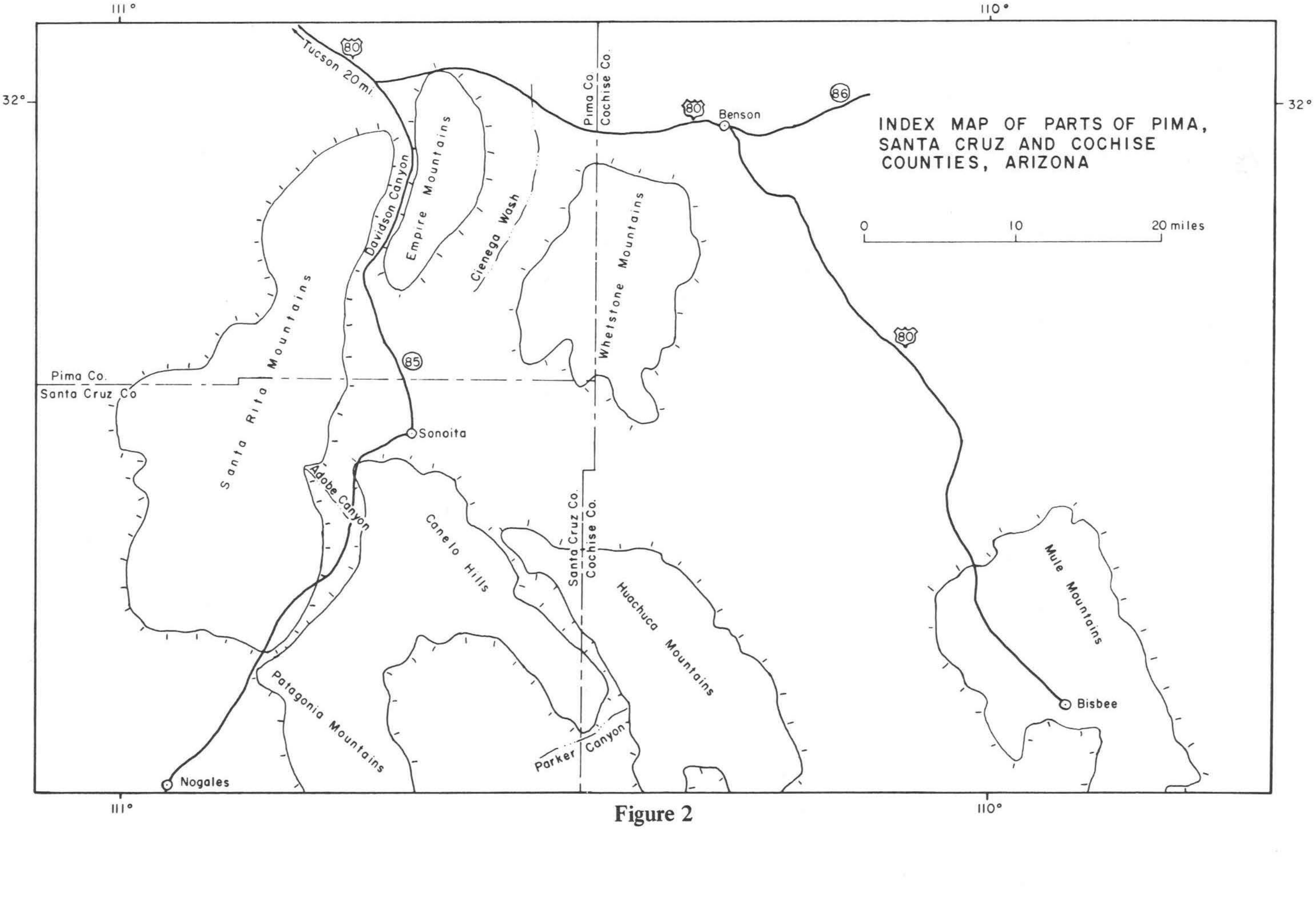

Figure 2

The upper member is composed of an alternating sequence of quartzose and arkosic sandstone with interbedded siltstone and shale. Some pebble conglomerate zones are found within the sandstone. The sandstone is normally white (N 9) or grayish orange (10 YR 7/4) in color, medium-to-coarse-grained and thick bedded. The bedding becomes somewhat thinner toward the top of the formation. The clasts are subangular. Forty percent of the total thickness is sandstone with the remaining 60 percent being nearly evenly divided between siltstone and shale. The siltstone is commonly some shade of red or green, as is the shale.

Simple wedge or lenticular cross-beds are common in the sandstone beds; graded beds, ripple marks and flute casts occur in a lesser amount. Euhedral magnetite is common in the cross-bed laminae, and, in several places, the cross-bedded units are also graded. Fossil wood is common.

Apache Canyon Formation

Conformably overlying the Willow Canyon formation is the Apache Canyon formation, an 870-foot thick sequence of dark gray (N 3) laminated limestone, grayish olive (10 Y 4/2) and very dark red (5 R 2/6) siltstone and shale, and a few beds of medium gray (N 5) and dark yellowish brown (10 YR 4/2) sandstone. The limestone contains a high percentage of organic matter as interstitial carbonaceous material. Some larger fragments were probably pieces of wood.

The clastic rocks in this section contrast sharply with the limestone in the amount of organic material they contain. The clastic rocks contain little or no organic matter, either interstitial or in the form of fossils, except for some large algal colonies in one shale bed near the top of the formation. The shale beds are normally thin-bedded to laminated, but the sandstone occurs in medium to thick beds, and in several units there is no distinct bedding. The cement in the clastic rocks is calcareous. Approximately 200 feet above the base of the Apache Canyon formation a 100-foot thick limestone and shale sequence contains some gypsum beds. Above this gypsiferous zone the normal limestone-shale sequence is again present and is approximately 200 feet thick. At the top of this 220-foot thick sequence the first sandstone in the Apache Canyon formation occurs. From this point upward the balance of the formation is composed of sandstone and shale, with shale predominating in the lower 150 feet. Sandstone becomes more abundant and comprises the bulk of the remaining 50 feet of the formation. Above the sandstone is a 4-foot covered interval overlain by a shale and limestone sequence 150 feet thick containing two beds of sandstone at the top.

Shelleburg Canyon Formation

The Shelleburg Canyon formation is incomplete on the west side of Cienega Wash. In the northern part of the valley between the Empire and Whetstone Mountains, part of the sequence has been removed by erosion. However, in Pump and Sanford Canyons, which are approximately two and three miles south of the Total Wreck Mine respectively, the lower portion of the formation is exposed. Still farther south a 2,650-foot section was measured by the writer, and these rocks, although higher in the section than the rocks present in Pump and Sanford Canyons, are definitely part of the Shelleburg Canyon formation. The presence of these rocks in an area where they would not normally be expected is the result of faulting, the outcrops displaced in a northerly direction.

The section measured in the fault block on the south flank of the Empire Mountains is composed primarily of quartzose and arkosic sandstone and thin-bedded to laminated siltstone and shale. Approximately two-thirds of the section is sandstone. The sandstone is light gray (N 7), grayish olive (10 YR 4/2) and light red (5 R 6/6), with grayish yellow (5 Y 8/4) and dark yellowish orange (10 YR 6/6) the predominant colors on weathered surfaces. Planar and lenticular cross-bedding is common, and some of the sandstone beds contain small lenses and thin layers of pebble conglomerate. The siltstone and shale are mostly within the lower half of the section and are grayish olive (10 Y 4/2), light red (5 R 6/6) or varying shades of gray, and weather light red (5 R 6/6) and moderate yellow (5 Y 7/6). At the base of the section are a few beds of dark gray (N 3) laminated limestone which are identical in appearance to the limestone in the lower part of the Shelleburg Canyon formation in Pump and Sanford Canyons to the northeast.

Dinosaur bones were found by Mr. E. P. Hilton about 1,200 feet stratigraphically below the top of the section. Several marine biostromes containing fragments of the pelecypod genus *Mactra* are present in this section. The same type of biostromes can be seen in many places on the north flank of the Empires and the east flank of the Santa Ritas. Immediately above the upper biostrome the writer found a very dark red (5 R 2/6) shale which contained unidentifiable silicified internal casts of ostracods. Silicified wood is very common in the lower 750 feet of this section, where complete limbs and trunks of

CORRELATION CHART OF SOME CRETACEOUS FORMATIONS IN SOUTHEASTERN ARIZONA

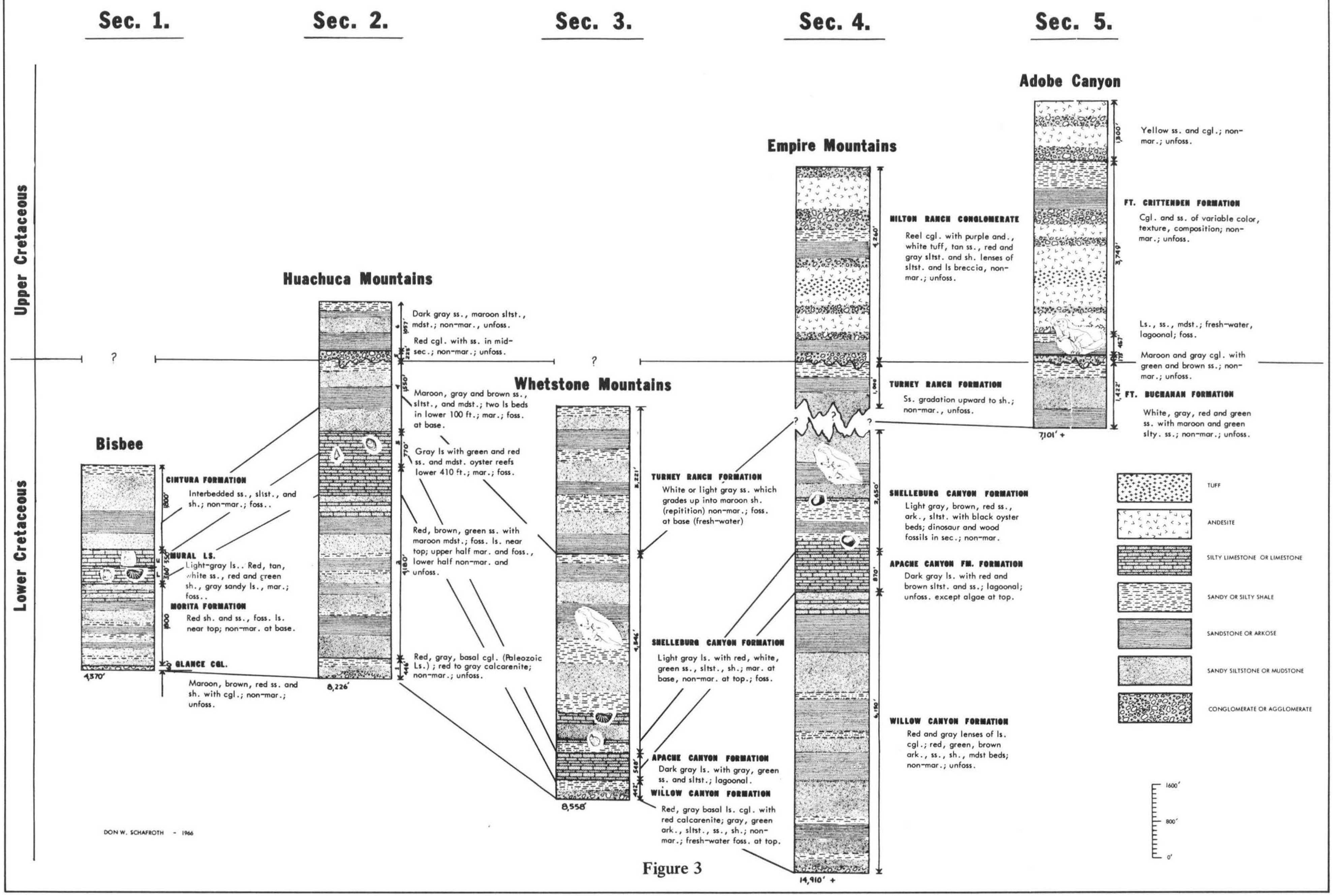

Figure 3

trees are relatively intact. These zones are good environmental indicators. The biostromes, being thin and physically distinctive, can be used for structural interpretation within the fault blocks and the displacements on some small faults can be determined by offset of the biostromes.

The blocks of the Shelleburg Canyon formation on the south and east flanks of the Empire Mountains do not fit together into an uninterrupted composite section, but they do represent a major portion of the sequence. The total thickness of the Shelleburg Canyon formation on the west side of Cienega Wash is approximately 3,600 feet, with an unknown thickness missing in the lower part of the formation and at the top.

Turney Ranch Formation

Only a small segment of the Turney Ranch formation, approximately 1,000 feet, is present in the Empire Mountains and Davidson Canyon. A fault marks the bottom of the measured section. South of the fault only a few outcrops of arkose and sandstone can be seen, and shale outcrops are rare. The formation is overlain unconformably by the Hilton Ranch conglomerate.

The Turney Ranch formation, as in the type section in the Whetstone Mountains, is composed of coarse-to-fine-grained clastic rocks which are assembled in a repetitive thin- to thick-bedded sandstone, siltstone and shale sequence. The upper and lower boundaries of the beds are commonly sharp, but some gradations upward into siltstone or shale were observed. The siltstone and shale are various shades of maroon, green and brown, are thin-bedded to laminated, and are siliceous. Some of the units contain thin layers of bentonite. Scour and fill structures are common throughout the sequence. Silicified wood, although observed in place in only one sandstone bed, is probably common throughout the section since it is abundant as float.

Hilton Ranch Conglomerate

A singular and most important feature of the stratigraphy of this area is the presence of a thick sequence of coarse red and green conglomerate units which are interbedded with tuff, andesite flows, agglomerate and some arkose and shale beds.

The exact stratigraphic position of the Hilton Ranch conglomerate is not known, but it is probably Late Cretaceous in age. The reason for this age assignment will be stated in the discussion following the physical description of the Sonoita Group in Adobe Canyon.

The most complete section of these rocks is exposed on and near the Hilton Ranch in Davidson Canyon. The name, Hilton Ranch conglomerate, is used in this report as a field name and is not at this time being proposed formally.

The thickness of the Hilton Ranch conglomerate is in excess of 4,260 feet. The lowest conglomerate bed rests disconformably on a purple andesite flow which has a very thin weathered zone at the top. The andesite was mapped by Wilson, *et. al.* (1960) as Cretaceous in age. On the south flank of the Empire Mountains the lowest conglomerate unit rests with angular unconformity on rocks assigned to the Turney Ranch formation. The formation terminates at a rhyolite dike occupying a normal fault zone. The thickness of the conglomerate in this locality is about 350 feet. Approximately one mile north of the line of measurement the Hilton Ranch conglomerate lies unconformably on rocks which are probably part of the Shelleburg Canyon formation. Near the south end of Davidson Canyon the formation is overlain unconformably by basin-fill gravels of Pliocene age.

The dominant lithology is a dusky red (5 R 3/4) cobble and boulder conglomerate. The cobbles and boulders are rounded to sub-angular and were derived from the underlying Cretaceous sedimentary rocks and volcanic flows. The matrix in all of the conglomerate units is medium-to-coarse-grained, angular to subrounded sand which is cemented with silica. The matrix also contains some clay. A few beds of light olive (10 Y 4/5) tuffaceous conglomerate occur near the top and bottom of the formation, and are identical to the red conglomerate except for color.

The tuff beds are white (N 9) and light gray (N 7) and weather to a moderate reddish orange (10 R 6/6) or light brown (5 YR 5/6). The clasts are in the size range of medium to coarse sand. Plates of biotite and quartz and potash feldspar grains are relatively abundant. Rock fragments are abundant in the agglomeratic tuff, but they rarely exceed 15 per cent in the finer tuff units.

Purplish andesite flows similar to those in the underlying volcanic sequence occur irregularly throughout the section. Some of the flows contain abundant plagioclase phenocrysts.

The quartzite interbeds are white (N 9) or light gray (N 7) to dark gray (N 3) and finely laminated. These clastic interbeds are local and are not continuous for a significant distance along strike.

Lenses of sedimentary breccia are present locally. The breccia is black (N 1) or dark gray (N 3) and is composed of platy pebbles and cobbles of laminated limestone and siltstone derived from the Apache Canyon or Shelleburg Canyon formations. The matrix is in the size range of coarse sand and is composed of the same material as the pebbles and cobbles except for some chert fragments. The cement is sparry calcite and microgranular quartz.

Lateral changes in grain size and color are rapid and pronounced. An example of this change is present where dusky red (5 R 3/4) cobble conglomerate changes to a pale red (10 R 6/2) quartzite in a lateral distance of 20 feet.

No fossils were found in this formation.

COMPARISONS AND CORRELATIONS

Most workers agree that the Glance Conglomerate in the type section is Early Cretaceous in age. This interpretation is based primarily on structural and stratigraphic evidence as fossils are unknown in these rocks. The rapid thinning and thickening of this unit indicates that the sedimentary materials accumulated on a very irregular depositional surface and possibly originated as alluvial fans.

The Morita Formation in the type section is probably predominantly non-marine. Ransome (1904, p. 65) suggests that these rocks are all marine, but no fossils have been reported from the lower part of the formation. However, marine fossils have been found in limestone beds near the top of the unit. This formation probably represents a transitional phase from the non-marine to marine environments, and the sediments were deposited near the margins of the transgressing Bisbee Sea. Most, if not all, of this formation is probably Lower Aptian in age.

The Mural limestone is exclusively marine. The sediments probably accumulated in deeper water during Albian time when the "Bisbee Sea" reached its maximum encroachment.

The Cintura Formation is much like the Morita Formation in lithology and thickness and is also unfossiliferous. The sediments were deposited near the sea margins as were those of the Morita Formation, except the sea was regressing rather than advancing. The age is probably Upper Albian.

The Lower Cretaceous sequence is approximately 4,300 feet thick, shore line deposition of the advancing and regressing "Bisbee Sea." The deeper-water Mural Limestone represents the maximum transgression, with the Glance Conglomerate and Lower Morita Formation being deposited on-shore and slightly off-shore during the Aptian advance. The upper part of the Cintura Formation was deposited in the same environment but during the Albian retreat. The lowermost part of the Cintura Formation is composed of near-shore marine units. These represent the gradation into and out of the deepwater Mural Limestone environment.

The faunas of the type Bisbee Group are definitive, making the placement of these rocks in time precise. These rocks are equivalent to the Nuevo Leon, Trinity and Fredericksburg Stages of Texas (Stoyanow, 1949).

The lithologic similarity between Moran's unit 1, a cobble and boulder conglomerate, in the Huachuca Mountains and the Glance Conglomerate in the type section is indicative of stratigraphic equivalency. The conglomerates in both sections rest with angular unconformity on older rocks which furnished much of the local conglomeratic material.

The similarity between Moran's unit 2 and the Morita Formation is apparent. In fact, the general description of unit 2 can hardly be differentiated from that of the Morita Formation as defined by Ransome (1904, p. 64-65). The only apparent difference between Moran's unit 2 and the Morita Formation is thickness; 1,800 feet for the Morita Formation and 4,180 feet for unit 2.

The marine fossiliferous zones in the lower 410 feet of Moran's unit 3 correlate, in a general manner, with the Apache Canyon formation in the Whetstone Mountains. In addition, the upper 100 feet of unit 2, a fossiliferous zone, is probably equivalent to the lower portions of the Apache Canyon formation. The lithologies are similar in that they are both predominantly limestone with some interbedded clastic rocks.

The stratigraphic position of the remainder of unit 3 and all of unit 4 is uncertain. The upper part of unit 3 and the lower half of unit 4 are similar to the Shelleburg Canyon formation in the Whetstone Mountains. The rocks are predominantly clastic and are marine at the base and non-marine at the top. The upper half of unit 4 contains light colored, cross-bedded sandstone beds which, in some instances, grade upward into shale and siltstone and display some scour and fill structures. Lithologically and structurally the rocks in the upper half of unit 4 are almost identical to the rocks in the Turney Ranch formation. The rocks in the lower half of unit 4 and the upper 250 feet of unit 3 are probably equivalent to the Shelleburg Canyon formation.

On the basis of lithologic similarity, thickness and faunal evidence, the lower 6,950 feet, units 1, 2, 3, and 4, of the Cretaceous section in the Huachuca Mountains is correlative with the type section of the Bisbee Group and the Cretaceous section in the Whetstone Mountains.

The conglomerate and finer clastic portions of the Huachuca Mountains section; units 5 and 6, can be correlated with part of the non-marine, Upper Cretaceous sequence in Adobe Canyon and the Hilton Ranch conglomerate. The correlation will be discussed later in greater detail.

The Willow Canyon formation in the Whetstone Mountains has been divided by Tyrrell (1957, p. 95) into two members. The thin basal limestone conglomerate is designated as the Glance Conglomerate member; the finer clastic rocks above are called the upper member. Tyrrell considers the lower conglomerate and arkose to be non-marine with a gradation upward into lagoonal and estuarine siltstone and shale. Fresh-water branchiopods are reported by Tyrrell from the upper portions of the formation.

Tyrrell (1957, p. 102) has divided the Apache Canyon formation into an upper and lower member, considering the formation to be lagoonal at the base, marine in the middle and lagoonal at the top.

The Shelleburg Canyon formation in the Whetstone Mountains is partly marine and partly non-marine with the transition between the rocks deposited in the two environments being rapid. This is not a simple transition, but, as sea level was fluctuating rapidly and in numerous pulses, a complex sequence of transitions between marine and non-marine rocks.

The Turney Ranch formation probably originated as a flood-plain deposit, with the sandstone and arkose deposited in the channels, and the siltstone and shale covering the inter-channel mud-flats. The cross-bedding, gradation from sandstone upward into siltstone and shale, scour and fill, and the presence of silicified wood is sufficient evidence for this interpretation.

According to Tyrrell (1957, p. 94) the Whetstone Mountains section is all Early Cretaceous in age with the possible exception of a portion of the upper part of the Turney Ranch formation. This is only a supposition on the part of Tyrrell as he states that he has no direct evidence to support this. It is the writer's conclusion, based on evidence found in Adobe Canyon and on the south flank of the Empire Mountains, that the entire exposed section is Early Cretaceous, Aptian and Albian, and that the boundary between the Lower and Upper Cretaceous lies to the south and southwest beneath the blanket of Pliocene basinfill. Thus, the Lower Cretaceous sedimentary rocks on the south flank of the Whetstone Mountains are in excess of 8,558 feet thick. This thickness of Lower Cretaceous rocks is more than 1,500 feet greater than the Lower Cretaceous portion of the Huachuca Mountains section. The increase in thickness may indicate a systematic thickening to the west and north at the rate of approximately 200 feet per mile, and this may be an indication of the source area for the bulk of the sediments deposited in and near the Lower Cretaceous "Bisbee Sea."

The sea apparently did not extend north beyond this general area. This is evidenced by (1) the abundance of lagoonal sediments, (2) relatively thin marine limestones which contain a littoral fauna, and which alternate with non-marine clastic rocks, (3) rapid and numerous transitions between marine and non-marine rocks, and (4) the predominance of non-marine rocks.

Exceptions can be noted in the local presence of marine biostromes contained within the Shelleburg Canyon formation where it is exposed on the north, east and west flanks of the Empire Mountains and on the east flank of the Santa Rita Mountains. Marine tongues probably penetrated into these areas from the main water body.

The similarity of the rocks in the Sonoita Group in Adobe Canyon to those in the Hilton Ranch conglomerate is evident, even though no fossils have been found in the finer-grained portions of the Hilton Ranch conglomerate. The contact relationships at the top and the bottom of these two sequences are very similar. The Fort Crittenden Formation is overlain unconformably by Tertiary sedimentary rocks which closely resemble the Pliocene basinfill to the north. The Hilton Ranch conglomerate is overlain unconformably by the Pliocene basinfill. Also, the Fort Crittenden Formation lies unconformably on clastic rocks which are similar to the rocks of the Turney Ranch formation.

On the south flank of the Empire Mountains the Turney Ranch formation is overlain unconformably by the Hilton Ranch conglomerate. The same type of relationship exists between unit 4 and unit 5 at the top of the section in the Huachuca Mountains. Unit 4 is, in its uppermost portions, correlative with the upper parts of the Turney Ranch formation and is overlain unconformably by a thick sequence of massive, reddish conglomerate which contains some inter-bedded sandstone and quartzite.

Several fault blocks of conglomerate, similar to the conglomerate units in the Hilton Ranch conglomerate are exposed on the east flank of the Santa Rita Mountains. These blocks of conglomerate are on a line which extends from the southernmost exposure of the Hilton Ranch conglomerate to Adobe Canyon.

All of the preceding factors strongly imply chronologic and environmental identity, and it is probable that the Hilton Ranch conglomerate is the same age, Late Cretaceous, as the Fort Crittenden Formation.

The Willow Canyon formation on the west side of Cienega Wash is composed of non-marine clastic rocks except for a few thin limestone beds near the top of the formation. These limestone beds are probably lagoonal and correlate with those near the top of the Willow Canyon formation in the Whetstone Mountains. These limestone beds represent the first incursion of the Lower Cretaceous sea into the area; all of the clastic rocks below are non-marine.

SUMMARY

Sufficient information is now available, both as a result of information gathered by the author and by others, to correlate the rocks belonging to the Cretaceous System which are located in parts of south-central Arizona. The Lower Cretaceous rocks in the area correlate with the type section, the Bisbee Group, and the Upper Cretaceous rocks correlate with the type Sonoita Group. The total Cretaceous System is tied together only in the small area on the south flank of the Empire Mountains where the Upper Cretaceous rocks rest with angular unconformity on Lower Cretaceous rocks.

ACKNOWLEDGEMENTS

The author wishes to express his appreciation to all those who tendered assistance and encouragement during the course of this work. Particular thanks go to Mr. W. R. Moran of the Union Oil Company of California for granting me permission to utilize information included in company reports. And finally, thanks to my secretary, Miss Carolyn Alexander, who spent a number of tedious hours typing several drafts, and deciphering my many scribbled changes.

This paper is an abridgement of a portion of a Ph. D. dissertation completed at the University of Arizona.

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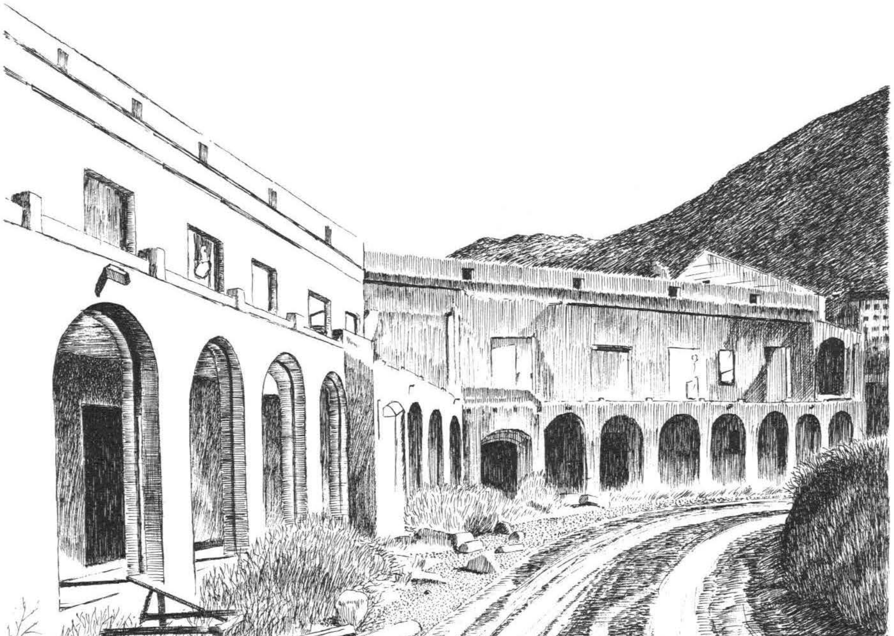

CORRELATION OF SOME POST-LARAMIDE TERTIARY UNITS GLOBE (GILA COUNTY) TO GILA BEND (MARICOPA COUNTY), ARIZONA

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GENERAL STATEMENT

Integration of field mapping by various geologists has resulted in the identification of some correlative Tertiary units along a zone 130 miles in length. The zone extends from the Globe-Miami area across the alluvial basin at Casa Grande into the Gila Bend area. The rock units are correlated on the basis of rock type, structural involvement, and sequence, but they are not necessarily exact time equivalents. This paper does not propose that any rock unit completely covered the region from Globe to Gila Bend, nor that similar appearing units in the various areas are necessarily from the same source. The units are post-Laramide (post-early Tertiary) in age.

I wish to thank ASARCO geologists for their written and verbal comments and, along with M. E. Cooley, for field checks. American Smelting and Refining Company (ASARCO) kindly permitted permission for publication of the paper.

DIVISIONS

The late Cretaceous-early Tertiary sequence of selected localities was reported in a paper by Richard and Courtright (1960). Summaries of the numerous problems of Late Mesozoic-Tertiary events involving sequence and correlations are given by Cooley and Davidson (1963), and Heindl (1962).

The post-Laramide Tertiary units rest on a widespread erosion surface termed the San Xavier surface (Heindl, 1962, p. 13). In this paper the following six divisions are proposed for this portion of the Tertiary sequence.

VI	Younger basalts	)	Late (?) Miocene-early Pliocene
V	Tuffs and ignimbrites	)	Late Eocene (?) to Middle Miocene (?)
IV	Younger conglomerates	)	
III	Older volcanics	)	
II	Andesitic volcanics	)	
I	Older conglomerates	)	

All divisions are not represented in each area discussed; however, the stratigraphic-structural break representing these divisions has been noted and commented on by various workers in Cenozoic geology. Field relationships of the rock units and their structural complexities indicate that a sequence of depositional-readjustment and volcanic activity was continuous for the entire time span as covered in this paper. The relation of structure to deposition, volcanism, and erosion is widely covered in the papers by Cooley and Davidson (1963), and Heindl (1962). Because of these complexities any of the Tertiary units may be in depositional contact with any Laramide or pre-Laramide sequence.

Unit names in this paper (generally in quotes) are those given in the various reports and thus are of local usage only. Widespread correlation with named units elsewhere in Arizona is speculative at this time, and work is continuing in correlating the Tertiary sequence of the Basin and Range Province in Arizona.

Division Description

I. *Older conglomerates.* The older conglomerates are generally tuffaceous and contain large quantities of locally derived debris but do not contain fragments of extrusive volcanic rocks. The gravels range from pebble to boulder size, angular to rounded, unsorted to poorly sorted. In the eastern area (Superior-Globe-Miami), the conglomerates appear to occupy restricted basins whereas westward in the Table Top-Sand Tank area they were deposited in more widespread sheets. A major unconformity separates the older conglomerates from the overlying units.

II. *Andesitic volcanics.* The lower flows of the andesitic volcanics may interfinger with the underlying conglomerates but the change occurs rapidly from dominantly sedimentary rock to dominantly volcanic rock. At the base of the andesitic volcanics are beds, often exhibiting waterlain characteristics, of brown to red-brown cinder and ash beds, and locally in the western area a white pumice bed. Overlying the cinders are non-vesicular light to medium grey andesite flows characterized by abundant red specks which are probably iddingsite derived from olivine.

The characteristic cinder and ash beds have been mapped from the Superior area to the Gila Bend area and constitute a very good marker bed even though they are thin and not present in all outcrops of andesitic volcanics.

III. *Older volcanics.* A dark gray, to black vesicular basalt lies disconformably on the underlying volcanic rocks, predominantly andesitic, in the western part of the report area. Associated with the basalt is a complex sequence of andesitic, rhyolitic, and latitic flows and vents. In the Superior-Globe-Miami area, the Division III unit is a complex of trachyte, rhyolite, glassy lavas, and other flows, which, in Arnett Creek is known to overlie the "red speckled" andesite and the red-brown cinder-ash beds of Division II. A major unconformity occurs at the top of the complex Division III.

IV. *Younger conglomerates.* The younger conglomerates appear to occupy very restricted basins and are primarily composed of material from the eroding and reworking of the nearby older volcanic-conglomerate sequence. Especially characteristic is the abundant debris derived from the older volcanics of diverse types. With the conglomerates are abundant tuffaceous sandstones, and some mudstones.

V. *Tuffs and ignimbrites.* A vast amount of ash material, ranging in composition from rhyolitic to dacitic, and of pastel colors, make up the units of this division. The material is characteristically a welded tuff or ignimbrite which often has a dense black vitrophyre layer near the base. The structural complexities of the ignimbrites are minor compared to the underlying units (especially the older volcanic rocks) although the ignimbrites are cut by faulting. A minor unconformity separates the units from the overlying younger basalts.

VI. *Younger basalts.* Dense, black basalts overlie the ignimbrite forming material. The basalts are found as isolated "caps" throughout the region, but are also found as widespread, though dissected, sheets.

DESCRIPTION OF AREAS

Five areas, from Globe to Gila Bend, and their sequence of post-Laramide rock units are discussed in this section. Figure 1 shows the geographical relationship of the areas. Figure 2 is the proposed correlation between the six divisions previously described.

Globe-Miami

In the Globe-Miami area the older conglomerate unit of Division I is represented by the Whitetail Conglomerate which may rest on any of the older rocks. The conglomerate is composed of coarse, bouldery diabase detritus with subordinate amounts of Pinal Schist, Apache Group, and Paleozoic limestones. N.P. Peterson (1962, p. 37) writes: ". . . . the lower part is wholly unsorted and unstratified. Higher in the section crude stratification can be recognized, and lenses of poorly sorted gravel occur that undoubtedly represent temporary stream channels. Approximately the upper 50 feet of the formation is well stratified and is composed of layers of dark sand and gravel interbedded with layers of white tuffaceous sand."

The andesitic volcanics, Division II, are not represented in the Globe-Miami area and the older volcanics of the complex Division III rest directly on the Whitetail. The correlation of N. P. Peterson's "Earlier Volcanics" with Division III is based on Blucher's (1958) and D. W. Peterson's (1962) work in the Superior area.

The Division III unit is a complex assemblage of bedded tuffs (some of which are waterlain), felsitic and glassy lavas, and perlitic glass. These volcanics are separated from the overlying volcanics by an "interval during which some erosion of the rocks of the first eruption occurred" (N. P. Peterson, 1962, p. 37).

This interval of erosion undoubtedly is the interval represented by Division IV, younger conglomerates, but no remnants of any conglomerate have been reported.

The Division V, tuffs and ignimbrites, ("Later Volcanics" of N. P. Peterson, 1962) have a base of white to gray crystal-tuff which grades upward into a black vitrophyre, which in turn is overlain by the massive welded tuffs or dacite which have a slightly variable light brownish-gray-orange color.

Superior

The Whitetail Conglomerate (Division I, older conglomerates) crops out in the Superior quadrangle in several places and in Queen Creek within the Thompson Arboretum area of the Picketpost quadrangle. The Whitetail Conglomerate, as described by D. W. Peterson (1962) is ". . . . fluvial deposits composed of angular to subangular fragments derived from all older rocks, mainly from underlying or nearby rocks. Most fragments are pebble size, some larger. Matrix is coarse-grained, poorly sorted arkosic to lithic sandstone, moderately well cemented; bedding planes poorly defined or absent."

Overlying the Whitetail Conglomerate north of Picketpost Mountain is the distinctive brown to red-brown ash bed which in turn is overlain by a massive blue-black andesite ("Blue Basalt" of Blucher, 1958) with altered red crystals - probably iddingsite after olivine. These volcanic units represent Division II, andesitic volcanics, of this paper. In Arnett Creek the ash beds rest directly on either Pinal Schist or Laramide granite,

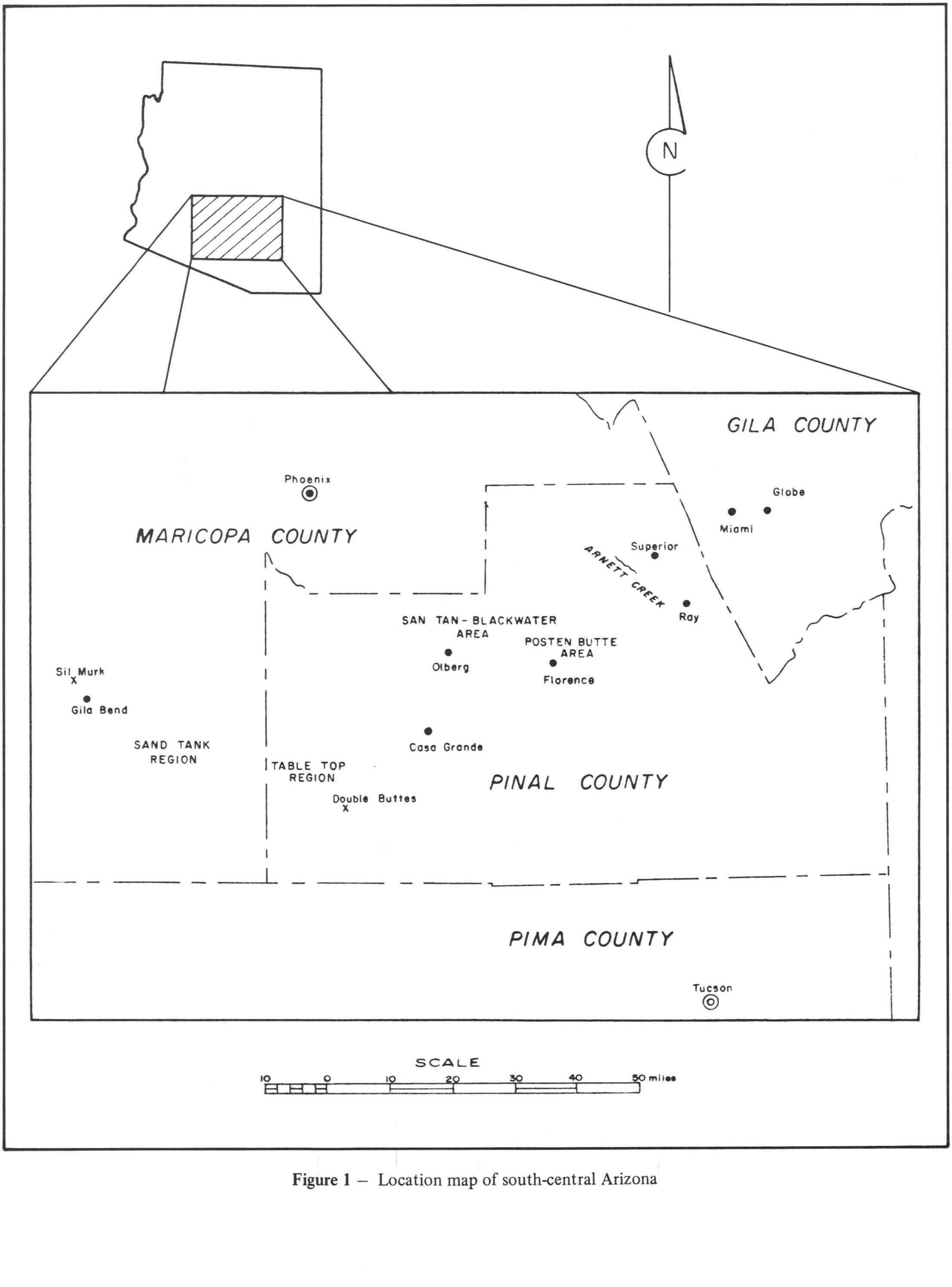

Figure 1 – Location map of south-central Arizona

while in the road cuts west of the Arboretum they rest on Pinal Schist and poorly preserved conglomerates.

Blucher and Kinnison in 1960 (Personal Communication) recognized a disconformity separating the Division II red ash and "Blue Basalt" units from the overlying complex (Division III) of tuff, spheroidal agglomerate with perlite, and rhyolite of the Arboretum area. Eastward the units are apparently part of the sequence which D. W. Peterson (1962) describes as: "Rhyolite: Lava flows composed of rhyolite and perlitic obsidian. Light to medium-gray rhyolite. . . .generally prominent flow laminations, locally contorted. Perlitic obsidian generally forms top or bottom of rhyolite flows. . . . Includes minor deposits of tuff, tuff breccia, and flows of andesite and trachyte."

D. W. Peterson (1966) suggests that the tuffs and rhyolites on Picketpost Mountain are younger than the dacite; however previously (1962), he maps and describes the thick rhyolite which underlies the dacite northeast of Picketpost.

A break suggesting an "unrecognized erosion cycle" (Blucher, Personal Communication) separates the complex sequence of Division III from the overlying dacite and welded dacite tuff of Division V. As in the Globe district, this interval is represented by Division IV.

The dacite of Division V is described by D. W. Peterson (1962) as ". . .ash-flow sheets; non-welded tuff at the base grades upward to densely welded black vitrophyre that is overlain by densely welded tuff with cryptocrystalline groundmass. Progressively upward from the vitrophyre the welding gradually decreases, the amount of crystallization in the groundmass increases and the color changes from light brown to moderate red to very light grey."

Blackwater-San Tan

ASARCO geologists Blucher and Kinnison conducted the bulk of the mapping in this area and the following descriptions are from their reports.

The lowest post-Laramide unit found was termed the "Yellow Peak conglomerate" for its excellent exposure on Yellow Peak northeast of Olberg. This Division I, older conglomerate, is equivalent in position to the Whitetail Conglomerate of the Globe-Superior region. The "Yellow Peak" (as reported by Blucher) ". . . .is a poorly sorted, poorly indurated, fluvial deposit. . . .made up principally of pebbles, cobbles, and boulders of Coolidge granite in a silty matrix." The Coolidge granite is the report term for the Laramide granite of the area.

The basal unit of Division II, not everywhere present, is red-brown cinders and ash beds ("Olberg Beds" of Blucher and Kinnison) which rest directly upon the "Yellow Peak conglomerate" as well as the Laramide granite. Overlying the red-brown cinders and ash beds is Blucher's "Blue Basalt" which is seldom amydaloidal or vesicular. The basalt weathers to a soft bluish-gray surface. This sequence of cinders and basalt is directly correlated with the Division II sequence at the Arboretum, Superior, Arizona.

Units composing the complex group of Division III, older volcanics are not exposed in the areas mapped by Blucher and Kinnison, but they may be present in the volcanic complex of the Malpais Hills to the north and west.

Overlying the "Blue Basalt" is the "Rock Peak conglomerate" which is assigned to the younger conglomerates of Division IV. This unit is composed of ". . . . tuffaceous sandstone, siltstone, and conglomerate which weathers to a light tan pock-marked surface" (Blucher, private company report).

The tuffs and ignimbrites of Division V cap Rock Peak and Yellow Peak and are exposed in most of the cliffs west of the peaks. This thick sequence of dacitic volcanic rocks is correlated with the dacites to the east and consists of tan dacite tuff, welded tuff, or tuff agglomerate with a brown to black vitrophyre near the base of the series.

The younger basalts (Division VI) cap many of the isolated buttes in the region. They were named the "Walter Butte basalt" by Blucher for exposures on the butte.

Table Top-Sand Tank

Throughout this region are numerous exposures of the older conglomerate - here termed the "Antelope Peak conglomerate" for its excellent exposure on that peak in the Antelope Peak quadrangle west of Casa Grande. The Division I conglomerate rests on Precambrian granite at Antelope Peak, on Apache Group rocks on Table Top Mountain, on Pinal Schist throughout the area, and on Paleozoic limestones and Laramide granite south of Freeman Underpass on the Casa Grande-Gila Bend Freeway. Mapping in this area was conducted by the author. The "Antelope Peak conglomerate" has a sandy-silty-tuffaceous matrix, often with waterlaid biotite tuff lenses and contains pebbles and boulders of Laramide and older rocks. Some volcanic porphyry-type pebbles are present in minor amounts but none resemble the overlying volcanics. Boulders of conglomerate similar to the Glance Conglomerate (Cretaceous) of the Vekol Mountains are also present.

Division II, andesitic volcanics unit, is composed of two distinct units. The lower member, the "Freeman beds" (exposed in the roadcuts at Freeman Underpass)

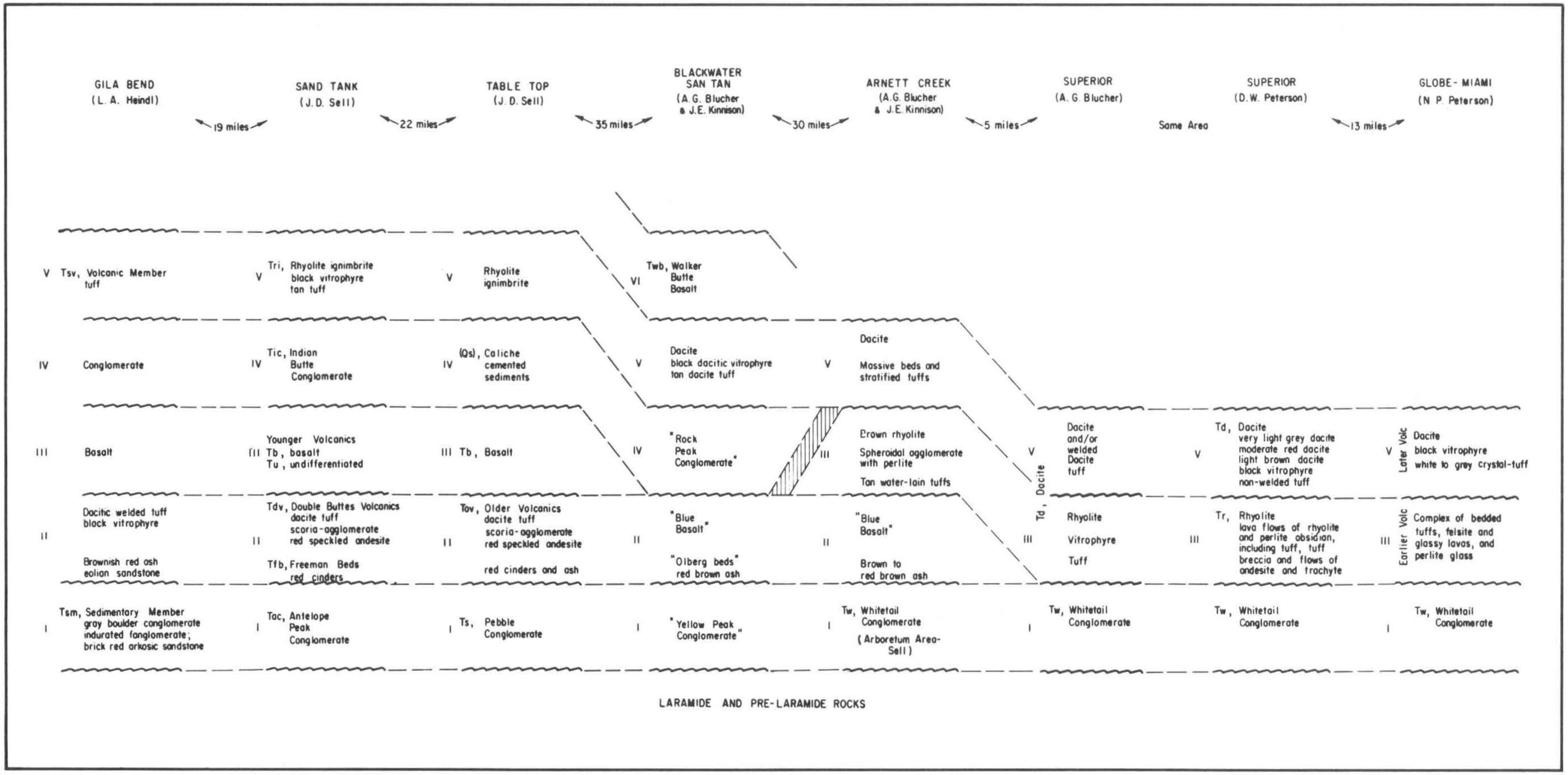

Figure 2 – Proposed correlation of post-Laramide units in central Arizona

is composed of brown-red cinders and ash with white pumice. The upper member, "Double Buttes volcanics" (named for the exposures in the Table Top quadrangle), is composed of purple-gray andesite containing the characteristic altered red crystals, lava scoria, cinders, agglomerate, and sometimes local units of dacitic tuff.

In the Sand Tank region, the volcanics of Division II are mapped as the Sauceda volcanics of Cretaceous age by Wilson et al (1957). As the volcanics overlie the older conglomerates which contain fragments of Laramide-type rocks, the volcanics must be younger than Cretaceous.

The interfingering of the lower conglomerate type unit with the first phases of extrusive volcanic action of the Division II units is well demonstrated in exposures in the region. However, it is not known whether the interfingered conglomerates are merely the result of erosion and reworking of the main conglomerate units or whether it reflects the continued inflow from the conglomerate source areas. The exposures show, however, that the change from dominantly sedimentary processes to dominantly volcanic processes is sharp and complete.

Overlying the andesitic volcanics are units of Division III. In the Table Top area, Division III is a basalt sequence of dark glassy basalt and dark andesitic basalt; whereas, to the west in the Sand Tank area the basalt is associated with a complex of andesitic, latitic, and basaltic volcanics interbedded with minor tuffaceous units.

The younger conglomerates of Division IV are poorly exposed throughout the region but scattered outcrops of conglomerate containing fragments of all previous volcanic types in the area can be found. One exposure is at Indian Butte (Table Top quadrangle) where a tuffaceous, often caliche-cemented, conglomerate contains numerous fragments of the older volcanics and basalts. Northwest of the Table Top Mountains an outcrop of conglomerate containing all types of volcanics is found underlying a rhyolite ignimbrite.

Capping many isolated buttes, especially north of the Freeman Underpass, is a distinctive pinkish rhyolite ignimbrite which generally has a basal tan tuff and black vitrophyre. The tuff, vitrophyre, and rhyolite ignimbrite are assigned to Division V. An unconformity separates Division V units from the underlying units, and the upper units have been subjected to only minor faulting and tilting.

No dense black basalt of the Division VI type was found in the area mapped.

Southeastern Gila Bend Mountains

The work of Heindl and Armstrong (1963), following the previous work of Babcock and others (1948), was a rapid reconnaissance of a small part of the south end of the Gila Bend Mountains. Heindl defined and described the "Sil Murk Formation" in this report and, although additional work is needed to definitely establish the correlation, the sequence of units they describe in this formation resembles the sequence of units in the Tertiary section farther east.

The Division I conglomerates are mapped over much of the Gila Bend area and were named the "Sedimentary Member" of the Sil Murk Formation.

The "Volcanic Member" overlies an angular unconformity cut on the conglomerate and is sequence in which Heindl lists the following, ascending, types: Eolian tuffaceous sandstone, brownish-red ash, black vitrophyre, and dacitic welded tuff (all Division II); a fine-grained black basalt (Division III); a conglomerate containing both gneissic and volcanic rocks (Division IV); and a lavender tuff, possibly dacitic (Division V).

Also found on the northwest side of the area (but not mentioned by Heindl) is the distinctive pink rhyolite ignimbrite of Division V, which is underlain by conglomerates having volcanic material and belonging to Division IV.

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SOME NOTES ON THE LATE CENOZOIC DRAINAGE PATTERNS IN SOUTHEASTERN ARIZONA AND SOUTHWESTERN NEW MEXICO[1]

By

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INTRODUCTION

The development of the drainage in southeastern Arizona and southwestern New Mexico has been controlled and modified repeatedly by pulses of large-scale faulting, epeirogenic upwarping or subsidence, and volcanic activity. As a result—in late Cenozoic time, mainly during the Pliocene and Quaternary—a close relation exists between these events and the evolution of the Gila and Salt Rivers, which are the two main streams in the area.

Much has been written about the development of the Basin and Range physiographic province and its drainage patterns since the early geological surveys of Gilbert (1875). These reports include studies by Lee (1905), McKee (1951), Heindl (1958; 1962), Lance (1960), Melton (1960), Cooley and Davidson (1963), Kottlowski and others (1965), and Cooley and others (1967) that cover all or parts of the area. This report presents a working hypothesis of the drainage development based on regional trends in sediment size and the association of the sedimentary deposits with the volcanic rocks and geologic structure, coupled with about 1,100 measurements of imbrication of pebbles and the direction of dip of the crossbeds.

The author gratefully acknowledges Mr. J. D. Sell for his aid in review of this report.

INITIAL GEOLOGIC SETTING

Toward the end of middle Cenozoic time (mainly in the Miocene), large-scale differential structural movements formed the mountain chains and valleys south of the Mogollon Rim. Pre-upper Cenozoic sedimentary rocks, such as the Helmet Fanglomerate near Tucson (Cooper, 1960, p. 95), and the volcanic rocks were involved in large-scale normal faulting and some compressional folding and thrusting (Sabins, 1957). Deposits of late Cenozoic age are not known to have been involved in the thrusting. Normal faulting, however, continued throughout late Cenozoic time, but with decreased intensity; by the beginning of Quaternary time, faulting was minor.

The drainage and the main centers of deposition are difficult to reconstruct before late Cenozoic time, owing to the difficulty in placing deposits of this age in their correct stratigraphic position. Some aid in correlation is obtained from the association of these deposits with the volcanic rocks, which, during Cenozoic time, show a rough transition in composition from silicic to more mafic basalt types. The volcanic rocks extruded before late Cenozoic time are rhyolite, light-colored andesite, latite, dark andesite, andesitic basalt, and dacite. During late Cenozoic time, however, the volcanic rocks were mainly basalt. Some indications of what the drainage may have been immediately preceding late Cenozoic time are shown in figure 1. In places, the drainage direction was similar to that of the present streams, but in other places, such as in parts of the Santa Cruz and San Pedro Valleys, the drainage direction was opposite to that of the present streams.

LATE CENOZOIC DRAINAGE

The main physiographic features and the ancestral stages of the present drainage patterns were developed by late Cenozoic time, mainly in Pliocene and Quaternary time. During the early part of late Cenozoic time, mainly in early to middle Pliocene time, the drainage was imponded and probably produced more internally drained basins in southeastern Arizona and southwestern New Mexico than during any other period (fig. 1). This was followed by a gradual integration of the internal drainage into through drainage and the establishment of the Gila River system (fig. 2).

A large amount of alluvium was deposited in the valleys throughout much of late Cenozoic time. Collectively, these deposits are more than 1,500 feet

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[1] Publication authorized by the Director, U.S. Geological Survey. Prepared in cooperation with the Arizona State Land Department.

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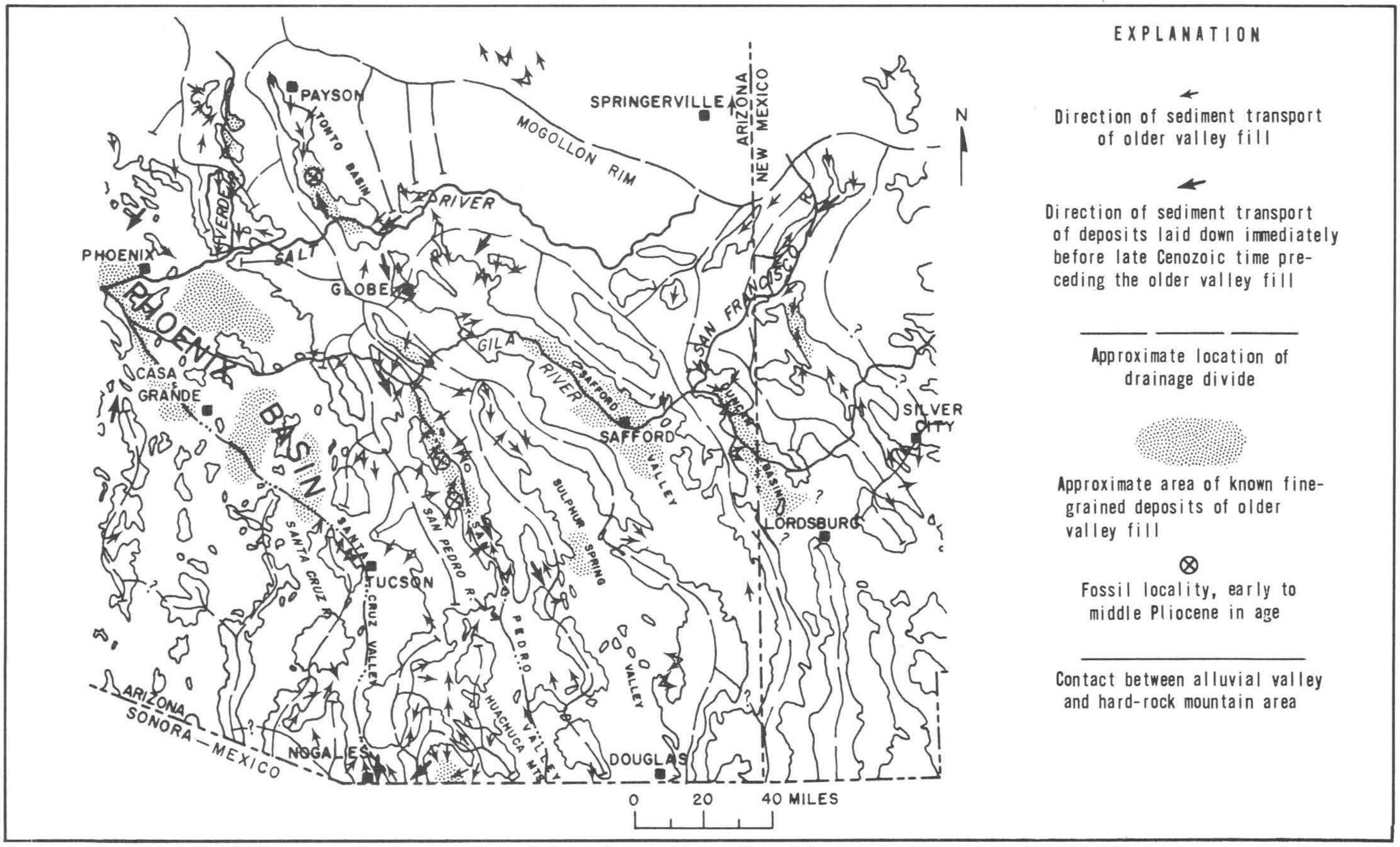

Figure 1 — Drainage during the deposition of the older valley fill, mainly in early and middle Pliocene time.

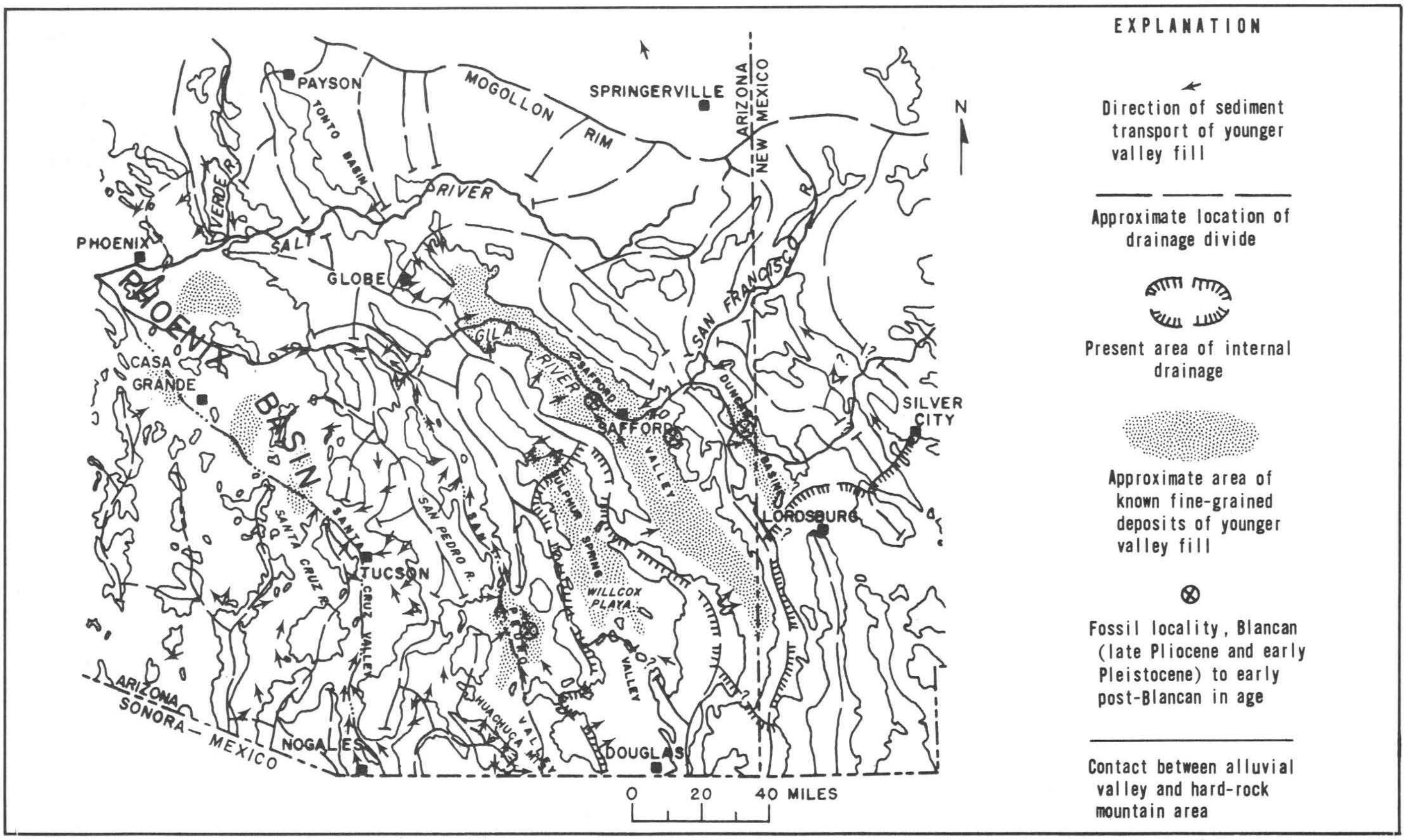

Figure 2 — Drainage during the deposition of the younger valley fill, mainly in late Pliocene and early Pleistocene time, and the present areas having internal drainage.

thick in many large valleys, particularly the Phoenix basin and Safford Valley. The alluvium is not a single sequence of deposits but chiefly represents two general periods of alluviation; in this report the deposits are referred to as the older valley fill and the younger valley fill. Many investigators (Peterson, 1962, p. 41; Gilluly, 1956, p. 118; Schwartz, 1953, p. 13-15) have called the bulk of the late Cenozoic deposits the Gila Conglomerate, or the Gila (?) Conglomerate (Gilbert, 1875), or the Gila Group (Heindl, 1963). In many places, however, the late Cenozoic deposits are referred to informally–the older alluvium and lake deposits in the San Pedro and Sulphur Spring Valleys (Cooper and Silver, 1964, p. 94-95), deformed gravel and basin-fill deposits in the Safford Valley (Davidson, 1961, p. C-151), and older and younger units of the basin fill adjoining the Huachuca Mountains (Brown and others, 1966, p. 15-18).

Many exposures in southeastern Arizona and southwestern New Mexico show the contact between the older and younger valley-fill deposits as a channeled erosion surface; in places, the contact indicates an angular unconformity generally along basin margins. In one place in the San Pedro Valley, sediment of the younger valley fill is deposited against a fault scarp formed from the older valley fill (Montgomery, 1963). In the central part of many valleys, such as Sulphur Spring and Safford Valleys and the Duncan basin, that probably had continued internal drainage during the deposition of the younger valley fill, this unit overlies conformably the older valley fill.

The older and younger valley-fill deposits consist of mixtures of clay, silt, sand, and gravel. The gravel of the younger valley fill usually contains more silt and is more weakly cemented than the gravel of the older valley fill. In most exposures, the younger valley fill has a reddish-brown hue, whereas the older valley fill is buff or gray. Fine-grained deposits, including some gypsum in the Tonto basin (Lance and others, 1962, p. 98-99) and San Pedro Valley, are widely distributed in the older valley fill and are present in the center of most of the valleys (fig. 1). In the younger valley fill, fine-grained deposits are not present everywhere, but there are large amounts of limestone in the Safford Valley (fig. 2). A few vertebrate fossils have been found in the valley-fill units. The fossils in the older valley fill are early to middle Pliocene in age, whereas the ones in the younger valley fill are late Pliocene to early Quaternary and early post-Blancan in age (Lance, 1960, p. 156-157; Wood, 1960, p. 141).

During the early part of late Cenozoic time, when the older valley fill was deposited and internal drainage was prevalent, the Gila River system did not exist in its present form (fig. 1). The water from part of the upper Gila drainage may have flowed to the San Francisco River and been imponded in a basin near the New Mexico-Arizona State line. The water in Santa Cruz Valley apparently flowed into the southern part of the Phoenix basin, where it became imponded, and the San pedro and Safford Valleys were large areas of internal drainage. To the north, however, the Salt River was through flowing as far downstream as the Tonto basin. Southwest of Tonto basin, the ancestral Salt River was imponded near Phoenix, and its main tributary, the Verde River, had not yet become a through-flowing stream.

During the period of upwarping and downcutting preceding the deposition of the younger valley fill, some drainages became integrated. During the deposition of the younger valley fill, the Salt, Santa Cruz, Verde, and possibly the San Pedro Rivers drained into the Phoenix basin, and perhaps part of the water continued westward across the basin (fig. 2). The Gila River, however, was still imponded in its upper reaches. During the deposition of the younger valley fill, the Gila(?)-San Francisco Rivers flowed into the Safford Valley, as indicated by the rounded gravel of different lithologies in the upper part of the younger valley fill east of Safford (E. S. Davidson, oral commun., 1960). The Gila River, however, may have been imponded in pluvial lakes in the southern part of the Duncan basin until late in Pleistocene time (R. B. Morrison, oral commun., 1964). The Gila River in Safford Valley became integrated with the lower reaches of the river after a pulse of regional upwarping that terminated deposition of the younger valley fill and established through drainages in early post-Blancan time in this and many other valleys in southeastern Arizona and southwestern New Mexico. The upwarping seems to be continuing at the present time, as evinced by the downward and headward cutting by streams, and only the Sulphur Spring Valley in Arizona and a broad area near Lordsburg and Silver City, New Mexico, are still internally drained (fig. 2).

As a result of the regional upwarping in the late part of Quaternary time, most streams removed large amounts of alluvium and deepened the valleys. The maximum amount of cutting probably was in the Safford Valley, where the valley was deepened by about 900 feet. In the Santa Cruz Valley near Tucson and in much of San Pedro Valley, the valleys were deepened by about 500 feet. Downcutting was slight in the Phoenix basin, and some subsidence must have occurred, because post-younger valley-fill flood-plain alluvium was deposited over a wide area to depths of 200 to 300 feet. The effects of the apparent subsidence on the drainage was slight, and the Salt and Gila Rivers and their main tributaries continued to be through-flowing streams.

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PRELIMINARY REPORT ON THE LATE QUATERNARY GEOLOGY OF THE SAN PEDRO VALLEY, ARIZONA

By

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INTRODUCTION

Like most rivers in southeastern Arizona, the San Pedro flows from south to north and extends 140 miles from its head near Cananea, Mexico, to its junction with the Gila River at Winkleman, Arizona (Fig.1). The valley fill consists of interbedded alluvial and lacustrine sediments which lie nonconformably against the bedrock of the mountains bordering the valley (Fig. 2) and contain vertebrate fossils of Pliocene-Pleistocene age (Gazin, 1942, Gidley, 1922 and 1926). In recent years the valley fill has been subdivided by geologists at the University of Arizona (Heindl, 1958, 1963, Gray, 1965, 1967, and Agenbroad, 1967) and studies of the fossil-vertebrate horizons by Lance (1960) and his students have more clearly related the valley fill to Hemphillian, Blancan, and Irvingtonian mammalian ages. Discoveries of Rancholabrean fauna have resulted mainly from investigations of Early Man sites in the upper part of the valley over the past 15 years (Haury and others, 1953 and 1959; Lance, 1959, Antevs, 1959), but until recently the relation of the late Quaternary deposits to the older valley fill had not been well understood. During geomorphological studies Bryan (1926), and *in* Gilluly, (1956, p. 121 and plate 10) defined three surfaces which he called the Tombstone, Whetstone, and Arivaipa "pediments" from oldest (highest) to youngest (lowest), and more recent geomorphological studies in the area have been conducted by (Melton, 1965 a and b).

LATE QUATERNARY STRATIGRAPHY

The most useful sequences of late Quaternary sediments have been exposed at Archaeological sites in the upper part of the valley and its major tributaries. Over the past 4 years the geology of some of these sites has been reinvestigated in order to provide detailed stratigraphic control for paleoecological studies and for establishing a radiocarbon-calibrated chronology (Mehringer and Haynes, 1961 and Haynes, in press).

In addition, numerous other sites, (Table 1) have been discovered that substantially increase our understanding of the geological and paleoecological events that have taken place over the last 40,000 years. The most enlightening sequence is that exposed at the Murray Springs site (Fig. 1, Loc. 3), where typical Rancholabrean elements occur in two units, the youngest of which contains Clovis artifacts in association with mammoth skeletons (Haynes and Hemmings, 1967).

Because the stratigraphic sequence (Fig. 3) exposed by Murray Springs arroyo is the most complete and best exposed, the geology there will be described in detail after which the distribution, as presently known, of the units throughout the valley will be reported. All of these units are informally designated pending formalization of the names.

Murray Springs arroyo is one of numerous drainages heading on the upper slope of the broad Tombstone surface that slopes 80 feet per mile from the base of the Huachuca Mountains to near the San Pedro River where the slope of the valley wall steepens to form a valley intermediate between the mountains and the inner valley (floodplain) of the river. These drainages become deeper and wider as they approach the intermediate valley and become shallow again as they cross the floodplain of the inner valley. Less than a century ago, at the time Mr. Murray homesteaded Murray Springs, these arroyos did not exist. Instead these tributary valleys were broad grassy swales commonly without a distinct channel and graded to the San Pedro River which had a similar configuration but on a larger scale (Bryan, 1928). The arroyo cutting of the main river that began in 1883 (Bryan, 1925, p. 342) progressed up the tributary at Murray Springs soon after 1900. It is this arroyo cutting of the turn of the century that revealed the Early Man sites. Two tributaries of Murray Springs arroyo, the East and West swales, are as yet undissected by modern arroyo cutting, whereas the main arroyo (Fig. 4, A) is a discontinuous gulley with two head cuts separated

The stratigraphy exposed below the lower head cut in Murray Springs arroyo is described in Table 2 and shown in the generalized cross section of Figure 3.

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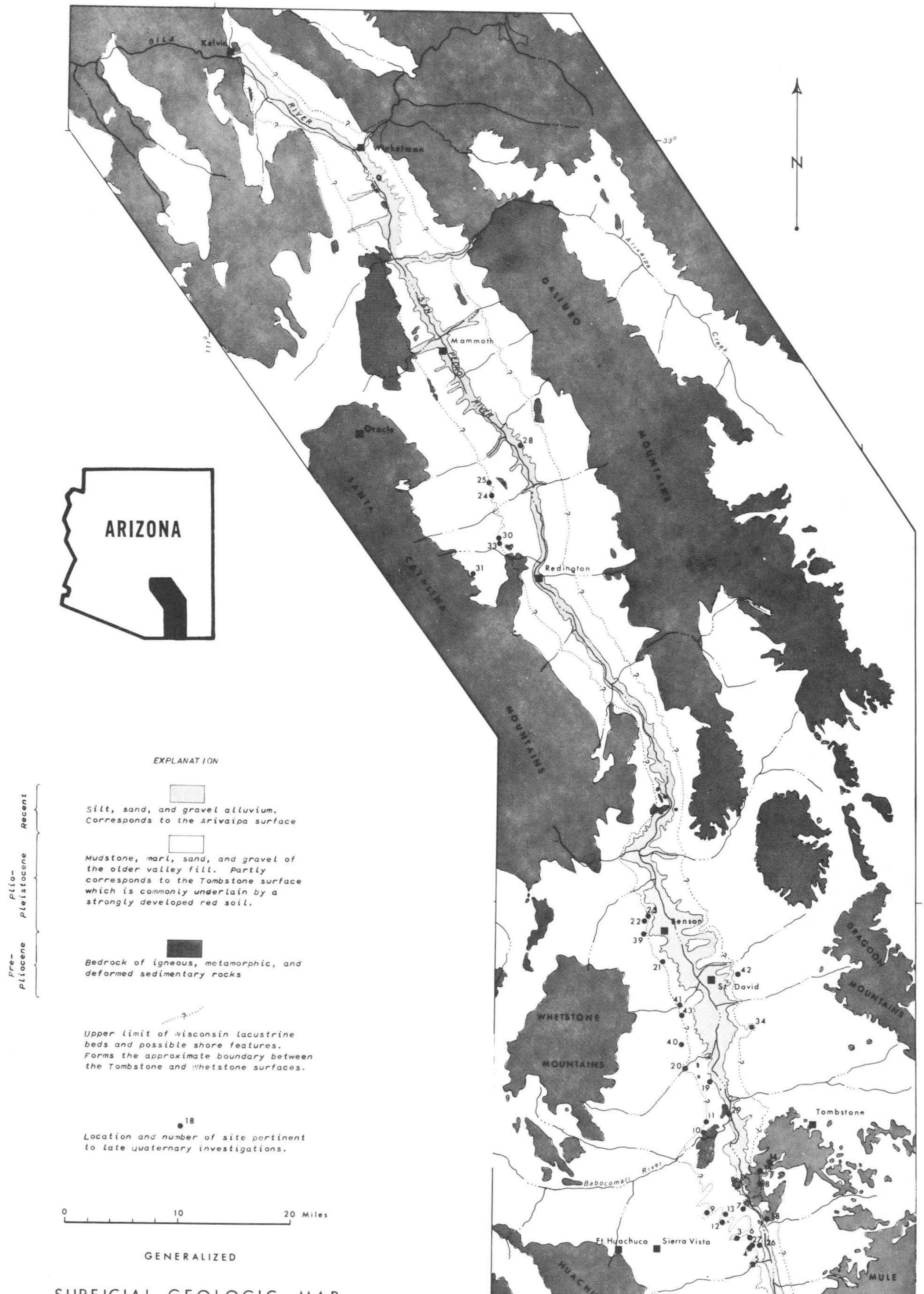
* Contribution no. 163 of the University of Arizona Program in Geochronology.



GENERALIZED

SURFICIAL GEOLOGIC MAP

OF THE

SAN PEDRO VALLEY, ARIZONA

Figure 1

Table 1 – Quaternary Localities of the San Pedro Valley, Arizona

Locality	Stratigraphic Units	Extinct Mammals						Carbon-14 Age in Years B. P.	Stage, Culture, or Complex	Remarks
		Horse	Mammoth	Camel	Bison	Wolf	Tapir			
1. Lehner Site	H									
(4190)*	G							1430 ± 160 (A-479b)	Ceramic	
								2550 ± 160 (A-450a)	San Pedro	
								3950 ± 180 (A-480)		
	F_4									
	F_3							7900 ± 400 (A-715BB)		
	F_2							10,410 ± 190 (A-33)		
								11,000 ± 1100(A-746A)		
	F_1	x	x		x		x	11,260 ± 360 (Av.)	Clovis	
	E							>11,600 ± 400 (A-478b)		
	D							>28,800 (A-574)		
	Z							>15,400 ± 700 (A-573)		
	Y							>30,000 (A-572)		
	X							>33,400 (A-571)		
2. Hereford Dairy Ranch	G_1							4150 ± 270 (A-903)	Cochise	
(4210)	F_3(?)									carbonate crust
3. Murray Springs Site	H							Post AD 1900	Historic	
(4175)	G_3							AD 1690 (?)		
	G_2							1550 ± 90 (A-617)	San Pedro	
	G_1							4230 ± 290 (A-497B:1)		
								4340 ± 250 (A-696A)		
								5890 ± 270 (A-696B)		
								5500 ± 400 (A-879)		
	F_4								Cochise	
	F_3									
	F_2									
	F_1							11,230 ± 340 (A-805)	Clovis	
	E							21,200 ± 500 (A-897)		
	D							29,000 ± 2000 (A-896)		
	Z									
	Y									
	X									
4. Escapule Site	F_4									
(4175)	F_2									
	F_1	x	x						Clovis	
	E			x						
	Z									
	X									
5. Garden Draw	G_1									
(4150)	F_2									

Table 1 – Quaternary Localities of the San Pedro Valley, Arizona (cont.)

Locality	Stratigraphic Units	Extinct Mammals						Carbon-14 Age in Years B. P.	Stage, Culture, or Complex	Remarks
		Horse	Mammoth	Camel	Bison	Wolf	Tapir			
6. Aqueduct Locality	G_2								Ceramic San Pedro	
(4150)	G_1									Cochise surface finds
	F_2									
	E(?)									tufa
7. Mosan Wash	G_2								San Pedro	surface site
(4050)	G_1									
	F_3(?)									
	F_2									
	E		x							
8. Lindsey Ranch	F_4									Cochise surface finds
(4105)	F_2									
	E	x	x		x					
	D									
9. Hurley Site	D		x							
(4175)	X									
10. Choate Ranch	F_4									Cochise surface finds
(4050)	F_3(?)									
	Z	x	x	x						
11. Abandoned Ranch	F_4(?)									Cochise surface finds
(4010)	F_3									
12. Schaldack Site	G_2									
(4175)	F_4									Cochise surface finds
	F_3									
	F_2									
	F_1	x	x							Cochise surface finds
	E									
	Z									
13. Jackie Site	F_4									Cochise surface finds
(4165)										
14. Clouse Locality	G									
(4140)	F									Cochise surface finds
15. Cottonwood Spring	G									Cochise surface sites probably buried sites
(4100)										
16. Wiek Ranch	F_4								Cochise	Buried hearths
(4275)										

Table 1 – Quaternary Localities of the San Pedro Valley, Arizona (cont.)

Locality	Stratigraphic Units	Extinct Mammals						Carbon-14 Age in Years B. P.	Stage, Culture, or Complex	Remarks
		Horse	Mammoth	Camel	Bison	Wolf	Tapir			
17. Greenbush Site (4245)	G								San Pedro	
18. Lewis Hill Site (4300)									Multiple Component	Ancient quarry site
19. Boquillas Station (3880)	F(?)									Cochise surface finds
	F_2									
	E	x	x		?					
	D									
20. White Tank Arroyo (3945)	G_2								San Pedro (?)	Buried hearths
21. Post Ranch Area (3880)	E(?)									Blancan fossil locality
	X									
22. Gray Locality (3700)	F_4(?)								Cochise	
	D(?)		x							
23. Seff Locality (3680)	F_4								Hearth	Cochise surface finds
	F_3									
	F_2									
	F_1	x	x	x						Clovis (?) surface finds
	E									
	D									
	Z									
	X									
24. Cerros Negros Loc. (3100)	F_4(?)									
	F_2(?)									
	E	x	x					12,000 ± 300 (A-854)		
	D									
	Z(?)									
	X									
25. North Cerros Negros (3020)	E									carbonate crust
	X									
26. Horsethief Fan (4040)	G_2(?)								Cochise	Buried hearth
27. Horsethief Falls (4140)	G_2								Cochise	Buried hearth
	G_1									

Table 1 – Quaternary Localities of the San Pedro Valley, Arizona (cont.)

Locality	Stratigraphic Units	Extinct Mammals						Carbon-14 Age in Years B. P.	Stage Culture, or Complex	Remarks
		Horse	Mammoth	Camel	Bison	Wolf	Tapir			
28. Coyote Draw Site (2640)	G_2							1360 ± 190 (A-861) 2270 ± 150 (A-862) 3210 ± 240 (A-866)	San Pedro	Buried occupational sites
29. Fairbank Bridge Area (3820)	H									
	G_3									
	G_2							2463 ± 310 (C-519)	San Pedro	Type Site
	G_1(?)									
30. Peck Spring (3200)	E									Cochise surface finds
	D(?)									
31. Lone Hill Site (3680)	F_4(?)									Cochise camp site
32. Hargis Site (4300)	H									
	G									Cochise surface finds
	F									
	F_1(?)				x				Clovis (?)	Scraper with bison bones
33. Arroyo S. of Peck Springs (3240)	E(?)									
	D(?)									
34. Curtis Ranch Loc. (3960)	E(?)									Beach (?) gravels & marl
	Y(?)									Irvingtonian fossil loc.
35. Ash Canyon Mammoth (6200)	?		x							In coarse alluvial fill
36. Wakefield Mammoth (5650)	Y(?)		x							In red calcareous mudstone
37. Naco Site (4530)	H									
	G									
	F									
	F_1		x						Clovis	
	E									
38. Leikum Site (4535)	H									
	G									
	F									Cochise surface finds

Table 1 – Quaternary Localities of the San Pedro Valley, Arizona (cont.)

Locality	Stratigraphic Units	Extinct Mammals						Carbon-14 Age in Years B. P.	Stage, Culture, or Complex	Remarks
		Horse	Mammoth	Camel	Bison	Wolf	Tapir			
	F_1 E		x						Clovis	
39. Mendevil Ranch Loc. (3750)	X									Blancan fossil locality
40. California Wash Loc. (3960)	X									Blancan fossil locality
41. San Juan Siding Loc. (3800)	X									Blancan fossil locality
42. McRae Wash Loc. (3950)	X									Blancan fossil locality
43. El Paso Loc. (3890)	X									Blancan fossil locality

* Approximate elevation in feet.

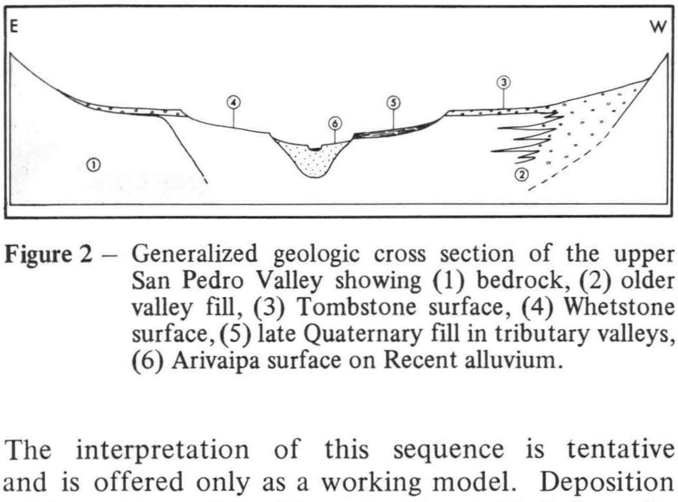


Figure 2 – Generalized geologic cross section of the upper San Pedro Valley showing (1) bedrock, (2) older valley fill, (3) Tombstone surface, (4) Whetstone surface, (5) late Quaternary fill in tributary valleys, (6) Arivaipa surface on Recent alluvium.

The interpretation of this sequence is tentative and is offered only as a working model. Deposition of the older valley fill, units X and Y (informally referred to as Benson beds and "granite wash" and partly a continuation of the Saint David Formation of Grey, 1967), was followed by a period of stability, during which a marked red paleosol was developed on alluvium throughout the valley (probably equivalent to the red soil discussed by Melton, 1965a, p. 11). Subsequent erosion led to the formation of the intermediate valley and its tributary drainage net. Unit Z is partly derived from Z, and Yand represents the initial bed load of the Murray Springs drainage.

As much as a meter of greenish gray lacustrine clay of the lower Boquillas formation (unit D) was deposited on the eroded surface of unit Z and older units, and represents a lake that existed approximately 30,000 radiocarbon years ago. Disarticulated remains of mammoth, horse, and bison occur sparingly in the lower Boquillas formation. The lacustrine clay is disconformably overlain by as much as two meters of white lacustrine marl, the upper Boquillas formation (unit E), with thin clay partings, which is believed to have been deposited between 12,000 and 22,000 radiocarbon years ago in a phase of the lake. Small molluscs which are locally abundant in the marl may provide evidence on the depth and chemistry of the water at the time of deposition.

Between 11,500 and 12,000 radiocarbon years ago the lake was lowered or drained, the marl was eroded, and new drainages were established across dried out lake beds within the Murray Springs Valley. Along these drainages Clovis hunters killed and butchered mammoths 11,200 radiocarbon years ago as witnessed by the remains of mammoth carcasses and Clovis artifacts within a channel deposit, the Graveyard member (unit F_1) of the Lehner formation, and on

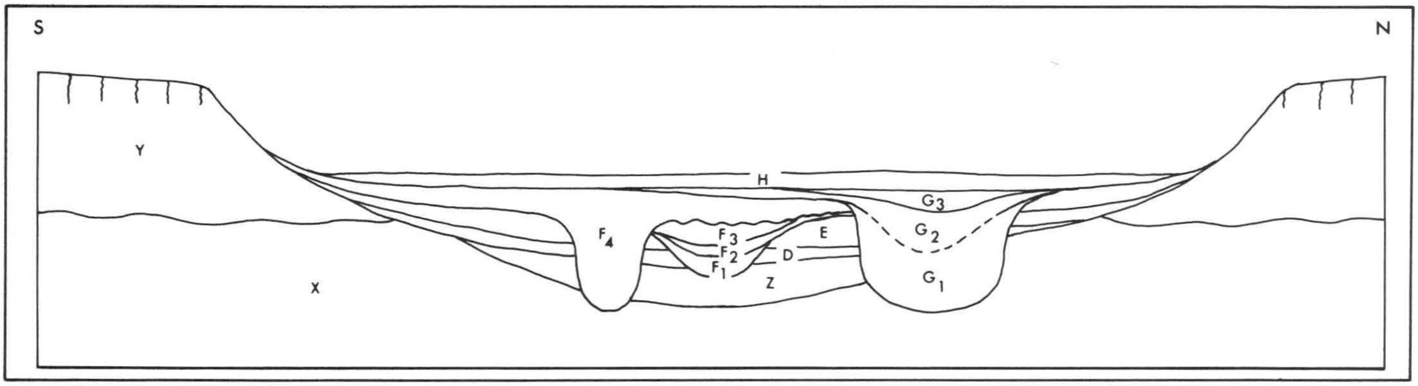


Figure 3 – Generalized stratigraphic cross section of Murray Springs arroyo. (Symbols explained in Table 2.)

the adjacent slope at the Murray Springs site. A black organic mat, the Clanton member (unit F_2), overlies the channel deposit in a manner that indicates very rapid deposition about 10,800 radiocarbon years ago. The black mat extends several tens of feet from the ancient channel and pinches out on adjacent slopes. It blankets the local topography and even follows the microtopography formed by what are thought to be footprints of mammoths at the archaeological site. The origin of the black mat will be better understood once the fossil pollen, rodents, and molluscs contained in it are studied.

Deposition of the black mat was followed by deposition of gray calcareous silt, the Donnet member (unit F_3), and locally by a soft marl facies containing numerous small molluscs. A period of erosion followed during which a 4-meter deep channel was cut and subsequently filled with light brown to gray clay and silt of the Wiek member (unit F_4) of the Lehner formation. This member was deposited over the banks of the channel in the lower part of Murray Springs Valley and covered most of the valley making it a swale. A gray paleosol in the middle of the Wiek member indicated a period of stability or reduced rate of deposition during which man camped at the site, as evidenced by a few Cochise artifacts found in the buried soil. The generally massive, fine grained, and well sorted character of the Donnet and Wiek members suggests a combined eolian and slope wash origin. After deposition of the Wiek member a period of soil formation followed, and this continued while erosional-depositional events were taking place. These events are (1) the cutting of a broad channel 4 to 5 meters deep soon after 8,000 radiocarbon years ago, (2) filling of the channel with coarse alluvium and laminated pond clays, lower and middle Fry members (units G_{1a} and G_{1b}), of the Escapule formation between 4,500 and 5,500 radiocarbon years ago (Mehringer and others, 1967), and interbedded sand and silt, upper Fry member (unit G_{1c}), (3) weathering, (4) erosion of the Fry member, (5) deposition of the McCool member (unit G_2) sand and silt over adjacent banks to form the floor of a swale approximately 1,000 years ago, (6) minor erosion, (7) deposition of the Bakarich member (unit G_3) brown sandy clay and thus raising the floor of the swale by less than a meter near the end of the 17th century, and (8) formation of a gray soil. During this sequence of events the Murray Springs Valley was occupied intermittently by people of the Cochise culture, later by pottery making cultures and finally by ranchers.

The valley remained a grassy swale for approximately 300 years because it was so described by Mr. Henry P. Murray before his parents moved to Tombstone soon after the beginning of the 20th century in order to be nearer to a school for their children. Today the floor of the valley (not the arroyo) is covered with as much as half a meter of loose silt, sand, and gravel alluvium, the Horsethief formation (unit H), that is the last deposition to occur in the valley before the modern episode of arroyo cutting. It may in part be derived from erosion of the headcut 0.7 miles upstream.

The caliber of the load suggests that the discharge must have been of torrential character, and the initiation of the lower headcut may have been due to the nickpoint formed by the coarse gravel facies of the unit or it could have simply progressed up the tributary from the San Pedro River as a continuation of the arroyo cutting in the master stream. An extension of the Horsethief formation in Greenbush Draw near Naco, Arizona contains artifacts of a U. S. Army encampment there between 1913 and 1918.

Table 2 – Descriptions of Stratigraphic Units at Murray Springs

Symbol	Name and Description of Unit	Maximum Thickness (m)
H	Horsethief formation–sand and gravel–reddish-brown (5 YR 5/4, 4/4 wet), loose, interbedded silt, and sand, and gravel alluvium. Upper 10 cm. has moderate, medium blocky soil structure gradational upwards to platy.	0.4
G	**Escapule formation**	
G_3	Bakarich member–silt–brown (7.5YR 4/2, 3/2 wet), firm, clayey silt alluvium with dispersed coarse sand and moderate, medium to coarse, prismatic soil structure breaking to angular. Upper 10 cm. is a greyish-brown (10 YR 5/2, 4/3 wet) silt B-horizon with moderate medium to coarse prismatic soil structure breaking to blocky. Sharp upper contact.	0.9
G_2	McCool member–silt, sand, and gravel–reddish-brown (5 YR 5/4, 3/4 wet), firm, interbedded, clayey silt, sand, and gravel alluvium, with strong medium to coarse prismatic soil structure and numerous root molds with calcareous coatings. Upper contact sharp erosional where overlain by H or G_3. Elsewhere forms the modern surface.	
G_{1c}	Upper Fry member–silt, sand, and gravel–reddish-brown (5 YR 5/3, 4/4 wet), firm interbedded, clayey, silt, sand, and gravel alluvium with calcareous root molds and moderate to strong, coarse, prismatic soil structure. Upper 40 cm. is iron stained yellowish-brown and has stronger, firmer soil structure. Upper contact is sharp and erosional in places.	2.5
G_{1b}	Middle Fry member–silt and clay–light reddish-brown (7.5 YR 6/3, 4/4 wet) to dark reddish-grey (5 YR 4/2), firm, rudely laminated, silty clay and clayey silt, mud pond alluvium with interbedded sand lenses. Contains calcareous root molds and dispersed carbonaceous matter. Upper contact sharp and erosional to gradational.	2.5
G_{1a}	Lower Fry member–silt, sand, and gravel–reddish-brown (5 YR 5/3, 4/4 wet), firm, interbedded clayey, silt, sand, and gravel alluvium with calcareous root molds and moderate to strong, coarse, prismatic soil structure. Upper contact is sharp and erosional in places.	3.0
F	**Lehner formation**	
F_4	Wiek member–silt, sand, and clay–dark-brown (7.5 YR 4/2, 3/2 wet) to pinkish-grey (7.5 YR 6/3, 5/4 wet), firm interbedded, silt, sand and clay alluvium with gravel channel	

Table 2 – Descriptions of Stratigraphic Units at Murray Springs (cont.)

Symbol	**Name and Description of Unit**	**Maximum Thickness (m)**
	fill at the base. Contains a brown paleosol at the top with moderate, medium, prismatic structure and calcareous root molds. Contains a grey, calcareous paleosol in the middle with very strong, medium, prismatic structure breaking to angular and carbonate coated peds and root molds. Sparse carbonaceous lenses. Sharp erosional upper contact in places, elsewhere forms the modern surface. Upland facies elsewhere is a pink (7.5 YR 7/4) massive, clayey silt.	4.5
F_3	Donnet member–silt, and marl–light gray (10 YR 7/2, 6/2 wet), soft, very calcareous, clayey silt and clayey marl in local low areas. Marl is laminated in places and contains snail shells. Upper contact is sharp and erosional to gradational and obscure where overlain by F_4.	0.6
F_2	Clanton member–organic silt and clay–black (2.5 YR 2/0), crumbly, organic clay and silt with very strong, fine, angular structure and numerous calcareous root molds, and ped surfaces. Thickness in low areas pinching out up slope. Snail shells locally abundant. Sparse rodent bones and iron stains. Sharp conformable upper contact except for minor rill erosion. Interfingers with F_3 in places.	0.2
F_1	Graveyard member–sand and gravel–pale yellow (5 YR 7/3) loose to firm, clayey sand gravel channel fill with interbedded lenses of clay and marl. Contains carbonized ash wood (Fraxinus sp.); bones of extinct horse, mammoth, camel, bison, and wolf; and clovis artifacts. Sharp upper contact.	0.9
E & D	**Boquillas formation**	
E	Upper member–marl–white (2.5 YR 8/2), soft to firm marl with clay partins and locally abundant ostracod and snail shells. Gradational to sharp erosional upper contact. Forms vertical walls.	2.2
D	Lower member–clay–pale olive (5 YR 6.5/2.5, 6/3 wet), firms, laminated clay with brown organic layers and strong, medium prismatic structure. Dispersed fossil bone fragments and locally abundant snail shells. Sharp conformable (?) upper contact.	0.8
Z	Unit Z–sand and gravel–reddish-brown (2.5 YR 5/4, 4/4 wet), hard, clayey sand and gravel alluvium. Sharp erosional upper contact.	3.0
X & Y	Older valley fill–undifferentiated mudstones, sands, gravels, and marls.	

SEDIMENTS FORMING THE ARIVAIPA SURFACE

In the alluvial sediments underlying the recent floodplain of the San Pedro River buried archaeological sites have been found and are the basis upon which the San Pedro stage of the Cochise culture has been defined by Sayles and Antevs (1941, p. 21). At the type site near Fairbank a climatic episode called the Fairbank drought was defined by Antevs (1955, p. 330) on the basis of an eroded buried soil near the middle of the alluvial fill containing San Pedro artifacts and dated 2463 ±310 B P (C-519, Libby, 1952, p. 113). Later ceramic cultures occur in the uppermost part of the alluvium and in younger terrace fills, and historic artifacts are common in surface sites.

Recently, another buried San Pedro site was found by Agenbroad (1957, p. 35) in Coyote Draw (Fig. 1, Loc. 28) where a tributary arroyo has exposed a 12-foot high cross section of the terrace fill underlying the Arivaipa surface. Radiocarbon analyses of charcoal from typical San Pedro stage rock hearths indicated the alluvium to be between 1,000 and 3,500 years old with a brief erosional episode occurring shortly before 2,200 years ago (Grey, Haynes, and Damon, in press). These ages are typical for the McCool and Fry members of the Escapule formation and for this episode of alluviation which was widespread throughout the southwestern United States (Haynes, in press).

The Arivaipa surface is less than 1,000 radiocarbon years old, but it is not known whether or not some of the lower terrace fills predate the historic period of arroyo cutting. Most of these are clearly younger, and one 14-foot high fill at Fairbanks contains household goods dating from a disasterous flash flood in 1890.

The maximum age of the Recent alluvium underlying the Aravaipa surface is not known precisely because of the lack of exposures of the basal units, but from the alluvial records at Early Man sites in the tributaries it is clear that during a severe period of erosion sometime between approximately 8,000 and 6,000 years ago much of the late Quaternary sediments were removed and the older valley fill was scoured by the tributary arroyos. No occurrence of sediments between 8,000 and 30,000 years old are known from the fill underlying the Arivaipa surface of the inner valley and such occurrences seem unlikely considering the stratigraphic record from the tributaries where sediments of this age appear to be graded to levels at or above the Arivaipa surface.

DISTRIBUTION OF THE BOQUILLAS AND LEHNER FORMATIONS

The sequence at Murray Springs at an elevation of approximately 4,195 feet was recognized as being very similar to that at the Lehner site 12 miles to the south (Fig. 1, Loc. 1, Fig. 4, B). Stratigraphic bulldozer cuts made in 1964 revealed that lacustrine clay and a white marl (Boquillas formation) underlie the small channel deposit containing mammoth bones and Clovis artifacts and a black organic mat (Lehner formation) (Haynes, 1965, Fig. 8-21).

Similar deposits of lacustrine clay and marl are exposed in Horsethief Draw at the Escapule site (Fig. 1, Loc. 4, Table I) 2 miles south of Murray Springs. An association of Clovis points with a mammoth skeleton was found between the Boquillas formation marl and the Clanton member black mat at the Escapule site in 1967. The Wiek member of the Lehner formation covers much of the bank area along Horsethief Draw and terraces of the Escapule formation are exposed by the arroyo. A similar situation exists in Woodcutter Arroyo (Fig. 4, C) where more articulated mammoth bones were found at the Schaldack site (Fig. 1, Loc. 12) 2 miles north of Murray Springs.

Outcrops of green clay, white marl, black mat, and buff silt (Boquillas and Lehner formations) occur 30 miles north of Murray Springs near Bensen at an elevation of approximately 3,680 feet (Fig. 1, Loc. 23, Table 1). These deposits have been reported by Gray (1965) and described by Philip Seff (unpublished manuscript). Scattered bone fragments of horse, mammoth, and camel, and undiagnostic artifacts, have been found on the surface.

The most northern occurrences of similar deposits have been reported by Agenbroad (1967) at Cerros Negros and Peck Springs, 70 and 66 miles north of Murray Springs (Fig. 1, Locs. 24 and 30) respectively. At Cerros Negros, in a tributary valley of the San Pedro River, the top of 15 feet of lacustrine mudstone and marls of the Boquillas formation is at approximately 3,085 feet and was deposited as late as 12,000 radiocarbon years ago. The deposits contain molluscs as well as bones of mammoth and horse.

Reconnaissance during 1967 has led to the discovery of eight other localities where similar lacustrine units have been found. All of the localities known so far are listed in Table 1 and shown in Figure 1. The most significant factor with respect to each of these occurrences is that the sequence of sediment types and the chronology of the depositional-erosional cycles are essentially identical.

THE POSSIBLE FORMER EXISTENCE OF A LARGE LAKE

The widespread occurrence throughout the San Pedro Valley of isolated patches of similar lacustrine sediments (Boquillas formation) of the same age, which contain a similar stratigraphic distribution of

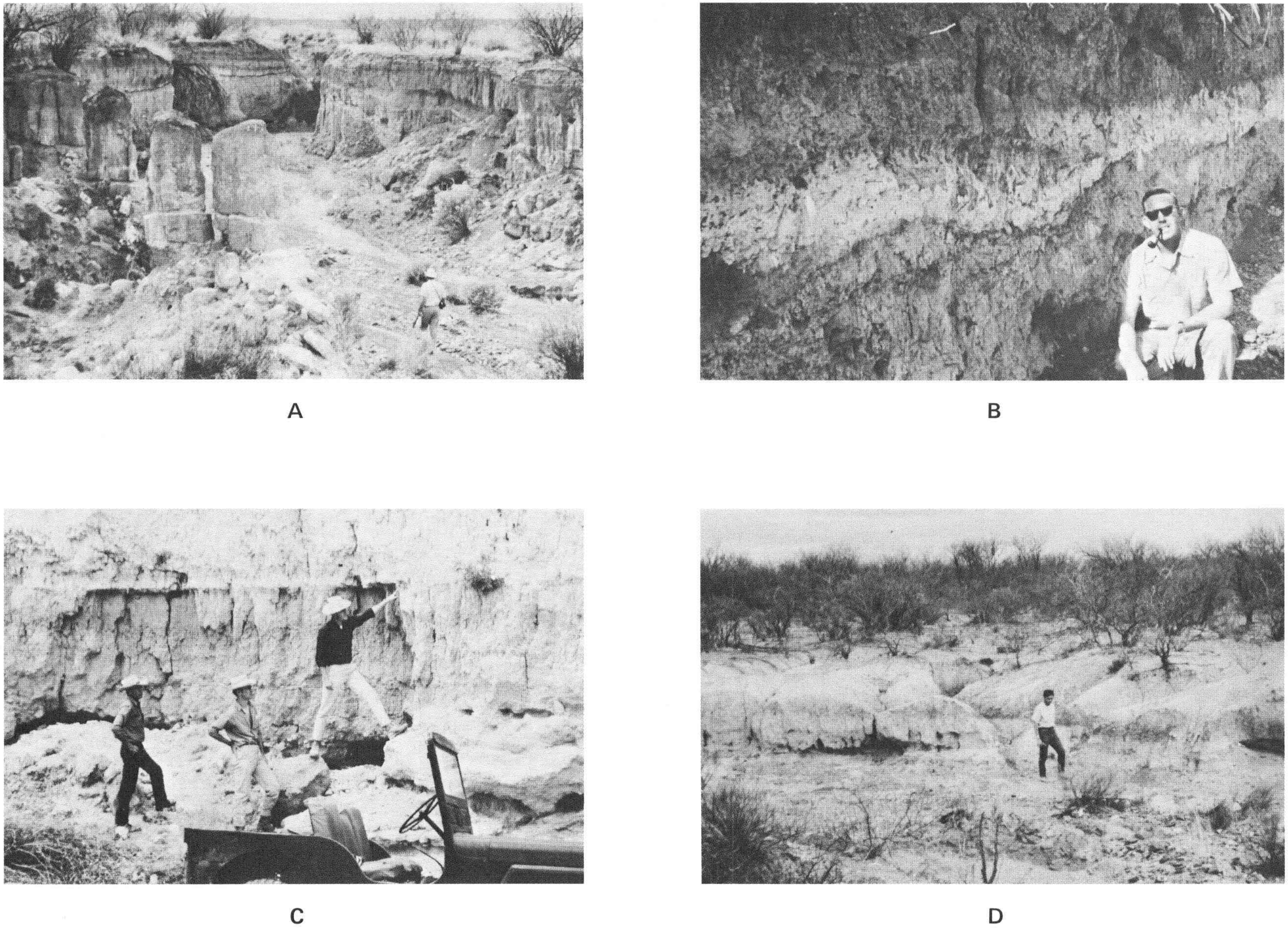


Figure 4 – Photographs of late Quaternary lacustrine sediments showing (A) lower headcut of Murray Springs arroyo, (B) trench at the Lehner site, (C) Woodcutter arroyo near the Schaldack site, and (D) Lindsey Ranch locality.

artifacts and vertebrate fossils, suggests that regional rather than local controls are responsible. The possibility that a large lake occupied the San Pedro Valley in late Pleistocene time must be considered. With this as a working hypothesis other evidence has been sought.

In addition to the lacustrine sediments, several geomorphic features are suggestive of a former large lake. At many places in the upper part of the valley, benches and scarps that could be wave-cut features on the older valley fill correspond closely to what Bryan (in Gilluly, 1956, plate 10) mapped as the Whetstone surface along the intermediate valley of the San Pedro River (Fig. 5, A). Between Horsethief Draw and Graveyard Gulch this surface is between 4,100 and 4,200 feet. At the higher elevation the surface ends at a scarp leading to Bryan's Tombstone surface (Fig. 5, B), and at the lower elevations a scarp connects the Whetstone surface to the Recent floodplain of the San Pedro River, which is Bryan's Arivaipa surface.

In the vicinity of the Curtis Ranch Irvingtonian fossil locality (Fig. 1, Loc. 34), five miles southeast of Saint David, a broad surface between 3,900 and 4,000 feet forms the floor of an amphitheater and is littered with gravel bearing desert varnish. On the opposite side of the valley between California Wash and Post Ranch numerous surfaces between 3,800 and 3,900 feet are capped with carbonate rubble and calcareous gravels. The surfaces appear to be remnants of a once continuous surface intermediate between the pediment of the Whetstone Mountains and the Arivaipa surface. The current mapping suggests that in this area the Whetstone surface should be redefined as being limited to this intermediate surface instead of including the Whetstone pediment as Bryan shows.

Patches of carbonate rubble and weathered and carbonate-coated gravel on the Whetstone surface could represent ancient beaches but they have been so disturbed by erosion that no characteristic features have been recognized. On the East Range of Fort Huachuca these gravels appear to occupy two benches at 4,200 and 4,100 feet, and cover the slopes between these elevations at numerous places on the west side of the San Pedro River from Graveyard Gulch to Lehner Ranch. The carbonate-coated gravels bear a close resemblance to the ancient beach gravels around Wilcox playa (Meinzer and Kelton, 1913, p. 63).

Igneous hills in the vicinity of Charleston and Lewis Springs are surrounded to various degrees by bedrock benches at approximately 4,100 feet which display carbonate rubble and carbonate-coated rocks and joints. A small hill on the west side of the river opposite Lewis Hill (Fig. 1, Loc. 18) when viewed from above displays a marked change in color and vegetation corresponding to a contour at approximately 4,110 feet (Fig. 5, C). This and other demarcations around the Charleston hills are suggestive of strand lines (Fig. 5, D).

The geomorphic features discussed here are by no means definitive of a lake shore because they could be explained by fluvial processes, representing a former grade of the river, but when combined with the distribution of the lacustrine sediments and the anomalous color demarcations just mentioned, the possibility of the former existence of a large lake is strengthened.

Furthermore it is of interest to note that so far the only 12,000 to 30,000-year-old sediments to be found within the area of the Whetstone surface are lacustrine beds of the Boquillas formation whereas farther up slope alluvial facies are found at Murray Springs, the Hargis site (Fig. 1, Loc. 32), and at Naco (Fig. 1, Loc. 37 and 38).

GEMINI IV PHOTOGRAPHY OF THE SAN PEDRO VALLEY

In considering the possibility of the former existence of a large lake in the San Pedro Valley, the photographs taken by James A. McDivitt and the late Edward H. White during the Gemini IV manned spacecraft mission are pertinent (Figure 7). On Color enlargements of photograph 4-8-12 provided by NASA I am currently mapping the surficial geology of the area. On the photograph there is a conspicuous zone of white areas that corresponds to the intermediate valley. Preliminary results show that these areas along the upper San Pedro Valley correspond to the Whetstone surface as redefined here. On this surface the prominent red soil so characteristic of higher surfaces, including the Tombstone surface, is absent and instead there are various occurrences of carbonate rubble, carbonate-cemented gravel, calcareous silt, and gravel with desert varnish. All of the outcrops of the Wisconsin lacustrine beds occur within this zone (Fig. 1) and are also partly responsible for the white color on the Gemini photograph.

It is possible that the strong calcification of soils and the carbonate coating on gravel on the Whetstone surface are due to subaqueous conditions and reflect the former presence of a large lake, but the problem is compounded by the fact that the white areas on the Gemini photograph are also areas where the older valley fill is most eroded and exposed so that part of the whitening is undoubtedly due to the exposure of carbonate beds within the older units (see Gray, 1967, Fig. 3). However, in the eroded areas normally noncalcareous older beds are calcified to depths of a foot or more on slopes that truncate the bedding. This calcification postdates the erosional episode in which the intermediate valley was first formed and is confined to the area of the postulated lake.

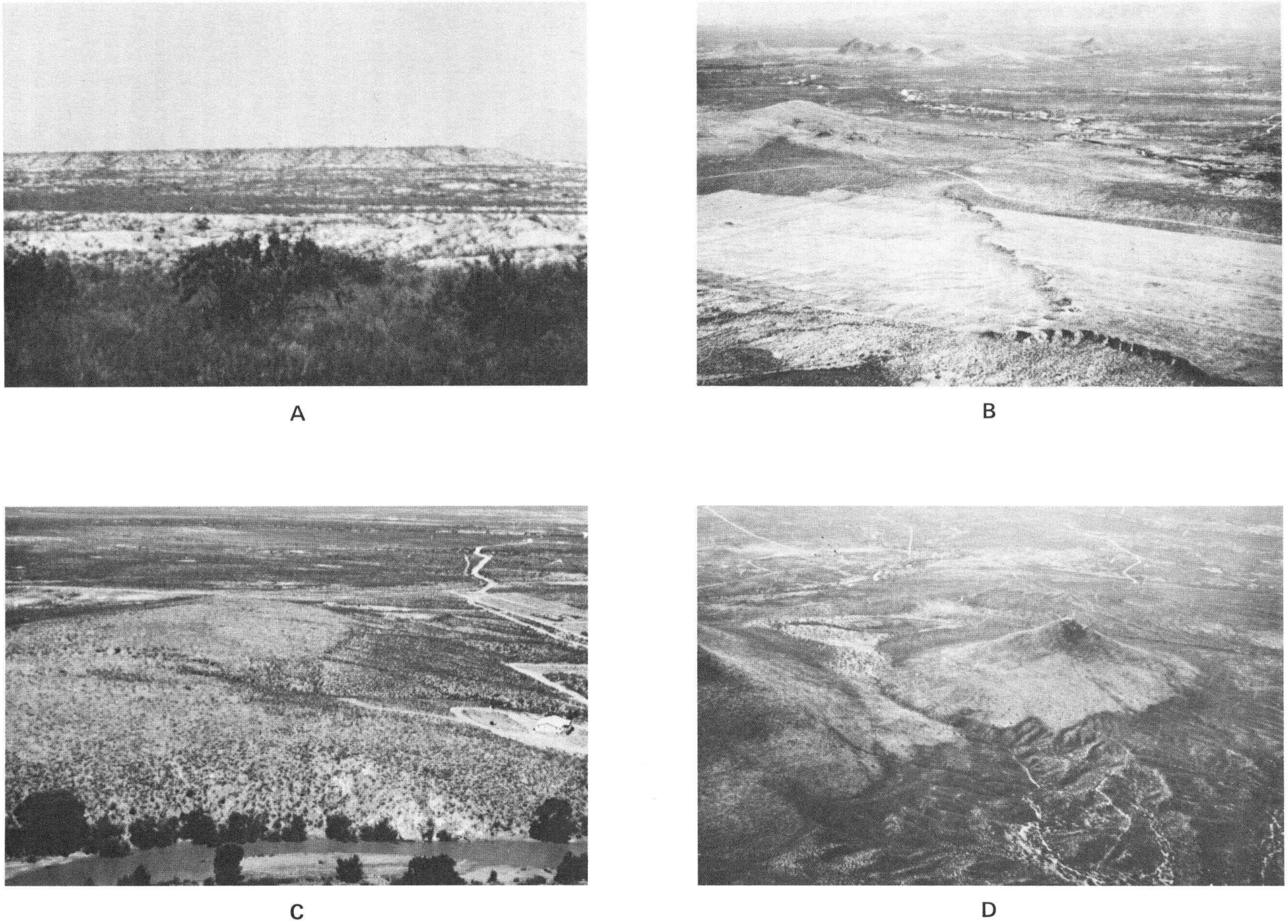


Figure 5 — Photographs of gemorphic features of possible lacustrine origin showing (A) Tombstone and Whetstone surfaces in view to the west across Woodcutter arroyo, (B) scarp between the Tombstone and Whetstone surfaces on the East Range of Ft. Huachuca in view to the southeast overlooking the San Pedro Valley, (C) possible strand line around volcanic hill near Lewis Springs in view to the northwest across the San Pedro River, (D) possible strand lines and wave-cut scarp around the north end of the Charleston Hills in view to the southwest.

STRUCTURAL IMPLICATIONS

The former presence of a single large lake explains many features in the San Pedro Valley but raises the important question of how the required damming occurred. The highest elevation for the top of the Boquillas formation is approximately 4,190 at the Lehner site in the upper San Pedro Valley. The water level must have stood somewhat higher than this, but no lake could fill the entire valley to this level today because the level of the pass between the Whetstone and Rincon Mountains at Mescal is less than 4,100 feet. Furthermore the elevation of the top of the Boquillas formation consistently decreases from one outcrop to another downstream. This is what would be expected if the lacustrine beds had formed in local ponds and lakes following the grade of the river or dammed up in its tributaries, but this explanation requires too many dams and, as stated earlier, the deposition of nearly identical sediments in an identical sequence in every pond appears most unlikely.

For a single lake to have existed requires either tilting of the valley, faulting, or a combination thereof. Plotting the elevations of the major marl outcrops and the adjacent river bed provides the profiles shown in Figure 6 and demonstrates that the amount of tilt required to bring the outcrops to a common elevation does not exceed 11 minutes of arc and the angle of tilt generally decreases up the valley until it is only 1 minute between Murray Springs and the Lehner site. The profiles of the San Pedro River and the lacustrine outcrops diverge down the valley independently of the distance of the outcrop from the river. The grade of the river truncates the bedding of the older valley fill so that successively older units are exposed progressively downstream (Lance, personal communication).

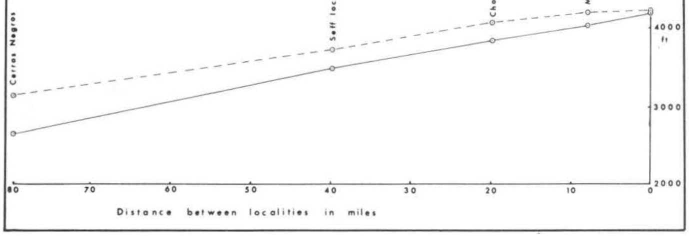


Figure 6 – Profiles of the San Pedro River and outcrops of Wisconsin lacustrine beds.

The amount of tilting required to distort the lacustrine beds and warp the valley is far too slight to be measured from the dip of beds so the best evidence for such an event must be sought elsewhere. Perhaps more detailed mapping of the beds will help define features that were once at a common elevation.

The most likely places for damming to have occurred in the San Pedro Valley are at the Charleston Hills, The Narrows near Tres Alamos Wash, and near Redington, but where the Wisconsin lake beds occur upstream of these potential damsites, the marls are up to 100 feet higher than any possible dam in late Pleistocene time without invoking tilting. For the deposition of lacustrine beds during formation of the older valley fill Melton (1965, p. 8) has suggested a dam on the Gila River near North and South Buttes east of Florence. The narrows 12 miles farther east at Kelvin would be a still more likely damsite for a Wisconsin lake, but tilting or local uplift would appear to be necessary to make any of these sites effective dams. If tilting of the valley actually occurred it would have been between 12,000 years ago, the youngest date on the marl at the top of the Boquillas formation, and 9,500 years ago, the estimated age of the first major buried stream or arroyo channel to appear in the record. This is considerably later than most investigators would admit for any significant tectonic activity in the Gila drainage area, (Damon and Mauger, 1966).

Very few faults with displacements greater than 10 feet and younger than the older valley fill are known in the valley, but detailed examination of some areas indicates that locally small faults are common in the Saint David and Sacaton formations (Gray, 1964, p.21 Smith, 1963, Agenbroad, 1967, p.42). Throws tend to be generally basinward but are recognizable only with detailed observations in favorable exposures. Small vertical displacements, perpendicular to the axis of the valley, would be even more difficult to recognize because they would undoubtedly be occupied by arroyos. The significance of the total sum of displacements of these "minor" faults may be pertinent to understanding the problem raised by the possible presence of a late Quaternary lake.

That the area is still tectonically active was evidenced in 1887 when the Great Sonoran earthquake created 26 foot-high scarps 60 miles south of the international border and was felt as far north as Phoenix (Richter, 1958, p.594). Also of interest is a story told in the late 1850's (Tevis, 1954, p.74) by Esconolea, a medicine man in Cochise's band:

> "He said that when he was a young man they were encamped in a natural fortress, the Dragoon Mountains, in what is now called Cochise's Stronghold. The country was very hot and dry. There had been no rain for a year, and there were

Figure 7 – Gemini IV photograph (S6532903) of southeastern Arizona showing the upper San Pedro Valley, Sulphur Springs Valley, and Wilcox playa. North is Uppermost. NASA Photograph

only a few springs to furnish water for the tribes. The Great Spirit became very angry and knocked the people around for a few moments making them feel as if they were drunk, and a loud rumbling noise was heard coming from the southwest. Indians who were out that day on the west side of the Dragoon Mountains, overlooking the San Pedro Valley, said that the whole earth split open from one side of the valley to the other sending forth a blue smoke heavenward for a mile. The same day it began to rain and continued for several days. When the storm ceased, all the earth on this side [east] of the San Pedro River had closed together again, while a crack in the earth about a mile long, five feet wide, and from ten to twenty feet deep, remained [on the west side]."

CONCLUSION

Late Quaternary deposits of the San Pedro Valley contain a Rancholabrean fauna and are inset against

Considering the regional picture, Melton (1965, p.6) has pointed out that the valleys north and east of an arc across Arizona from Patagonia to near Wickieup contain Plio-Oleistocene lake beds that were dissected in late Pleistocene time, whereas valleys south and west of the arc are not known to contain lake beds and have apparently undergone nearly continuous alluviation to Recent time. Melton (1965a, p.8) invokes volcanism and diastrophism as the causes of damming in valleys of the Gila system and attributes the subsequent downcutting to the disequilibrium caused by the higher base levels.

Morrison (1965) provides evidence for Pleistocene lakes in the Duncan basin of the upper Gila. The latest lake was apparently drained immediately before Wisconsin time. Entrenchment of the older valley fill in both the Safford and San Pedro valleys began in early or pre-Wisconsin (post red soil) time, hypothetically, as a result of the Gila River taking a more westerly course and cutting through the Mescal Mountains (Melton, 1965, p.14). The cause of this diversion could have been tilting or lowering in the area west of Melton's arc. Regardless of the cause the fact should be emphasized that during late Quaternary (post red soil) time there has been a general loss of sediments by stream action north and east of the arc whereas the reverse has generally been true south and west of it. The San Pedro Valley may be anomalous in that during this time there was a reversal in the trend during which the valley aggraded by either lacustrine or fluvial action or both. Whether or not this reversal occurred in any other valleys remains to be seen.

an older valley fill containing an Irvingtonian fauna in upper units of the fill. The oldest units of the late Quaternary deposits contain lacustrine sediments of Wisconsin age which were preceded by an episode of marked erosion during which a distinctive red soil on the surface of the older valley fill was partially eroded. This soil could, therefore, be of Sangamon age as suggested by Melton (1965, p. 14).

In the period 30,000 to 12,000 B.P. lacustrine clays and marls were deposited, apparently to the exclusion of significant alluvial deposits. This observation, in addition to the similarity in the sedimentary sequence displayed by the few outcrops scattered through much of the valley, suggests the former presence of a large lake, and certain geomorphological features in the upper San Pedro Valley support, but do not prove, this hypothesis. An alternative hypothesis is that the lacustrine deposits reflect the presence of local lakes along a valley with considerably less grade than the present San Pedro River.

After 12,000 B.P. the lake or lakes were drastically reduced in size or disappeared altogether and mammoth hunters killed their prey along small streams incised into the former lake deposits. The origin of an organic black mat deposit that covered low ground approximately 11,000 B.P. is uncertain, but local deposits of marl on, and as a facies of the black mat suggest the presence of ponds in many areas between 10,000 and 11,000 B.P. In the past 9,000 to 10,000 years there have been at least two major cycles or erosion and alluvial deposition throughout the valley, and most of the Wisconsin lake beds were removed during this period.

The distribution of lacustrine deposits, Rancholabrian fossil localities, Early Man sites, and anomalous white areas on satellite photographs of the San Pedro Valley conform to the Whetstone surface which may be an effect of the postulated lake. The older Tombstone surface hosts a red soil of possible Sangamon age, and the Arivaipa surface forms the top of alluvial deposits generally younger than 6,000 years.

The decreasing elevation of outcrops of the Wisconsin lake beds down the valley requires it to have been tilted approximately 11 minutes of arc between 10,000 and 12,000 years ago if at one time the tops of the marl (upper Boquillas formation) were all at approximately the same elevation. If faulting accompanied tilting then displacements of the lacustrine units should be observed. The large volume of sediment removed from the San Pedro Valley since 12,000 B.P. is surprising and suggests other than a climatic cause. It is hoped that further mapping of late Quaternary deposits will resolve these problems.

ACKNOWLEDGEMENT

The purpose of this paper is to present new data that more clearly define the late Quaternary geology of the upper San Pedro Valley and the relation of these younger strata to the older valley fill, and to present evidence for the former existance of a major lake in the valley during late Quaternary time. I am indebted to John F. Lance, Philip Seff, Robert S. Grey, and Larry D. Agenbroad on whose works I have drawn freely. The constructive commentary of L. K. Lustig and P. E. Damon is sincerely appreciated.

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DISTRIBUTION OF PORPHYRY COPPER DEPOSITS IN THE LIGHT OF RECENT TECTONIC ADVANCES

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ABSTRACT

Two lines of thought are merged in this paper: first, that metallogenic belts and the intrusions which spawn them are real and of too systematic and regional an aspect to have been fortuitously or unsystematically derived; and secondly, that global structures involving oceanic and deep continental crust, and possibly the mantle, are of sufficient scale as to link ore deposits genetically, especially the porphyry copper deposits. A corollary is that the porphyry rocks and ores themselves are of deepseated origin. Modern findings concerning the evolution and mass movement mechanisms of oceanic crust integrate concepts of mid-oceanic ridges, island arcs, sea floor spreading, and the recently-described transform and transcurrent faulting. The definition of transform faulting is of special significance to the southwest since the San Andreas fault and the Texas zone are probably of this type. Evidence that porphyry copper intrusion, and thus probably its mineralization, is of deep origin leads to the practical conclusions that global structures warrant more avid study by land-based geologists and that the Texas zone remains the single most significant structural element in determining the distribution of porphyry copper deposits in the southwestern United States.

INTRODUCTION

A subject of both practical and scientific importance especially to southwestern geologists is that of the fundamental factors of the genesis of this porphyry copper metallogenic province. Great strides have been made in the last decade, first toward explanation of persistent sea-floor global structures and second toward their usefulness in the solution of continental crustal problems. Publication of this guidebook affords an excellent opportunity to evaluate recent progress in marine geophysics and its impact upon porphyry copper genetic problems.

Part of the problem, the distribution of ore districts with respect to deep and shallow structures, has been discussed by many authors, chief among them Billingley and Locke (1941), Mayo (1958), and Schmitt (1966). Many of the published conclusions, particularly those by earlier workers, were quite logically based mainly on ore-deposit distribution with respect to prominent, mappable structures in the continental crust. In the last decade, however, these powerful 'lines of evidence' have been supplemented by progressively more compelling marine structural-geological and geophysical data. So much more is now known about the structure of the earth's crust and upper mantle, mechanisms of mass movement and crustal faulting, geomagnetism, heat flow, and continental drift that some older hypotheses can reliably be eliminated. Other hypotheses are strengthened to the point that firm answers to old ore deposit distribution problems are rapidly taking form.

Explanations of many structural relationships in the continental crust can be most readily developed from oceanic geophysical surveys because the earth's crust at sea is thinner and is less obscured by erosion and sedimentation. Marine measurements are easier to make. Continuous seismic profiling can be run without shot-hole drilling, heat flow and magnetic field data can be continuously and simply recorded, and submarine topographic data are easily compiled onto bathymetric maps. The thinner oceanic crust is more responsive to mantle movements and apparently is much less complex than its continental counterpart. Direct visual geologic mapping of the oceanic crust is not yet possible, but increasingly sophisticated and compelling knowledge of marine crustal and mantle movements can be applied with certainty to the continental crust. Data pertinent to global structural geology and to porphyry copper deposit distribution are accumulating rapidly.

This paper will discuss the results of recent, basically geophysical, far-reaching tectonic studies important to exploration for mineral deposits, especially in southwestern North America. Reasons for the relative abundance of porphyry copper deposits in Arizona and New Mexico are now clearer than ever, and appeals for more specific data by Butler (1933) and Schmitt (1966) can now be met.

BACKGROUND

The following summary of the development of metallogenic belts and geophysical concepts involves consideration of the relationships of the crust and mantle. The mantle is that portion of the earth beneath the Mohorovičić discontinuity which extends from the earth's core to the crust. It is composed of dense mafic to basaltic material commonly referred to as sima. The crust is the lighter, more sialic outer layer of the earth above the 'Moho.' It is complex, and may consist of two or three sublayers. The average continental crust is 20-30 miles thick and is composed of an upper granitic layer and a lower, more mafic one, each 10-15 miles thick. The oceanic crust is more homogeneously simatic and thinner, but probably less mafic than the mantle. Mid-oceanic ridges, described more fully below, are broad, gentle ridge structures which are found in the ocean basins around the world (see Figure 3).

Many investigators have written on the distribution of ore districts. Only skeletal summaries of the most important of these papers can be given here, the serious reader being referred to the papers themselves and to excellent summaries by Turneaure (1955) and Burnham (1959). The following paragraphs pay particular attention to the growth of ideas concerning metallogenic belts and their relation to continental and marine structure and, in recent entries, to pertinent geophysical milestones.

Butler (1933) and Turneaure (1955) provided global and continental consideration of the relation between structural zones, or belts, and mineralization. Butler noted the strong, temporally persistent structural and intrusive trends which parallel the western edge of the North American continent and described the concentration of ore deposits around structural zones such as the Columbia and Colorado Plateaus. He also cited the importance of each to northwest-trending ranges in southern Arizona as loci of mineralization, but did not attempt to explain them. Turneaure, in his major summary paper, discussed the Laramide Belt, a complex of folding and faulting within the Rocky Mountain belt. Although the detailing of local zones and trends was beyond Turneaure's subject, his suggestion that structural patterns of regional nature control both the shapes of intrusives and the orientations of subsequently mineralized fractures in Arizona is significant.

Billingsley and Locke (1941) attempted rigorous development of the relationships between ore districts and continental structure. They cited the detailed structural geology of eight major ore districts and developed the concept of a continental structural framework. They then described the "parade of orogenic belts" across the Cordillera, from west to east through geologic time, and presented a map of orogenic belts of the U. S. The northwesterly trending Walker line was shown as separating southern and southwestern Arizona from Basin and Range regions to north, but little attention was given to the porphyry copper province. The authors stressed the importance of orogenic belt "cross roads," particularly of belts of different ages, and noted that many manifestations of geologic activity, including mineralization, may be by-products of heat transfer along channels made by tectonic forces at specific foci.

Spurr's (1923) discussion of the 'great silver channel' and Billingsley and Locke's (1933) Montana, Utah, Colorado, and Arizona 'structural intersections' were among the first attempts to name and appraise metallogenic belts in the United States. It remained for Mayo (1958), however, to systematize and compare the significance of the many structural ore depositional belts in the southwestern states. Mayo described eleven northwesterly, nine northeasterly, five easterly, and five northerly structural zones, and ranked their many intersections in terms of known ore deposit distribution. He developed four classes of structural foci of at least potential economic significance according to the interplay of the following guides: (1) geographic-structural persistence, (2) prominence suggesting recent structural activity, (3) the presence of two or more intersecting zones, (4) igneous activity along at least one direction, (5) small to moderate-sized post-Nevadan intrusions at the intersection, and (6) adjacency of intersections to major Nevadan intrusions. Mayo assigned special structural and economic significance to the Texas lineament as part of the regional Cordilleran framework, and further developed the integration of such persistent and prominent zones into the world wide, or regmatic, shear pattern.

Progress in the study of island arcs and their significance to global stress patterns was reported by J. Tuzo Wilson (1954). He classified island arcs into types according to their geometric expression and complexity, starting with the simple primary type of island arc. Besides giving a comprehensive resumé of the literature dealing with global crustal structures, Wilson speculated on the cause of orogenesis as related to island arcs.

Ewing and his group at Columbia University's Lamont Observatory have been major contributors of geophysical oceanographic data to the literature. They studied the Mid-Atlantic ridge in detail using seismic, gravity, and heat flow methods. The deep arc-like structure of Puerto Rico (Worzel, 1959) has also been investigated by them.

Burnham's (1959) studies of trace element distribution in chalcopyrite and sphalerite in the southwestern U. S. and northern Mexico depicted what he termed the Eastern, Central, and Western metallogenic belts in the western U. S. These belts generally run north northwest in Colorado, Utah, and Nevada respectively, merging and swinging around to a southeasterly strike in west central Arizona and eastern California before heading generally southward into Mexico from southeastern Arizona. The belts, geometrically similar to Schmitt's orogen zones but curiously displaced from them, also suggest a strong northwesterly trend in southern Arizona. Burnham concluded that the metallogenic belts and the major tectonic features consistent with them stem from a combination of compositional heterogeneities and associated physical discontinuities in the deep-seated source regions of the related ore deposits.

Further consideration was given to deep discontinuities in the mantle and crust by J. Tuzo Wilson (1965a and b) and J. Gilluly (1965). Wilson's attention focussed on the possible mechanisms of continental drift, particularly on the role of the continuous yet offset system of ocean ridges over the earth. Accepting the theory of ocean floor spreading (Hess, 1962), Wilson noted complex magnetic anomaly patterns associated with major fracture zones off Vancouver Island. Wilson (1965b) proposed that fractures which offset ocean ridges and which are related to sea-floor spreading are a new type of fault which he named the transform fault. The San Andreas fault system is such a transform structure (Wilson, 1965a) which connects the ocean ridge in the Gulf of California with the Gordo ridge off the coast of northern California.

Gilluly (1965) asserted that orogeny and plutonism are not necessarily contemporaneous, and that although they overlap in many areas they cannot be considered synonymously in the western United States. He suggested that eugeosynclinal sediments of Phanerozoic age in the northwest may have been deposited on oceanic crust while miogeosynclinal sediments were deposited on continental crust to the east. Plutonic rather than volcanic activity occurred at the junction of the two crustal types. Retention of igneous activity at depth and the fact of "Moore's quartz diorite line" were tentatively related to a persistent tendency for the continent to override the oceanic crust. Laramide plutonism might thus represent the time when oceanic and continental crust first became firmly attached to one another, "an event unique in Phanerozoic history" (p. 2). The felsic igneous rocks east of Moore's line and along Gilluly's boundary thus represent mobilization of continental sialic masses involved in continent-bordering convection currents, perhaps in an island arc relationship.

Cook (1962) considered problems of the crust-mantle interface primarily from a geophysical viewpoint. Damon and Mauger (1966) integrated the geochronology of southwestern American igneous rocks with considerations of magmatic processes and with Menard's (1960, 1964) conclusions on the East Pacific Rise, a mid-oceanic ridge which approaches North America from the south. The authors note Menard's (1964) assertion that the East Pacific Rise disappears beneath the North American continent at the head of the Gulf of California but can be projected beneath the continent on the strength of high heat flow and seismicity. Menard also observed that continental topography and structure in the western United States can be described as a "bulge . . . . comparable in scale to the rise on the sea floor . . ." (p. 119) along the projection of the Rise. Damon and Mauger further develop the model with K-Ar dating results, topographic and slope similarities between the continent and marine rise flanks, similarity of Basin and Range profiles to those of oceanic rift zones, and epicontinental marine transgression and regression. They conclude that the evidence is strong that the East Pacific Rise is the driving force behind the epeirogenic warping of the west-central United States and, by deduction, behind subsequent pulses of orogenic and magmatic activity.

Bostrom and Peterson (1966) collected data showing anomalously high Fe, Mn, Cu, Co, Ni, and Pb contents in bottom sediments on the present East Pacific Rise crest and its immediate flanks. Barium and strontium are enriched on the flanks of the Rise. Water samples collected along two traverses across the ridge and roughly 1200 miles apart were clear on either side of the ridge crest but progressively cloudy with a fine, orange, metal oxide precipitate over the Rise itself. The authors attributed these thermal and compositional anomalies to solutions of deep-seated origin emanating from fractures along the Rise. They consider the Rise to represent a zone along which submarine emanations are issuing, probably from the mantle and of possible ore-forming significance. Qualitatively similar sets of data collected 18° of latitude apart indicate significant continuity of emanative phenomena along the crest of the Rise.

The most comprehensive recent analysis of metallogenic–structural problems is given by the late Harrison Schmitt (1966). Schmitt reviews and involves earlier work by others, stressing again the importance of structural intersections particularly along the Texas zone. He describes the northwesterly Texas, Salt Valley–Las Vegas (N. M.), Uinta–Wichita, and Butte–Little Belt zones and the north-south Sierra Nevada, Wasatch–Jerome, and Front Range zones. The Texas zone has acted as a hinge line and wrench fault zone of long geologic standing, perhaps back into the Precambrian era. Schmitt observed that the Texas zone projects to the linear northeast coast of Brazil, and postulates that the zone was actively involved in continental drift phenomena. He concludes that there are at least four principal structural systems which bear on porphyry copper deposit localization: (1) the Precambrian northeast system, (2) the late Precambrian (?) to recent meridional system which has produced the north northwest Cordilleran ranges, (3) the west to northwest system, including the Texas zone, and (4) an obscure northwest system. These major systems observed on the continent are relatable to portions of the regmatic shears described by Mayo and the submarine fracture zones in the Pacific basin described by Menard (1955). Schmitt's paper stands as the most thorough consideration of local, regional, and global structure related to ore deposition published to date, and the reader is referred to it for greater detail.

Landwehr (1967) has prepared rose diagrams of the strikes of Nevadan and Laramide hypothermal and mesothermal mineralized fractures in six western states. Data were collected almost entirely from published maps, and although statistical techniques used are insufficiently described, a general northeast strike of mineralized fissures in Arizona, Colorado, Idaho, New Mexico, and Utah is indicated. Landwehr depicts seven northeast trending belts of mineralization interpreted to have originated simultaneously during Precambrian time and to have been active in Nevadan, Laramide, and mid-Tertiary times. Volcanic belts and northeast elongation of intrusives are also cited as evidence for a northeast system of deep crustal ruptures.

Lustig (1968) reports a quantitative geomorphic study of the Basin and Range region. One of the parameters analyzed is that of orientation of escarpment trends. Each trend surface, particularly the third order map, shows strong north-south alignment in northern Nevada and Utah with progressively greater deviation, in the range of 30°-40° northwest, in southern New Mexico and Arizona and southeastern California. Rose diagrams of escarpment orientations prepared by one of Lustig's students (Richardson, pers. comm.) shows a marked shift from predominant north to predominant northwest orientations respectively north and south of N 37° Latitude (the Utah-Arizona border) in the Basin and Range region. Lustig deduces that ' very substantial topographic differences of a quantitative nature exist . . . . (between) these portions of the Basin and Range region." If the results of Lustig's study can be considered with the tenet that crustal structure substantially controls range orientation, particularly in the areas studied, the provinces can be significantly related to many of the zones described in the context of ore deposits by Mayo, Schmitt, and others.

Vine (1966) has compiled the most complete review of evidence for the spreading of the ocean floor in subparallel bands away from oceanic rises, a concept which he helped develop. The actual rate of spreading can be measured by determining the widths of bands which show alternating magnetic polarity reversals away from the ridge. The magnetic anomaly pattern is similar and symmetrical on either side of the ridge everywhere that it has been measured, and is due to periodic reversals of the earth's field with attendant remanent magnetism in apparently upwelling rock material.

Roy (pers. comm.) measured thermal gradients and heat flow throughout the United States, particularly in the Southwest. Roy's results, when published, will help clarify many of the questions of continental heat flow.

RECENT ADVANCES IN MARINE AND CONTINENTAL TECTONICS

Probably the most striking new and significant concepts which bear on the porphyry copper metallogenic belt and upon structural elements of this portion of the globe are those involving ocean floor spreading, transform faulting, and their relationship to mid-oceanic ridges.

Ocean Ridges

During recent years, results from oceanographic geophysical surveys have given support to earlier geological ideas concerning genetic relationships between ocean ridges and island arcs. Although oceanographic surveys are generally easier to carry out than are surveys on land, large areas remained completely unstudied until only recently. Within this decade, however, precise bathymetric and marine geophysical data have greatly clarified our knowledge of the topography of the ocean floors and of the mechanics of their formation. One of the outstanding achievements has been the detailed depiction of mid-oceanic ridges and the fracture zones which cut them.

Bathymetric surveys over mid-oceanic ridges reveal similar patterns in many places over the globe. A median rift valley is flanked by a veneer of sediments which thicken and are older away from the ridge. Gradients are gentle, but overall relief may be as much as several thousand feet, with flanks extending for hundreds of miles on either side of the crest. The generally continuous ridges are commonly offset by seismically active fracture zones. Earthquake mechanism analyses by Sykes (1967) show that these shallow focus events are associated with normal fault movement near and parallel to the ridges, and strike-slip displacement on the fracture zones. Refraction seismic surveying shows the Mohorovičić discontinuity to be somewhat shallower under marine ridges, and seismic compressional wave velocities to be anomalously low in the upper mantle in these regions. Gravity surveys indicate that the low velocity upper mantle material also has a lower density under ridges than is normal in the upper mantle.

The ridges are found to be continuous in all of the major ocean basins of the world (Cook, 1962, Schmitt, 1966). Among the better known are the Mid-Atlantic ridge and the East Pacific Rise. Both ridges are offset into en echelon segments by generally easterly to northwesterly fracture zones. The East Pacific Rise, extending eastwardly from between Antarctica and Australia, swings northerly west of South America. The Rise then can be traced northward where, although it is cut and offset by several fracture zones, its crest comes to the Gulf of California. It then appears to project under the continent in the vicinity of western Arizona, but is probably complexly offset. Portions of the rise may lie in the Gulf of California and to the northwest, and it is almost certainly reencountered off the coast of Washington.

Sea Floor Spreading

Hess (1962) first proposed that such oceanic ridges mark the loci of rising columns of convecting mantle material. This concept has now been expanded by Vine and Matthews (1963), and many others, in the light of magnetic survey data and their paleomagnetic interpretation. Magnetic surveys of deep ocean areas show a linear pattern of alternating magnetic high and low intensity zones. This type of pattern has not been recognized on continents. The anomaly pattern is generally symmetrical about the ridge, a typical profile of which is shown as Figure 1. Convective rise along the ridge crest, with outward movement of crustal rock, is compatible with a rift valley structure. The magnetic highs and lows are presumably caused by remanent magnetization of crustal rock as it forms at the oceanic ridge, the polarity having been 'locked in' according to known reversals of polarity of the earth's magnetic field. The exact mechanism of crustal and mantle flow at the ridge itself is not yet well understood, but it is probably similar to that proposed by Orowan (1965). He points out that a non-Newtonian type of plastic flow, such as is observed in the hot creep range of metals, must be responsible for the flow phenomenon.

Heat flow measurements show consistently higher values over mid-oceanic ridges and support the spreading sea floor concept. A profile across the East Pacific Rise is given in Figure 2. Maximum values of over 8 microcalories per square centimeter per second are several times the background of 1.4 heat flow units measured elsewhere.

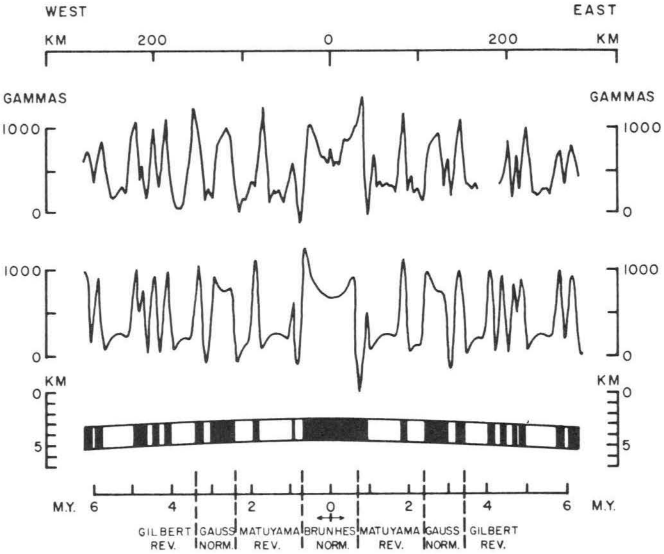

Figure 1 – Magnetic anomaly curve across the Pacific-Antartic Ocean Ridge. The upper curve was actually observed, and the lower curve was calculated from the crustal model at the bottom of this diagram. Rate of spreading is 4.5 cm per year. (After Pitman and Heirtzler, 1966, p. 1164).

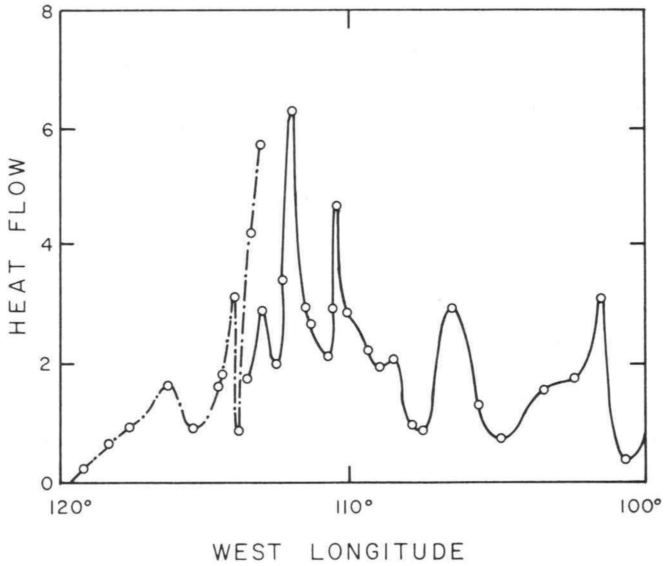

Figure 2 – Heat flow across the East Pacific Rise. The east half of the profile is along Lat. 13°S, the west half along Lat. 14°S. (After Von Herzen and Uyeda, 1963, p. 4219).

The rate of sea floor spreading can be measured by correlating durations of known periods of reversals of the earth's magnetic field with band-widths of the magnetic highs and lows. This correlation is seen next to the bottom of Figure 1, where zones of normal field direction are shown in black and reversed zones in white. The time scale, as determined radiometrically on samples of known magnetic field direction, is on the bottom of Figure 1. The spreading rate of different ridges over the earth is 1 to 4.5 centimeters per year. The fact that the rate of spreading can actually be measured to this precision is quite impressive. Of far-reaching significance is the fact that ocean floor crust is being formed along active mid-oceanic ridges, most acceptably by convective upwelling of mantle material. The question of how the crust thus coming into existence is compensated for by crust consumption elsewhere must be considered.

Island Arcs

In a deep structural sense, the counterpart of an ocean ridge is an island arc. Characteristically there is a deep oceanic trench on the oceanward side of an arc, and earthquake foci deepen on the continent side down to 400 miles (700 km). The island chain of Japan, with oceanic deeps to the east, is an outstanding example, the island arc system extending south past the Philippines, then east past Indonesia.

Recent studies of earthquakes recorded from island arc areas (Oliver and Isacks, 1967) show that lower seismic velocity oceanic crust is apparently dragged downward under island arcs by convective movement of the earth's mantle. This downward circulation also accounts for the very strong low and high gravity anomalies which are associated with island arc structures, the observed depths and distributions of earthquakes, and the presence of the trench on the ocean side. They represent downward consumption of crust in a way complementary to its formation along oceanic ridges.

Continental Drift

Clearly, one cannot discuss recent tectonic theories and ignore the topic of continental drift. Besides being an intriguing idea, it also has a real bearing on the regional aspects of ore deposits. If one accepts the interpretation set forth in previous sections on island arcs, ocean ridges, and sea floor spreading, then it is apparent that land masses can move relative to one another and that in some cases their rate of separation might be determined.

There are several other modern lines of evidence which convincingly support continental drift, but space does not permit more than their brief mention. Matching radiometric dates of almost-certainly once contiguous structures in Africa and Brazil which are now separated by the Atlantic ocean have been cited by Hurley, et al. (1967). Many stratigraphers see lithologically and faunally similar sequences in South America, Africa, and elsewhere, and accept the drift hypothesis. Fit of continental shelves at 500 meters below present sea level is excellent between Africa and South America, and elsewhere at the west and east margins of the Atlantic ocean basin. Paleontologists and zoologists require that drift be real unless "land bridges" occasionally linked flora and fauna from different parts of the globe. Unless the continents have moved, past geomagnetic pole positions apparently are at variance at specific times from continent to continent. That continents are mobile seems now assured. That they might transport continental structures, and override oceanic structures, is corollary.

Concerning the tectonic history of the west coast of North America, the structural and stratigraphic record of the southwestern United States indicates the presence of persistent geosynclinal conditions throughout most of Paleozoic time. Eugeosynclinal axes showed a northeasterly trend in response to the transcontinental arch of early Paleozoic times, but by middle Paleozoic time their axes had become parallel to the present coastline and a few hundred miles inland. Geosynclinal activity along the Cordillera was also well developed in early Mesozoic time and fold and thrust belts along the geosynclinal axes appear to have continued into the Mesozoic era.

We interpret this long-term geosynclinal activity and its subsequent orogenic events to be related to a continent-bordering island arc system. The term 'island arc' here refers not necessarily to the presence of an arcuate system of offshore volcanic islands but rather to arcs in the context of their association with mid-oceanic ridges. Oliver and Isacks (1967) have described such a system of deep island arcs and its geologic implications from seismic measurements near the Tonga Trench. Gilluly (1965) notes the activity of many orogenic belts along the western continental margin of the U. S. in Paleozoic and early Mesozoic time.

In middle and late Mesozoic time, the western edge of the continental margin appears to have lost its dominantly geosynclinal characteristics, and it may be supposed that the western continental edge had by then overridden portions of the East Pacific Rise system. Precise timing can of course not be established; in fact some conflicting evidence is recorded in, for example the apparent island-arc related genesis of late Jurassic portions of the Sierra Nevada batholith. The onset of basin and range type tectonics, the widespread occurrence of both plutonic and volcanic rocks,

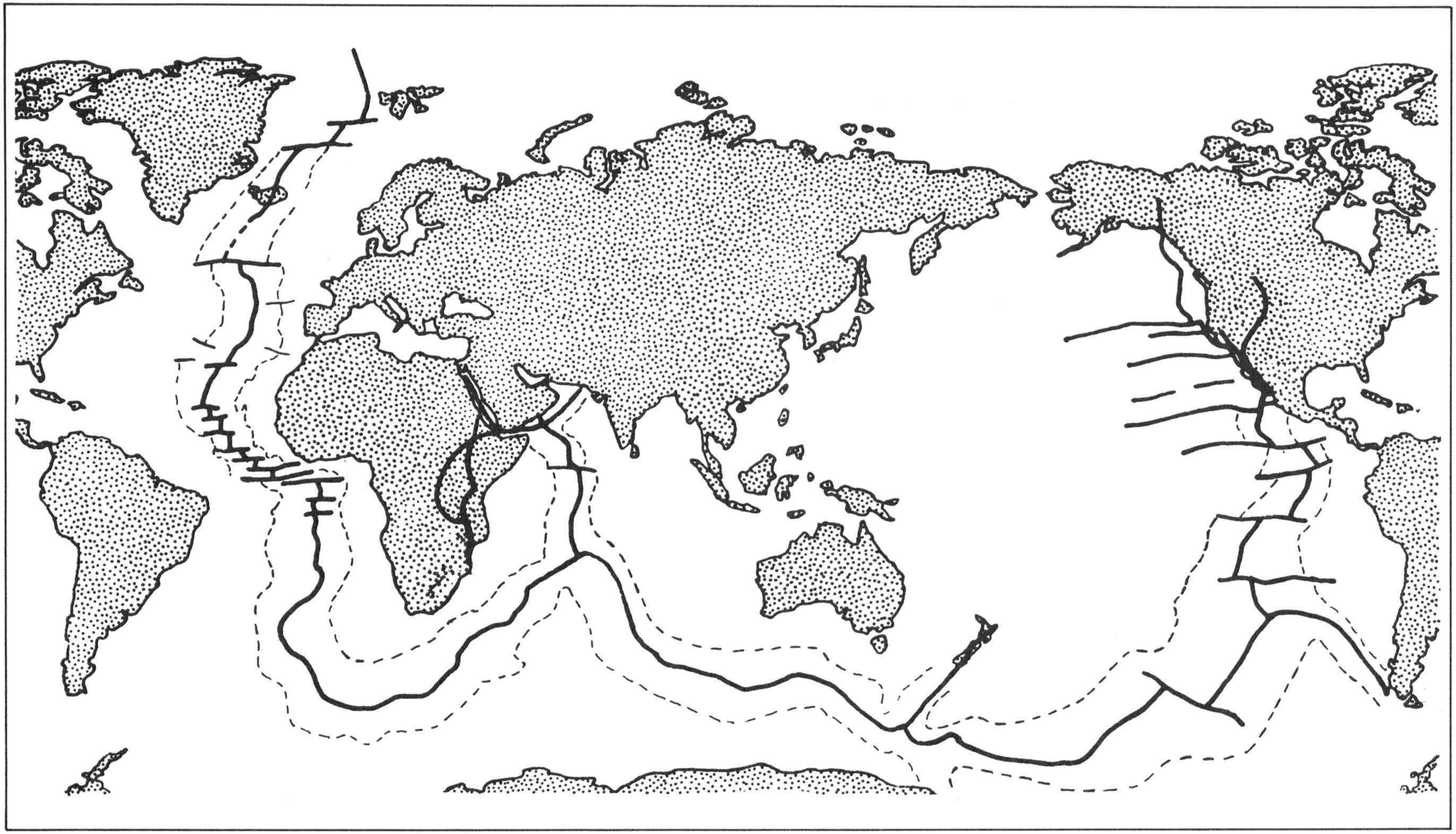

Figure 3 – The world wide Ridge system, emphasizing offsetting transform faults.

and the many other evidences of great change in the geologic fabric of the western U. S. in this interval, however, can reasonably be referred to this shift in subcrustal characteristics from island arc to 'mid-oceanic' ridge phenomena. The position of the ridge relative to a point on the continental surface may not have remained fixed very long, and the ridge may have migrated as far east as central New Mexico. Mechanisms of this movement are related both to continental drift and to transform faulting described below.

Convection

If one inquires into the means of moving entire continents over the earth, at least three different mechanisms are possible: thermally driven convective currents in the mantle, driving movements of the earth's core, and geoidal compensation. Thermal convection would arise from temperature differences between the lower mantle and the base of the crust. Convective currents would be in semi-turbulent flow, moving continents in due time at the earth's surface. The convective hypothesis is the most widely held concept in the explanation of continental drift. The sizes of convective flow cells and rates of flow postulated can be made to agree satisfactorily with observations if continental drift is assumed.

Observations of the nature of the geomagnetic field strongly suggest that the earth's core is in motion. These motions could be due again to convection in the core, or to tidal eddies generated by the moon's varying position. Such core-motions could in turn create movement of the earth's mantle, and might thus cause continental drift. A third means of displacing continents would result from broad-scaled differences in the earth's geoidal surface. Such variations are known to exist, and they could lead to the "floating" of lower density land masses toward regions of lower gravitational potential.

True thermal convection is a problem which cannot be completely evaluated in the earth because we do not know the thermal conductive properties of deep earth materials. Nevertheless, we can measure heat flow and its anomalous differences and draw conclusions about conditions of the earth's interior. Although the specific conditions of convection are not thoroughly known, it could exist under thermal gradients as they are currently understood. Thermal convective overturn is suggested by high heat flow data along the East Pacific Rise (Menard, 1960, 1964) and the Basin and Range region (Cook, 1962).

Transcurrent and Transform Faults

Figure 3 shows the worldwide ridge system with offsets slightly exaggerated. The genesis of these offsets has long puzzled structural geologists and geophysicists. The discovery of sea-floor spreading away from mid-oceanic ridges has in turn prompted inquiry into the dynamics of mass movement associated with ridges. Strike-slip offsets like the prominent scarps offshore from California and nearly perpendicular to the coastline have acquired new significance in these recent tectonic analyses.

We can first separate strike-slip faults into two general categories, those related to sea floor spreading and those related to external shear couples which are in turn related to conventional compressional or tensional stresses. The former are called transform faults by Wilson (1965a); the latter are called transcurrent faults. Figure 4 shows the characteristics of the two types.

We can by no means be sure of the exact mechanisms which produce transform faulting. The following description of the currently most acceptable model (Wilson, 1965a and b and others) assumes that sea-floor spreading results from convective upwelling of material which, upon rising to the ridge crest, spreads laterally in opposite directions away from the

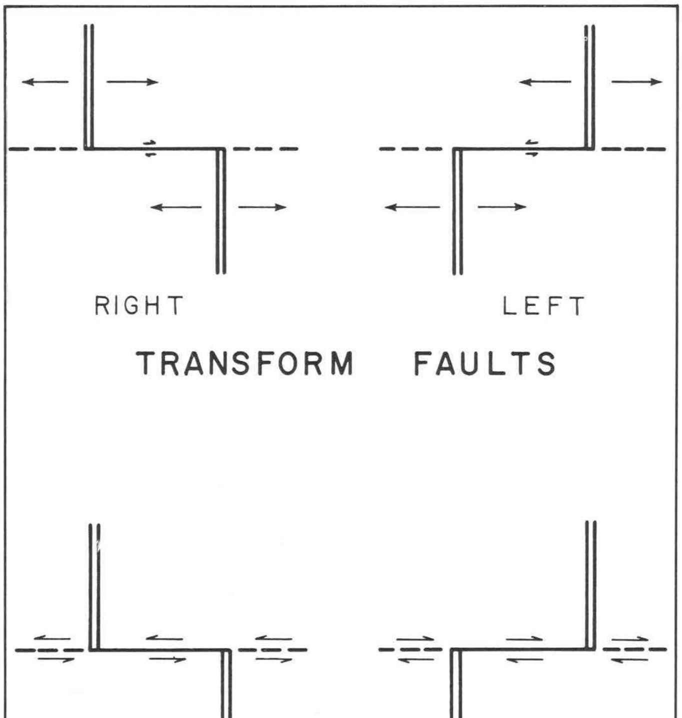

Figure 4 – The sense of motion associated with transform faults. The terms "left" and "right" describe the sense of motion along the fracture zone, not the relative ridge position.

ridge. If, along a given section of ridge, upwelling material spreads or outflows more rapidly in one portion than in an adjacent portion, a cross shear stress must develop where the two sections abut. This cross shearing, if rupture develops, causes a transform fault. Figure 4 shows the essential elements of a ridge-ridge transform fault, the double-barbed arrows showing the direction of flow of material from the crest, in bands like those in Figure 1. The relative movements of material along the fault plane is the reverse of that of the transcurrent fault, a necessary consequence of the active versus passive role of the displaced linear feature. Ridge displacement could be constant even during active faulting. Sense of displacement is a function of relative rates of movement of material from the ridge. Implicit in this model is the fact that the convection cell itself is offset at least near the surface. The lateral offset of a transform fault could only extend downward as far as there exists an outward component of mass movement, although a discontinuity, separating portions of different relative vertical flow, might extend far deeper.

Most significant here is the fact that large offsets in mid-oceanic ridges can be produced with differential flow rates alone, that is, without the existence of an external shear couple. Great offsets in mid-ocean ridges can then result from irregularities in convective flow rate.

Sykes (1967) finds that most of the earthquake activity near mid-oceanic ridges is related to the offsetting fracture zones. In particular, seismic activity is greatest on those parts of fracture zones between offset portions of the ocean ridge. Further analysis of earthquake records from seismic events in these areas shows that the relative motion is predominantly strike-slip, in the same sense as that predicted by the transform fault theory.

Vacquier (1962) and Wilson (1965b) have found large offsets in the magnetic anomaly patterns at ocean fracture zones off the west coast of North America. The most direct explanation of these offsets, and thus the condition which brings about the definition of the term, is that these offsets are indeed transform faults. It follows that transform faulting is a valid new class of structure which is very important to global geophysics and structural geology.

Presently Active Faults

Figure 5 shows the most recent interpretation of existing ridge and transform fault relationships along the west coast of North America. At the present time, the East Pacific Rise underlies part of the west coast, specifically as en echelon faulted segments lying on a line along the deeps of the Gulf of California. That the Gulf of California is in fact sharply cut by numerout northwest crossfault scarps is strikingly shown by bathymetric data (Rusnak, Fisher, and Shepard, 1964). The San Andreas fault system, although much more complex than is shown here, is a type of transform fault at the zone of weakness between continental and oceanic crust. Notice also that the direction-of-movement arrows reporting the sense of movement along the San Andreas fault zone are the reverse of what might be supposed to describe strike faulting of a static linear feature. They result from consideration of relative movement of material away from ridge crests, net displacement of the ridge crests depending upon relative rates of movement of points on either side of the fault zone. The San Andreas fault zone is not a conventional strike slip fault and can no longer be considered as such.

STATUS OF THE EAST PACIFIC RISE, PACIFIC FRACTURE ZONES, AND THE TEXAS ZONE

The exact positions of segments of the East Pacific Rise structure under the western edge of the continent of North America are still open to question. Cook (1962, p. 309) shows the Rise much as it is given in Figure 3, running northward along the Gulf of California and then splitting into three branches. One branch diverges northward, then northwestward, projecting into the Rocky Mountain trench structure of western Montana; the central branch projects straight northwestward beneath western Arizona; and the third, western branch continues along the western coast, going offshore to meet the Gorda and Juan de Fuca segments off the coast of Washington, Oregon, and British Columbia. It is not easy to trace the present course of the crest of the East Pacific Rise under the continental crust, although seismic and heat flow data imply its presence. Deep fracture zones in the mantle or deep crust also appear to have been overridden. However, if the North American continent has moved westward with respect to the East Pacific Rise, and Figure 5 is essentially correct, the present position of the Rise, or at least its westernmost branch, cannot be looked to as the source of southwestern Laramide metallogenic belts. The complexities of transform faulting make the interpretation of past positions of ridge structures in southwestern North America extremely difficult. Schmitt's Wasatch –Jerome orogen, implications from Burnham (1959), and Cook's (1962) representation confidently relate to deep structures on the basis of heat flow and seismicity, but continental geophysical data are as yet too incomplete to specify that they are segments of the East Pacific Rise crest. It must be noted that

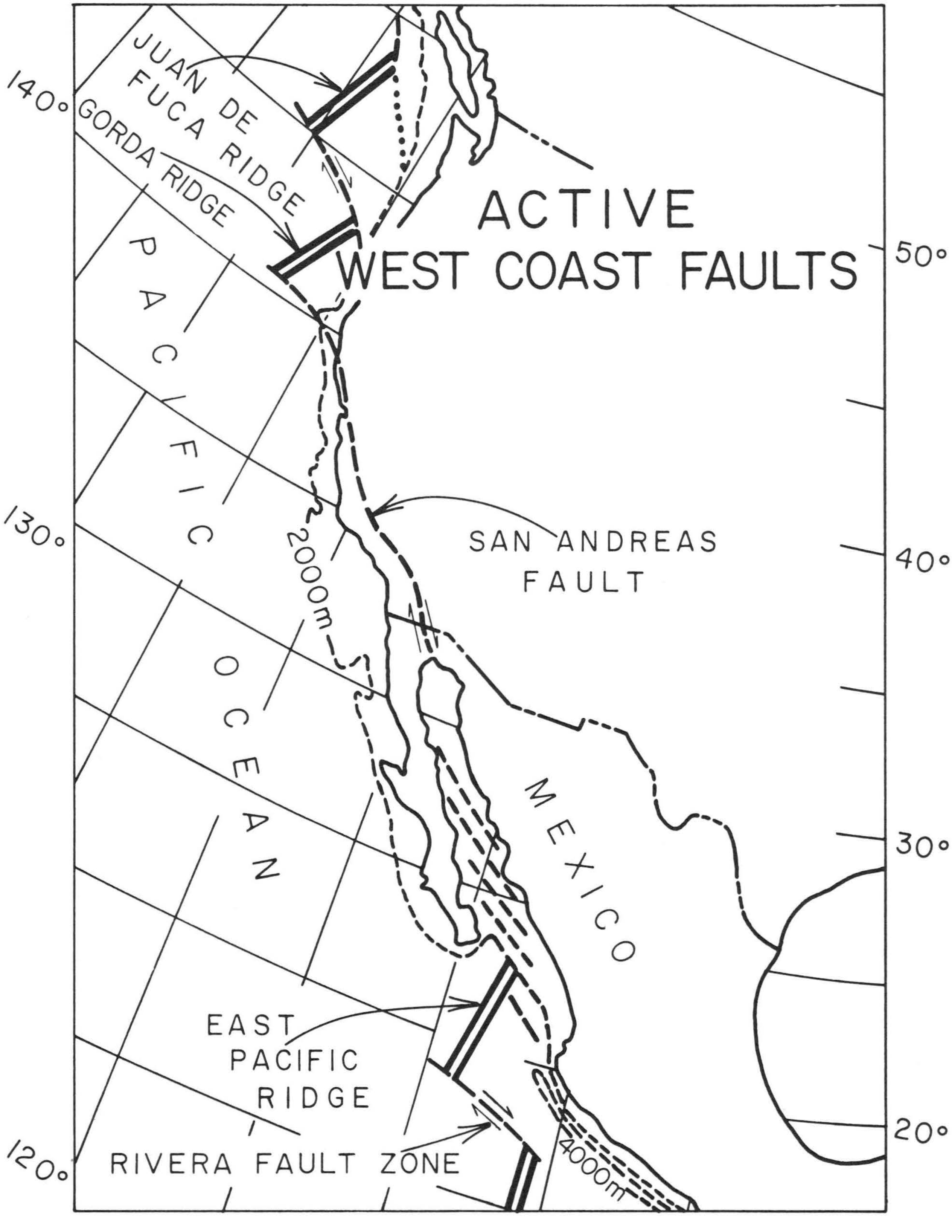

Figure 5 – Presently active West Coast faults. Ocean Ridges are heavy double lines. Transform faults between ends of ridges are dashed lines.

branching of mid-oceanic ridges is not without precedent (Figure 3); quite possibly one segment is cut and displaced by the San Andreas fault system, while other branches continue northward as in Figure 3. Judging by magnetic anomalies over the Gorda and Juan de Fuca ridge segments in the vicinity of Vancouver Island, several structural complexities exist in the region, and the exact positions of the ridges and transform faults here are in question. Figure 5, the most reasonable interpretation of existing data, will doubtless be refined by future heat flow and seismic information.

Several older, roughly east-west fractures zones cut the Pacific basin west of North America. From north to south these fracture zones (shown in part by Schmitt, 1966, Figure 3, p. 26) are the Medocino, the Pioneer, the Murray, the Molokai, and the Clarion-Rivera. These zones are currently seismically-inactive transform fault zones consisting of rift and fracture sea scarps. The Rivera zone, slightly offset from the east end of the Clarion zone and west of central Mexico, is seismically active. It in turn offsets the East Pacific Rise as shown in the lower portion of Figure 5.

The structural identity of the Texas zone with respect to Pacific basin fracture zones has not been clearly established. It is almost certainly related to them in the global sense, and like many of them, is now seismically inactive. The Texas zone may swing into the San Andreas fault zone, thereby representing a currently inactive branch of that transform system. Schmitt (1966) described the Texas zone as a zone of wrench faults, nearly vertical strike-slip faults, of long geologic standing. Schmitt stated that the likelihood of its involvement with continental drift and continental margin tectonics is high in view of its projection toward island arc structures as at Puerto Rico, to the northeast coast of Brazil, and into offsetting structures at the Mid-Atlantic Ridge. The topographic, geophysical, and structural similarity of the Texas zone to some of the marine fracture systems strongly suggests that it is a continental crust analog to such features in the oceanic crust, a persistent zone of steeply-dipping structural planes extending to great depths in the crust.

PORPHYRY COPPER DEPOSITS, REGIONAL ZONING AND STRUCTURAL ZONES IN SOUTHWESTERN NORTH AMERICA

Porphyry Copper Deposits and the Texas Zone

If all of the variously-oriented and differently-spaced metallogenic belts in the literature were drawn on an overlay of western North America, most of the known ore deposits would be covered several times over with an alarming diversity of trends. Most of the zones, however, from Billingsley and Locke's (1941) Walker Line through Schmitt's (1966) Texas zone show a strong north northwest to northwesterly trend in Arizona. Averages are not valid in this circumstance, but several factors independently support such a trend. Many workers have noted the strong directionality of mountain ranges and escarpments in southern Arizona, a feature quantitatively established by Lustig (1968). Mayo (1958) and Schmitt (1966) noted and stressed major regional structural control in the porphyry copper region, focusing attention upon the Texas zone. The zone is not strikingly expressed at the surface throughout its length, but it is the principal, most consistent linear crustal feature associated with porphyry copper mineralization. It almost parallels the southern border of Arizona, the position of that border probably having been influenced by ease of travel parallel to mountain ranges from southern Arizona toward the Colorado River for both early explorers and later border surveyors. Compilations of structures associated with ore deposits (Schmitt, 1935, Billingsley and Locke, 1941, and Titley and Hicks, 1966) show prominent involvement of northwest-striking faults and mineralized fissures. Aeromagnetic contours commonly show an apparent northwesterly "grain." Figure 6 is a schematic diagram showing the relationship of porphyry copper deposits to structural trends in part mapped, in part inferrable from the air, and in part obvious from physiographic maps in southern Arizona and New Mexico. The northwesterly trend is apparent. Also apparent, however, are several persistent north to north-northeast trending offsets within the Texas zone which appear to be of penecontemporaneous or more recent origin. Landwehr (1967) reports a strong preferred northeast orientation of mineralized fractures in Arizona. These northeast fractures have been attributed to mechanical weaknesses in the crustal basement which have been inherited from an older, underlying Precambrian foliation direction. That the Texas zone has been able to breach this well-developed grain suggests that the crustal tectonics which created the zone are of deep-seated, persistent, regional, if not global, proportions.

Sumner (1967) has compiled a map (Figure 7) showing the distribution of copper and iron deposits in southwestern United States. Most of the copper deposits are of porphyry affinity and of Laramide age, having been selected according to these criteria: (1) association with porphyritic igneous intrusive rocks; (2) predominantly disseminated and micro-veinlet sulfide mineralization; (3) mineable in bulk,

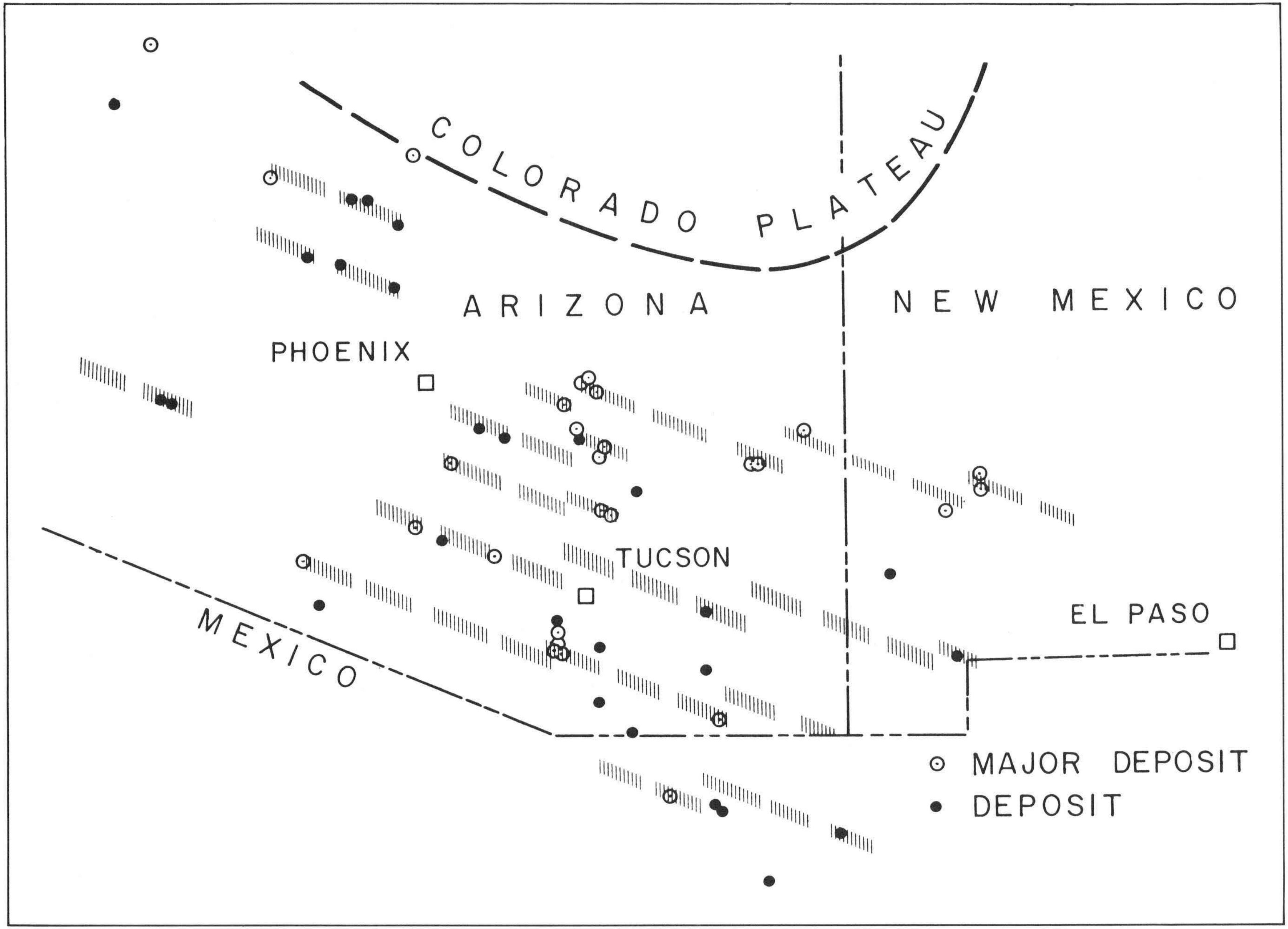

Figure 6 – The Texas Lineament zone in the Southwestern United States (After Sumner, 1967).

with large tonnages of low grade ore commonly secondarily enriched; and (4) minor molybdenum commonly recoverable, with coextensive or peripheral values in silver, gold, zinc, and lead. For the sake of completeness the Precambrian deposits of the United Verde district at Jerome, Arizona, are included along with the pre-Cretaceous Bisbee, Arizona, and the mid-Tertiary Bingham, Utah, deposits. Many small, not demonstrably "porphyry" deposits such as those of the Planet district in west central Arizona are omitted, as is by-product copper as at Goldfield, Nevada, and Tombstone, Arizona. The reader is referred to Kinkel and Peterson (1962) for a complete list of copper occurrences in the U. S. known to that date. Iron deposits in the southwest are commonly also associated with igneous rocks, although their ages and geologic derivations are generally less well known. Most of them are dominantly oxide ores although pyrrhotite is importantly involved in several. Magnetite and pyrrhotite are relatively rare in porphyry copper deposits in the area of greatest copper deposit clustering but they appear to increase in relative abundance toward the margins of the porphyry copper province. Magnetic susceptibility is correspondingly low (Brant, 1966) in Laramide intrusive rocks associated with major copper mineralization.

Regional Zoning and Derivation of Porphyry Copper Deposits

Damon and Mauger (1966) have shown that many of the porphyry copper deposit intrusives are temporally related. Of the plutons with associated ore-grade copper mineralization which have been dated, 20 out of 22 fall in the interval from 55 to 75 million years ago. The average date is close to 64 m.y., with some skewness of the histogrammatic presentation toward younger dates such that the greatest number of dates, 7 of the 22, falls in the 55-60 m.y. interval, with another 6 in the 60-65 m.y. range. Although exceptions such as United Verde, Bingham, and Bisbee are recognized, the porphyry copper deposits are convincingly shown to be part of a metallogenic epoch and province.

Perhaps even more significantly, Moorbath, Hurley, and Fairbairn (1967) have shown that for several major porphyry deposits studied, including Ray, Arizona, Santa Rita, New Mexico, and Bingham, Utah, the rocks were not derived by melting of deep sialic materials of direct continental origin but that they were intruded "from a source region that had a (low) Rb/Sr ratio similar to, or only marginally above, that of the source region of basaltic magma. Such a source could be either the upper mantle itself, or a basic layer–possibly ancient–in the lower part of the crust." (p. 232) They also note that "in the British Isles, granites with high, uniform initial Sr^{87}/Sr^{86} ratios, believed to originate by partial melting of sialic basement, are virtually devoid of mineralization." (p. 234). The growing list of porphyry-type copper deposits associated with island arc structures, for example the deposits of Bougainville, the Philippines, and Puerto Rico, further argues for the deep derivation of the intrusives. The 65 m.y. Puerto Rican occurrence (Mattson, 1966) is of particular interest since no rocks older than Cretaceous which might have served as source rocks through local remobilization or downwarping are known. Strontium data also indicate mantle or deep crust derivation of the Puerto Rican materials.

In view of uncertainties shrouding the geology and geochronology of the iron deposits of the southwest, speculation concerning their distribution with respect to copper porphyries is hazardous, but it is noteworthy that the large, elongate, roughly oval copper porphyry zone is bordered by copper porphyries with associated iron occurrences, principally pyrrhotite, and finally by magnetic iron replacement deposits. If this distribution proves to be real with respect to geologic time, and a copper-iron zoning pattern is thereby indicated, the width of the broad metallogenic province suggests a source of copper, iron, and sulfur deep in the earth, perhaps even in the mantle.

Several other lines of evidence indicate a deep source of the metals in the copper porphyry metallogenic region. Bostrom and Peterson's (1966) work forcefully suggests that deep exhalations of copper and iron can be called upon. Although the lead and strontium of the O'Neill wells near Niland, California, are of near-surface derivation, it is significant that strontium data of associated volcanic rocks suggest (Doe, Hedge, and White, 1966) their derivation in large part from basaltic or gabbroic material. The wells lie very near the projection of the San Andreas fault system. Potential ore-forming fluids seem also to be associated with the ridge structure of the Red Sea (Hunt, et. al., 1967). An evaluation of heavy metals in deep waters of the Gulf of California along the lines of Bostrum and Peterson (1966) might be extremely significant. Although their data were scanty, Murthy and Patterson (1961) found that lead isotopes in ore minerals at Butte, Montana, indicate a 400 million year age while host rock lead is of 60-70 million year (Laramide) age. They then suggest that ore lead was not derived directly via crystallization of the Boulder Batholith but rather was mobilized from deeper, older levels in the crust or mantle. The well-known zonation of diminishing copper-molybdenum ratios eastward, Billingsley and Locke's "Parade of orogenies," Moore's quartz diorite line along the east

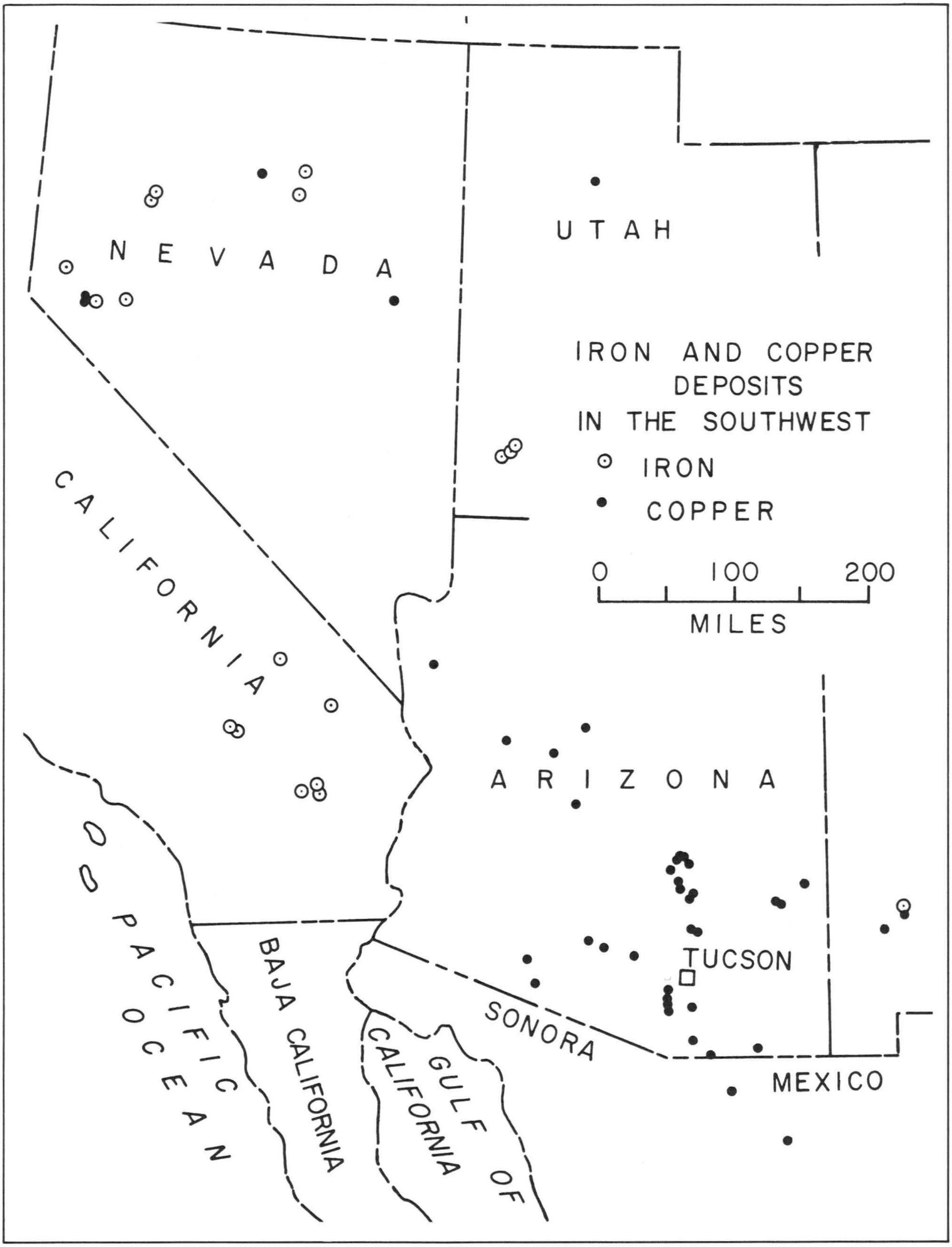

Figure 7 – Iron and copper deposits in southwestern North America implying regional zoning (After Sumner, 1967).

side of the Sierra Nevada mountains, and Gilluly's oceanic versus continental crust interface all indicate some degree of deep and/or regional structural and source control on what are now near surface phenomena.

PORPHYRY COPPER DEPOSIT LOCALIZATION

It has been shown that there are substantial bodies of data which indicate with increasing conviction that (1) the deposits of the porphyry copper province have been derived from either the sublayer of the continental crust or the upper mantle; (2) that metalliferous and rock-forming materials are issuing today from oceanic crust or the mantle itself along mid-oceanic ridge structures and/or fracture zones; (3) that transform fault mechanisms have greatly modified our concepts of continental faulting; and (4) that continental drift can no longer be considered hypothetical. A drifting continent must encounter and override both island arc systems and mid-oceanic ridges, as has occurred at the western border of North America. Regional-scale ore deposition related to continental movement can then be related to (1) zones of deep convective downturn (island arcs) and upflow (oceanic ridges), (2) fracture zones in the crust, and (3) corrosion-mobilization of old sediments and metamorphic rocks at the base of the crust by upwelling convective material. The precise role of the Texas zone in transform faulting and continental drift cannot yet be firmly established, but it is increasingly certain that it represents a set of steep, deep-cutting structural planes which relate to global tectonic phenomena. Although the coincidence of porphyry copper deposits with the Texas zone is striking, it is not proposed that the Texas zone is the only such deep-cutting structural system. It does appear, however, to be the single most dominant control. Other factors, perhaps relatable to complementary structural systems, are clearly involved to explain the more east-west aspects of regional zoning. Copper-molybdenum zoning, for example, is perhaps more closely related to former now-buried island arc or ridge structures.

The genetic model which appears most consistent with modern geophysical data involves continental drift against and over island arcs which have bordered the North American continent and over mid-oceanic ridges and fracture zones which penetrate the oceanic crust. More specifically, it is indicated that the North American continental plate has overridden portions of, or branches from, the East Pacific Rise and its related structures, thereby providing a major, generally north-south axis of plutonism, intrusion, and mineralization of regional proportions and deep-continental crust or mantle affinity. The roots of the western elements of this north-south axis are transected by the modern and active San Andreas transform fault system, and more easterly elements of it were actively cut by the Texas zone system during Laramide time. It is this intersection of these deep and persistent structures to which the clustering of porphyry copper deposits in Southern Arizona can now, more reasonably than ever, in large part be ascribed. Pacific basin fracture zones have been tentatively mapped (the Galapagos arch and the Chilean Rise) which project from the East Pacific Rise toward the coast of South America in approximate positions to account for the major porphyry copper deposits there. The presence of major oceanic- and continental-crust breaks such as the Texas zone must then be interpreted as providing access to deeply-derived materials and as providing cross-grain to older or more local, "merely" continental structures.

Practically, these considerations suggest that further exploration along the Texas zone, as for instance in west Texas and perhaps southern California, is indicated. Continued refinement of the cause and effect of marine structures, and their application to continental tectonics and localization of igneous activity, appears portentious both to the understanding of metallogenic zones and to successful prospecting.

CONCLUSIONS

We have pointed out in this paper that there is good evidence, from oceanographic and geophysical measurements, that sea floor spreading and continental drift are real and important earth phenomena. Island arc structures effectively consume oceanic crust and are responsible for geosynclinal activity when they are adjacent to continents. If we are to understand the more complex continental tectonics, we must be familiar with basic structural conditions of the thinner crust of oceanic areas.

Ore deposits are related to island arcs and oceanic ridges and their offsetting transform faults. Deep fractures into the earth's mantle appear to be a potentially important mechanism to provide upward passage to ore fluids. Consideration of regional deposit zoning, as for the porphyry copper province, demands depth consistent with apparent great breadth. Porphyry deposits of the western hemisphere are apparently related to a complex orogenic structure whereby the continental margin has overridden portions of the East Pacific Rise and related deep structures. Clustering of porphyry copper deposits in southern Arizona and New Mexico is relatable to transection of deep structures by the Texas zone, probably itself a transform fault system in Laramide time.

It is the intention of the authors that this paper will stimulate further inquiry into the relation of ore deposits with major tectonic patterns, past and present.

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SUBSIDENCE AT SAN MANUEL COPPER MINE, ARIZONA

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INTRODUCTION

The three subsidence pits shown in figure 1 are the result of the removal of nearly 100 million tons of copper ore from beneath the surface of the ground. The San Manuel deposit is one of the nation's major low-grade porphyry copper discoveries and is located about 50 airline miles northeast of Tucson, Arizona.

Active mining by the block caving method has been carried out at the property since 1956. Block caving utilizes two parallel levels of drifts below the portion of the orebody to be mined. Block caving requires no attempt to fill or to otherwise shore up any portion of the mine which has been drawn and the result of this practice is the continuous failure of the roof until breakage reaches the ground surface and a pit is formed.

THE SUBSIDENCE PITS

Subsidence conditions at the surface of the mined area are described as they appeared in 1965. Two portions of the mine were inactive at this time and the two related subsidence pits had become quiescent. These areas were those over the North Orebody and are represented in figure 2 by the two smaller pits.

The largest of the pits is that corresponding to the South Orebody, and during 1965 it had attained a depth of more than 500 feet. Maximum dimensions in plan were 3000 feet in length by 2000 feet in width. Each pit is surrounded by a series of near-vertical peripheral tension fractures. The most important of these fractures are shown in figure 1. Downward movement of blocks of conglomerate occurs at the surface in response to a general lowering along the center-line of the pits as ore is removed through draw raises many hundreds of feet below. This movement is marked by an advancing pit escarpment and the formation of new tension fractures as mining stresses are concentrated against the surfaces bounding the pit.

GEOLOGIC SETTING

Lithology

The granitic rocks composing the orebody form part of a basement complex that is exposed at the surface in a few places, but which is largely buried by more than a thousand feet of conglomerate. It is this wedge-shaped caprock of conglomerate that figures most prominently in the surface expression of subsidence. Geologic conditions before mining are shown in figure 3, where the caprock is represented by the Cloudburst, San Manuel, and Quiburis formations of early Tertiary to Pliocene age.

Geologic Structure

Both the massive rocks of the orebody and the beds of overlying conglomerate have been cut by three major northwest-trending faults. Associated with these major faults (San Manuel, Mammoth, and Cholla) are many near-vertical normal faults that exhibit opposing dips to the northeast and southwest. Faulting has substantially weakened the host rocks so that the effects of removal of ore are easily transmitted to the surface along these and other planes of weakness.

The San Manuel fault has resulted in the placement of the wedge of conglomerates against the older igneous rocks of the basement. This single feature (Fig. 3) transcends all other structural elements in the area in its influence on the character of subsidence.

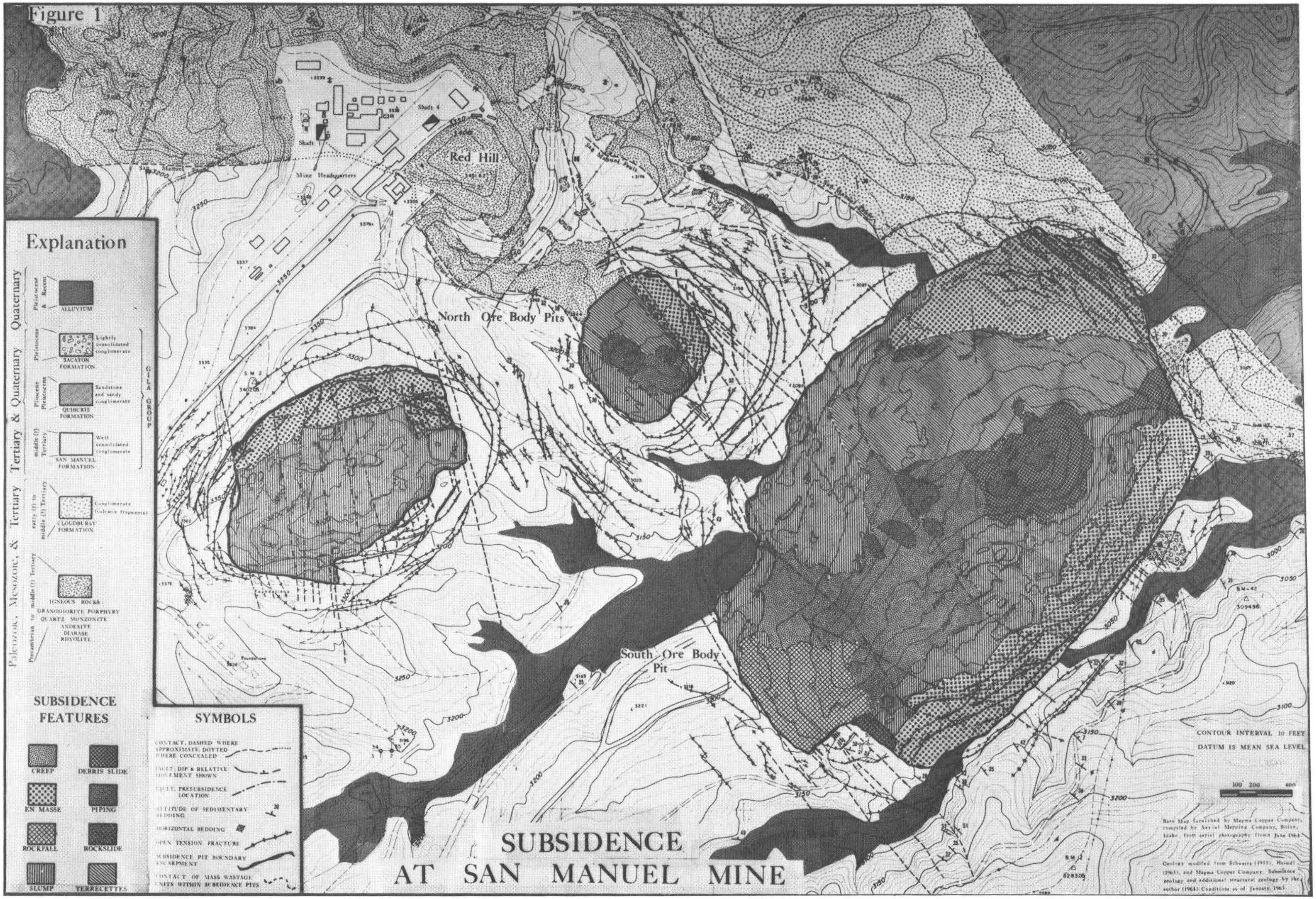
PHYSICAL CHARACTER OF THE ROCKS

The rocks involved with subsidence at the mine are not strong when considered as gross units. As small blocks, free of discontinuities, the sedimentary rocks of the caprock are probably quite strong. However, the discontinuities in both the caprock and the orebody have combined with hydrothermal alteration in the orebody to destroy any appreciable strength when the units are considered as a whole. Rock strengths have been referred to in general descriptive terms due to an inability to make meaningful bulk strength measurements.

The Orebody (Quartz Monzonite and Granodiorite Porphyry)

An important requisite and key to success in mining the orebody is the relative ease with which the rocks will break into relatively small fragments for block

Figure 1



Base Map furnished by Magma Copper Company, compiled by Aerial Mapping Company, Boise, Idaho, from aerial photography flown June 1964.

Geology modified from Schwartz (1953), Heindl (1963), and Magma Copper Company. Subsidence geology and additional structural geology by the author (1964). Conditions as of January 1965.

caving. The structural weakness of the ore is entirely due to the widespread fracturing and completeness of alteration that Creasy (1965, p. 11) noted as being common throughout the orebody. Creasy found that this rather intensive alteration consisted of varying amounts of unidentified clay minerals as well as sericite, chlorite, calcite, and epidote. Clays and sericite are well known as agents destructive of rock strength. Utilization of the rock classification for engineering purposes proposed by Coates (1964, as modified by Burton, 1965) places the rocks of the orebody in the category of "blocky continuity", with fracture spacing ranging from about three inches to six feet.

The Conglomerates

The structural integrity of these units has been weakened by faulting and the presence of poorly bonded contacts at bedding planes separating the intercalated tuff beds and the surrounding rock. Shear strength within fault-separated blocks of the conglomerate is probably relatively high, as the critical (maximum possible) height of free faces found along the boundary escarpments of the pits approaches 50 feet. Natural breaks in these faces occur at approximately 90° and the faces will stand for months. Collapse occurs only when weathering and saturation by rain have combined with removal of support at the toe of the faces by mass wastage movement.

Thickness of the conglomerate caprock affects the process of subsidence in three ways; 1) it increases the lithostatic pressure (or vertical applied stress) on any given portion of the caprock that is bounded by faults, 2) it increases the thickness of the slab of conglomerate that must be broken, as support is lost through caving activities going on at depth, and 3) it aids in breaking underlying ore after the initial stages of subsidence have occurred.

GROWTH AND DEVELOPMENT OF THE PITS

Growth of subsidence at San Manuel Mine has been marked by two general stages; a preliminary period of tensile fracturing, together with gentle settlement of the ground surface, and a final period of slowly developing, pit-like sinking of the ground surface. The first noticeable effects at the ground surface came after approximately 100 days of draw and are referred to in mining terminology as "pipes". These features are not to be associated with those of "piping" in soils caused by removal of the fine fraction by flowing water. Pipes are upward extensions of caved areas that provide a path for the transport of broken fragments of conglomerate into the mined area below. Pipes are illustrated diagramatically in figure 6 and can be seen in figure 2 as crater-like depressions resembling those formed by chemical explosives in soil.

Peripheral Tension Fractures

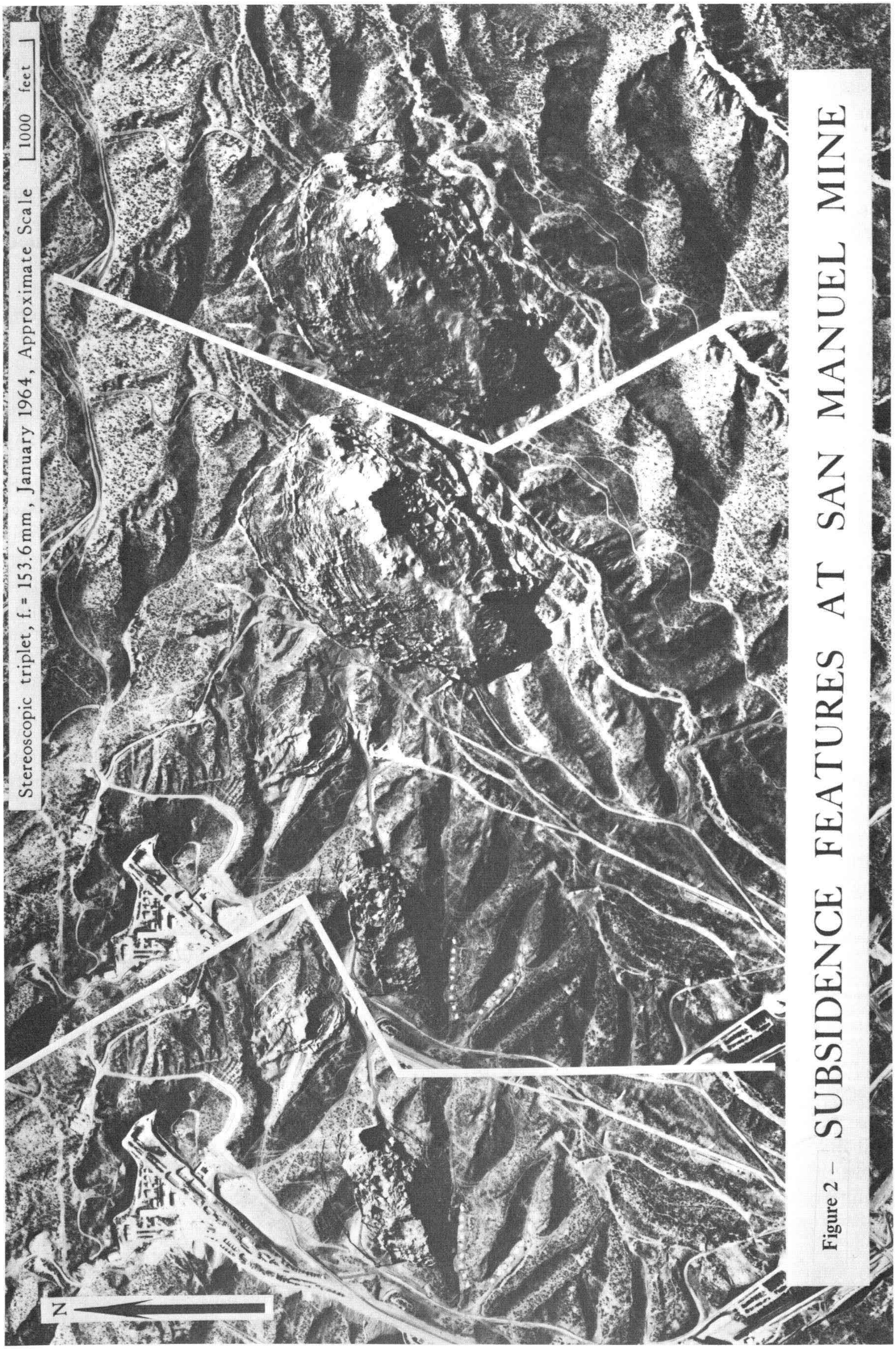
These fractures are initially produced by a gentle settling of the ground surface accompanying the first withdrawal of ore. These fractures widen and often become as deep as 300-500 feet. Continued widening of the fractures results in varying amounts of vertical and horizontal movement, together with a general shifting of individual blocks of conglomerate toward the center of each subsiding area.

The South Orebody was the site of the first ore withdrawal and the fractures first formed over this locality. After two years of active mining, the first well-developed boundary escarpment began to form along the former fractures, and a nearly equidimensional subsidence area was outlined (fig. 4). As each of the orebodies was caved and drawn, tension fractures developed and ringed each pit with a series of both straight and arcuate fractures. In all cases these fractures have remained remarkably parallel to existing escarpments and have reflected the future expansion of each pit. Stable ground surrounding the fractured areas remains intact until tensile stresses are concentrated against it to form new peripheral fractures.

Orientation of the fractures follows two modes: 1) parallel to (and including) existing normal faults in the area, and 2) perpendicular to both the long dimension of the caved area below and to the boundary escarpment that marks the longest dimension of each pit (figures 1 and 2).

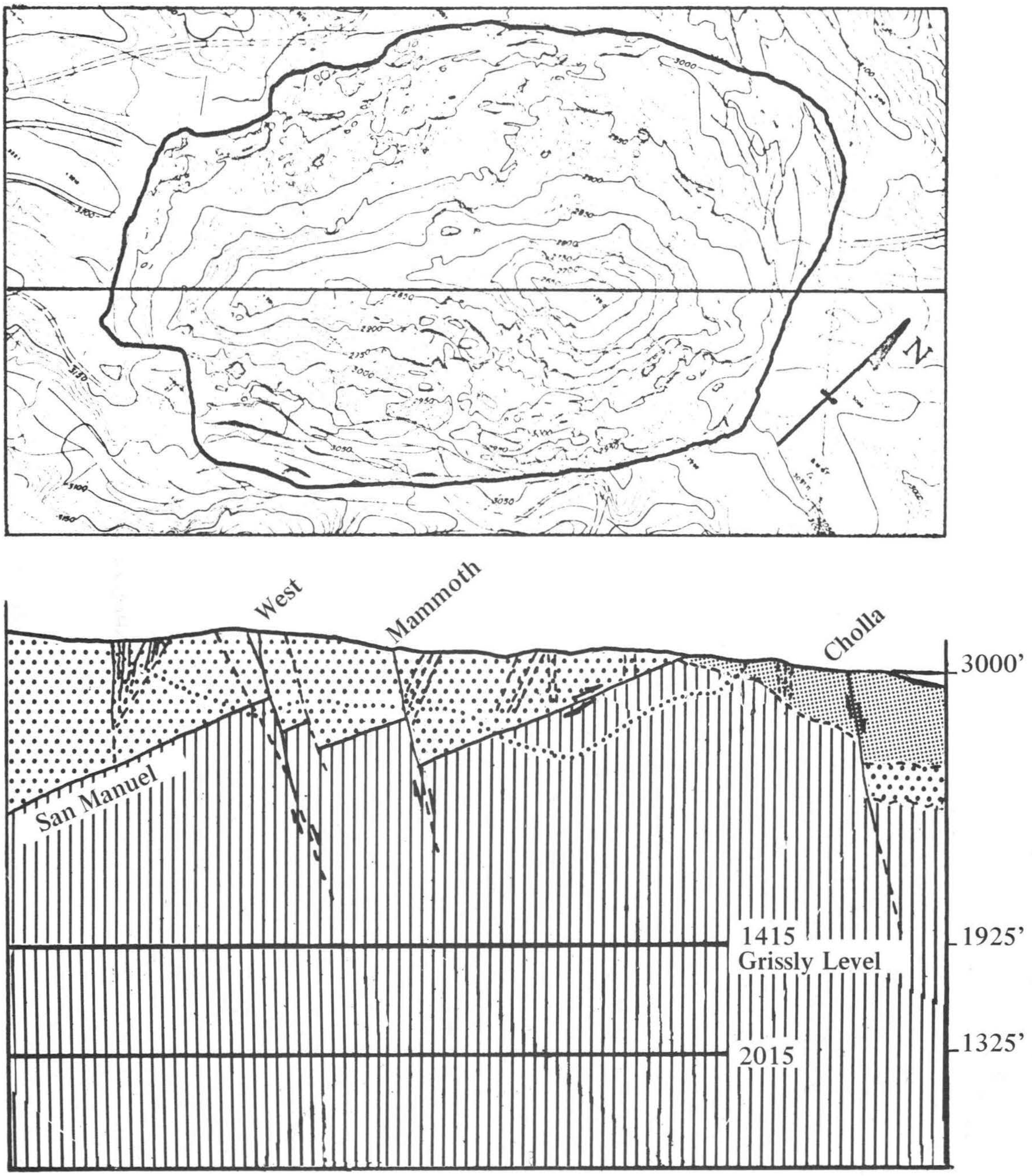
The fractures are formed as a result of tensile stresses in the caprock as it attempts to form an arch to resist widespread caving. The fracturing develops in response to vertically applied loading imposed by the weight of the caprock itself. The loading also induces further breakage in the caprock as underlying support is removed through drawing of ore in the mine workings below.

The general state of stress surrounding the formation of peripheral tension fractures is illustrated in figure 5. Here it may be seen that the underlying igneous rocks are structurally weaker than the overlying conglomerate and a cantilever effect, combined with the varying thickness of conglomerate, makes vertical stress Sv_1 greater than Sv_2. Tensile stresses are concentrated at the pit escarpments where a lack of constraint toward the pit will cause failure of the slope. If uniform removal of support from a given area should occur during mining, that portion of the area under the greatest vertical loading (i.e. thickness



Stereoscopic triplet, f.= 153.6mm, January 1964, Approximate Scale 1000 feet

Figure 2 – SUBSIDENCE FEATURES AT SAN MANUEL MINE



Conditions Before Mining

QUIBURIS ☐
SAN MANUEL ⁘
CLOUDBURST ▒
GRANITIC ROCKS ▥

PIT PROFILE 8–1964 ·········
SCALE 1: 9600

Figure 3

Peripheral Growth, South Ore Body Pit (1956 -1965)

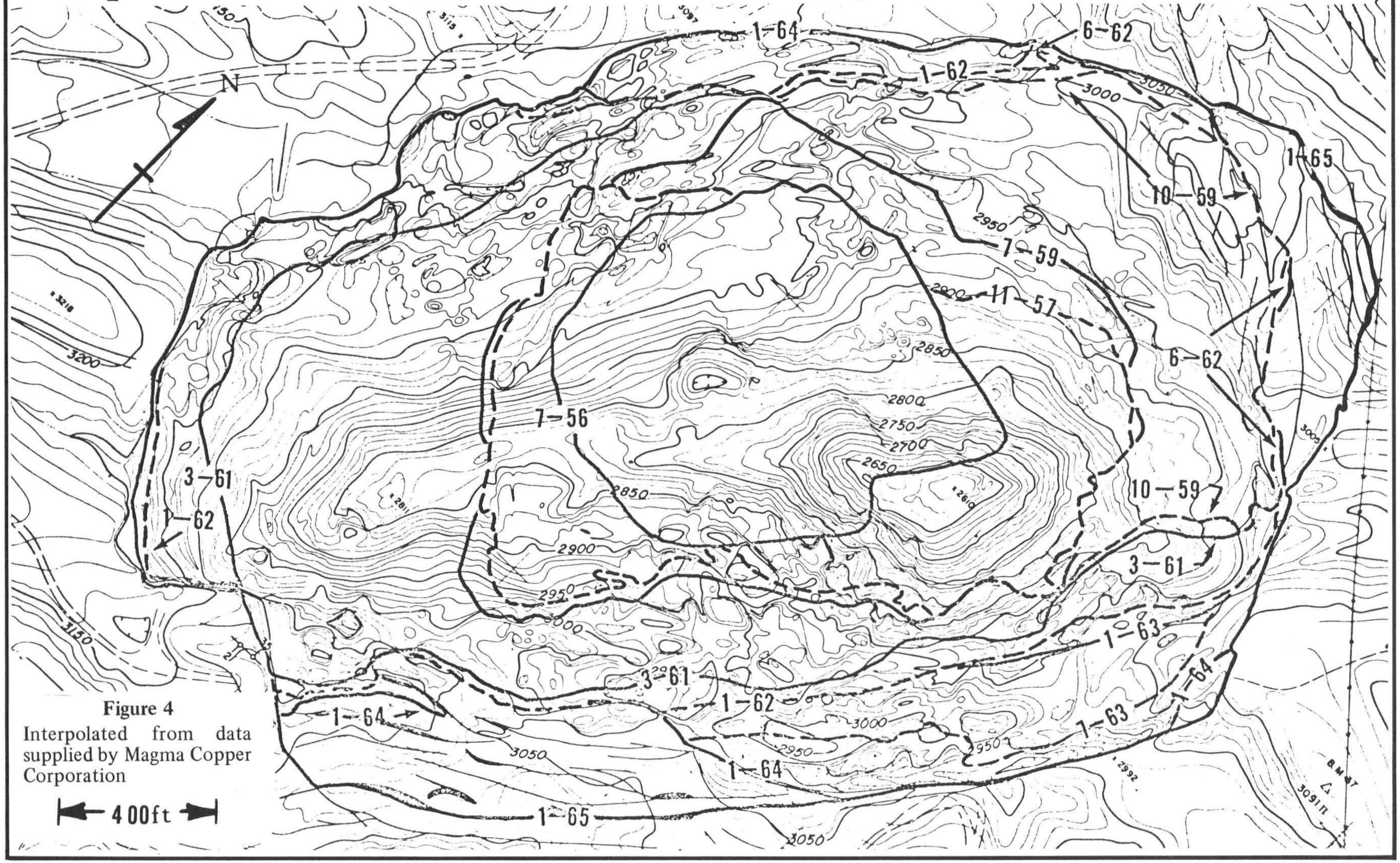


Figure 4
Interpolated from data supplied by Magma Copper Corporation

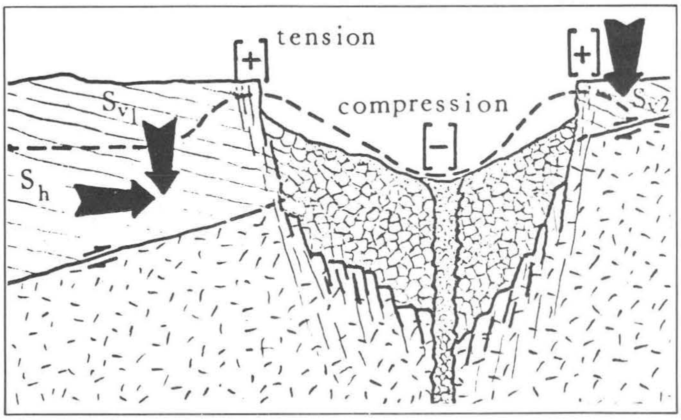


Figure 5 – Diagram showing the effect of attitude of bedding and removal of lateral constraint on the formation of tension fractures.

of caprock) will certainly rupture first. This assumes that all other factors are equal and that there is virtually no lateral constraint.

General Trend of Development

Growth rates for the pits have been studied and show a uniform semi-logarithmic relationship between total footage of the periphery and time. An eventual stabilization of the process is indicated by a flattening of the curve with time. This stabilization trend actually began to appear about seven years after mining commenced in the South Orebody.

Subsidence over the South Orebody began at the center of the present pit about three months after draw was begun. Expansion of the pit was rather uneven with respect to time and initial development of the escarpments favored growth in a northwesterly direction (fig. 4). This would indicate that the effects of subsidence first extended into the area of thinnest caprock. This initial growth was from a central area not coincidental with the center-line of the pit. Recent mining has brought the center-line of the pit into coincidence with the center-line of the caved blocks of ore below. There is no indication of a linear relationship existing between the depth of the mined area and the horizontal influence of subsidence at the surface. Previous workers in the field of mining subsidence have suggested this relationship.

The effect of faulting is such that there has been some parallelism between known fault locations and the positions of the boundary escarpments. This relationship is modified locally where unrecorded faults and fractures have altered the traces of the escarpments.

Conditions in the intermediate pit (North Orebody, west pit) have been substantially different from those of the other two pits. A total time lapse of 560 days occurred between initiation of draw and measurable ground settlement.[1] During this period it is most likely that the caprock was arching over the caved blocks. When settlement reached a critical point, the ensuing subsidence was rapid and large amounts of conglomerate broke and caved into the forming pit. Thickness of the caprock in the vicinity of this pit ranges from 350 to nearly 1,100 feet. Density of faulting is greater than at any other location over the mined area.

Growth of the smallest pit (North Orebody east pit) has been curtailed by cessation of draw. Conditions here may be taken to represent a subsidence pit in its early stages of growth. Thickness of conglomerate over the pit is minimal and growth is centered about a tongue of quartz monzonite exposed at the surface. Because the pit did not have sufficient opportunity to enlarge and become stabilized, the area covered by pipes is abnormally large. Peripheral tension fractures have extended laterally to a greater distance than in the other two pit areas. This is partially due to slight thicknesses of the conglomerate caprock which cause greater fracture development and in part due to the timing of mining under the pit. The pit began to form in 1962, which means that some degree of fracturing by mining stresses probably originated over the previous six years of mining immediately adjacent to the pit area.

MECHANICS OF SUBSIDENCE

There are a number of parameters acting in the formation of these large pits. These factors are both geologic and man-initiated and must be considered in relation to each other and in terms of time and of relative magnitude. At San Manuel Mine it is quite evident that the surface pits have been created by the removal of support at depth and a general collapse of the igneous rocks and overlying conglomerate. What is not nearly as evident is the order of importance of the factors that have influenced the formation of each pit. The initial failure begins in the porphyry copper ores at depth and is transmitted upward into the conglomerate. Once broken, the caprock adds the effect of a displaced mass of rock acting downward upon the underlying porphyry.

Behavior of the Igneous Rocks

For any given area of the mine which is undergoing an initial draw, it is believed that breakage in the

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[1] Personal communication with C. L. Pitlar, former Mine Superintendent, March 1965.

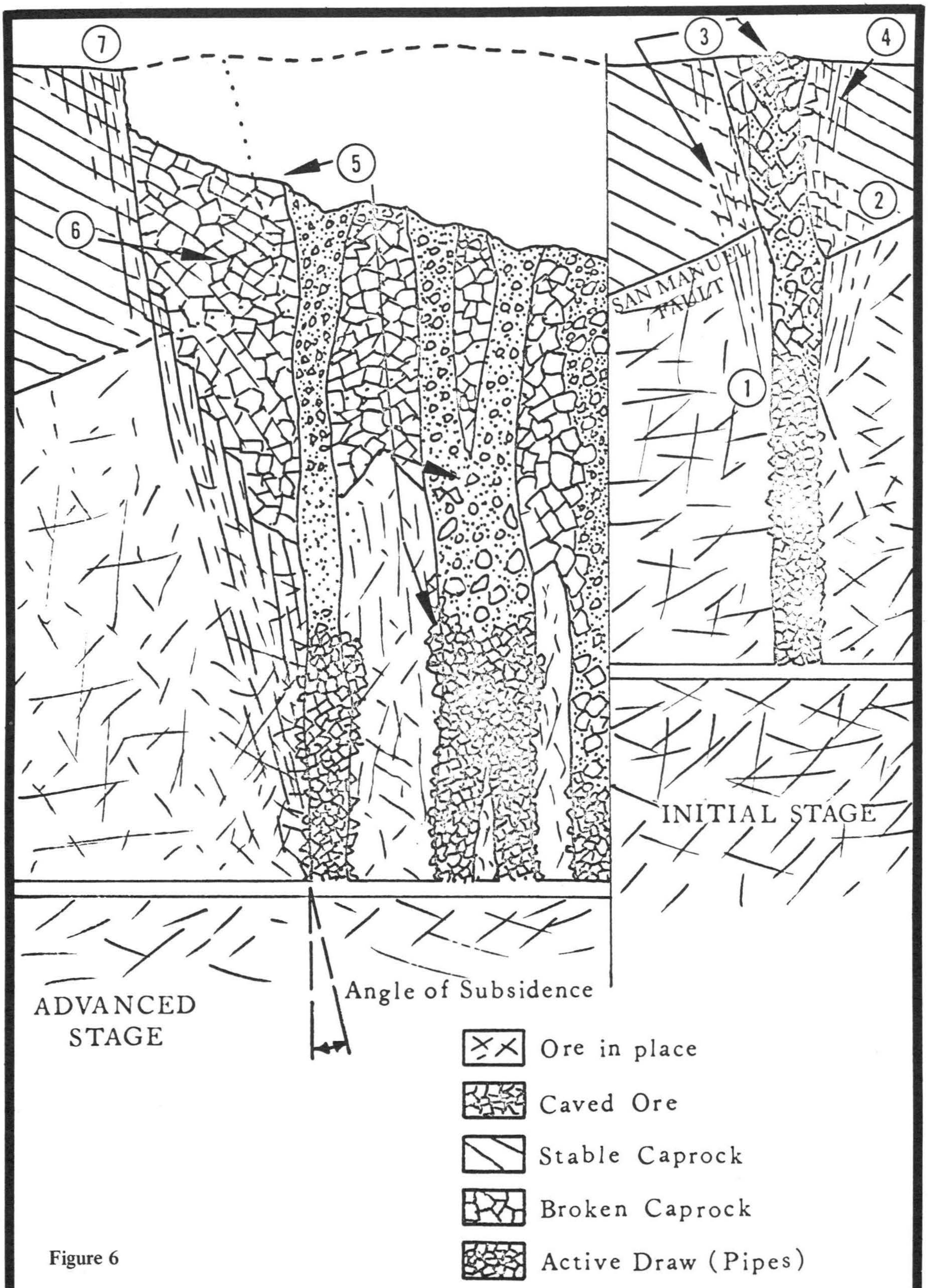

Figure 6

Mechanics of Subsidence

porphyry progresses upward toward the ground surface with little lateral deviation. Because the ore is heterogeneous with respect to strength characteristics and the fracture systems are not at all uniform, there may be some local variation in the angle of break (angle of draw) in the rock and in the upward direction of growth of the advancing break line in the porphyry. These changes are caused by anomalous stress concentrations and the presence of areas of varying rock strength. Residual stresses accumulate within the mine workings as mining shifts loads from one area to another. Concentrations of these stresses damage drifts in the mine from time to time.

The term *angle of subsidence* is often used to record data concerning the inclination of a line drawn between the outer edge of the underground workings and the boundary escarpment of the overlying subsidence pit (fig. 6). Early theories held that the failure surface between the underground workings and the surficial extent of subsidence was curvilinear. However, it is more reasonable to think of the breakage boundary as a series of parallel, planar surfaces, such as those seen in the left portion of figure 6. These surfaces have been formed in shear through vertical loading imposed by the dislocated masses of conglomerate.

Rock Breakage along the Pipes

Growth of the pipes is directly upward, without appreciable widening of the diameter of each pipe. There is probably a slowing of the process upon reaching the interface between the granitic rocks and the overlying conglomerate at the San Manuel fault plane. Direct transmission of stresses across the interface occurs after a short period of time involved in the initiation of failure in the dipping beds of the conglomerate. After penetration to the surface by a pipe has been completed, and large masses of conglomerate have been displaced into the forming subsidence pit, localized breakage occurs in the quartz monzonite and granodiorite porphyry making up the walls of the pipes. Pressure distribution from the moving masses of broken conglomerate cause renewed breakage from the upper levels of the pipe walls downward (point 5, fig. 6). Shear failure, then, is responsible for new downward propagation and lateral expansion of the subsidence area is achieved.

Behavior of the Conglomerates

Initially the state of stress in the conglomerate may be closely approximated by a non-deflecting of heterogeneous and anisotropic material. The ultimate degree of arching short of failure is directly dependent upon the structural defects located in the beam of caprock. There is no deflection while the unit is intact and it benefits from support at its interface with the underlying igneous rocks.

To an extent, stresses are accomodated within the mass by readjustment along the many discontinuities that are present in the rock. However, whatever degree of arching (i.e. lack of appreciable deflection) that is present is eventually destroyed by increasing amounts of deflection and failure in the caprock. Localized tensile failure also destroys the effective clamping or holding of beams over given voids (nonpenetrating pipes). Removal of support leaves gravity-loaded slabs of rock partially unsupported over these voids. With movement of blocks of conglomerate into the subsidence pits, there is a removal of lateral constraint at the escarpments, and the rock is free to spall from the faces bordering the pit at the surface.

Effects of Faults

In addition to the overall effect of faults in creating structural weakness in the caprock, these structures have also affected the angle of subsidence and general surface growth of the pits. At the stage of development in 1965, the end escarpments of the pits had formed directly on fault planes. The presence of faults and fractures in the caprock is such that the conglomerate is more likely to break into smaller fragments in the areas paralleling the long dimensions of the pits. The angle of subsidence is largest when measured in a plane parallel to faulting. This case of preferential breakage has permitted the pits to grow faster in their long dimensions and has enlarged the angle of subsidence along these sides.

Attitude and Thickness of the Caprock

An excessive thickness of conglomerate occurs in conjunction with break lines in the porphyry to cause the surface breakage to occur nearer the caved area. In both the South Orebody and North Orebody, west pits, this asymmetry occurs placing the closest escarpment in the area of greatest thickness (thickness increases to the southwest, paralleling the lip of the San Manuel fault).

Summary of the Subsidence Process

A chronological sequence is presented for the subsidence process at San Manuel Mine. The following stages are keyed to the two hypothetical cross sections in figure 6:

1. Static loading begins with removal of ore and disturbance of the material supporting

the overlying caprock. Upward, near-vertical caving occurs mainly along stopes in the form of pipes.

2. A pipe is shown extending to the interface between granitic rocks and the conglomerate at the plane of the San Manuel fault. A small amount of lateral breakage occurs, followed by readjustment and continued vertical expansion of the pipe into the conglomerate.
3. As a pipe reaches the surface, increased downward pressure begins as masses of conglomerate begin to weaken and fail along fractures and faults within the mass. Breakage is the result of tangential stresses surrounding the surface of the pipes and the pipes enlarge laterally.
4. Tension fractures open along planes of weakness in a downward direction from the surface. Initially the fractures do not transect the entire thickness of the caprock. Tensile breaks occurring in the sound rock have a characteristic angle of 85° to 90° as measured from the horizontal. Tensile stresses are predominant, and if contemporaneous compressional stresses do exist, they would appear along the edge of the mass of intact conglomerate. This condition is analogous to the flexural stresses developed through loading of a cantilevered beam.
5. Displacement of independent masses of conglomerate increases as a pit develops at the surface. This forces an increased area of breakage along the walls of the pipes. There is some breakage of rock along the throats of the pipes due to relief of radial stresses. Increased widening and coalescence of pipes occurs with contemporaneous weakening of the caprock. The pipes are filled in their upper reaches and an uneven blanket of broken conglomerate is formed over the entire caved area.
6. A lateral component of movement is introduced. This is produced by the shifting of broken conglomerate toward the center of the pit as sufficient amounts of rock are removed through the pipes.
7. Faults occasionally limit the lateral growth of the pits by releasing large masses of caprock. Eventually, incipient tension fractures develop into escarpments as failure occurs along the faces of existing escarpments.

MASS WASTAGE

As soon as subsidence has developed sufficiently to allow for vertical movement of broken rock at the surface, there is an introduction of downslope movement of broken conglomerate toward the pit bottom. Distinct types of movement and units of movement appear in time and are easily recognized on aerial photographs. These units may be seen when figure 2 is examined in conjunction with figures 1 and 7. All units of mass wastage represent landslide movement.

The essential factor involved in mass wastage is the withdrawal of ore in the mine, which has resulted in a center-line along the lowest level of each subsidence pit. Appreciable amounts of material at the surface are fed into the subsurface through the ever-present pipes and there is a constant removal of material from the lower levels of the pits. Stimuli for movement changes slightly with time, and in response to the changing areas of draw in the underground workings. Because rock breakage continues during downslope travel, there is a change in the physical character of each unit of mass wastage during the transport from one point to another.

The greatest difference between mass wastage in the subsidence area and that associated with the classical types of landslide movement is a lack of a well defined failure surface. Because block caving has displaced the supporting material from beneath the subsiding ground, there is only a continuation of the fractured and broken ground beneath the sliding mass.

The types of mass wastage that surround the centers of the subsidence pits are five in number. These are transformed into three additional types of movement in the lower areas of the pits. The three latter types of movement are made up of finer particles and are labeled *debris slide, creep,* and *pipes.* These three types are noticeable in the finer-textured portions of the aerial photographs (fig. 2). Debris slide and creep are found only in the South Orebody pit due to lack of sufficient time for development in the two remaining pits.

The classification presented here conforms as closely as possible in terminology to that presented in Eckel (1958).

En masse Movement

A pronounced, but gentle settlement occurred early in the history of subsidence. *En masse* subsidence consists of initial vertical settlement of the area resulting in the lowering of large masses of conglomerate. Interior breaks form in tension along discontinuities and parallel to areas of maximum vertical subsidence. Separation along the breaks is minimal and enough lateral restraint is present to limit rotational and translational movement. *En masse* units develop initially in all areas of the pits

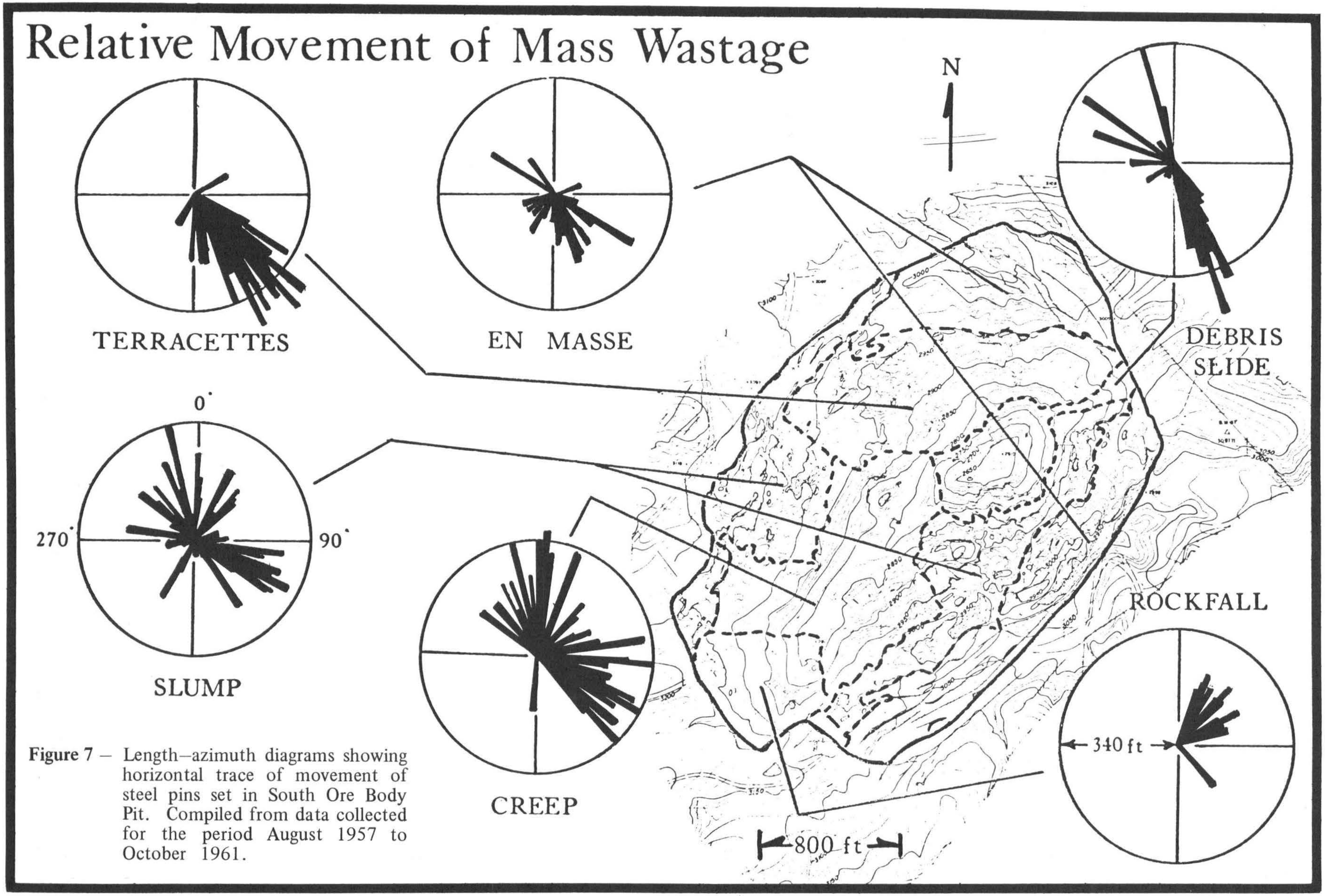

Figure 7 – Length–azimuth diagrams showing horizontal trace of movement of steel pins set in South Ore Body Pit. Compiled from data collected for the period August 1957 to October 1961.

and are not dependent upon the thickness or character of the conglomerate caprock. Areas supporting *en masse* units in 1965 ranged in thickness from less than 90 feet to well over 800 feet. As the subsidence process develops, and continued vertical movement and increased lateral movement occurs, there is a transformation of *en masse* wastage into various other types of movement. The *en masse* units have also shown relatively small amounts of lateral movement in a control survey conducted by the U. S. Bureau of Mines and the Magma Corporation (operators of the mine) (fig. 7). *En masse* subsidence is the parent unit for all other types of mass wastage with the sole exception of pipes.

Slump

Increased lateral movement in the pits is brought about by relief of lateral restraint on the blocks of conglomerate in the pits. *En masse* units deform by breaking into smaller independent blocks and there is a general shifting and readjustment of the unstable mass to allow for some rotational movement. Blocks of conglomerate then rotate slowly, over a period of time, both backward and forward, and, at times, tumble very short distances downslope. Continued transport and weathering erodes the blocks until they are no longer found in these areas. Blocks moving into the pit bottoms remain there only for short periods of time before breaking up, as implied by their absence in these areas (fig. 2). Slump blocks are also derived directly from the escarpments, where faulting and fracturing break blocks into units measuring three to ten feet in diameter.

Terracettes

Terracettes are a derivative of *en masse* subsidence and form terraces of broken conglomerate in the pits. These blocks of conglomerate follow the outlines of former peripheral tension fractures that were formed early in subsidence. Fragmentation of the conglomerate is greater in this unit than in the corresponding slump blocks. The finer resulting material is carried in waves of irregular step-like character toward the edge of the debris slide unit, and thence into the pipes below. Terracettes result from freedom of lateral movement but do not occur directly over areas of active mining.

Rockfall

Sloughing directly from the steep southwestern face of the South Orebody pit accounts for a large area of rockfall and its associated talus. Rockfall has occupied this portion of the pit only after *en masse* subsidence had lowered the surface of the area enough to have formed dominant scarps along its border. Fragments that slough from the free face of the escarpments are generally small in size and move rapidly downslope as far as 650 feet. Travel beyond, into the creep area, is slower.

Rockslide

A single exposed bedding plane in the extreme southeast corner of the South Orebody pit is the only current site of rockslide. Fragments of conglomerate slide down a dip slope, moving directly into the opposing slump area (fig. 7).

Creep

The largest area of movement entailing sand and gravel-sized particles of broken conglomerate is that of creep. The slightly hummocky surfaces are covered with grass and fragments of conglomerate that move downslope slowly. The movement is primarily along the surface and at the toe, where material is fed into the pipe areas at the pit bottom. It is clear that this type of movement will cover larger areas of the pit as mining is continued.

Debris Slide

Debris slides are similar to creep in their appearance, however, movement is rapid over steeper slopes than that of creep. Particles sometimes travel continuously the entire slope of the pit from top to bottom (fig. 7). Because movement here is constant and rapid over the entire slide area, grass does not grow on its surface. There is a sharp contact between debris slides and areas in which other types of movement occur. Debris slides often undermine adjacent areas and result in their erosion.

Pipes

Pipes constitute the ubiquitous type of movement that takes place at the onset of subsidence and which occurs throughout its development. Pipes are centered directly over the active blocks in the mine. Eight of these features were active in the South Orebody in 1965 and they were prevalent in the remaining pits during active mining under these locations. It is important to reiterate the fact that all movement in the pits tends to be channeled toward the pipes. At one place or another, all types of mass wastage furnish material to pipes for transport to sublevels of the mine.

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THE GEOLOGY OF THE ESPERANZA MINE*

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INTRODUCTION

The Esperanza copper deposit is in the Pima mining district, Pima County, Arizona, about 30 air miles south of Tucson. This property is the southernmost porphyry-type copper deposit in the district.

The old New Year's Eve mine made the first actual penetration into the area that is now the Esperanza mine. This mine was worked spasmodically from 1895 to the present, dependent on metal prices. The Duval Corp. acquired the property in February 1955 from C. D. Wilson of Tucson, on the advice of Dr. Harrison A. Schmitt, consulting geologist, Silver City, New Mexico.

Capping criteria that favorably impressed Dr. Schmitt are as follows: moderate to intense clay alteration, megascopic sericite, quartz veins, copper staining, moderate to strong brecciation, prominent goethite, and minor jarosite and hematite.

Rock types in the area range from Cretaceous fragmental and welded tuffs and quartzite through intrusive granodiorite, quartz monzonite porphyry, quartz latite porphyry, dacite porphyry, quartz diorite, and andesite porphyry. The igneous rocks were intruded and extruded in a number of individual pulses. All rock types contain sulfides in varying amounts. Strong hydrothermal alteration persists throughout the area. Potash metasomatism is a particularly distinctive feature. Metallization consists of chalcocite, chalcopyrite, pyrite, molybdenite, covellite, and native copper along with azurite, malachite, tenorite, melaconite, and minor ferrimolybdite. Of negligible importance are galena, sphalerite, and torbernite.

The most prominent structural features of the area mapped are faults and fault fissures. Major trends are northeast to east-northeast, dipping northwest and southeast, north-northwest to northwest, dipping northeast and southwest, and north-south, dipping east and west.

Previous Work

The earliest paper concerning the Esperanza mine area is a report by Anderson and Kupfer (1944) for the U. S. Geological Survey. Their examination of the property was conducted from 1943-44. After Duval's acquisition of the property in 1957, detailed mapping of the area was undertaken by D. M. Clippinger, W. J. Roper, H. B. Toombs, and E. H. Lewis, under the direction of Dr. Harrison A. Schmitt. Cooper (1960) mapped the entire Pima mining district, and his report was published in 1960. Other references to the Esperanza property are by Richard and Courtright (1960), Lutton (1959), Lacy (1959), and Lacy and Titley (1962).

Location and General Setting

The Esperanza mine is in the Pima mining district, Pima County, Arizona, in the southwestern foothills of the Sierrita Mountains about 30 miles south-southwest of Tucson. It is in the Sonoran Desert section of the Basin and Range physiographic province and varies in altitude from 3,800 to 4,500 feet. Steep, sharp, spined ridges divided by narrow gullies and washes constitute the primary topographic features, and these are surrounded by a pediment to the north and east. South of the mine are the volcanic Tinaja Hills.

History and Development

The New Year's Eve mine made the first actual penetration into the area that is now the Esperanza mine. According to Anderson and Kupfer (1944), these claims were first located and recorded by P. H. Chambers in 1895 and later became known as the Snyder claims. In 1907-08, the Calumet and Arizona Mining Co. conducted considerable exploration in the area, working largely in the New Year's Eve mine, known then as the Red Carbonate mine. A 200-foot shaft was sunk, and crosscuts, winzes, and drifts were driven at this time; however, the tenor of the copper mineralization and indicated tonnage did not justify a commercial venture. Consequently the property was

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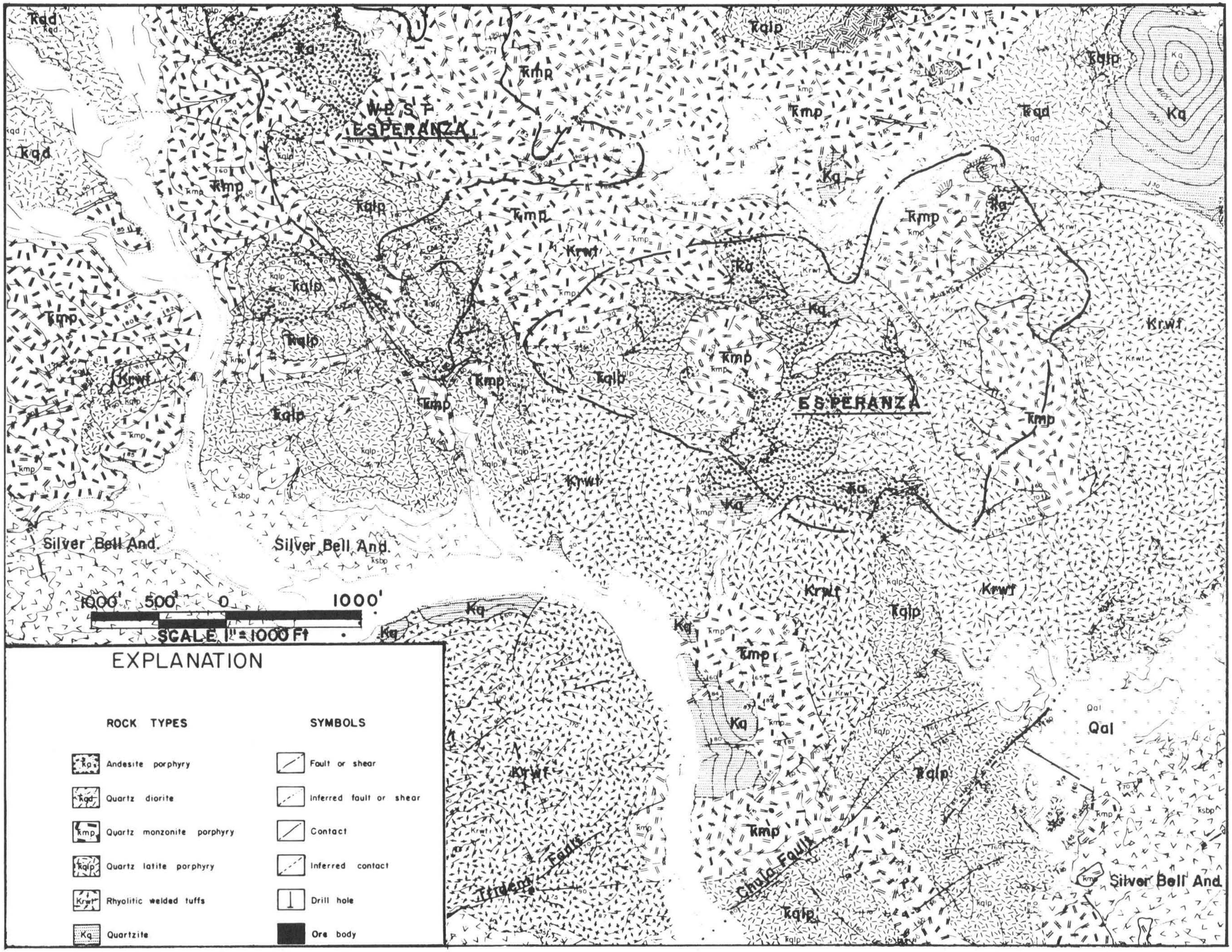

Figure 1 — Geologic Map of Esperanza Mine and vicinity

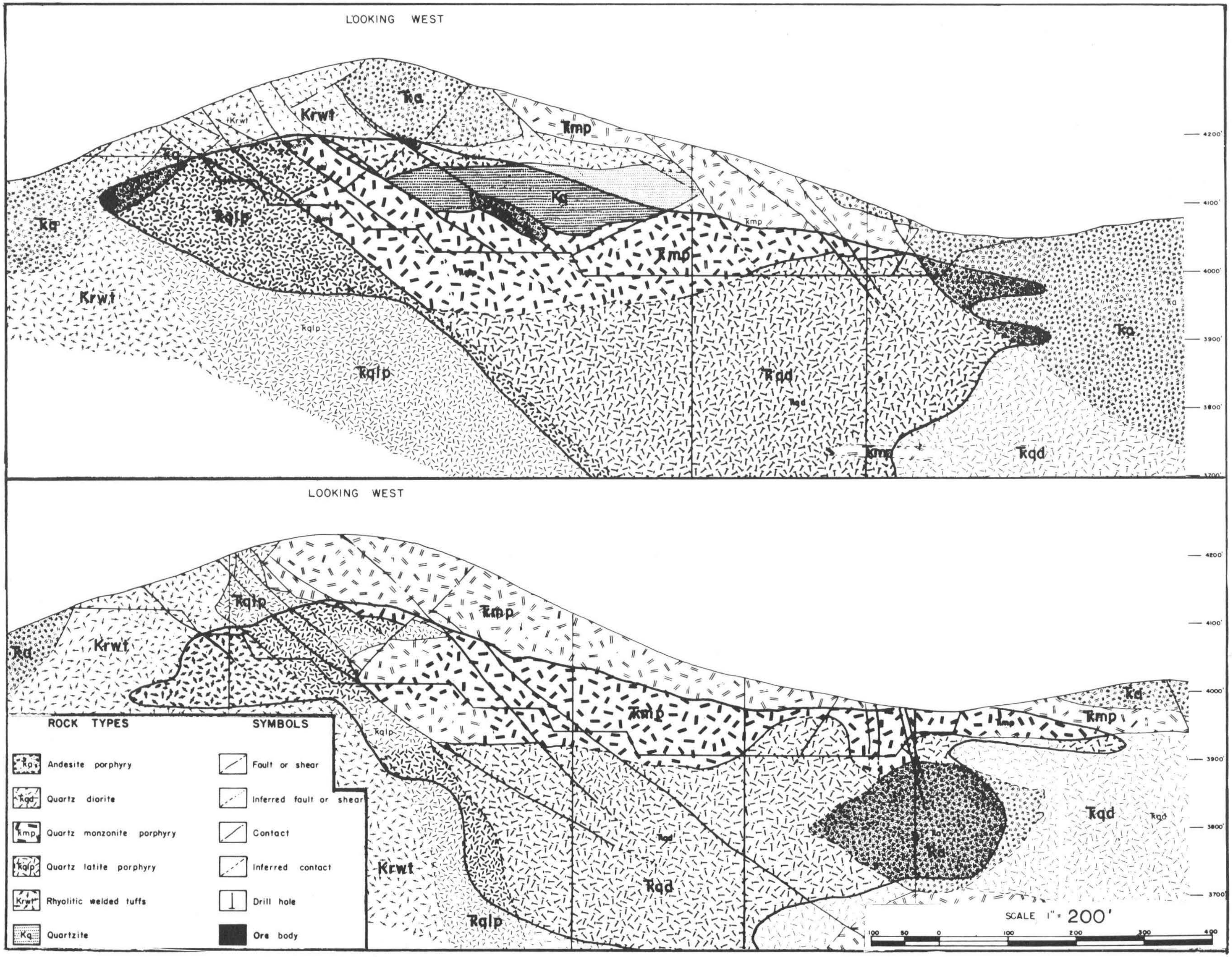

Figure 1a – Geologic Cross Sections of the Esperanza Mine and vicinity abandoned. From available records, about 2,000 tons of carbonate ore averaging 4 percent copper were shipped between 1912 and 1916. In 1912, 30 tons of sulfide ore averaging 10 percent copper were also shipped.

No further work was done until 1936, when the Arizona Molybdenum Corp. dewatered the mine and examined it for molybdenum possibilities. However, the grade was not sufficiently high to be of interest.

In 1939, an organization known as the Southern Arizona Molybdenum Corp. again dewatered the mine and engaged C. J. Sarle of Tucson to make an examination of the property. Again, the property did not appear to contain ore of encouraging value, and operations were allowed to lapse with no additional work being done.

The property was picked up in 1942 by Dr. S. Isermann, president of the Amargosa Molybdenum Corp., Catalina Foothills Estates, Tucson, and dewatered again. No production was recorded.

Subsequently, the Sierrita Mining and Ranching Co. acquired the claims and leased them to C. D. Wilson of Tucson. In turn the claims were brought to the attention of the Duval Corp. (formerly known as Duval Sulphur and Potash Co.), who retained Dr. Harrison A. Schmitt, consulting geologist, to conduct a geological reconnaissance. Acting on the recommendation of Dr. Schmitt, the Duval Corp. purchased the claims in February 1955.

Mention must be made here of the fact that the ore body today, as delineated by drilling, varies only from 50 to 75 feet from the ore body as outlined by Dr. Schmitt on his original surface geologic map. In May 1955, an exploration drilling program commenced under the supervision of Dr. Schmitt. A total of 88 holes was drilled by churn and diamond drills on a 500-foot equilateral triangle grid pattern. Ore was encountered after drilling through an average overburden depth of 95 to 100 feet.

A report by Tainter (1947), published in 1947 by the U.S. Bureau of Mines, indicates that the Bureau drilled three holes aggregating 1,500 feet in Copperos Gulch (from p. 270 in M.S.) to determine the molybdenum and copper mineralization. Drill-hole logs in the report show very poor core recovery and low assays, which undoubtedly discouraged further exploration until the Duval Corp. became interested and began drilling in 1955.

ROCK TYPES

Sedimentary Rocks

Occurring in the lower center of the mine, northeast of the mine, and to the southwest, quartzite is found in isolated pods and lenses interbedded or interfingered with Cretaceous(?) rhyolitic welded tuff. North-northeast of the New Year's Eve shaft, this highly durable rock type forms a conically shaped hill that is encompassed by quartz diorite, quartz latite porphyry, granodiorite, and rhyolitic welded tuff. On the south and east sides of the 3,900 and 3,935 benches, quartzite is interfingered with rhyolitic welded tuff, and in most instances definite contacts are extremely rare and difficult to recognize, owing to strong alteration along the contact zone.

Metallic minerals observed in quartzite consist of chalcopyrite, pyrite, chalcocite, azurite, and minor malachite, which occur as blebs and stains and rarely as small fibrous nodules. Cuprite, chalcotrichite, and molybdenite are found in vugs, seams, veinlets, and along joint and fracture planes. Dissemination of metallic minerals is rare in this rock type, owing to its impermeable character.

Quartzite is thought to be either older than the Cretaceous(?) welded tuff or nearly the same age. The possibility exists that the lenses and pods of quartzite were rafted in by the rhyolitic welded tuffs. Cooper (personal communication) states that he has seen similar occurrences of quartzite with Cretaceous(?) volcanic rocks in the Esperanza area and southward.

Extrusive Rocks

Rhyolitic Welded Tuff. Rhyolitic welded tuff is the most abundant rock type in the general mine area and includes: 1. vitric welded tuff; 2. fragmental welded tuff with both rounded and angular xenocrysts of pre-existing rocks that have been incorporated in the host rock; 3. a highly siliceous aphanitic tuff with occasional euhedral phenocrysts of sanadine; and 4. a poorly consolidated tuff with little welding and devitrification. This unit has a distinct wedge-shaped areal distribution with a northeast-southwest trend. Rhyolitic welded tuff extends through and beyond the Esperanza mine in both these directions (fig. 1). The open end of the wedge is to the northeast. From the 3,900 bench upward through the 4,075 bench on the southeast side of the mine, the fragmental welded tuff underlies quartz monzonite porphyry along a fault contact. Elsewhere in the mine area, andesite porphyry, quartz diorite and dacite porphyry have intruded rhyolitic welded tuff along old faults. Lutton (1961) published a paper on the banded tuff southwest of the Esperanza mine and classified the rock as a lensoidal rhyolite.

Alteration produced in rhyolitic welded tuffs consists of clay of weathering origin in surface outcrops and sericite, biotite, and quartz of hydrothermal origin. The fragmental welded tuffs are little effected by alteration due to the highly siliceous nature of the rock. This rock unit is a host for copper mineralization, which varies from low grade in the fragmental varieties to average in the banded tuff, dependent on the density of the rock and the amount of fracturing. Chalcocite, chalcopyrite, pyrite, minor magnetite, sphalerite, and galena and in the oxide areas azurite, malachite, covellite, and cuprite are found in the rhyolitic welded tuff both within the mine limits and the general mine area.

This rock type and its attendant variations have been tentatively assigned to the Cretaceous Period.

"Silver Bell" Welded Tuff. South and east of the mine is a sequence of welded tuff that has been locally designated by Richard and Courtright (1960) as "Silver Bell" welded tuff, the name being derived from the type locality that is near the Silver Bell mine.

This sequence of welded tuff consists of breccia, andesitic welded tuff of several varieties, and rhyolitic welded tuff. Along the eastward-flowing Cascabel Wash, the base of the low range of hills is composed of brecciated and fragmental andesitic welded tuff with fragments of pre-existing rock as much as 2½ feet in diameter. Ranging from angular to rounded, these inclusions were either ingested by the ash-flow tuff as it flowed over an erosion surface or are lithic fragments torn from the vent. Oval-shaped fragments of andesitic welded tuff contained in a matrix of the same rock type suggest autobrecciation of the flow while in a viscous or semiviscous state. Above the fragmental layer is a sequence of andesitic welded tuff that is virtually free of xenoliths. The attitude is fairly flat, and good contacts can be found on the north side of the ridge facing Cascabel Wash. Above this rock type, and also having a very gently dipping attitude, is the rhyolitic welded tuff. The rhyolitic welded tuff is readily distinguishable by the light-tan color of the rock. Good jointing is preserved by the migration of silica to the joint faces, forming a hard shell about a fourth of an inch thick. Where this silica shell has been breached, the exposed rhyolitic welded tuff disintegrates rapidly. In this area the thickness of this volcanic sequence is at least 700 feet, and Richard and Courtright place it as ±12,000 feet near the Silver Bell mine. Quartz latite porphyry and quartz monzonite porphyry intrude the "Silver Bell" series south of the Esperanza mine.

"Silver Bell" andesitic welded tuff varies in color from light gray green to dark gray green to black and purple. It is moderately hard with a fair amount of silicification. Nodules of epidote, tourmaline mats on joint faces, and the fragmental nature of this rock are distinguishing characteristics. Fragments of pre-existing rocks range from angular to rounded and exhibit sharp boundaries. These fragments vary in composition from granitic through volcanic and sedimentary rock types. Immediately above this basal member is a layer of unbrecciated andesitic welded tuff, having a gradational lower contact, and it is probably part of the same ash flow. It is dark gray to black in color and moderately hard. Phenocrysts of hornblende and plagioclase are visible without the aid of a hand lens, but the texture is characterized by fine-grained phenocrysts in an aphanitic groundmass. Overlying this member of the volcanic sequence is a very light tan rhyolitic welded tuff.

Richard and Courtright (personal communication) have tentatively assigned this series of welded tuff to the early Tertiary and agree that the previously discussed rock types are identical to the series near the Silver Bell mine.

The "Silver Bell" series is a very poor host rock for copper mineralization in the Esperanza area, and the usual visible metallics consist primarily of pyrite and magnetite and rarely chalcocite and chalcopyrite.

Intrusive Rocks

Quartz Latite Porphyry. Within the mine limits, quartz latite porphyry is restricted in areal extent to the southwest side of the mine. Quartz latite porphyry is younger than rhyolitic welded tuff and older than quartz monzonite porphyry. The contact between quartz latite porphyry and quartz monzonite porphyry strikes northwest and dips about 55° NE. on the southwest side of the mine. In the West Esperanza ore body area, this rock type forms two northwest-trending ridges and a conical-shaped hill. The author does, however, recognize the possibility that there are two different ages of quartz latite porphyry—the older being post-rhyolitic welded tuff and pre-quartz monzonite porphyry in age and the younger being post-quartz monzonite porphyry in age. The latest quartz latite porphyry intrusive forms small northeast-trending dikes in biotite granodiorite and small pods and lenses in the "Silver Bell" volcanic series.

Between the Chula and Black Bottom faults south of the mine, quartz latite porphyry forms a breccia pipe that is roughly circular in plan and has a maximum diameter of 1,000 feet. Brecciation extends westward across Esperanza Wash for about 225 feet. Angular fragments rarely are more than 2 inches in any dimension and are tightly cemented together with rock flour and quartz. Sericite, quartz, jarosite, goethite, and hematite are prominent around the margins of the breccia pipe. On the very peak of the pipe, copper oxides, such as azurite and malachite, are present as seams and stains. Holes drilled on the flanks of the breccia pipe were not conclusive in proving or disproving the presence of ore-grade copper.

Quartz latite porphyry is light tan to brownish-red in color in weathered outcrops and cream white to light gray on a fresh surface. The groundmass is aphanitic with conspicuous euhedral to subhedral phenocrysts of orthoclase and plagioclase. Predominant alteration products are sericite and clay. Occasionally this rock type will present a banded appearance because of oriented one-fourth inch quartz stringers.

As a host rock for copper mineralization, quartz latite porphyry is quite favorable. Metallization in the form of chalcocite, chalcopyrite, pyrite, and molybdenite is present both as disseminated grains and as seams and stringers in fractures and along joint planes. On the upper benches, covellite coating pyrite and chalcopyrite is common along with secondary chalcocite; on the lower benches, chalcopyrite predominates. Owing to its associations in the mine area, quartz latite porphyry has been assigned an age between that of the rhyolitic welded tuff and the quartz monzonite porphyry.

Biotite Granodiorite. North and east of the Esperanza mine is a large biotite granodiorite batholith that contains three or four textural variations (not mapped separately) and a quartz monzonite porphyry. Biotite granodiorite does not crop out within the mine limits. No igneous contacts have been located between the quartz monzonite porphyry and the biotite granodiorite; instead, there is a gradational zone about 100 feet wide in which this rock gradually changes characteristics and finally emerges as a quartz monzonite porphyry. Fine-grained dikes of quartz latite porphyry have intruded this rock along a north-northeast trend and, after intrusion, have been faulted. These dikes and faults follow the predominating joint-plane trend and usually have a high-angle dip (fig. 1). Cooper (1960) classified this rock as a granodiorite.

Biotite granodiorite is a very poor host rock for copper mineralization, although azurite and malachite can be found occasionally in a few of the fault fissures. Magnetite is prevalent in this rock type, and after rainstorms, washes that traverse biotite granodiorite will be streaked with this metallic mineral. Cooper places this rock type in the Late Cretaceous or the early Tertiary Periods.

Quartz Monzonite Porphyry. Quartz monzonite porphyry is a lithologic facies of the granodiorite and occurs along the southern margin of the granodiorite batholith. Apophyses of this rock intrude the mine area to the southeast, south, and southwest (fig. 1) with an overall northwest trend to the outcrop pattern. Quartz latite porphyry, rhyolitic welded tuff, and "Silver Bell" andesite porphyry are all intruded by this rock type.

Hand specimens from surface outcrops are orange-brown to saddle brown in color and display minute grains of sericite along with quartz stringers and sulfide casts. Minor veinlets of turquoise, azurite, and malachite, usually as stains or blebs, are scattered throughout outcrops over the ore body. The distinctive color of weathered quartz monzonite porphyry easily delineates this rock type from the reddish hues of the more pyritic clastic volcanic rocks. Orthoclase and plagioclase phenocrysts have been almost completely obliterated by kaolinization and sericitization. Casts of these feldspars give the rock a distinctive "honeycomb" texture. Remnant biotite books are sometimes the only remaining clue to the nature of the original rock along with doubly terminated quartz crystals. Limonite, jarosite, goethite, and hematite are ubiquitous in the capping over the ore body. Surface and near-surface exposures of quartz monzonite porphyry have a more dense aphanitic groundmass and smaller phenocrysts than are found deeper in the mine.

Unaltered quartz monzonite porphyry specimens are a light to pinkish gray with distinctive pink phenocrysts of potash feldspar, light-gray to white plagioclase, glassy quartz "eyes," and biotite imbedded in a fine-grained groundmass of feldspar and quartz. Secondary orthoclase–occurring as stringers, veinlets, and coatings on joint and fracture planes–is more prevalent along the contact between quartz monzonite porphyry and Cretaceous (?) rhyolitic welded tuff.

Quartz monzonite porphyry is unquestionably the most favored host rock for both hypogene and supergene metallization. On the east side of the pit, vertical seams of massive chalcocite and chalcopyrite 3 or 4 inches thick increased the grade considerably over that indicated by the exploration drill holes. Copper metallization occurs both as disseminated grains and veinlets, and molybdenite is usually found as seams and coatings on fractures and in quartz veinlets.

Quartz monzonite porphyry has been assigned tentatively to the time span between Late Cretaceous-early Tertiary.

Quartz Diorite. Quartz diorite occurs in widely scattered locations. North-northeast of the mine, this rock type forms a rather small elongate depression enclosed by quartz monzonite porphyry, biotite granodiorite, quartz latite porphyry, and quartzite. It crops out in the mine area adjacent to the New Year's Eve shaft (Fig. 2) and in the gulch on the west side of the mine. In both the Esperanza and West Esperanza ore bodies, quartz diorite is intermixed with andesite porphyry–a rock type which it resembles so closely that it was not mapped as a separate rock type in the early stages of pit and field mapping. In the mine area, this rock type has intruded Rhyolite welded tuff, quartzite, and biotite granodiorite. Younger quartz latite dikes intrude quartz

Figure 2 — Aerial photograph of the Esperanza Mine as of June, 1963, looking southwest. —Photograph by Ray Manley

diorite in a few places northeast of the mine.

Quartz diorite is a fine-grained igneous intrusive rock that varies in color from black to gray green. This rock type was mapped as a biotite-quartz granulite by Anderson and Kupfer. (1944)

Cooper (1960), in his microscopic examination of quartz diorite, describes it as having an intergranular texture. He further states:

> "Laths of plagioclase (calcic andesine) make up about 60 percent of the rock and have subparallel orientation. Biotite and actinolitic (?) hornblende, in nearly equal amounts, make up much of the rest and have random orientation. Potassium feldspar and quartz rim and embay the other minerals, and are largely or wholly of replacement origin."

Metallic mineralization occurring in quartz diorite consists of chalcopyrite, chalcocite, pyrite, molybdenite, covellite, cuprite, and magnetite. This rock type is considered to be a good host rock for both hypogene and supergene copper mineralization.

Dacite Porphyry. Dacite porphyry is limited in its occurrence at the Esperanza mine to vague poorly-defined dikes and stringers, and it is usually associated with andesite porphyry. Immediately north of the mine, beyond the ore limits, dacite porphyry crops out as a small semicircular body at the base of a quartz latite plug (Fig. 1). A few small outcrops are visible north and south of the main intrusive body. Cretaceous (?) rhyolitic welded tuff and quartz monzonite porphyry are intruded by this rock in the pit area. Possibly a genetic relation exists between dacite porphyry and andesite porphyry. However, there has been no evidence collected to substantiate this hypothesis.

A typical specimen of dacite porphyry is dark gray to dark gray-green in color and exhibits a very hard aphanitic groundmass. Dacite porphyry weathers in the same manner as quartz monzonite porphyry and presents the same "honeycomb" appearance as the result of feldspar destruction. However, the gray-green groundmass color is distinctive. Potash feldspar metasomatism has affected this rock type, and it is not unusual to find disseminated orthoclase crystals 3 cm by 5 cm in size as well as stringers of orthoclase.

This rock type, which occurs only sparingly in the pit area, exhibits metallic mineralization very similar to that of quartz monzonite porphyry.

Dacite porphyry is believed to be younger than quartz monzonite porphyry but older than the quartz latite porphyry plug.

Andesite Porphyry. Andesite porphyry is confined in areal distribution to the Esperanza mine, West Esperanza mine, and a few small scattered outcrops along fault zones in the "Silver Bell" volcanic rocks. Faults and zones of structural weakness are the primary control for the distribution of andesite porphyry. In the mine area, this rock type, which characteristically occurs as tabular bodies, may be discordant on one bench and concordant on others.

Andesite porphyry is an important host for hypogene ore and is also the most favorable host for supergene ore. Examination of a specimen from the secondarily enriched zone by eye or with a hand lens does not reveal the pervasiveness of chalcocite mineralization, which has assayed as high as 4 percent copper. Andesite porphyry intrudes Rhyolitic welded tuffs and quartzite.

Zebra Quartz. Zebra Quartz, perhaps more logically considered to be a structural-textural feature than a separate rock type, is included under rock types because of the fact that it is a mappable lithologic unit. Taking its name from the banded arrangement of breccia fragments, this tabular-shaped unit, which averages 70 feet thick, is situated almost in the exact center of the Esperanza pit.

A hand specimen of Zebra Quartz shows creamy-tan elongate fragments of quartzite (?) imbedded in a groundmass of vitreous quartz. Dimensions of the fragments, which are distinctly angular and show no evidence of rounding, range from 1 cm to 14 cm long and 1 cm to 4 cm wide with an increase in fragment size with increasing depth. Microscopic examination of the Zebra Quartz indicates that the fragments are composed of very fine grained quartz with minor sericite in a groundmass of larger grained quartz. This rock, before brecciation and cementation, may have been a quartz latite dike.

The Zebra Quartz is a poor host for copper mineralization, either supergene or hypogene. However, excellent molybdenum values occur in the brecciated fault zones on the east and west contacts along with minor chalcocite, chalcopyrite, and pyrite.

The age of this distinctive unit is not known, but it is probably a product of the stresses that produced much of the major faulting prior to and during the period of metallization.

METALLIZATION

The Esperanza mine can be included under the loose classification of mineral deposits known as "porphyry coppers" and contains the type of metallization generally associated with an ore body of this type, at least as they occur in the Southwest. The ore of the Esperanza mine is a mixture of hypogene and supergene metallization occurring in veins and as disseminated grains. Roughly surrounding the copper-molybdenum ore zone is an aureole of vein-type deposits that was worked for lead, zinc, and silver about the turn of the century. Metallization was syngenetically associated with more than one intrusive pulse and was followed by a post-intrusive metallization period associated with hydrothermal alteration and potash metasomatism.

Metallization Summary

Hypogene	*Supergene*	*Oxidation Products*
Chalcopyrite	Chalcocite	Tenorite
Molybdenite	Covellite	Melaconite
Galena		Cuprite
Sphalerite		Chalcotrichite
Pyrite		Azurite
Marcasite		Malachite
Magnetite		Turquoise
		Torbernite
		Ferrimolybdite
		Limonite
		Goethite
		Hematite
		Jarosite

STRUCTURE

Geologic Setting

The Esperanza and West Esperanza ore bodies are associated with a broad contact zone that consists of Cretaceous (?) volcanic-sedimentary rocks and Tertiary (?) igneous intrusives. Ore mineralization has a definite northwest-southeast trend, while the prominent structural features have a northeast-southwest trend. Daily mapping in the mine limits has not shown any strong linear structures on a northwest-southeast bearing, but the ore zone and structural alignments are obvious (Fig. 1). Cretaceous (?) rhyolitic welded tuff and quartzite have a northeast trend, and Tertiary (?) igneous intrusives have a rough northwest trend.

One of the outstanding geologic features that influenced the localization of copper mineralization in the Esperanza area is the complex history of intrusion and extrusion that preceded, accompanied, and probably followed the period of metallization. Rock types varying from diorite to monzonite and their fine-grained equivalents were intruded in a number of pulses as stocks, dikes, and sills. Volcanic rocks, apparently derived from the same magma chamber, and more or less contemporaneous with the period of intrusion, vary from latite to andesite in composition. Deuteric alteration, best expressed by potash metasomatism and hydrothermal alteration, have substantially modified the igneous rocks in the mine area. Ore tends to be associated with the monzonite stocks and andesite dikes and their altered equivalents.

Ore Controls

Assay-contour overlays show that faulting in the mine area acted as the "plumbing system" for the upward movement of hypogene metallization and was also the main channelway for downward-percolating enriched solutions. Primary metallization is best developed in the quartz monzonite porphyry, and andesite porphyry is the preferred host rock for secondary enrichment.

Faults

Faults exerted an important control on the location and tenor of both the hypogene and supergene ores. Faults can be divided into three major sets, based on strike trend. The most important set strikes from northeast to east-northeast and dips both northwest and southeast. Second in importance are those faults with a northwest trend, and last is the group aligned in a north-south direction. A few of the important faults in the northeast group are the Searchlight, Cooper, Trident, Chula, and Hardshell faults. All these are located outside of the proposed mine limits. Two prominent faults in the mine limits are the New Year's Eve and the Bluenose faults. Of the northwest-striking group of faults and fault fissures, only two faults are of major importance—the Copperos Gulch and Buzzard's Roost faults. North-south faults are narrow in width as compared to the other two groups and are best developed in the "Silver Bell" series of volcanic rocks (Fig. 1). All faults mapped in the area are considered to be pre-metallization in age, although some have had several post-metallization movements.

Near the west end of the mine, two northeast-trending reverse faults are exposed. Three nearly horizontal faults are also present in this same area. No specific evidence has been uncovered to substantiate a thrusting origin; however, the three flat faults are in quartz diorite and andesite and are about 35 feet apart. The faults contain lenses of hypogene gypsum as much as 4 feet thick, and adjacent joint faces and fractures are also coated with gypsum. The gypsum coatings and lenses do not extend above the 3,970 bench.

The Buzzard's Roost fault, which is typical of the pre-metallization faults in the mine area, is 28 feet wide on the 3,900 bench and narrows to 4 feet on the 4,040 bench. Massive, crushed, and brecciated quartz, along with chalcopyrite, chalcocite, pyrite, galena, molybdenite, and sphalerite fill the fault from hanging wall to footwall as disseminated grains and veinlets. Quartz characteristically exhibits comb structures. Smeared chalcocite and molybdenite in the gouge on the hanging wall and footwall along with brecciated and mineralized quartz monzonite porphyry indicate that this fault has had post-metallization movement. From the south-center of the mine to the west end, a series of north-northwest-trending shear zones is the predominating structural feature and, through normal fault movement, has destroyed the continuity of earlier structures. This shear zone could also logically account for the lack of jointing and the strong amount of brecciation and clay in this part of the mine. The dip along these shear zones averages 55° NNE.

North-south-trending faults are the least significant of the three classifications. The largest in this system is the 70° E. dipping "Black Bottom fault," which is located south-southeast of the mine and which separates quartz latite porphyry on the west from "Silver Bell" andesite porphyry on the east. In the southern part of the mine area, north-south faults are the major control of andesite porphyry intrusives and the Zebra Quartz dike.

Joints

Joint systems are well defined on the east side of the pit and are almost totally obliterated on the west side by the north-northwest-trending shear zone. Prominent joint directions are east-west dipping 45°–50° N., north-south dipping 60° W., and northwest dipping 55° NE. These joint systems are important in ore localization; they not only served as channels for hypogene solutions but also served as channels for downward-percolating solutions that caused both oxidation and secondary enrichment. Geochemical studies indicate that the chalcocite ore is shifted to the north relative to the protore. The prominent east-west striking north-dipping joint system has been an important factor in this shift. Joints tend to be spaced 3 to 4 feet apart in quartz monzonite porphyry but are only about 4 inches apart in quartz diorite and andesite.

Structural Sequence

A hypothetical sequence of geologic events is postulated as follows. During and after consolidation, devitrification, and welding of the tuff, faulting trending northwest to east-northeast modified the areal pattern of these units. Erosion, followed by the deposition of tuff of the "Silver Bell" series, is believed to be the next step. Again, cooling, compaction, devitrification, and welding of the tuff were accompanied and followed by north-south faulting. A biotite granodiorite batholith along with its quartz diorite and quartz monzonite porphyry facies intruded the area. The exact relation of dacite porphyry to andesite porphyry is not known at this time, but a strong possibility exists that two units are contemporaneous, as is quartz diorite and andesite porphyry. Quartz latite of Tertiary (?) age intruded along faults in biotite granodiorite and the "Silver Bell" welded tuff. After emplacement, the quartz latite was in turn subjected to stresses that produced faulting.

ALTERATION

Hydrothermal alteration at the Esperanza mine, as is usual in the porphyry copper deposits of the Southwest, consists of the development of silica, sericite, clay, biotite, and potash feldspars. Alteration diminishes in intensity away from the ore zones. Over the ore zone, the composition of different rock types has influenced the mineralogy and the apparent intensity of alteration. The addition of potash in the form of orthoclase feldspar along with sericite and silica are the most prominent alteration features. In the ore zone, the abundance of sericite associated with quartz in the form of veinlets and plugs suggests that the introduction of quartz and the formation of sericite are closely associated. Quartz-sericite-potash feldspar associations are quite obvious in quartz monzonite porphyry and dacite porphyry in the ore zone; however, sericite shows a marked decrease in abundance away from the ore zone, and quartz and K-feldspar are still fairly abundant.

Silification

Hydrothermal silica in the form of veinlets, doubly terminated crystals, quartz plugs, and flooding is prevalent throughout the Esperanza area. Quartz monzonite porphyry on the east side of the mine contains very fine grained intergranular flooding of silica, and quartz in the form of veinlets is more common in quartz monzonite porphyry on the west side of the mine. Rhyolitic welded tuff is silicified in varying degrees, and the alteration is probably a combination of inherent and introduced silica. Except for recrystallization, quartz is not affected by any type of alteration.

Argillization

Argillization varies according to rock type. Andesite porphyry and quartz diorite show the most intense alteration of this type. Both the kaolin and montmorillionite groups of clay are present. Quartz monzonite porphyry in the west side of the mine exhibits moderate to strong argillization that is best developed in areas of intense faulting and brecciation.

Sericitization

Sericite is usually associated with quartz as veinlets or quartz plugs in the ore zone. Outside the ore zone, sericite is negligible, and quartz still may be persistent. Sericitization is practically limited to igneous intrusive rock types in the Esperanza area. Quartz latite porphyry and quartz monzonite porphyry are the rock types that exhibit intense sericitization. Weak to moderate sericitization can be found in rhyolitic welded tuff in the mine area. In the center of the mine adjacent to the east edge of the Zebra Quartz dike, a small pod of welded tuff and one of andesite porphyry have been completely replaced by quartz and sericite. This area of intense hydrothermal alteration represents the eastern edge of the zone of strongest hydrothermal alteration. Westward from this point for about 600 feet, the rock types consist principally of quartz, sericite, biotite, and K-feldspar.

Biotite

Hydrothermal biotite development is prominent in a few of the andesite porphyry dikes and sills.

ECONOMIC GEOLOGY

The Esperanza ore body, as outlined by exploration and development drilling, is roughly an ovate shape with an approximate length and width of 4,200 by 2,300 feet. The maximum known thickness of ore-grade mineralization is 420 feet, measured at the deepest point. The thickness at the extremities of the ore zone narrows to a mineable 35 feet.

The West Esperanza ore body has an irregular boundary (Fig. 1) with average dimensions of ore-grade mineralization of about 2,000 feet long by 1,800 feet wide. The maximum thickness of the ore-grade mineralization has not as yet been precisely determined due to the inability of the rotary air-swept exploration drill to penetrate and remove cuttings from a water-bearing zone that was encountered above the bottom limit of the ore-grade mineralization. The ore-body thickness must be estimated because a number of drill holes must be deepened to determine maximum depths of ore mineralization.

The ore cutoff limit at the Esperanza mine is 0.4 percent copper equivalent, based on the combined copper-molybdenum assay values. This copper equivalent is computed by subtracting half the oxide copper assay from the total copper assay and adding this difference to five times the difference of the molybdenum sulfide assay. Mineralized material with copper equivalent value of less than 0.4 percent, but more than 0.15 percent total copper, is mined as leach material. Copper assay contour-map overlays, based on total copper content only, are prepared for each geologic bench map. These data are compiled from engineering ore control blast-hole maps. Blast holes are drilled about 22 feet apart and have a vertical assay weight of 35 feet. Actual blast-hole depth is 42 feet for toe breakage to aid in keeping bench levels to uniform elevation.

An average of 12,000 tons per day of ore-grade material is mined and milled. At the present time (1967), the waste-ore stripping ratio is 1:1. The projected overall stripping ratio for total reserves is estimated to be 1.3:1. Production as of January 1, 1963, includes 177,834,097 pounds of copper by flotation, 1,406,189 pounds of cement copper from the leach plant, and 4,709,705 pounds of molybdenum. Copper concentrate averages from 25 to 30 percent Cu and 3 ounces of silver. Molybdenum sulfide concentrates average 52 percent Mo, which is later calcined to a final product of technical grade molybdic trioxide. Cement copper averages 75 to 80 percent Cu.

ACKNOWLEDGMENTS

The author is indebted to the following people for previous geologic work in the Esperanza area, which greatly facilitated the writing of this paper: Dr. Harrison A. Schmitt, consulting geologist; Donn M. Clippinger, senior geologist, Duval Corp.; Ezra H. Lewis, former resident geologist, Duval Corp.; and Dr. John R. Cooper, geologist, U. S. Geological Survey. For the many helpful suggestions, editing, and supplying mining data, appreciation is expressed to the following Duval personnel: Royce A. Hardy, director of development; Tom Jancic, chief mine engineer; and Bruce L. Wilhelm, geologic draftsman.

Special thanks go to John E. Frost, chief geologist, Duval Corp., for his guidance, constructive criticism, and encouragement in the preparation of this paper.

Charles H. Curtis, resident manager, Duval Corp., generously contributed suggestions and material from his paper on "The Esperanza Concentrator."

The author wishes to express his gratitude to Messrs. W. P. Morris and G. E. Atwood, President and Vice President, respectively, of the Duval Corp. for permission to prepare and publish this paper.

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