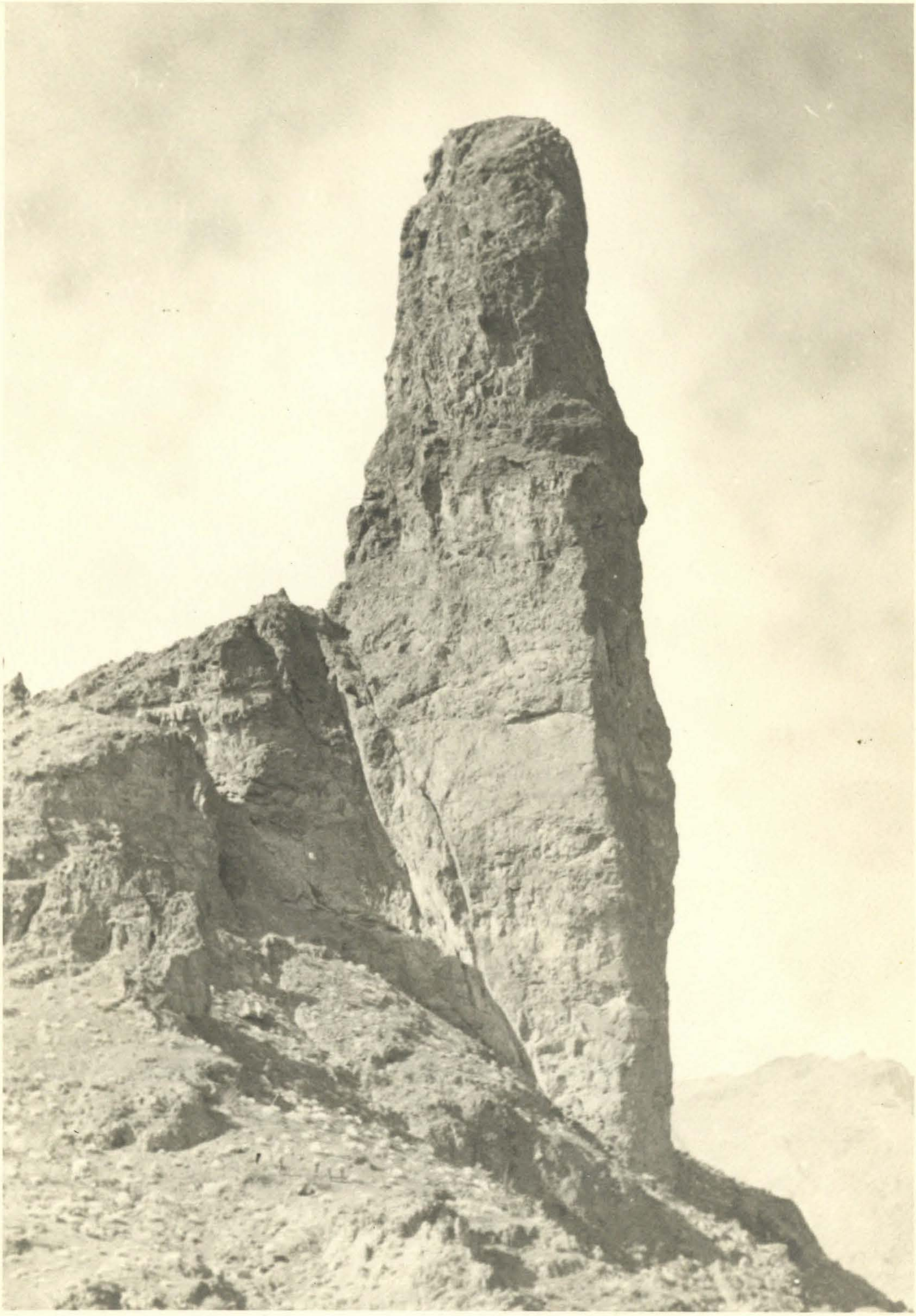
Looking northwest at Monument Peak, a spire of Copper Basin volcanic rock. Note the steep minor fault at the base of the spire.



STRUCTURAL STUDIES IN THE WHIPPLE MOUNTAINS
SOUTHEASTERN CALIFORNIA

Thesis by

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PREFACE

The original aim of my research in the field of structural geology was to study the phenomena of low angle thrust faults. In order to lessen the degree of speculation usually practiced in the study of such a problem, I was led to search for an area where a low angle thrust fault might be exposed. An area where both the over-riding and the over-ridden block would be well exposed might afford detailed examination of the structural features and also lead to conclusions which would put more reality than imagination into the consideration of buried or partially revealed low angle thrusts. The scientific urge of such a study is evident. Added to this was an economic motive derived from previous work in the disturbed belt of southwestern Alberta, where the misinterpretation of thrust fault phenomena has led to the loss of millions of dollars in the search for oil. However, like many pieces of research, no matter how strong the appeal is to follow along a certain preconceived line, the primary purpose is forgotten for the time being, when, after preliminary work, another problem equally entrancing discloses itself. Such is the case with the problem here to be presented.

In his several reports to the Metropolitan Water District on the geology of the aqueduct line through the Whipple Mountains, the late Dr. F. L. Ransome expressed the belief that there existed in these mountains a fault with younger sediments thrust over a basement of older metamorphic rocks. From his reports it appeared that the Whipple Mountains would be an ideal locality for the study of thrusting. In the consideration of the zone of thrusts extending from the Lewis Mountains in Alberta to the Muddy Mountains in southwestern Nevada, already mapped by several workers, the area is of importance. A thrust fault in the Whipple Mountains would throw light not only on this type of structure as such, but would also contribute to the Rocky Mountain and Basin Range problems. Ransome expressed doubt in his interpretation, for he had found certain contradicting and perplexing relationships. However, in spite of his doubt, it was not without considerable additional field work that it was concluded that thrust faulting has not occurred in the Whipple Mountain area. On the contrary it was found that the faults in the area are of the normal type, with the most obvious block faults in the interior of the range having a directional consistency compatable with the so-called Basin-Range type.

On first consideration special structural studies in the Basin Range province might be presumed to be an attempt to revive a dead issue. However, an examination of the literature on this problem will reveal few instances where individual ranges have been studied in detail, most workers treating the province as a whole and the ranges generally. The southern limit of the Basin Range Province is not definite, and the Whipple Mountains might be considered by some to be outside of the type area. Inasmuch as the fault block structure within the range suggested Basin Range affiliation, the problem was approached from this angle.

Since the period of national surveys in the west there has existed a controversial attitude toward the structural interpretation of the Basin Ranges, although the majority of published opinions is more or less in accord with the concept of Gilbert.[1] In 1873 Gilbert first brought out the idea that there existed in western America mountain ranges "formed by the tilting or relative uplift of great blocks of the earth's crust, acting as comparatively rigid masses, with subordinate or no flexing or folding of the strata."[2]

The early workers in the Basin Range region interpreted the structure of the mountains, not from the Mesozoic or older beds, but rather from the relationships of the Cenozoic, which they were convinced

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1. Gilbert, G. K., U. S. Geographical Survey West of the 100th Meridian. Wheeler Survey, Vol. III, pp. 21-42.
2. Louderback, G. D., Basin Range Structure of the Humboldt Region. Bulletin, G. S. A., Vol. 15, p. 289. 1904.

indicated a predominance of faulting, with folding a minor and local phenomenon. They also recognized compression and folding in the older rocks, which deformation had produced an extensive system of great ranges at the end of Jurassic time. That this folding had had little control over the present topographic appearance or broad structural aspect of the Basin Ranges is indicated by the observation that after the close of Jurassic time there was a long period of denudation during which time the district furnished a great body of sediment to Cretaceous seas farther east. The region was eroded to a surface of subdued relief -- possibly a peneplain, over large areas -- until Tertiary time when a sedimentary series, consisting mainly of lava and tuffs, fanglomerates and lake deposits were generally deposited. (A definite agreement of the time of the inception and duration of block faulting has not been reached, but probably the normal faulting has been going on since late Tertiary to the present.) In late Tertiary a period of deformation by fracturing started which continued through the Pleistocene and until the present in some localities. This regional orogeny has resulted in what has been recognized by most geologists as "Basin Range structure", though Davis proposed "fault-block structure." Gilbert modestly or cautiously conceded

Davis's term as the safer in view of the possibility of subsequent field work proving the Basin Ranges not due to fault block structure. Russel[1] summarized the Basin Range type: "They are long narrow ridges, usually bearing north and south, steep upon one side where broken edges of the composing beds are exposed, but sloping on the other with a gentle angle conformable to the dip of the strata. They have been formed by the orographic tilting of blocks that are separated by profound faults, and they do not exhibit the anticlinal and synclinal structures commonly observed in mountains but are monoclinal instead." In an effort to give credit to the men who first presented the major events leading to the development of the Basin Ranges, Davis was wont to epitomize their history in this manner: "The raising of the King Mountains by folding and compression in post-Jurassic time, which mountains were nearly peneplained to form the Powell surface, and the region broken to form the Gilbert blocks." That this statement is far too simple for such a complex and vast geologic province is recognized, but essentially it sums up the concensus of opinion.

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1. Russel, I. C., Geologic History of Lake Lahontan. U.S.G.S. monograph 11, p. 8.

Gilbert's original concept of the Basin Ranges was accepted in the main by most geologists and stood without formal challenge until 1901 when Spurr[1] refused to accept the fault block theory. Spurr's paper is typical of many that have been written on the Basin Ranges, presenting ideas rather than facts and based on generalities rather than on detail. Attempting to refute Gilbert's theory he postulates the view that erosion and folding are the controlling factors in the development of the desert mountains and basins. In spite of Spurr's attempt to foster new ideas on this controversial subject, he made little progress toward its solution. From time to time since other authors have presented additional papers on this province, all adding to the bulk of literature, many only contributing ideas for the detailed worker to consider in his individual problem.

Insofar as the Basin-Range problem is concerned, it is the writer's opinion that the need is for more detailed work on the individual ranges in hope that actual evidence can be brought to light to support a generalization. One might feel submerged in tediously working an isolated piece of geology, but in doing it well the results may then be con-

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1. Spurr, J. E., Origin and structure of the Basin Ranges. Bulletin, G.S.A., Vol. 12, pp. 217-270. 1901.

sidered with confidence by a subsequent worker in studying the provincial problem. The compiled results may eventually be tied together in support of a logical conclusion and each geologist can feel that a worthy contribution has been made. Longwell's[1] paper on the Muddy Mountains is such a paper. After a detailed study of the mountains he broaches the Basin Range problem by stating: "In this part of the Basin and Range province, therefore, there is a definite 'basin-range structure' superimposed on an earlier 'Appalachian structure' of thrusts and folds. Strong influence of the earlier structure lines is seen in details of the present topography, and erosion has modified greatly the effect of the 'basin-range' faults. Nevertheless, highland and intermontane valleys owe their location and general form in large part to normal faulting."

The geology of the Whipple Mountains has been studied in order to determine their origin and to disclose any structural affinities to other regions. Certain geologic provinces have been established by earlier reconnaissance surveys, and attempts have been made to generalize on the struc-

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1. Longwell, Chester R., Geology of the Muddy Mountains, Nevada. U.S.G.S. Bul. 798. 1928.

tural types of each province. If the results obtained in this area can be used as a criterion, I would be of the opinion that it is impossible to generalize on the structure of an area so far flung as the Basin Range Province, especially when it is impossible to obtain data in the basin parts of the province.

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ABSTRACT

The rocks of the Whipple Mountains include a basement complex of pre-Cambrian age overlain by middle Tertiary volcanics and sedimentary. These are unconformably overlain by flat-lying Pleistocene and recent beds. The broad structural feature of the mountains is a faulted dome, elongated roughly east-west. The dome is outlined on the north and northeast flanks by an arcuate fault which dips away from the mountains. The northeast area of the mountains is broken into southwest-tilted blocks, bounded by northeast-dipping normal faults, roughly parallel to the southeast-trending portion of the arcuate fault. The block faulting is not of the orthodox basin range type, but is considered to be closely associated with the doming. There is no evidence of large compressional forces, and these mountains are believed to belong to the belt of transverse ranges of southern California. The major faults are presumed to have been active in post and pre-Miocene times. There is no evidence of recent fault activity and volcanics and sediments presumably of Quaternary age are not cut by the faults.


Index Map
THE METROPOLITAN WATER DISTRICT
OF SOUTHERN CALIFORNIA
MAP OF
SOUTHERN CALIFORNIA
AND
LOWER COLORADO RIVER
F. E. WEYMOUTH CHIEF ENGINEER
FEBRUARY 1933
Scale of Miles
0 10 20 40 60
CONDUIT
TUNNEL
PRESSURE LINE
INDICATES CITIES IN DISTRICT
N
NEVADA
CALIFORNIA
ARIZONA
MEXICO
HOOVER DAM
BOULDER CITY
LAS VEGAS
BAKERSFIELD
MOJAVE
MOJAVE DESERT
LANCASTER
VICTORVILLE
BARSTOW
NEEDLES
PARKER
BLYTHE
YUMA
EL CENTRO
BRAWLEY
IMPERIAL
CALEXICO
MEXICALI
SAN DIEGO
LOS ANGELES
PASADENA
BURBANK
GLENDALE
SAN MARINO
BEVERLY HILLS
SANTA MONICA
COMPTON
TORRANCE
LONG BEACH
SANTA ANA
ANAHEIM
FULLERTON
POMONA
ONTARIO
RIVERSIDE
SAN BERNARDINO
COLTON
REDLANDS
BANNING
BEAUMONT
SAN JACINTO
HEMET
PERRIS
ELSINORE
SALTON SEA
COLORADO RIVER
BILL WILLIAMS RIVER
GILA RIVER
KINGMAN
SIERRA NEVADA MOUNTAINS
Los Angeles City Aqueduct
Lat. 36°00'
Lat. 35°00'
Lat. 34°00'
Lat. 33°00'

Map no. 1

INTRODUCTION

Location and Access

The Whipple Mountains are in the southeastern corner of San Bernardino County in southeastern California immediately west of the Colorado River. This stream forms the California-Arizona state boundary line at this locality. The position of the mountains is shown on the index map (Map 1).

The district is about 300 miles east of Los Angeles, and is most easily reached over U. S. Highway Number 70 to Desert Center and thence over the Metropolitan Water District's paved road to Parker Dam. It also can be reached by graveled state road from Needles which lies approximately 40 miles north of the mountains. The Santa Fe Railroad also serves the area via the Parker cut-off. Before the beginning of construction of the Parker Dam and the Colorado River Acqueduct by the Metropolitan Water District the only town was Parker just south of the mountains on the Arizona side of the Colorado River. Since the commencement of the aqueduct and dam construction, however, mushroom settlements have sprung up in addition to the construction camps. Most of the groups are situated along the Colorado River on the eastern fringe of the mountains. These include Parker Dam which is really the construction city containing construction company and government buildings, Cross Roads which is a squalid but ingenious settlement of aqueduct workers and hangerson, and Earp which is an enlarged auto-camp and railroad siding. Scattered between these groups and farther west along the aqueduct are shacks, make-shift houses, camps, stores, saloons, gas stations, and honkey tonks appearing like one prolonged hobo~~s~~ jungle. In spite of the temporary and uninviting character of the colony, supplies are available at many places.

Scope

The United States Geological Survey has made a topographic map of the area and its Parker Sheet covers the Whipple Mountains. The scale of this map is 1:125,000 but in using this as a field map it was enlarged two and a half times. The area studied in connection with this work was that portion of the Parker Sheet west of the Colorado River and embraces approximately 225 square miles. The field work was done during two field seasons: the first, from January until the middle of June 1935, and the second from January until May 1936, with about two-thirds of this time actually in the field. As the settlements and the construction camps are located only on eastern and southern borders of the mountains, work in the inner portions and the other borders necessitated dry camping. Water was available at the settlements, at one spring near Whipple Wash, and at West Well. Although other springs are noted on the topographic map, these were found to be dry.

Travel within the mountains is facilitated by various construction roads and by poor but for the most part passable trails used by prospectors who have futilely explored the range for mineral wealth through several decades. In spite of the many roads there is a large portion which can be examined only on foot, and camps were placed so that no packing was necessary.

Mining

Although there are a number of prospectors still working in the Whipple Mountains and the area has been explored during several decades, no encouraging results have materialized. There are many prospect workings and a few abandoned locations where there is evidence of considerable capital expenditure, but a paying mine has never been developed. Mining in the Whipple Mountains has had a poor past, a worse present, and, in the writer's opinion, little chance for future success.

Climate and Vegetation

The climate and the flora and fauna of the Whipple Mountains area are not unlike that of the

Figure 1

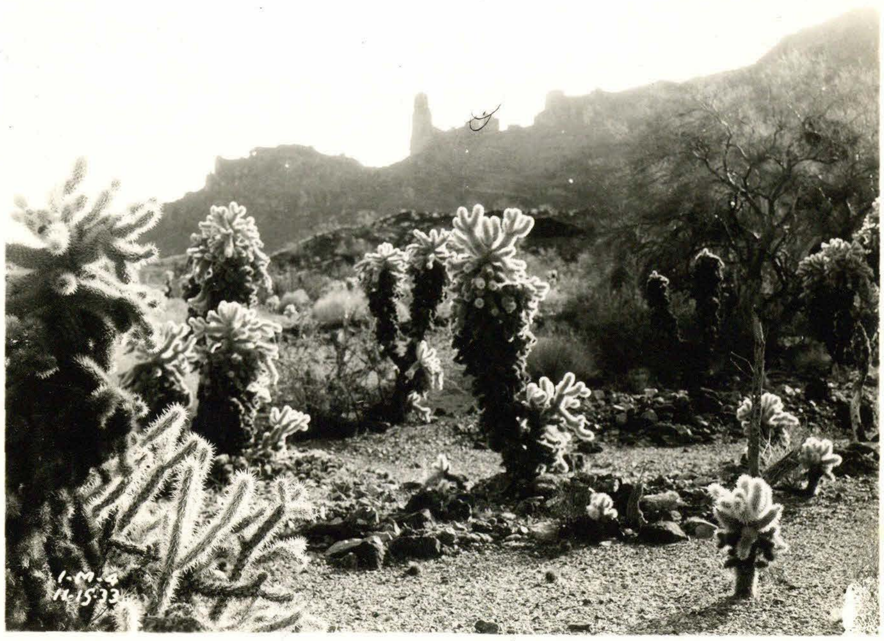

Figure 2

Typical topography and desert flora in Copper Basin

Mohave Desert region (Figs. 1 and 2). These subjects have been treated quite fully by Thompson.[1] His general statement of the climate is: "The climate of the Mohave desert region is characterized by slight annual precipitation [less than five inches here], low humidity, comparatively high temperatures in both summer and winter, great daily ranges in temperature, and strong winds at certain seasons of the year." Vegetation of the desert type is seldom so dense as to create an obstacle to field work, and only in some of the washes and along the Colorado River is the water table high enough to support much growth. For the most part the individual plants are widely spaced and the foliage is reduced to a minimum. The gravel covered bench lands and the mountain slopes support mostly creosote bush and several varieties of cactus including prickly pear, barrel, the sahuaro, ocotillo, and cholla, while the large arroyos contain sparse growths of palo verde, ironwood, cat's claw, and mesquite.

<u>Previous Work</u>

There are some vague references in the early exploration reconnaissance works to the existence of

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1. Thompson, D. G., The Mohave Desert region, California. U.S.G.S. Water Supply Paper #578, pp. 41-95. 1929.

metamorphic rocks and Tertiary lavas but otherwise the writer knows of only one short reference to the geology of the Whipple Mountains. This is in a United States Geological Survey bulletin in which Jones[1] gives a concise general statement of the geography and geology. Ransome worked the geology of a strip about two miles wide along the aqueduct line through the mountains and his results were incorporated in reports to the Metropolitan Water District.

Acknowledgements

This work has been carried on under the guidance of Dr. John P. Buwalda, Chairman of the Division of Geological Sciences at the California Institute of Technology. His suggestions and continued interest are acknowledged. Other members of the faculty also have given helpful suggestions. Some of the air photographs were obtained by Dr. John H. Maxson while others were purchased from Erickson, a commercial photographer, who worked for the Metropolitan Water District. The Metropolitan Water District was helpful in many ways in facilitating work in the field.

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1. Jones, E. L., Deposits of manganese ore in southeastern California. U.S.G.S. Bulletin #710, pp. 189-193. 1920.

TOPOGRAPHY

The Whipple Mountains occupy an area of some 200 square miles inside a great bend in the Colorado River. They drain to the north, east and south to the Colorado River, and for the most part the streams have deposited large areas of fanglomerates and gravels on the flanks of the mountains, although in places the mountains actually reach the river. This latter is true on the northeast and east.

Relief

The maximum elevation is 4110 feet above sea level, the highest point being about five miles east of the western border of the Parker sheet just north of the east-west center line. The Colorado River averages about 395 feet above the sea in this area, being 418 feet in elevation at Pittsburg Flat and 373 feet about two miles north of Parker. The maximum hypsometric difference is about 3700 feet.

The Whipple Mountains have two distinct types of topography: that developed in the area of the basement complex, mainly in the western half of the mountains, and that developed in the area dominated by the Tertiary volcanics and sediments.

Basement Complex Area

The whole mountain mass is intricately and deeply dissected by many arroyos and washes, but the area of basement complex appears to be more disordered than elsewhere. There are few flat areas and the ridge-tops are sharp with little arrangement. However, in the extreme western part near Chambers Well the ridges and arroyos have a general northwest-southeast direction suggesting a structural control. (Plate 3.) The main bulk of the basement complex comprises a broad irregular ridge steep-sided to the northwest and more gradual to the southeast, running in an east-northeast direction from about Chambers Well to near the Colorado River at little Chemehuevi Valley. This master ridge reaches its high point, which is also the maximum elevation in the mountains, about six miles northeast of Chambers Well. The northeast escarpment is deeply incised with many steep arroyos which drain northwesterly, but those to the east of 4110 peak turn rather suddenly to flow northeastward to the Colorado River. On the southeast slope the drainage pattern appears to be less consistent for the arroyos and washes radiate from the Whipple Peak area toward the Colorado River. Even though this is a generally gradual slope the arroyos and washes have cut deeply into the bedrock giving the area a very rugged and steep surface. (Plate 3.)

Tertiary Covered Area

The area in the eastern half of the mountains where the later volcanics and sediments overlie the Basement Complex is dominated by northwest-southeast ridges of upturned beds separated by like trending basin-like depressions and washes. (Plates 8 and 9.) Toward the central area where the volcanics predominate there are flat or gently sloping topped promontories as well as castellated and spirelike forms. (Plates 5, 6, 7, 8, 9 and 11.) Monument Peak, 2446 feet in elevation, is the largest and most conspicuous of these spires and has been used as a well known landmark and point of reference for many years. (Frontispiece and Fig. 19.) There is a decided structural control of the topography in this sector, and the drainage has a vague rectilinear pattern on this account.

North Hills

Northwest of the main mountain mass and separated from it by a roughly east-west depression is a small group of hills about ten square miles in area which show a topographic grain similar to that of the area covered by Tertiary formations. Although they are of lower elevation they are just as rugged and intricately dissected as any part of the Whipple Mountains. They are composed of a confused association of Basement Complex and Tertiary rocks, mostly volcanics. The northwest-southeast structural control is not as evident here as in the Copper Basin and Gene Basin areas.

West Hills

Still farther west and separated from the last mentioned hills by five miles of alluviated area, is a small group of hills covering about three square miles. These hills are composed of Tertiary rhyolitic lavas. They are well dissected and the topography appears to be the result of differential erosion with little structural control. Their isolation has made it difficult to correlate them topographically, structurally, or stratigraphically with the rest of the Whipple Mountains. These hills are surrounded by alluvial material, patches of which occur relatively high on the slopes, and inasmuch as all the drainage is northeastward toward the Colorado River it seems likely that these hills were at least partially exhumed and dissected subsequent to the rejuvenation of the drainage.

Alluvial Plains

Flanking the Whipple Mountains to the northwest, between the bedrock and the outliers, is a large area of outwash material. This area is itself thoroughly cut up by box-like canyons and large washes with broad interstream ridges, covered with desert pavement. As the river is approached the present washes become deeper and their beds wider. Here the outwash material merges sometimes into river gravels, but both phases of alluvial material unconformably overlie horizontal lake beds. In this area several terraces can be traced, representing periods in the Pleistocene or Recent history of the Colorado River, and near the river the alluvial outwash and river gravels remain as patches on the now exposed old lacustrine deposits.[1] It is believed that these terraces as well as the down cutting of the Whipple Mountain drainage are the effects of changes during the development of the Colorado River.[2]

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1. Noble, L. F., Nitrate deposits in southeastern California. U.S.G.S. Bulletin #820, pp. 36-45. 1931.
2. Blackwelder, Eliot, Origin of the Colorado River. Bulletin G.S.A., Vol. 45, pp. 551-565. 1934.

STRATIGRAPHY

General Features

The Whipple Mountains contain few stratigraphic units, although the divisions mapped contain a variety of rock types which include metamorphic, igneous and metamorphosed sedimentary rocks, basic and acidic dikes, lavas and pyroclastics, and an assortment of land laid sedimentary strata. The age determination is not certain in any case, but the writer feels fairly confident of the Tertiary age of the sediments in spite of the almost complete lack of fossils. Lithologic comparison for the determination of age is often not safe or conclusive, but for the lack of more positive criteria a tentative statement on this basis will have to suffice. However, in a purely structural study this information is not vital although zoning of the sedimentary series would facilitate and strengthen conclusions of fault movements. Consequently I have been forced by field circumstance to bulk the older metamorphics into a rather uncertain and not altogether satisfactory group: the Basement Complex. Overlying this Basement Complex unconformably are two Tertiary sedimentary formations, which have both been dated as post-Eocene, although they are separated by an angular unconformity. Pleistocene sediments rest unconformably and remain sporadically on either basement or Tertiary as do the more recent alluvial deposits.

A summary of the stratigraphic section is tabulated on the following page.

STRATIGRAPHIC SECTION

Geologic Age		Formation	Approximate thickness in feet	Character
Quaternary	Recent	Alluvium	0-300	Fanglomerate and mountain outwash, river gravels and silt.
		----Unconformity----		
	Pleistocene	Chemehuevis River gravels) Lake Bed series)	0-300	Lacustrine deposits, river gravels, silts merging to mountain wash
		Older River Gravels	?	
		----Unconformity----		
Tertiary (Post-Eocene)	Miocene (?)	Copper Basin	2500-	Pyroclastics and volcanic flows interbedded with red sandstones, grits, conglomerates and breccia. Lacustrine deposits. Carnivore tracks.
		----Unconformity----		
	Oligocene (?)	Gene Canyon	1735	Pinkish and gray grits, breccia conglomerates, sandstones, local shales, and occasional lavas. Artiodactyl. (Elothers?) Tracks.
		----Unconformity----		
	Pre-Cambrian (?)	Basement Complex	?	Metamorphosed igneous and metmorphosed sediments. Granite gneiss, mica schist, chlorite schist, thin quartzites, and limestones. Much shattered, tilted and brecciated.

Pre-Cambrian - Basement Complex

A large area of the Whipple Mountains is classified as Basement Complex. This designation is made because the associations within these older rocks are so involved that further refinement would be extremely difficult if not impossible.

The Basement Complex is composed of metamorphosed sediments, metamorphosed extrusives and metamorphosed intrusives in a complex association. Their structural relationship is intricate and no attempt was made to map what might be the several units. The basement has suffered extreme shattering (much of it prior to the present systems of deformation) which condition increases the difficulty of identification as well as the projection of post sedimentary faults. Thin sections have been made and studied to permit a specific statement of opinion as to rock types.

The ancient crystalline rocks were granites of varying texture, but are now metamorphosed to gneiss ranging from fine grained to coarse grained augen gneiss. Certain specimens show cataclastic metamorphism with little new mineral formation. The degree of crushing and granulation is not constant, and although not within the scope of this study my notes indicate that the deformation increases from southwest to northeast and is especially strong in the hills about two miles south of B. M. 438 on the Colorado River, three miles west of Pittsburg Flat. Here a rather perplexing zone of basement rock shows crushing and brecciation on a large scale. The zône is several hundred feet wide and strikes roughly northwest and southeast, although its extent is indeterminant because it grades into basement in which cataclastic metamorphism is not megascopically apparent. This zone is now injected and cemented with volcanic material and it may represent a former fault zone which furnished an easy conduit for volcanic material. The granite gneiss likely is an ancient plutonic mass, now metamorphosed and thoroughly fractured and jointed, which had intruded a still older series of sediments which contained some volcanic rocks. The sediments also are now metamorphosed into mica schists, chlorite schists, limestones, thin quartzites, and banded gneiss. Bands up to one foot thick persist over a long distance and the formations retain an appearance of sedimentary origin. This is well exhibited along the northwest slope of the mountains where the Basement Complex gives the banded appearance of regularly northwesterly dipping sediments. (Plates 15, 16, 2 and 3.) The flow lines seen in some of the fine grained and prophyritic specimens indicate the presence of meta-volcanics. The limits of meta-sediments and meta-igneous rocks are not established, but meta-sediments predominate in the area to the northwest and west, while the central and northeast portions are mainly meta-igneous. Chloritization is rather extensive in the central area although it is present in some degree elsewhere.

This metamorphic series has been intruded by many dikes, most of which are found in the border areas of the mountains, but are especially abundant in the western portion, the northern segment and the northeast area along the Colorado River. The dark dikes are an amphibole lamprophyre approximately malchite (Grout) while the lighter ones are aplite. They appear to vary in time and neither consistently antedates the other, although neither type has been observed to intrude any of the rocks younger than the Basement complex.

Evidence of later granitic intrusion is found in the central part of Copper Basin. This prominent area of new granite is much less metamorphosed, being only slightly gneissic and lighter colored than any of the older basement rocks. (Plate 8.)

<u>Age</u>. The exact age of the basement series is not known, and there is no apparent reason to alter

the opinion expressed by E. L. Jones[1] that it is pre-Cambrian, though it is likely that the "new granite" is Mesozoic.

Tertiary Rocks

In the Whipple Mountains there is a hiatus between the formations of pre-Cambrian and Tertiary age. Rocks of intervening age are not represented unless it be the "new granite." At least no sedimentary beds are present between the Basement Complex and the earliest Tertiary sediments shown here.

The names given to the Tertiary formations are those assigned by Ransome in his reports to the Metropolitan Water District. They were named from the areas where the formations are best exposed, Gene Canyon and Copper Basin.

The great difference in time between the Basement Complex and the Tertiary indicates the presence of an unconformity. That deformation and erosion took place prior to Gene Canyon deposition is certain, but the scope of these changes is difficult to estimate. However, the metamorphism and shattering of the basement indicates severe diastrophism. Widespread erosion is indicated by the time difference and the extended erosion surface upon which the Tertiary beds are deposited.

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1. Jones, E. L., Deposits of Mangonese in southeastern California. U.S.G.S. Bulletin #710, p. 191.

Gene Canyon Formation. The Gene Canyon formation is not complete and outcrops with certainty at only a few places. Fossils are lacking so identification is based entirely on lithology and stratigraphic relationship. Inasmuch as the appearance in some phases resembles parts of the overlying Copper Basin formation the designation, especially of some of the smaller patches, might be questioned. Caution has been used in this regard and the writer feels confident that the areas mapped as Gene Canyon are correct. Additional areas of this formation might be mapped with less certainty.

Lithology and Thickness. An angular unconformity occurs between the Gene Canyon formation and the overlying Copper Basin formation. The Gene Canyon now covers the basement only sporadically. Consequently any section is a partial one. The fullest exposure occurs in Desilt Wash just east of Gene Canyon in the vicinity of Parker Dam where over 1700 feet are exposed. This section is described from top to bottom as follows:

Character	Feet
Reddish, well bedded sandstone grit with subangular grains. In the middle is a nine foot bed of "baseball" conglomerate carrying vesicular lava boulders. Boulders in this conglomerate are subangular. . . .	50

Character	Feet
Blocky, purplish gray vesicular lava	150
Massively bedded conglomeratic brick red sandstone with finely bedded sandstone partings and bouldered areas (boulders up to 2½ feet in diameter). Toward the top this phase becomes well bedded conglomerate and sandstone.	220
Well bedded brick red sandstone with occasional conglomeratic beds. Sandstone grains medium size and subangular.	200
Dirty gray, breccia with huge angular to subangular fragments of coarse and fine grained acidic igneous rocks which are very little altered and are held firmly together with grit. Lenticular up to....	300
Gray to black-gray, fine to medium grained, subangular, well bedded sandstone.	60
Interbedded, fairly well cemented buff, grayish and pinkish sandstone, grit and conglomerate. Grains are angular to subangular. Becomes greenish buff toward the top with a bit more pronounced bedding. . . .	210
Well cemented hard sandstone, grit, and shale. Greenish, buff and pinkish. Occasional pebble beds. . .	40
Fairly well cemented, well bedded grit and conglomerate. Buff to pinkish with some pinkish and greenish sandstone layers. Particles subangular with conglomerate size ranging from 1/4 inch to 8 inches.	175
Bedded and massive layers of red conglomerate and grit with greenish acidic igneous boulders. Boulders are subangular but they become more angular and more plentiful toward the top.	120

Character	Feet
Red and gray fanglomerate with rounded and angular heterogenious boulders up to 6 feet in diameter. The majority of the boulders are acidic.	150
Dark gray structureless breccia with angular fragments ranging from 1/2 inch to 3 feet but averaging about 4 inches in diameter, all cemented with grit.	15
Dull red, gray and buff well bedded grit and subangular conglomerate.	45
	1735

Conditions of Deposition. The character of the sediments in the Gene Canyon formation indicates the presence of an arid climate at that time. Erosion and accumulation took place apparently under desert mountain conditions approximating present day Whipple Mountain sedimentation. The predominance of angular and subangular particles and boulders in the grits and conglomerates, the lack of continuous bedding, and the lenticularity together with the fanglomeratic beds indicate a nearness to the source, probably an ancient Whipple Mountain. These points together with the rarity of shale or similar sediments and the freshness of the particles and dominant pinkish and gray color are also indicative of a lack of moisture necessary for oxidation and other forms of decomposition. Shale patches occur but these are small and lenticular areas probably ancient small drainage basins or sag ponds.

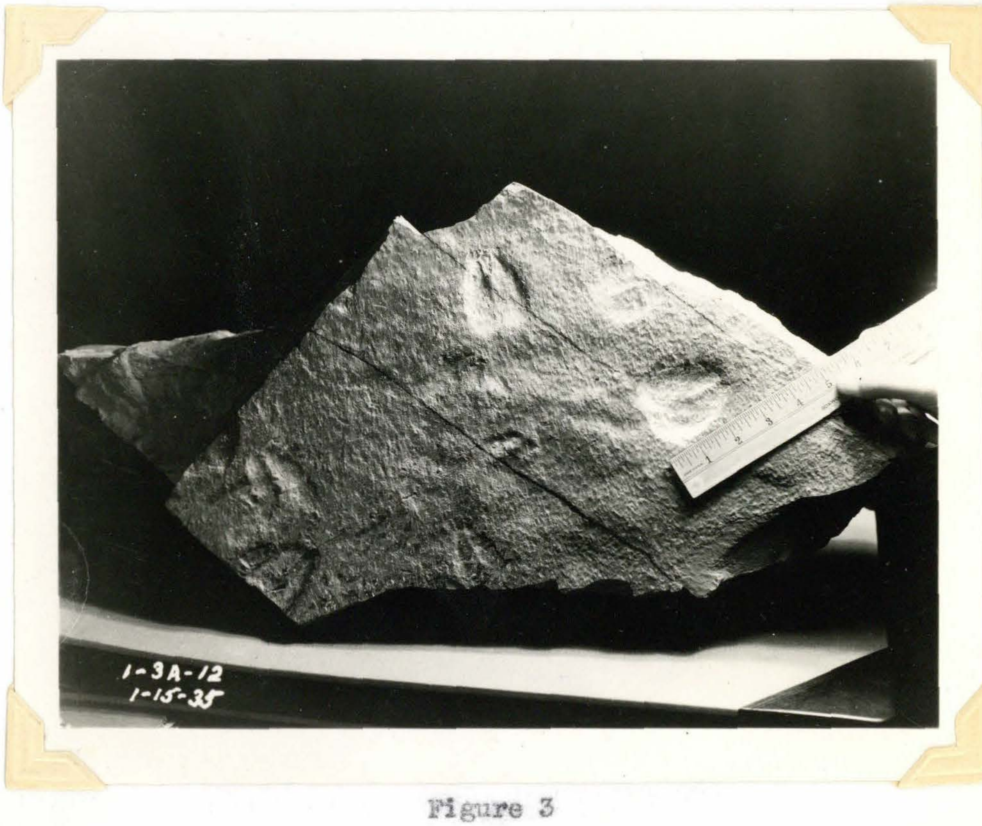

Figure 3

Artiodactyl hoof prints found in Gene
Canyon shale bed in Colorado Tunnel

Age. Evidence of the age of these beds is vague. They are probably early Tertiary and likely post-Eocene. The only fossil evidence is some artiodactyl hoof prints which were found in a pinkish shale bed during the driving of the Copper Tunnel by the Metropolitan Water District. (Fig. 3.) The writer did not collect the impressions, but he feels certain of their authenticity. In discussing these impressions with Professor Stock it was concluded that they could be the imprints left by one of the giant pigs, possibly Elothere, an Oligocene and very early Miocene artiodactyl. Moreover, the structural and stratigraphic relationships tend to point toward this age.

Copper Basin Formation. Unconformably overlying the Gene Canyon formation and the Basement Complex is a series of red and reddish brown sandstones and conglomerates, with hard shales, lava flows and volcanic breccia, presumably Tertiary in age. The unconformity is angular and the discordance varies from place to place. (Fig.) The time interval was long enough and the erosion sufficiently vigorous to have removed much of the Gene Canyon formation and subdue the landscape at the end of Gene Canyon time. The deformation which affected the Gene Canyon formation prior to the deposition of Copper

Basin beds apparently followed the same general system as that which has tilted and broken the younger Tertiary strata. The Copper Basin formation then rests on patches of tilted Gene Canyon beds and on subdued and weathered basement rocks.

Distribution. Although the largest area and the highest points of the Whipple Mountains are composed of Basement Complex, it is the red colored Copper Basin formation which has transformed the drab monotony of pre-Cambrian rocks into a picturesque mountain máss. The physiography becomes bolder and more varied in the areas covered by the Copper Basin formation, especially where the volcanics are present.

Much erosion has taken place since Copper Basin time and the remnants of this formation remain as a dark capping on dull basement rocks or form tilted rims of interior basin-like areas. This series of lavas, pyroclastics, and sediments is found mainly in the eastern half of the mountains where the outcrops command the scenery with their rugged expression.

The Copper Basin formation occurs mainly in the eastern part of the area studied, forming irregular strips oriented northwest-southeast. The trend of the areal distribution is controlled by structure, for the blocks are roughly outlined by faults. About three miles northwest of the eastern mass of Copper

Basin formation, across an area of Basement Complex, is a group of lower hills parted from the main Whipple Mountain mass by a major fault. In this group of lower hills are strips of Copper Basin beds which also have a northwest-southeast trend and are also roughly outlined by like-trending faults. In addition to these areas the southern border of the mountains is fringed with patches of Copper Basin volcanics and sediments at lower elevations, which lie in depositional contact on the Basement Complex. Several somewhat isolated patches of Copper Basin volcanics which cap promontories within the range suggest an earlier and more extensive distribution of this formation, much of which has since been eroded. It seems probable that the greater portion of the Whipple Mountain area was once covered by the Copper Basin formation.

Lithology. Volcanic rocks in the formation disappear eastward, probably fingering out into sediments. The sections taken near the southeast ends of Gene Basin and Copper Basin show no volcanics, but some of the lower sandstones and conglomerates appear to be cemented with volcanic material. Proceeding northwestward is a gradation into pyroclastic material and then into lava. The demarcation is never sharp. Where the volcanics are present they are found in the lower part of the formation overlying the Basement

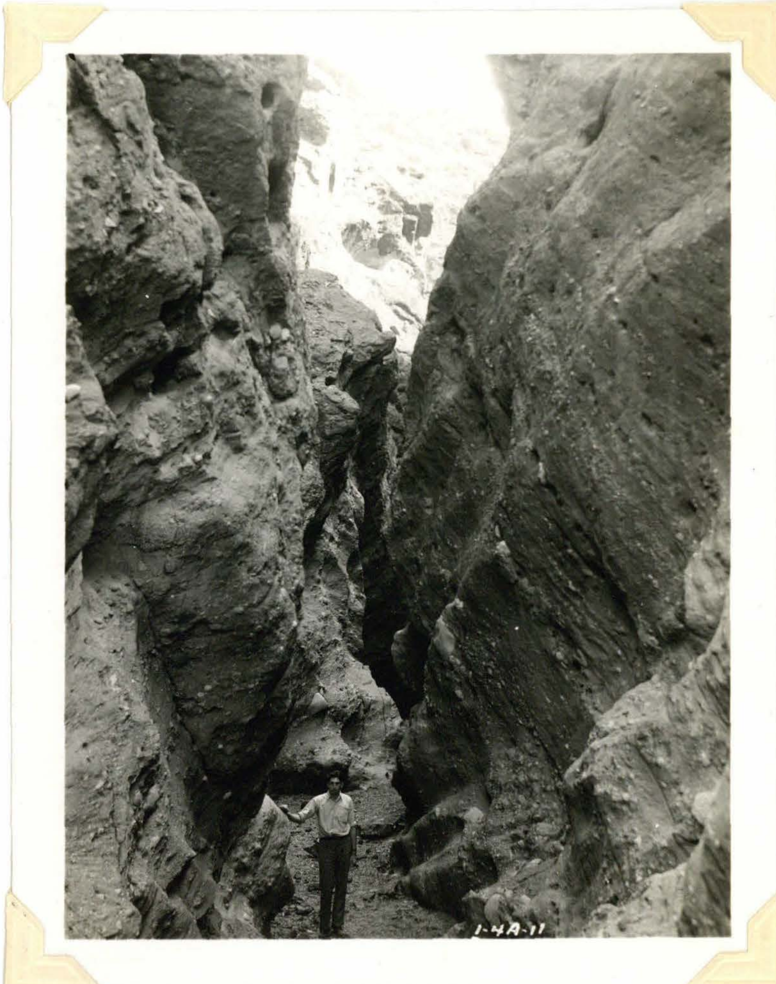

Figure 4

Southwest dipping Copper Basin conglomerates, very severely indurated, at the narrows in Gene Canyon.

Complex. The volcanic rocks of the Copper Basin formation are mainly andesites with some basalts. Some rhyolite occurs in small patches in the low hills to the north, probably small plugs. The maximum thickness estimated is 800 feet in the Monument Peak mass. (Figs. 19 and 20.) Lava flows and breccias occur in such complex association that it is impossible to distinguish individual flows. The central area mapped as Copper Basin formation is all volcanics.

The sedimentary portion of the Copper Basin formation is generally made up of interbedded conglomerate, grit sandstones and some flaggy sandstones. (Fig. 12.) Some phases are massive but mostly they are well bedded in layers a few inches to several feet thick. Shale is inconspicuous and is found only as partings between coarser clastics and as lenticular phases of small areal extent. The predominant color is brick red, but it varies from dirty brownish red to pink with occasional grayish and yellowish areas. The degree of cementation varies somewhat, but on the whole the beds are well indurated. (Fig. 4.) Toward the upper part of the section, especially in the Gene Basin area the coarse clastics are only loosely held together, changing gradually downward to the more intensely cemented beds. The degree of induration appears to have lateral variation also, which condition has contributed to the formation of the interior basin-like areas of Gene Basin and Copper Basin. In these basins the low lying subdued floors are underlain by the softer sediments of the upper portion of the section, while the harder lower portions form the resistant ridges. The entire sedimentary section of the Copper Basin formation represented by a continuous succession of sandstones and grits and conglomerates and conglomeratic beds depicts rhythmic sedimentation of the coarser clastics.

The sediments south of the Monument Peak mass are somewhat finer in texture than elsewhere in the area, but coarse to medium grained sandstones dominate with some finer conglomerates interbedded. (Plate 8.) The well bedded nature is still characteristic with individual beds persisting over the extent of the exposures; ripple marks and sun-cracks are frequently found; cross-bedding is rare and when found it is on a small scale. Conditions found point to the inference that these beds are part of a more extensive basin deposit. The basin probably lay south of the Whipple Mountains and the coarser bedded sediments found in the Copper Basin and Gene Canyon areas may indicate phases deposited closer to their source.

Figure 5

Carnivore tracks in an indurated grit bed in the Copper Basin Formation. One-third natural scale.

Thickness. A complete section is not to be found because of the erosion and deformation and because the nature of the units of the section vary in different localities. However, the general character is similar throughout, so that even though lithology is again the only means of identification the correlation is dependable. The maximum thickness of the Copper Basin formation is measured in Gene Basin from the east side of Black Metal Peak to the Gene Fault. Here 2500 feet are exposed, but as in the other localities the beds are cut off by faulting, so the measurements are incomplete. In Copper Basin the section is 1750 feet thick; the Monument Peak mass shows 1800 feet; southeast of Whipple Wash 2250 feet are exposed. In the area of low hills to the north the exposures are so discontinuous that an estimate of thickness has little value.

Age. The age of the Copper Basin formation cannot be determined accurately. The only fossil evidence found is a few carnivore tracks discovered in an indurated marooh grit bed in the northeast rim of Gene Basin. (Fig. 5.) This evidence places the formation as post-Eocene, and the unconformity shows it to be younger than the Gene Canyon formation which has been judged to be possibly Oligocene or early Miocene in age. It is possible that the

Copper Basin formation is upper Miocene, maybe closely related in time to the Rosamond series[1] which is upper Miocene in age. There is a general resemblance in the sedimentary type and the degree of deformation is about the same. The volcanics of the Rosamond series are predominantly rhyolitic while those of the Copper Basin formation are predominantly andesitic. Longwell[2] places the age of the andesites of the Boulder Dam area as pre-Pliocene. The volcanics of the Boulder area resemble those of the Whipple Mountains area and the degree of deformation is similar. However, correlation of volcanics is unsafe and these instances are mentioned merely to show a consistency of opinion regarding the age of this type of formation.

<u>Tertiary (Undifferentiated).</u> The rhyolite series of the West Hills area is mapped as Tertiary undifferentiated because these isolated hills are separated from known beds by about five miles of alluviated area. The rocks of these low hills are considered as Tertiary because of the rhyolitic character

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1. Baker, Charles Laurence, Notes on the Cenozoic History of the Mohave Desert. U.C. Pub. Dept. Geology Bulletin, Vol. 6, pp. 333-383. 1911.
   Hershey, Oscar H., Some Tertiary formations of southern California. Am. G., 29, pp. 365-370. 1902.
2. Longwell, Chester R., Geology of the Boulder Reservois Floor, Arizona-Nevada. Bull. G.S.A., Vol. 47, no. 9, pp. 1414-1419.

Figure 6

Nearly flat-lying Quaternary gravels northwest of Earp and south of Bennett Fault.

Figure 7

Looking northwest at unconformity between flat-lying Chemehuevi gravels and southwest dipping Copper Basin gravels near mouth of Whipple Wash.

and the degree of deformation. Moreover, the undeformed Pleistocene and younger beds lap onto the volcanics in a depositional relationship.

This rhyolite series consists of light colored lava flows, tuffs and breccias and has an estimated thickness of about 1250 feet.

Pleistocene and Younger Deposits

The younger sediments which are included in the Whipple Mountain area are all nearly flat lying, apparently unaffected by the faulting of the mountains. (Figs. 6 and 7; Plates 19 and 20.) These beds rest unconformably on the Basement Complex and the tilted and faulted Tertiary series. They are grouped as Pleistocene and Younger deposits because no fossils have been found and there is no adequate means of accurate age determination. Several units can be designated by lithologic differences and by unconformable association. The principal units of this younger series are similar to those presented by Longwell[1] in his study of the Boulder Reservoir floor and agree in sequence if not exactly in character. Briefly the units of this younger series in the Whipple Mountain area are in order of their formation: (1) partially cemented river gravels, sands and

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1. Longwell, Chester R., op. cit., pp. 1440-1456.

silts; (2) poorly cemented lake-bed deposits of shales, clays and silts; (3) river gravels and mountain outwash deposited on alluvial fans. Contemporary river and stream gravels, silts and slope washes are also related.

Longwell[1] suggests the abandonment of Lee's[2] term, "Temple Bar conglomerate", on the grounds that the term was applied to deposits of widely differeht lithology and origin. I agree with Longwell, for it is apparent that Lee[3] includes the Copper Basin formation and possibly the Gene Canyon formation in his Temple Bar conglomerate. These have been determined as early Tertiary in age.

Older River Gravels. The presence of older river gravels is suggested only by the occurrence of flat lying partially cemented river deposits underlying lake beds in the Chemehuevi Valley. The exposures are few and poor and are seen only in the deeper washes in the Chemehuevi Valley. It is possible that they should be included in the next overlying unit, but they probably represent a period of river activity prior to the impounding of the Colorado River to form a lake in the Chemehuevi Valley.

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1. Longwell, Chester R., op. cit., p. 1443.
2. Lee, Willis T., Geologic Reconnaissance of a part of Western Arizona. U.S.G.S. Bulletin #352, p. 32. 1908.
3. Ibid., p. 45.

Chemehuevi Formation.

Lake Series.[1] In the northwestern part of the Whipple Mountain area in Chemehuevi Valley, the Chemehuevi formation overlies the Older River Gravels, eroded basement rocks, and tilted Tertiary sediments. In this section the sediments are lake deposits; they were studied in some detail by Noble.[1] His description of the lake-bed series is consistent with my field observations: "Underneath the alluvial mantle lie strata of the lake-bed series and older rocks of Tertiary and pre-Tertiary age. In the higher parts of the tract the lake-bed strata are either covered entirely by the alluvium or crop out only in bluffs along the deeper gullies; but in the lower parts, where the gullies widen out and where much of the alluvium has been removed by erosion, they are exposed over considerable areas and are carved into clay hills or badlands. At some places in the tract low rocky hills of the older rocks project above the lake-bed series and the alluvium. The largest of these hills form the group that rises across the path of Chemehuevi Wash just east of West Well..." Overlying the conglomerate of the older river gravels "...is a bed of brilliantly white

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1. Noble, L. F., Nitrate Deposits of Southeastern California. U.S.G.S. Bulletin #820, pp. 38-47. 1931.

loose-textured shale that ranges in thickness from 15 to 50 feet. In the field this shale was thought to be very fine volcanic ash, but a specimen of it sent to the chemical laboratory of the Geological Survey for determination proved to consist largely of calcium carbonate and was classified as calcarous marl, or chalk...." "Above the white shale is greenish shale 25 to 50 feet thick which is more or less gypsiferous and very thinly laminated, many laminae being as thin as cardboard. This shale passes up into light yellowish-brown or buff shale which here and there contains lenses of sandy material. Both the greenish shale and the buff shale contain a considerable amount of sodium chloride. The greatest thickness of the buff shale as exposed in the area is 175 feet. It is overlain by alluvium so that its thickness as originally deposited is unknown." (Plates 19 and 20.)

River Gravels. Probably contemporaneous with the lake-bed series, but certainly of different lithology, are river gravels which range from thin veneers to continuous sections measuring about 200 feet thick. Also isolated patches are present, the connection with larger bodies presumably destroyed by erosion. The patches and the less continuous gravel beds are found along the Colorado River from

Little Chemehuevi Valley to below the junction of Bennett Wash with the Colorado River, whence broad continuous stretches of nearly flat-lying, crudely bedded and partially cemented gravels are found. (Fig. 6.) Laterally these grade to mountain outwash material, but largely the material resembles present stream gravels with rock types of pre-Cambrian, Paleozoic and Tertiary represented. Degree of rounding and size also vary within the beds and from place to place. On the whole, the pebbles are smoothed and but a few inches to a quarter inch in size although boulders more than a foot long are not uncommon. Occasional silt or clay layers and lenses occur.

These are correlated with the lake-bed series because of association and sequence, for they also rest unconformably on eroded basement rocks and tilted and faulted Tertiary sediments. They are overlain also by still younger outwash material as well as river terrace deposits. All these have been gullied by intermittent streams as has the lake-bed series in the Chemehuevi Valley. Both units are unaffected by the post-Tertiary faulting within the mountains.

Younger River Gravels. Unconformably overlying the Chemehuevi formation, both in the lacustrine phase and the river gravel phase, is a thin layer of loose river gravels which merge to mountain outwash deposited in alluvial fans. This gravel now occurs only as an alluvial capping up to 50 feet thick on the gently sloping mesa-like areas between gullies cut through the Chemehuevi formation. The character varies from poorly sorted sand, gravel and clay, washed from the nearby hills and spread out as alluvial fans, to distinct river gravels with sorted and well rounded pebbles of exotic origin. Distinct river gravels have been found as high as 200 feet above the present level of the Colorado River.

Recent Deposits. Recent river gravels, sands and silts are found along the Colorado River and on the low flood plains. Diamond drill borings at the Parker Dam site showed river detritus to a depth of about 280 feet. The intermittent streams which lead from the Whipple Mountains into the Colorado River have gravel of varying coarseness in their channels. This channel covering is probably at the most only about 25 feet thick, for in many localities within the hills bedrock is exposed in the stream beds.

STRUCTURE

Summary of Structural Relationships

Deformation in the Whipple Mountains is characterized by tilting and faulting and doming on a large scale. Folding exists in a restricted portion of the area and is interpreted to be of minor importance and purely local in effect. Ransome[1] reported the probable existence of a low angle thrust fault in the Whipple Mountain area, but field work proved that preliminary impression to be wrong. Ransome's frankly stated doubts were confirmed, but not without considerable study and additional field work, for the evidence was quite perplexing especially in the strip worked by Ransome along the route of the aqueduct. Fortunately for the writer the Metropolitan Water District's tunnels through the Whipple Mountains were completed during the course of the field work; so some of the baffling points were cleared up by the additional observations made available. It is concluded that the major fault type is normal.

Basement Complex. The area studied in most detail is that eastern portion where the basement

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1. Ransome, F. L., Oral communication and unpublished reports to the Metropolitan Water District.

complex is covered by Tertiary beds. This is because the basement rocks have suffered so much deformation and are so shattered that it is impossible to interpret the structure accurately in the area solely covered by this series. Good structural relationships are exposed in the area studied, but the lack of fossils and definite zone markers preclude the possibility of accurate displacement estimates ever here.

Gene Canyon Formation. A great unconformity exists between the basement complex and the earliest Tertiary beds, the Gene Canyon formation. It is certain that deformation and a great deal of erosion took place during the time interval, but the character of both erosion and structural change is unknown for the data are incomplete. Minor erosional unconformities occur within the Gene Canyon formation, but these have little effect on the whole sequence of sedimentation during this time. Between the end of Gene Canyon time and the beginning of the next deposition, which is closely related in time, the region suffered deformation and erosion. The record of Gene Canyon rocks is incomplete and no determination of the extent and character of the movement can be made. However, from the attitudes of the beds, it is postulated that the deformation was by tilting and normal faulting with very little folding. It was presumably similar to that which occurred later in post-Copper Basin time and was studied in more detail. The average degree of tilting of the Gene Canyon formation was approximately 25° to the southwest, which is the angular difference between the dip of the Copper Basin and that of the Gene Canyon. There are also vague indications of slight folding in one exposure of Gene Canyon a mile south of Parker Dam and another about a mile northeast of Eagle landing.

Copper Basin Formation. The Copper Basin formation, consisting of sedimentary beds and lavas sometimes interbedded and sometimes interfingered, is structurally the most important series in the area, for these beds form the basis for the general structural comparisons. As in the case of the Gene Canyon formation, minor erosional intervals exist within the Copper Basin series but these have little effect on the general problem. As has been stated previously, the Copper Basin beds follow the Gene Canyon in unconformable sequence and are found resting on tilted and eroded older Tertiaries or on the old erosion surface of the Basement Complex. The nature of this contact will be treated later in the consideration of thrusting. The general attitude of the Copper Basin beds shows a northwest strike with a southwest dip, and local variations do not alter the structural grain of the area. Most of the major interior faults are observed in the association of Tertiary beds with the basement complex, and in few cases has a fault been projected for any great distance in the basement rocks unless there is a reasonable degree of certainty that the faults have experienced post-Copper Basin activity. The basement rocks are so shattered and altered and erosion has proceeded so far that in most cases it would be impossible to differentiate safely between pre-Tertiary and post-Copper Basin movements. Moreover, in many localities the basement complex is in such a deformed condition that one could designate a fault to aline with any projection he might choose. I have used caution in this regard.

Pleistocene and Younger Deposits. Pleistocene and younger deposits apparently have been little affected by the deformation which has resulted in the building of the Whipple Mountains and the changing of the attitudes of the older rocks. These younger beds are all nearly flat-lying and demonstrate only depositional and erosional anomalies. Small minor faults and folds observed in these beds are interpreted as being purely local features confined to the individual beds and caused by creep and slippage closely following deposition. Such features are observed in the soft lake-bed series in the Chemehuevi Valley. However, it is possible that the general down-cutting around the Whipple Mountains may be due to a general upwarping of the entire area.

Folds. Folding is of minor importance. As mentioned above, the folds in the Gene Canyon formation are indistinct and the evidence is too incomplete to postulate their cause or consequence. The Copper Basin formation overlies these truncated structures and it is possible to interpret only the later activity. The folding which involved the Copper Basin sediments occurs at one locality in the southeastern part of the Monument Peak mass in the lower area northwest of Cross Roads. Here the folds are shallow open flexures. No other localities show folding.

Faults. Deformation by faulting and tilting has resulted in the building of the Whipple Mountains. Faulting is of the normal type. A few small reverse faults occur, not mappable on the scale used, associated with the tilting and faulting of the blocks. The north and east flanks of the mountains are roughly bounded by a large normal fault with a broad arcuate trace which is easily followed for approximately 25 miles along these margins. The movement along this fault has resulted in the raising of the Whipple Mountains to their present prominence. The interior of the mountains has been broken into several wedge-shaped blocks, which are bounded by normal faults which dip toward one another. The blocks are tilted to the southwest with the Tertiary beds dipping into a northeasterly dipping fault and the basement rocks.

Possibility of Thrusting

It seems necessary, in view of reported investigations, to consider definitely the possibility of the Tertiary mantle being thrust for an uncertain distance over the basement pre-Cambrian rocks. It is my opinion that this type of deformation is not manifest though it is evident in places that some movement has taken place along the contact between these two markedly different formations. As already stated, the area was primarily chosen with the hope of studying a well exposed area of thrust faulting. Preliminary work had indicated some thrusting and because the usual association of older rocks thrust over younger rocks presumably was reversed, other evidence than discordant stratigraphic sequence had to be found. Accordingly, the contact between the basement rocks and overlying beds was followed wherever possible and the relationship examined. Fortunately surface evidence was enhanced by the data revealed in the Metropolitan Water District tunnels. True relationships were seen in these new underground localities.

Surface Observations. During the first few weeks of field work it was thought that the contact was one of great movement, for during that time study was confined largely to the area around the Monument Peak mass. In many places in this area the contact shows several feet of crushed and brecciated material with gouge and some slickensides, all now quite indurated. The grooves and striations in this zone of movement are poorly preserved. Continued and extended examination showed the evidences of movement along the contact to be local and further indicated the Tertiary beds to be laid down on a comparatively even surface with only occasional low swells and depressions. In the area about two miles northwest of Barometer Wash, along the southwest side of hill 2520, a beautiful exposure of the even erosion surface of the basement rock can be seen over a distance of about a mile and a half. Here the Copper Basin volcanics rest concordantly on this even surface. From a distance it appears that the Copper Basin dips steeply into this plain surface, but closer examination proves the deposition to be parallel to it. In the Monument Peak mass apparent discordance -- that is, Copper

Basin beds dipping into the contact surface -- is found to be caused by rather low angle (40°) normal faults in close association with the exposure of the contact at a point where local slippage occurred and where there is a considerable amount of crushed material.

The contact was followed carefully around all of the blocks and evidence of movement was found only in the Monument Peak mass, principally in the vicinity of Barometer Wash and along the base of the cliff on the north side of the mass below Monument Peak. Small areas of slippage were found near the base of the cliff on the southeast side of hill 2760. The Gene Block, the Spring Block, the Copper Block and the isolated smaller cappings in the interior show normal depositional relationship. This condition is also true of the smaller irregular blocks in the lower north hills. The fringe outcrops of Copper Basin material along the southern and southeastern borders show Copper Basin volcanics and sediments lapping the basement rocks in regular depositional contact.

<u>Tunnel Observations.</u> During the driving of the several tunnels through the Whipple Mountains by the Metropolitan Water District the contact between the Tertiary beds and the basement rocks was

cut several times. The steeper fault contacts on the west side of the tilted blocks, with the sediments abutting the basement rocks, are due to normal faulting and are not considered here. The contact in question is seen once in the Colorado Tunnel, once in the Copper Tunnel, and six times in the Whipple Tunnel. In each case the bedding was parallel to the contact, and the basement rocks show up to 220 feet of oxidized zone, which is attributed to be surface alteration now buried. In at least three cases in the Whipple Tunnel a coarse basal conglomerate occurs at the contact. In short, the evidence as exposed in the tunnels points to deposition of the Tertiaries, principally Copper Basin beds, on the eroded and oxidized surface of the Basement Complex, with no testimony of thrust faulting.

Folds. In addition to the direct data predominantly pointing to normal deposition of Tertiaries on the eroded surface of the basement rocks, it can be inferred that if there had been any large amount of thrust movement which involved the relatively thin mantle of Tertiary beds as an overriding mass, these beds would show more compressional features than they do. As it is, these features are conspicuously absent and the blocks of tilted Tertiary material are remarkably intact and unwarped. Minor thrust faults are not present and there is a decided lack of contortion and folding, even in the less competent phases. The minor folds which occur on the southeastern side of the Monument Peak mass have been mentioned. These can be accounted for by other means than compression due to thrusting. A section through the Whipple Mountains taken from northwest to southeast shows a broad warp of the Copper Basin volcanics with the volcanics nearly flat-lying northwest of Monument Peak for a distance of about five miles. (Cross-section of E-E', Plate 5-6.) From the section as well as in the field there is indication that these beds probably extended across the mountains at one time but have been eroded since. Southeast of Monument Peak the beds dip sharply up to 35°, and the volcanics are overlain by sediments which flatten and then become gently folded into a series of two anticlines and two synclines over a distance of about four miles to the Colorado River where the Tertiary beds are lost under a thin covering of younger beds. It has been stated also that the Copper Basin sediments in the Whipple Mountains probably were deposited in an extensive basin lying to the south and southeast. It is now assumed that these open undulations might be due to compression developed by slumping during the rise of the Whipple mass and the related subsidence of the basin. The Monument Peak mass is the only block in which there appears to have been slippage along the contact; it is the only block in which folding is seen; and it is in this same general broad mass that a section shows large scale warping.

North Hills. The low hills to the north are complex on a smaller scale. They show both reverse and normal faults, but in an association which indicates upthrust and downdropped wedges rather than extensive overthrusting. There is no evidence here that would alter the opinions stated.

The Fault Pattern

General Features. The fault map of the Whipple Mountains shows two major sets of fractures: (1) a broadly arcuate fault, the Whipple Fault, which outlines the entire mountain mass on the north and east sides; and (2) the interior faults which trend in a general northwest-southeast direction. Northwest trending breaks in the North Hills area for the most part agree in direction with the interior faults. Fracturing in the West Hills, although too remote for direct comparison, show a roughly east-west set of normal faults displacing a northwest trending set. The direct evidence of movement in these two sets indicates the movement is normal in character.

Major Faults.

Whipple Fault. The most important fault in the entire area, the Whipple Fault, is discussed in detail later in this section on page 104.

Interior Faults. Observation of the fault pattern shows the fractures mapped to be grouped toward the eastern limb of the arcuate trace of the Whipple Fault but still inside the arc. This grouping may be apparent only, for it is possible that similar faults exist in the area west of the Tertiary covered area, but there is no justification to assume post-Copper Basin activity west of the Monument Peak Block.

Another significant factor to be gleaned from the fault map is the apparent, but not distinct, tendency for the interior faults to radiate or flare toward the southeast from a central area along Whipple Wash. It should also be noted that these interior faults terminate not far beyond the Whipple Wash area and that a zone in which no faults have been mapped varies up to three miles wide between the Whipple Fault and the ends of these interior faults. In this zone, devoid of fractures, there are no signs of faulting; even the basement metamorphic rocks show no signs of contortion or breakage. The schistocity of the rocks in this area dips regularly northwest. (Plate 15.)

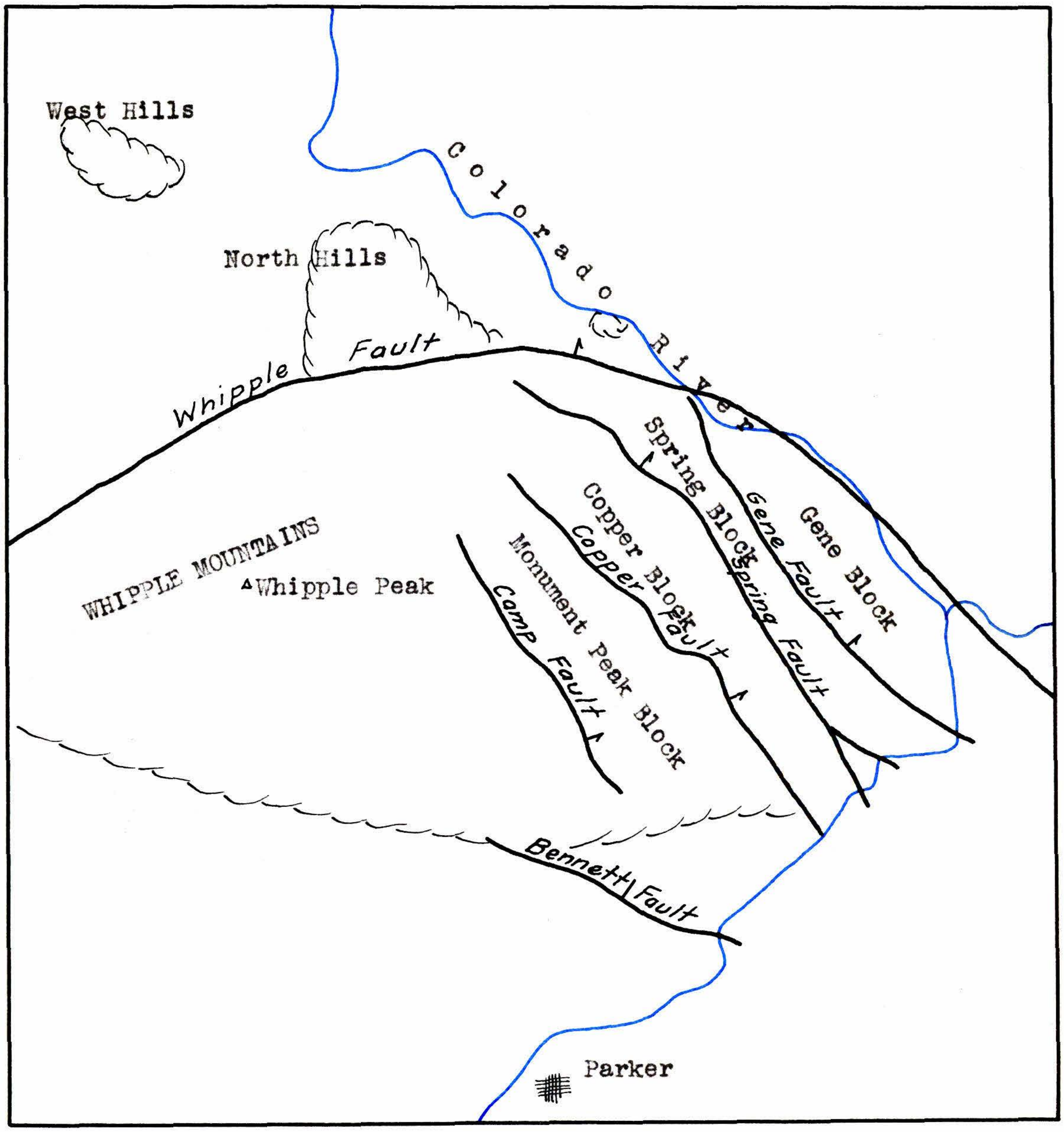
The major interior fractures are normal faults of the hinge or rotary type with the axis of rotation located roughly near a central area running from the Colorado River at Murray Flat southwestward along a line about 1 1/2 miles northwest of Whipple Wash for a distance of about five miles. This termination of the interior faults before they intersect the Whipple Fault makes the consideration of the relative ages of the movements indefinite, and the conclusion in this regard is largely one of opinion.

There is an increase of displacement on the interior faults toward the southeast, a condition readily seen from the oblique air photographs, in the sequence of cross-sections, and on the maps showing the areal geology. (Plates 8, 9, 11 and 16.) The geologic map shows that in the northwest portion of the main mass of the Tertiary covered area in the vicinity of Whipple Wash the streams have cut through the cap rock and exposed Basement Complex only in the channels. This condition precludes faulting of any appreciable amount of displacement. It is true that these capping rocks have been broken and tilted slightly, but they are cut by faults which have comparatively little displacement. (See section B-B'.) Southwest along Whipple Wash the stream channel is all in basement rocks and the capping volcanics appear to have been broken by nearly vertical normal faults of small displacement with the blocks of Copper Basin tilted somewhat but not shattered. The rotational movement during the slight tilting here was probably taken up in the further shattering of the already fractured basement rocks. A similar condition is exhibited in the northwest end of the Spring Block where the Spring Fault dies out. (Plate 16.) Moreover, the elevations of the contacts of the several isolated remnants of Copper Basin volcanics in the central portion of the area are such that these separate patches could be connected without postulating intervening faults, but rather a once continuous volcanic covering, broadly warped.

The outcrops of the Tertiary rocks in the interior show little tilting or faulting, but proceeding southeastward displacement on the breaks becomes greater and the areas of Tertiary rocks are separated and tilted markedly. Displacement varies from zero to at least 1500 feet on some faults in a distance of about eleven miles. This condition is well shown in the oblique air photographs, especially Plates 8, 9 and 11.

<u>Minor Faults.</u> Minor faults are numerous and their strikes are varied. However, those minor breaks which are mappable on the scale used show a tendency to follow the general trend of the larger faults, to form auxiliary slices within the major

Map no. 2



Sketch showing the relation of the structural blocks in the Whipple Mountains blocks, or outline smaller blocks which are within or broken from a major block. In the former case the pattern tends to assume a braided character which is quite pronounced in the area immediately north of Whipple Fault. In the latter case nearly east-west or north-south minor faults occur to outline minor blocks.

Fault Blocks. The interior faults comprise one system based on the general trend, but there are pairs of faults with opposing directions of dip but like character of movement. The faults in the interior system have divided the area into irregular blocks elongate in a direction parallel to the strike of the faults. Four main blocks are thus delimited which in themselves contain minor blocks delimited by minor faults. The major blocks are from northeast to southwest: (1) the Gene Block, (2) the Spring Block, (3) the Copper Block, and (4) the Monument Peak Block. (Map 2.) The structural character of the individual segments as well as the features of the faults which outline them is considered in sequence from northeast to southwest.

Description of Faults and Fault Blocks

The Gene Block.

General Features. The Gene Block lies in the northeast portion of the area south and west of the Colorado River. It includes an elongate segment oriented northwest-southeast about eight miles long and about 2 1/2 miles wide. The northeast boundary is indefinite, but is taken to be the projection of the Whipple Fault which nearly parallels the Colorado River here. The southwest boundary is the northeast dipping Gene Fault which is traceable for the full length of the block. (Plates 12, 13 and 14.) The block as a whole is tilted approximately 30° to the southwest, for the Copper Basin beds show an average dip of about this degree in that direction; they vary from 10° to 45°. The Copper Basin beds are exposed over almost half the area of this block and are mainly well-bedded coarse sandstone and conglomerates which grade into agglomerates and volcanic breccia near the northwest end of the outcrops. The lower part of the Copper Basin section is hard and forms the crest of the ridge of the northeast rim of Gene Basin. The upper portion of the formation becomes gradually less indurated to poorly cemented and loose gravels, and underlies the floor of the comparatively low lying Gene Basin. The contact between the Copper Basin formation and the Basement Complex on the northeast is clearly a depositional contact and for the most part lies high on the northeast side of the ridge at the base of the cliff

Figure 8

Looking northwest across Gene Canyon at the tilted Gene Block. About $1\frac{1}{2}$ inches to the left of the pole steep dipping Gene Canyon beds can be discerned below the Copper Basin beds.

formed in the hard blocky conglomeratic beds. The contact is irregular and shows occasional scour channels filled with coarse clastic sediments. No evidence of movement along this contact was observed.

Southeast of Gene Canyon in Desilt Wash the best section of the Gene Canyon formation is found. These beds also show tilting, and they dip to a greater degree than the Copper Basin beds. Although the beds are nearly vertical at the contact with the basement rocks to the northeast, the contact is depositional and no fault evidence was observed except some bedding plane slippage in the occasional shale layers near the bottom of the section.

The unconformity between the Gene Canyon formation and the overlying Copper Basin formation is well exposed in Gene Canyon and can be followed southeastward from this point to the Colorado River over a distance of about three miles. The angular difference, although varied, will average about 25°. (Fig. 8.)

The presence of a fault on the southwest side of the block is evident, for sedimentary beds are seen to dip directly into basement rocks toward this margin. The character of the movement is not

Figure 9

Looking northwest at an exposure of the Gene Fault about $1\frac{1}{2}$ miles northwest of the Colorado River. Copper Basin beds to the right; basement rocks to the left.

so clear. This fault is termed the Gene Fault.

The Gene Fault. The Gene Fault is traceable over a distance of approximately ten miles in a general northwest direction from Gier's Basin to the Colorado River about 1 1/2 miles southeast of Whipple Wash. For the first 6 1/2 miles its trace is clearly followed by the anomalous relationship between the Tertiary sediments and the basement rocks, but for the remaining 3 1/2 miles the break is entirely in basement rocks where its course might be questioned. However, there is a distinct alinement of topographic features such as saddles, weathered areas, ridges and drainage grooves, accompanied by a greater amount of brecciated basement rocks, with the projection of the definite fault trace in Gene Basin. This extension of the Gene Fault into the basement area does not show the hinge character of this fault, but the lack of any escarpment in this northwest extension may be due to a lesser amount of displacement.

The actual break is exposed in several localities and although these exposures are not excellent the average dip was taken as 40°-45° to the northeast. The best exposures of the Gene Fault are found over the first three miles northwest from the Colorado River at Gier's Basin. (Fig. 9.)

There is considerable gouge and fault breccia up to eight feet thick accompanying the fracture, but the material is either so severely cemented or subsequently weathered that detailed examination yielded no information concerning movement. The breccia included both sedimentary and basement material, but the basement material is decidedly predominant. Drag is exhibited in the sediments both on a small and on a large scale. Close to the fault, in two cases, short synclinal folds about 150 feet wide occur, while over the entire exposure the Copper Basin beds flatten from 45° at the northeast contact to as low as 10° near the fault. This break is then considered to be a normal fault dipping northeast at 45° with the hanging wall of Tertiary material relatively dropped at least 1500 feet.

Aside from the actual exposures of the Gene Fault, its surface trace through the southwest side of Gene Basin can be closely followed by the topographic difference between the basement rocks and the Tertiaries. For the most part the fault is covered by recent outwash material, but the Basement Complex stands higher, forming a distinct escarpment which faces northeast above the soft sediments of the upper portion of the Copper Basin formation.

Faults within the Gene Block. It has been stated that the sedimentary beds overlie the basement rocks in depositional contact, so any tilting of the block involved basement rocks as well as the Tertiary mantle. The surface evidences of faulting within the basement northeast of the Tertiary beds are indefinite, and are limited to the agreement of topographic features such as saddles, grooves, ridges and weathered zones which might run across the drainage pattern, there being no definite escarpment. (Plate 14.) Brecciated and fractured zones in these gneissic rocks are omnipresent. However, the Colorado Tunnel section disclosed some rather helpful information. Throughout the tunnel in the area of basement rocks fracture zones were seen, mostly striking northwest and dipping southwest from 20° to vertical. It would be difficult to choose a single fault, the movement along which could be deemed most intense. The impression is that the movement has been cumulative on all of the breaks, creating a zone of movement throughout the basement area. Two areas which showed the greatest amount of gouge and brecciated material in the tunnel were projected along their dips to the surface. They have been chosen more as representatives of the zone of faulting rather than as individual faults. The topographic features on the surface where these projected fractures emerged were consistent with faulting. Alinement of the topographic features indicates a northwest strike and a steep dip slightly southwest. Being all in basement rock, direction of movement is uncertain, but probably it is normal with the southwest side depressed. Also the topography indicates that the two faults chosen in the tunnel join to the south to form a single break. The probability is that the many slip surfaces seen in the basement rocks as penetrated by the tunnel represent a fault zone in which the planes should be represented by a braided pattern both in plan and section.

Other fractures within the Gene Block are vertical or steeply dipping normal faults, and are either bifurcations from the major Gene Fault or adjustment breaks running nearly north-south and ending against northwest trending fault.

The Spring Block

General Features. Topographically the Spring Block, at first glance, seems to be a northwest extension of the Gene Block, but closer inspection shows it to be a separate unit. (Plates 13 and 16.) It appears that there might have been a tectonic attempt to create a large single structural unit to include these two blocks, but the incompetence of the rocks to act as a unit caused them to separate in the vicinity of Black Metal Wash. The Spring Block also lies in the northeastern part of the area south of the Colorado River near the central part of the arc formed by the trace of the Whipple Fault. The block is elongate in a northwest-southeast direction, about six miles long and up to two miles wide in the area where definite information is obtainable. From the standpoint of structural unity, it probably should include an additional six miles between Black Metal Wash and the Colorado River at Gier's Basin. This latter six miles is all Basement Complex in which little definite or conclusive data are available. That portion in which there are pertinent details extends northwest from Black Metal Wash across Whipple Wash to Little Chemehuevi Valley and the Whipple Fault. The northeast limit is the Gene Fault extension, while the southwest limit is the Spring Fault.

The block as a whole is tilted about 40° to the southwest, though the Tertiary sediments flatten to 15° in the vicinity of the Spring Fault. The average high degree of tilt is due to secondary tilting by the complex faulting in the central part of the area. However, at either end of the block, on the "three-fingered" promontory and near Black Metal Wash, the tilting is less, about 30°.

The capping rocks in the block, which disclose the tilting and faulting, are the lower part of the Copper Basin formation which is here composed mainly of volcanic material of different types in complex association overlain by coarse bedded sediments. The lower hard volcanics form the ridge tops and the base of the formation, as in the Gene Block, lieshigh on the northeast side of the ridge at the base of the steep cliff formed by the massive volcanics in regular depositional contact with no slippage apparent. In the central portion of the block the volcanics are only about 300 feet thick but they thicken northwestward. The sediments overlie the rough flow surface of the lavas and show a partial section up to about 600 feet thick. As in the case of the Copper Basin formation in the Gene Block, the Tertiary rocks are remarkably intact for the degree of tilting and the amount of faulting.

Similar to the conditions in the Gene Block, the Copper Basin rocks dip toward and into the basement rocks to the southwest, so a fault on this southern margin is evident. The break is readily followed in a somewhat sinuous trace. This fracture has been termed the Spring Fault from Willow Spring which issues from the fault zone about a mile southeast from Whipple Wash and from which good potable water can be obtained the year round.

The Spring Fault. The Spring Fault forms the southwest boundary of the Spring Block. This fault can be followed definitely from the northwest end of the "three-fingered" ridge southeastward for a distance of at least six miles to Black Metal Wash, after which the trace is less definite. The trace then apparently swings a bit to the south and follows a zone of intense fracturing through basement rocks for about four miles after which it swings eastward again to connect with a fault exposed at the Colorado River at the south end of Gier's Basin. The trace of the fault in the first six miles is broadly sinuous, but on its extension into the basement rocks the trace is nearly straight across the rugged topography, curving to connect with a vertical fault at its southeast end.

Exposures of the fault are numerous in the neighborhood of Whipple Wash and northwest from it. As is the case of most fault exposures in the area, slickensides and breccia are strongly cemented and slip surface is badly weathered. Detailed examina-

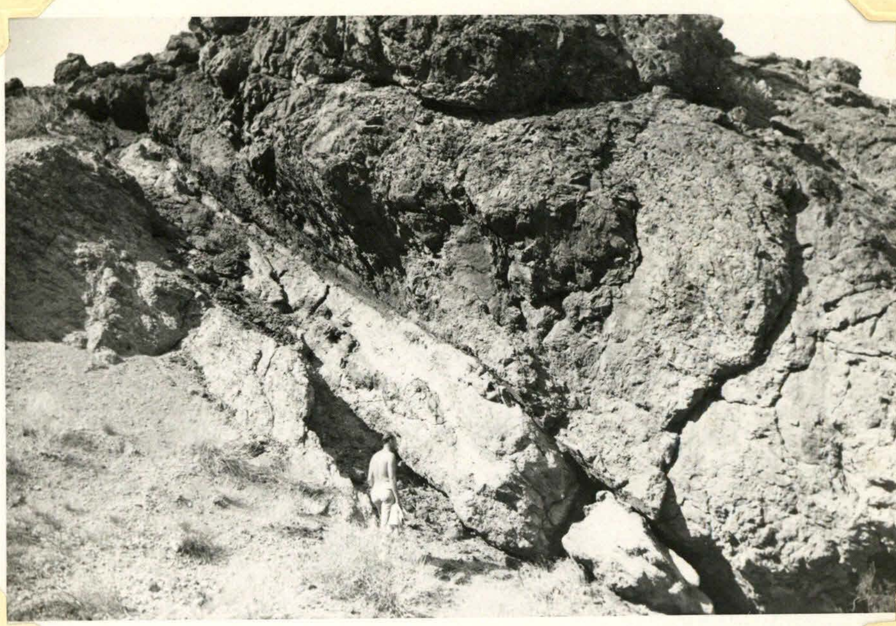


Figure 10

Exposure of the Spring Fault in Whipple Wash

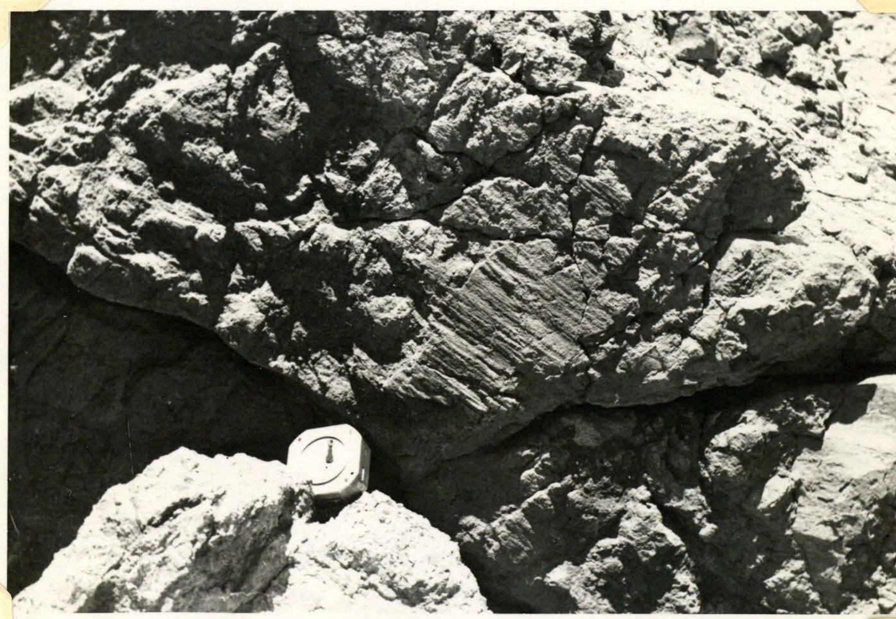


Figure 11

Detail on the hanging-wall of the Spring Fault tion yields meager data. The fault is exceptionally well exposed where the Spring Fault crosses the Whipple Wash, at the south side of the deep gorge cut through massive volcanics of the Copper Basin formation. Up to thirty feet of gouge and brecciated material composed mostly of altered schist are exposed here. The fault dips northeast about 40°. The hanging wall is sharp and still retains patches of slickensides with scratches. These grooves pitch to the southeast about 45° and indicate an oblique movement. (Figs. 10 and 11.) However, other cases indicating oblique movement are so rare that it is unsafe to postulate conclusions as to this type of slippage. Exposures of the fault are almost continuous northwestward for about a mile, where it bifurcates. At this point the fractures steepen to 60° and these two faults cut through the volcanics. The branching of the fault is responsible for the "three-fingered" character of the ridge. South of Whipple Wash the Spring Fault cuts off a large block of Copper Basin volcanics which are nearly flatlying in depositional contact on basement rocks. This mass although close to the Spring Block really belongs to the next block southwest -- the Copper Block. There are further exposures of the Spring Fault in Willow Spring Wash which show a northeast dip of about 45°, but after about a mile southeast up this wash the break is covered by outwash material. However, a slight escarpment marks the path of the fault until it is again recognizable northwest of Black Metal Wash. Southeast of this point the fault is projected through basement material on the basis of a continuous strongly altered zone. The straight path of the intensely fractured area through the basement rocks indicates a steep dip on the plane. This is partially verified by fractures in the basement rocks themselves as well as by a dip of 80° to the southwest where a large fault in the same alignment is cut by the Copper Tunnel. Continuity of the steepness of this fault in a southeast direction is seen in the vertical slip surface exposed at the Colorado River.

The hinge or rotary character of the Spring Fault is evident. The movement at its northwest limit is slight, and the two branches of the Spring Fault have broken the ridge into three segments. The volcanic capping of this ridge is surrounded by basement rocks on three sides and the contact is one of deposition. (Plate 16.) Proceeding southeastward there is a gradual increase in displacement until at the locality of cross-section B-B' the displacement is at least 1000 feet. Southeast beyond Black Metal Wash displacement estimates are impossible, basement rocks being on both the hanging and foot-wall sides. It should also be noted that in this latter area there is no perceptible escarpment which might establish a recency to the activity of the fault here.

Faults within the Spring Block. There has been no tunnel through the Spring Block, so there is no evidence corroborative of the topographic indications of faulting. The basement rock on the northeast side of the Copper Basin material contains more definite information, for there exist continuous fractures which are easily traced. These fractures are steeply dipping to the southwest and join a nearly vertical fault which follows the cliff face of the volcanic capping. This latter fault in turn is shown to branch from the Spring Fault southeast of Black Metal Wash. The branch faults in the north-east portion of the block end at a steep cross break which runs northeast from the Spring Fault just south of Whipple Wash. In this area near Willow Spring is a complex group of minor fractures all of which end at the northwest trending faults or at the Whipple Fault. This is probably a zone of breakage in the adjustment to the tilting of the Spring Block, complicated by its proximity to the Whipple Fault. Small secondary blocks in this adjustment area show abnormal tilting up to as high as 60°.

It should be noted also that even in the less indurated beds of the Copper Basin formation there are practically no minor faults or contortions, the block of Tertiary remaining virtually a unit throughout the deformation. The basement rocks on the other hand are highly fractured.

The Copper Block.

General Features. Southwest from the Gene Block and the Spring Block lies the Copper Block, so called because of its association with Copper Basin. Like the previous two blocks, the Copper Block is elongate in a northwest direction, extending for about ten miles from the Colorado River at about Eagle Landing to about 1 1/2 miles northwest of Whipple Wash. (Plate 9.) The block is about two miles wide between the Spring Fault on the northeast and the Copper Fault on the southwest.

The block is considered here as a structural unit though along its length adjustments to tilting and faulting have caused the Copper Block to break, dividing it into three minor blocks still of considerable magnitude. The most pronounced break of this kind is at about the mid-point of the length of the block in Bandit Pass. Another is in the slightly constricted area of Copper Basin rocks two miles northwest of Bandit Pass. These two adjustment areas divide the Copper Block into (1) the West segment, (2) the Middle segment, and (3) the East segment.

Rocks included within the Copper Block belong to the Basement Complex, the Gene Canyon formation and the Copper Basin formation. The Basement Complex lies wholly on the northeast side of the block; the Gene Canyon formation occupies the southeast mile or so and has isolated cappings of Copper Basin material; the Copper Basin formation covers the southwest part of the block and several segregated promontories within the basement area. Everywhere within this block where the Copper Basin formation is in depositional contact with the basement no evidence of slippage occurs. Tilting in the block is not everywhere the same, but varies in the several segments and is shown by the attitude of the Copper Basin beds which dip southwestward into the Copper Fault.

The West Segment. The west segment is capped by lavas and pyroclastics which dip about 35° southwest at the Copper Fault near the divide between the Whipple Wash drainage and the Copper Basin drainage.

However, in crossing this segment toward the northeast it is observed that the capping is warped upward and the bedded rocks near the crest of Hill 2854 dip in the opposite direction. This warped condition is substantiated by the contact along the east side of Whipple Wash, and also by the fact that the bases of the isolated cappings of volcanics between the main ridge and the Spring Fault agree in elevation to conform to a gentle upwarp between the Copper Fault and the Spring Fault. The contact between the Copper Basin volcanics and the underlying basement rocks is depositional along the northeast side and the northwest side of 2854 ridge. The contact on the northeast side lies high up on the ridge slope at the base of the almost vertical cliff formed in the massive lavas, while in Whipple Wash the contact displays the warping and approaches the channel, although it is still well up on the slope.

The Middle Segment. The middle segment shows the most evidence of tilting, for the bedded material dips on an average of about 40° to the southwest. The Copper Basin material in this section consists of indurated, interbedded and interfingered lavas and pyroclastics and sediments of about 600 foot thickness in the lower portion of the section, but in the upper part of the formation there is a thickness of up to 800 feet of well bedded softer, coarse sediments. The beds show quite a variety of dips all to the southwest; they average 35° to 40° in the steep slopes in the harder rocks of the ridge, but out in the basin the softer bedded sediments show dips as high as 80°, with some overturning near the Copper Fault. Warping is not as evident in this segment as in the west segment, but it is suggested in the steepening of the beds toward the southwest. The contact between the Copper Basin beds and the Basement Complex on the northeast side of the ridge, as usual, lies high up on the northeast side at the base of the steep cliff. The contact is depositional, although it is not as easily followed in this segment because of a wide vertical fault zone which closely follows the margin of the cliff. (Figs. 17 and 18.)

Between the west and middle segments is an area of complex but not intense faulting. This is probably a zone of weakness in the Copper Block brought about by the southeastern limit of the more massive volcanic rocks of the west segment which give way to thinner flows and pyroclastics.

The East Segment. The east segment begins at Bandit Pass and extends southeastward to the Colorado River. With the exception of the Gene Canyon beds at the southeastern end of the block and small remnant patches near the center of the northeast side, the Copper Basin formation, which demonstrates the structural relationships, is composed of well bedded coarse sediments of varying hardness. No warping of the type found in the west and middle segments is found in this part of the block. On the contrary, the beds show a diminishing dip toward the southwest and the Copper Fault. The average dip of this segment is about 30° with the beds varying generally from 45° to 20°. The contact between the basement rocks and the Copper Basin formation is not well exposed in this segment, for a zone of closely spaced northwest trending vertical faults follows the northeast limits of the Copper Basin rocks high up on that side of the ridge. (Figs. 17 and 18.) In the Copper Tunnel the contact was penetrated and found to be depositional, showing a zone of weathering in the basement material and the Copper Basin beds parallel to the old erosion surface. At the few localities where the contact was exposed at the surface it was found to be depositional with no evidence of slippage.

Near the mid-point of the northeast limit of sediments there is a small patch of Gene Canyon formation. The unconformity between the two Tertiary formations is clearly seen for the Gene Canyon beds dip 65° to the southwest while the Copper Basin beds dip 45° in the same direction. The extent of this remnant cannot be defined beyond the area exposed, for these beds were not encountered in the Copper Tunnel.

At the southeast end of the Copper Block there is one of the most extensive exposures of Gene Canyon formation. The structure in this area is difficult to unravel, for undoubtedly there is a complication between post-Copper Basin and pre-Copper Basin deformation. Pre-Copper Basin movement cannot be judged from data obtained from such a limited area. I have mapped only those main structural features which are clearly post-Copper Basin. Tilting, if any, in this part of the area is not clear in the Gene Canyon beds, but in the narrow slice block one capping of Copper Basin material dips as high as 45°. However, this cannot be attributed to tilting on a large scale, for other isolated cappings in the same general sliced zone are nearly flat-lying or prove to be down-dropped wedges of material broken from the main block. The Gene Canyon formation itself has a general southwest dip, although it also shows some folding and steepening near its contact with the basement rocks.

The Copper Fault. Again it is evident that the southwestern side of the main block is a fault with the Copper Basin beds dipping down into the basement rocks. (Plate 9.) Because the fault was recognized first in Copper Basin, it has been named the Copper Fault. The Copper Fault is well exposed almost throughout its length and might be considered the type fault of the interior faults. The break can be followed easily from Whipple Wash southeastward for a distance of about twelve miles to the Colorado River just north of Eagle Landing whence it continues in the area eastward. The trace of the fault is sinuous due to changes in dip, changes in strike and differences in topography.

In the first 2 1/2 miles southeast from Whipple Wash the actual fault is poorly exposed. The straight course of its path up the steep tributary canyon indicates a rather steep dip, at least steeper than that recorded in the first point of observation. Near the drainage divide the slip surface is exposed and shows a northeast dip of 45°, which dip is sustained until about 1 1/2 miles southeast of Copper Basin. Southeastward from this point the plane steepend and exposures show dips of about 60 to the northeast. There is an indication of even further steepening across the Colorado River to the east from

Figure 12

Looking southeast toward the lower end of Copper Basin, showing the bedded character of the Copper Basin formation and the tilting of the Copper Block. The Copper Fault runs diagonally from narrow notch in the skyline about an inch from the right hand side to the center foreground.

Figure 13

Looking southeast at the bedded Copper Basin sediments in the tilted Copper Block.

Figure 14

Looking southeast at an exposure of the Copper Fault in a prospect shaft at the southeast end of Copper Basin.

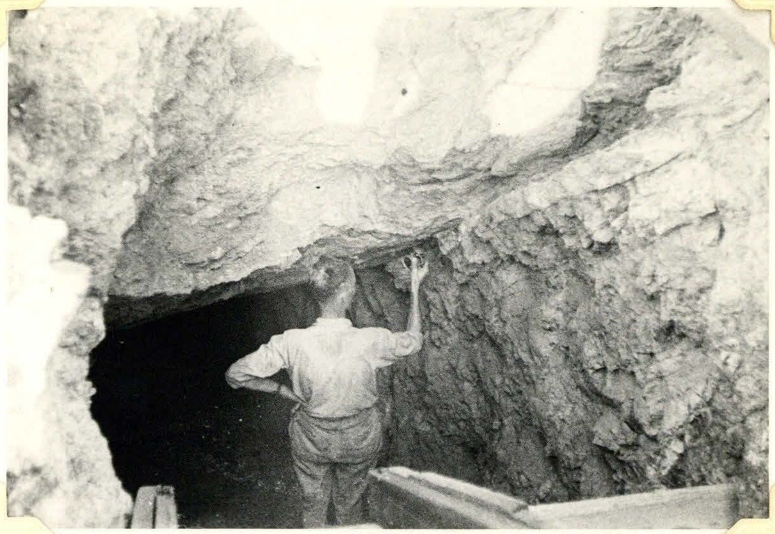


Figure 15

Exposure of the Copper Fault dipping northeast near the southeastern end of Copper Basin. Copper Basin formation in the hanging wall and Basement Complex in the foot wall.

Figure 16

Looking northwest at an exposure of the Copper Fault near the southeastern end of Copper Basin. Copper Basin sediments to the right; basement rock to the left.

the straight incision seen in the air photographs. (Plate 9.)

Through Copper Basin numerous exposures of the Copper Fault substantiate the dip and give some idea of the movement on the fault. (Figs. 14, 15 and 16.) Considerable drag is exhibited in the softer sediments indicating down throw of the hanging wall. In the central part of Copper Basin, opposite the middle segment, is a sharp overturned syncline close to the fault. In the lower end of the basin near the Copper Basin damsite the flattening of the beds from 45° to 20° is probably due to drag on a larger scale. (Figs. 12 and 13.)

The fault material is all well cemented and weathered, and for the most part little evidence of direction of movement is preserved. However, at a point about a half mile southwest of the damsite near the lower end of the basin a beautiful exposure of the fault has been opened up by an inclined prospect shaft. (Figs. 14 and 15.) This prospect shaft was sunk in order to test the mining possibilities of copper mineralization along the fault zone at this point. The hanging wall is clean cut and forms the back of the shaft. Striations are parallel to the dip, but no data were obtainable on the movements of the two sides. A good exposure on the south side of a wash about one mile northwest from the Colorado River also showed vertical striations.

About three miles northwest from the river the fault map shows the Copper Fault dividing into two branches toward the southeast. The south branch was not mapped in the field but has been taken to be present from a straight incision which continues on both sides of the river in perfect alignment, seen in the oblique air photograph (Plate 9). This southern branch cuts across rugged basement rocks, keeping a straight course regardless of the elevation, so it must be steep or vertical. Its connection with the Copper Fault is clear.

The movement on the Copper Fault has been also of the hinge or rotary type. The displacement is greatest at the southeastern points near the Colorado River and decreases to nil northwestward just beyond the Whipple Wash. Whipple Wash has cut through the capping of volcanics, and the Basement Complex is exposed deeply in the channel. The volcanics on the northwest side of Whipple Wash are entirely surrounded by basement rocks and at the point where the Copper Fault should pass through this mass practically no sign of displacement shows. The displacement at section B-B' southeast of the wash is about 300 feet; at section C-C', about four miles still farther south-

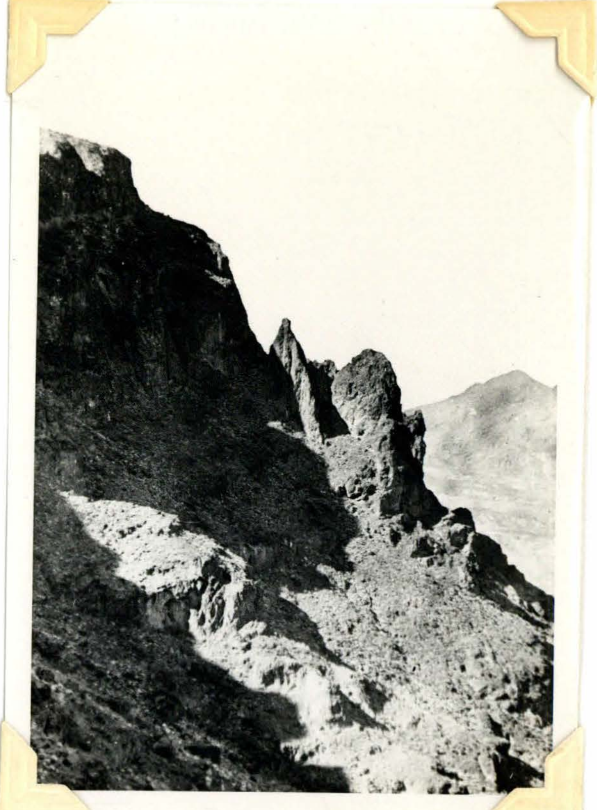


Figure 17

Looking northwest along the zone of steep faults on the northeast side of the Copper Block.

Figure 18

Looking southeast along the northeast side of Copper Block -- West segment.

east near Bandit Pass, the displacement is about 2500 feet; and near the southeastern end of the Copper Basin outcrops in the block, the displacement is at least 3000 feet.

Faults Within the Copper Block. Along the northeast side of the ridge formed by the hard tilted Copper Basin rocks, a fracture a few hundred feet wide continues practically the length of the block. (Figs. 17 and 18.) The faults in this zone are very steep to vertical. They are discontinuous and tend to swing out into the basement rocks or cut back into the Copper Basin beds where they are lost. The zone is one of thin slices with some of the pieces dropped farther or tilted more than others. A good example of this is seen on the northeast side of the east segment where a wedge-shaped piece of Copper Basin formation has been dropped and tilted southwest, while just southeast a portion of the Copper Basin material rests almost horizontally on a relatively higher base. Continuing southeastward this zone swings to join the Copper Fault just northwest of the Colorado River.

No faults in Basement Complex are shown on the map. This is not a true picture for, as reiterated, the basement is notably fractured. The section in these rocks penetrated by the Copper Tunnel shows many fractures which strike in a northwest direction and dip steeply southwest.

On the southeast end of the Copper Basin outcrops in the Copper Block a strong fault strikes N70°E and dips 60° northwest. The area relationships indicate this to be a normal fault.

The Monument Peak Block.

General Features. The Monument Peak Block lies southwest of the Copper Fault and embraces a larger area than any of the blocks so far discussed. (Plates 8 and 9.) The name is chosen from Monument Peak, a tall spire of volcanic rock seen for miles around and used as a triangulation station and prominent landmark. (Frontispiece.) The block extends northwest from the Colorado River at Cross Roads to about two miles northwest of Whipple Wash. Its width averages about three miles southwest from the Copper Fault. The block contains several prominent northwest striking faults and some conspicuous minor tilted blocks on the southwest side of the main block.

The rocks involved in the Monument Peak Block are parts of the Basement Complex, the Gene Canyon formation, and the Copper Basin formation. The Basement Complex lies in the area northeast of the Monument Fault and completely surrounds the volcanic area to the northwest in the vicinity of Whipple Wash. The Gene Canyon formation is, as usual, sporadically represented by a fair sized, complexly broken area on the west side of the Colorado River at Empire Flat, a narrow fringe near the base of the cliff on the northeast side of Monument Peak, and a tiny patch on the south side of hill 2760. The Copper Basin formation covers the main portion of the area. It is composed of dark andesitic lavas and pyroclastic in the high comparatively flat-lying area northwest of the folded area (Fig. 18), and is made up of brick-red, well bedded sandstones and conglomerates in the lower lands toward the Colorado River.

It is rather difficult to summarize the structural adjustment of the Monument Peak Block for it has some characteristics peculiar to itself as well as features common to the general area.

Northwest of Monument Peak and separated from it by about 1 1/2 miles of basement rocks is a lava capped area which extends to the limits of the block beyond the Whipple Wash. The capping here is up to 800 feet thick and is entirely surrounded by basement rocks, exposed in many places by the deep ravines which have cut through the volcanics. (Fig. 19.) Faults which show considerable displace-

Figure 19

Looking southwest across Copper Basin at the nearly flat-lying Copper Basin volcanic of the Monument Peak Block.

Figure 20

Looking northwest across Copper Basin at the broken but not greatly displaced area of Copper Basin volcanics of the northwest part of the Monument Peak Block.

ment to the southeast cut this part of the block, but the movement has not been great in this section. In the immediate vicinity of Monument Peak the base of the lava capping conforms in elevation to the base of that to the northwest to form the gently warped surface as suggested by section E-E' and Plates 5 and 6. About a mile southeast of the spire the beds dip down in that direction as much as 35° after which they become gently undulating to flat. Cross-section E-E', taken in a northwest-southeast direction, shows a monoclinal structure with the northwest limb broadly warped and the southeast limb gently folded.

Tilting of the block as a whole is not as clear or intense as it is in the blocks already treated, but there is a tendency for the block to dip slightly to the southwest. Two small blocks on the southwest side of the Monument Peak Block and bounded by the Barometer Fault and the Camp Fault show as much tilting as the other larger blocks. The relationship is shown on cross-section C-C' and B-B'. A gentle up-warping occurs also in a northeast-southwest direction. (Figs. 19 and 20.)

In a previous paragraph it was pointed out that there is a certain amount of ground-up material at the contact between the Copper Basin formation and the Basement Complex. The point is that even in this block the existence of a brecciated zone is not universal, but rather limited in its occurrence. It is, therefore, thought that the occasion for its creation is local.

Folds. The folds in the Monument Peak Block have been touched upon. Two anticlines and two synclines occur in the area of well bedded sediments northwest of Cross Roads. Proceeding southeast from the Monument Peak area where the sediments dip off the escarpment is a gentle open syncline, the axis of which can be traced for about two miles from the Monument Fault. The axis tends to swing a bit north near its western end where the beds dip off the higher mass to the southwest into Barometer Fault. About 1 1/2 miles southeast of the axis of the syncline is an anticline, both limbs of which dip about 25°. The axis of this fold can be traced westward from Monument Fault for about 2 1/2 miles, but proceeding in that direction the dips become flatter and the fold is lost in a general southeast dipping homocline. The syncline which follows the anticline about 3/4 mile southeast is still gentler, its limbs dipping only about 10°. This fold is traceable only over about 1 1/2 miles southwest from Monument Fault. The folds are cut off by Monument Fault but the dips steepen near the fault.

Faults. As is the usual case in the interior faults, the strike is generally northwest-southeast. In the discussion of the other blocks, the predominant faults have been those on the southwest boundary of the blocks with the other breaks less definite. In this case, however, the fault best exposed over the longest distance is one near the northeast limits of the block, while those on the southwest side are shorter and clear only at certain localities. The major fractures in the Monument Peak Block are the Monument Fault, the Barometer Fault and the Camp Fault.

The Monument Fault runs near the northeast side of the block roughly parallel to the Copper Fault and can be followed for about eleven miles northwest from the Colorado River at Empire Flat to about 1 1/2 miles northwest of Whipple Wash. (Plate 9.) The dip is everywhere to the southwest and varies from 58° to 75°. Northwest from the Colorado River for about 4 1/2 miles the Monument Fault is the boundary between Copper Basin Formation and Basement Complex. For the next three miles the fracture is in the basement rocks and , although this might be considered indefinite, its prolongation is clear, especially over the first mile where the break is clean-cut and the zone of breccia-

Figure 21

Looking northwest at an exposure of the Monument Fault in Copper Basin. Both sides are in basement rocks.

tion narrow. Northwest beyond this point the zone of fracture widens to over 100 feet, but the severely fractured area continues through to the southwest side of hill 2760 where the fracture again becomes clean-cut and can be followed through the volcanic cap rocks to beyond Whipple Wash. The dip in the northwest portion is about 75° southwest, in the middle portion it is about 58° southwest (Fig. 24), and in the southeast part it is about 75° southwest. In the Whipple Tunnel this fault has a strike of N45°W and a dip of 70° SW.

This fault also demonstrates a hinge or rotary action, increasing in displacement toward the southeast. At the northwest end the displacement is nil and throughout the nearly flat-lying volcanics the movement is slight, not over 200 feet at the most. In the central part where the fracture is wholly in basement rocks the displacement can only be guessed. The indication of displacement from cross-section C-C' is more than 500 feet, but at the fault there is no basis for comparison and no escarpment remains. In the southeast portion of the fracture, Copper Basin sediments are in fault contact with basement rocks and although there has been no means of zoning the Copper Basin the volcanic beds are probably below the sediments. The displacement in

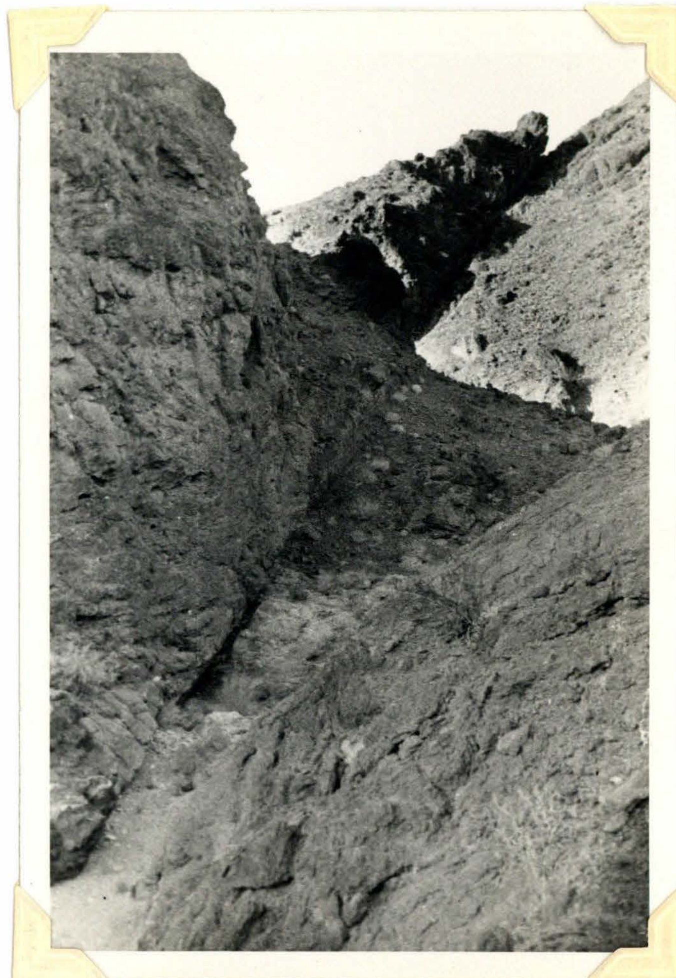


Figure 22

Looking southeast at an exposure of the Barometer Fault. Both walls of the fracture zone are Copper Basin volcanics at this locality.

this area should be in the neighborhood of 1500 feet.

<u>Barometer Fault</u>, named from its location in Barometer Wash, lies near the southwest side of Monument Peak Block four miles northwest of Cross Roads. The fault strikes northwest and can be followed definitely for two miles throughout the length of Barometer Wash. The fracture dies out to the southeast, and its extension northwestward through the basement area is questionable. In the area of flat-lying volcanics to the northwest there is evidence of a break, but the actual location is not found. However, consistent with other faults in this part of the area the displacement is not great and its connection with the Barometer Fault would be in accord with the action of the other fractures of the interior. The Barometer Fault dips northeast at an angle of 50° (Fig. 22), and forms the southwest margin of a tilted lenticular slice about two miles long which is defined on its northeast side by another northeast dipping fault. These breaks join at both the northwest and southeast ends of the slice. Both fractures were encountered in the Whipple Tunnel and both dip around 60 northeast. The dip of the beds within the slice varies from 10° to 30° southwest, while that of the beds to the northeast of this area

is about 30° in the same direction to nearly flat-lying in the main mass. These two faults are probably part of a wide zone which includes the next conspicuous fault to the southwest, the Camp Fault.

<u>The Camp Fault</u> is located on the southwest margin of the Monument Peak Block just southwest and roughly parallel to the Barometer Fault. It can be followed definitely for about three miles from a point about three miles northwest of Cross Roads, southwest of the paved road to the Whipple Camp. Also toward the northwest through the area of basement rocks the projection is uncertain and its continuation through the area of broken volcanic capping is presumed on the basis of a fracture in the northwest area aligning with the Camp Fault. The Camp Fault dips northeast at an angle of 60° at its surface exposures. Where it was penetrated in the Whipple Tunnel the average dip of the fault was 50° in a gouge zone about thirty feet wide. The beds in the narrow block between the Barometer Fault and the Camp Fault dip southwest about 32° indicating a tilt of the block of this amount. The Camp Fault branches near the mouth of Barometer Wash, with the northeast branch paralleling the main fault for about two miles and then swinging back to join the

Camp Fault to the southeast. This auxiliary fault also dips to the northeast but about 15° more steeply than the main one. If the extension into the northwest area be correct, then there is also evidence on this fault that the displacement increases toward the southeast, for in the lava capped area the displacement is small while in the central part of the fault the displacement has been of the order of 1000 feet.

As mentioned in the discussion of the Barometer Fault, it seems that this group of faults on the southwest side of the Monument Peak Block represent one zone of faulting half or three-quarters of a mile wide with a combined normal movement. The displacement is of the order of 2500 feet or more. All of these parallel faults are normal and dip to the northeast and it is likely that more detailed mapping would prove them interconnected in a braided fashion.

Faults within the Monument Peak Block. In the low lying area of Copper Basin rocks northwest of Cross Roads there are practically no faults. Even the faults of the southwest side of the block do not extend through the area. In the area northeast of the Monument Fault near the Colorado River where there is shown a patch of Gene Canyon formation several minor faults occur. These faults are mappable but there is no means of deciding whether or not they are post-Copper Basin in age. The likelihood is that they are pre-Copper Basin for they are cut by the Monument Fault. In the neighborhood of Monument Peak steep northwest trending faults have small displacements. (Frontispiece.) These are comparatively small fractures in lava capping which has been slightly tilted. Near the central part of Copper Basin is a down dropped wedge of Copper Basin volcanics. The faults which outline this wedge dip toward each other and are cut by the Whipple Tunnel. The northeast fault dips southwest at 60° while the southwest fault dips northeast at 45°.

After leaving the vicinity of Barometer Wash the tunnel section eastward was under the capping of Copper Basin formation and was driven almost entirely in basement rocks. Many fractures and fault zones were encountered and the general condition of the rock corroborates the opinions already stated concerning its shattered condition.

In the northwest area around Whipple Wash there are some secondary faults connecting the northwest trending breaks, but they are conspicuously few in number and weak in effect.

The Southern Border Areas.

General Features. In the area south and west of the Monument Peak Block the structural evidence is rather of a negative character. In the high land area of the west only Basement Complex exists, and there is no possibility of analyzing this complexly shattered area from a structural standpoint. However, I have had the temerity to map a few faults in the southwest corner of the mountains from topographic evidence and a few actual exposures. Positive structural features are intermittent over this large remaining area, but some indirect features point toward logical inference.

In the higher area southwest of Monument Peak Block are several promontories and ridges capped by Copper Basin volcanics. These include the ridge connecting hill 2520 and hill 2970, a nearly flat-topped ridge about three miles southwest shown as hill 3350, and a smaller promontory between the two ridges. The contact between the volcanics and the basement is in every case one of deposition and the elevations of the several contacts indicate a once continuous connection. It is significant to note the lack of faulting or tilting in this area, but rather a broad warping upward as shown on cross-section B-B'.

In the lower border area in the neighborhood of Bennett Wash, except in the immediate vicinity southwest of the Camp Fault, the Copper Basin formation is represented by bedded sediments slightly folded near the northwest part of the Tertiary covered area, but for the most part dipping gently southeastward. Southeast of the Whipple Tunnel line these Copper Basin sediments are in depositional contact with the basement rocks. A reconstructed section northwest through this area up Bennett Wash to the higher elevations would be similar to cross-section E-E' taken through the Monument Peak Block. This also would show a broad upwarp, appearing as a monocline tilting slightly to the southeast. As a matter of fact, adjacent to the Colorado River no fault occurs in the area between the Monument Fault and the Bennett Fault.

In the Whipple Tunnel section southwest from the Camp Fault to the Bennett Fault, the tunnel passed through only Basement Complex. The fractures in these rocks firmly established the point already made concerning the intensity of the deformation of the basement rocks. Many of the fractures are faults with zones of gouge and brecciation up to 100 feet wide. None of these faults is directly traceable on the surface, for the basement rocks at the surface also exhibit the completely shattered condition and no clear physiographic discrimination of faults is seen. However, a branch from the Bennett fault is shown to connect with a particularly strong zone of faulting found in the tunnel; on the other hand, there is no authority to project the fault beyond the tunnel line.

The Bennett Fault. The Bennett Fault is poorly exposed, but none the less certain of existence. It can be traced west-northwest from the Colorado River about one-half mile south of B.M. 371 for a distance of about six miles. The fault is shown by the contact of Copper Basin sediments to the north which dip gently into basement rocks. A few actual exposures of the fault zone in the vicinity of the river are so weathered that direct observation is unreliable. Over the remaining distance of the Bennett Fault trace alluvial deposits cover the zone and its existence is verified by outcrops of Tertiary sediments and basement in close association in the wash channels. The trace of the fault is drawn rather straight on the map and would indicate a steep or nearly vertical fault, but in this area covered by alluvium the slope to the mountains is gentle and the fault would conform to the northeast dip found in the Whipple Tunnel. The exposures near the Colorado River yield uncertain dips of the order of 60° northeast, whereas the more certain dip in the Whipple Tunnel shows 65° northeast.

About four miles northwest from the Colorado River a branch fault leaves the Bennett Fault toward the north. This branch fault also dips northeast about the same amount as the Bennett Fault and is traced for two miles by its actual exposures and the abnormal dipping of the Copper Basin sediments into basement. The fault is projected to connect with a strongly faulted zone encountered in the Whipple Tunnel. The action on both the Bennett Fault and the branch fault is normal, with the northeast block depressed.

About a half mile northwest from the point where the first mentioned branch fault leaves the Bennett Fault, the Bennett Fault bifurcates to enclose a wedge-shaped block. This small narrow block near the west portal of Whipple Tunnel is tilted slightly to the southwest, but is capped by Copper Basin volcanics. Underlying the volcanics unconformably are steep-dipping flaggy impure limestones and buff sandy shales which are designated as Gene Canyon formation. The south branch of the Bennett Fault encountered in the tunnel dips northeast at 65°, while the north branch of the same fault dips southwest at 70°, thus forming a tilted block similar to some of the larger blocks to the northeast but on a smaller scale.

Other Faults in the Southern Border Area. South of the Bennett Fault about a mile or half mile is another fault, the dip of which is uncertain. However, near the river, in the block enclosed by these two faults, Copper Basin volcanics overlie basement rocks, and steep and somewhat folded Gene Canyon beds in the vicinity of the Bennett Fault. At the south fault the volcanics are cut off. Inasmuch as the Gene Canyon beds are exposed still farther south with capping of Copper Basin volcanics in patches at slightly higher elevations, it is presumed that movement on this fault was such that the north side was depressed. In the section this fault is shown as indefinite because of the inability to observe a dip. On the fault map it has been drawn solid because its existence is certain even though younger alluvial material covers a considerable portion of the trace.

Along the southern border of the mountains the Copper Basin beds outcrop in isolated and rather widely separated patches. These outcrops are, for the most part, surrounded by Basement Complex or show outwash material lapping them on the south side.

Only one or two patches have alluvial material on all sides.

The farthest east outcrop of Copper Basin rocks has a vertical fault passing part way across the north side of the outcrop, but along the north side of the western end of this ridge of volcanic material the rocks are in direct undisturbed contact with the basement. The contact appears to slope gently south from the hills. The vertical fault shown along the north side of this ridge trends northwest and is in alignment with an indicated zone of fracture through the basement rocks. (Plate 3.) Following this projection the topography seems in accord with a fracture in this line. There is certainly a through fault along this line, but whether this faulting is post-Copper Basin or not is indeterminate for there is no escarpment and no means of estimating the amount of movement. Only a small displacement can be assigned this fault on the basis of the observations taken where it is seen in association with the Copper Basin volcanics, but the relative movement seems to have been such that the south side is depressed.

What has been said about the above fault may be repeated for the two faults shown farther southwest, with the exception that the southernmost fault seems to have had the opposite movement; that is, the north side is depressed.

The point to be brought out in this connection is that no fault was found along the southern border with sufficient displacement in post-Copper Basin time to account for the elevation of the Whipple Mountains. Physiographically there appears to be a fault between the Tertiary low-lying patches to the southwest and the high land pre-Cambrian rocks with Tertiary capping to the northeast. To the contrary, in the field the evidence points to normal deposition of the Tertiary material, now much eroded, lapping up on the basement rocks. (Plates 3, 4, 5 and 6.) Cross-section B-B' shows a broad upwarping of the mountains to account for the difference of elevation. The faults shown are probably relic faults with slight resumed movement in post-Copper Basin time.

Whipple Fault. The Whipple Fault is the largest and most important fault in the Whipple Mountain area. Moreover, extended field work will no doubt prove this fault to be one of regional significance. In the Whipple Mountain area this fault can be followed clearly over a distance of twenty-five miles; its path forming a broad arc which outlines the north and east limits of the mountains. Regional physiographic maps of the desert mountains of southern

Figure 23

Looking east toward north face of the Whipple Mountains. The dark hills are Copper Basin beds on the north side of the Whipple Fault.

Figure 24

Looking west along the strike and crushed zone of the Whipple Fault in the vicinity of Whipple Well. The wide saddle in the distance marks the path of the fault.

California indicate the probability of the Whipple Fault extending many miles westward.

As the steep northwest side of the Whipple Mountains is viewed from a distance of about ten miles, one is immediately impressed with the probability of this abrupt slope being due to faulting. (Fig. 23.) The crest line of the Whipple Mountains runs in a general east-west direction and rises about 2000 feet above the outwash covered areas to the northwest. The existence of the fault is not obvious at first observation, for the escarpment has retreated a few miles south from the actual fault. The topographic map, as well as vertical air photographs, indicates that the fault should lie close to the base of the slope. Even in the field one feels that east-west striking faults should exist not only near the base of the slope, but also within the escarpment because of the perfect alignment of ridge ends and interior saddles. Refuting these ideas is the absolute lack of fault evidence within the escarpment. Along the north side of the mountains the covering of outwash material in front of the range is thin for a distance of about four miles and the basement rocks are exposed in the stream beds. (Fig. 24.) The north face of the mountains was climbed in several places and it was found that the

Figure 25

Looking southeast along the strike of the Whipple Fault about a mile west of Whipple Wash. Basement rocks are on the right of the lighter area which marks the fault trace; Copper Basin sediments are to the left.

Figure 26

Looking northwest from the same locality as Figure 25. The trough marks the path of the Whipple Fault. Note the curve to the left of the dark pyramid form. Basement rocks are to the left, Tertiary to the right.

metamorphic rocks, consisting mainly of schist with thin quartzite layers, dip regularly off the mountains to the northwest. This is the prevailing condition throughout the length of the north flank and there is no evidence either of east-west faulting or of the northwest faulting so prevalent in the area discussed. (Plates 15 and 16.)

As has been stated, the Whipple Fault can be followed easily for about twenty-five miles along the north and east flanks of the mountains. The trace describes a broad arc with the main curvature taking place in the neighborhood of Little Chemehuevi Valley. (Plate 16 and Fig. 26.) The curvature is not apparent at first, for that segment of the fault which follows the Colorado River is parallel to the interior faults. (Plates 14 and 17.) It was thought at first that the fault northwest from the Williams River mouth was another fault of that type. Careful field studies in the area of curvature proved the arcuate condition.

Actual exposures of the fault are found in many places, but the dip is observable only in a few localities for the zone of fracture is so wide and the crushing so intense that data on the movement are impossible to obtain. The actual zone of faulting was discovered near the western border of the quadrangle in the neighborhood of Whipple Well, one mile north from the base of the escarpment. (Fig. 24.) Here the zone of intense crushing and brecciation is at least half a mile wide. This fractured area is bounded on both sides by basement rocks. The zone can be followed northeast from the margin of the quadrangle for about seven miles whence the zone narrows and follows a trough for another five miles. (Plates 15 and 16.) In this second section of the fractured zone a decided trough is developed along the strike of the fault and the streams flowing northwest from the mountains are perceptibly offset to the east. The lower north hills are separated from the main mass of the Whipple Mountains by this fault. These north hills show a northwest grain to their fault system similar to that of the interior section, but on a smaller scale. (Plate 15.) Although the actual junction of any of the northwest faults of the north hills and the Whipple Fault is hot seen, as far as they can be followed a drag to the east is indicated. They may possibly branch from the Whipple Fault, but if that be the case it is likely that these faults would not have a course so nearly at right angles to the Whipple Fault. The rocks on the north side of the Whipple Fault are different from

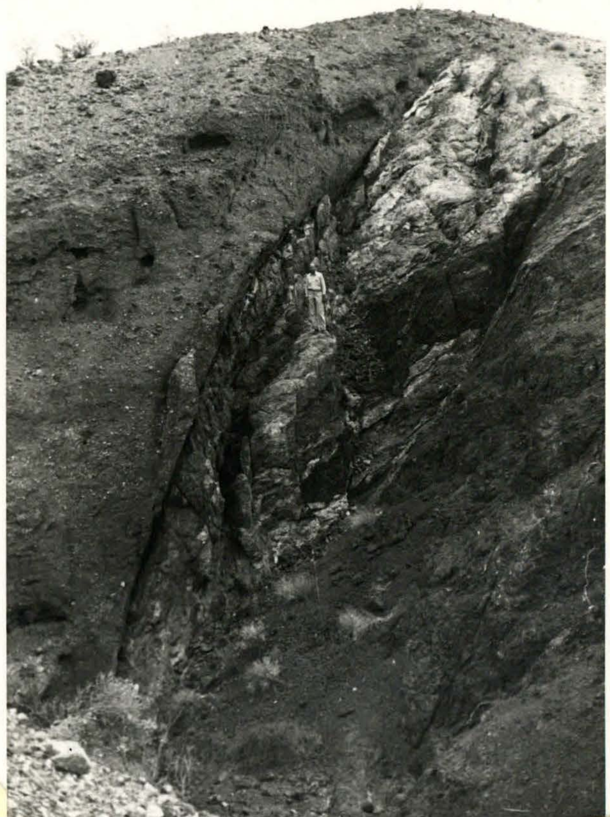


Figure 27

Looking southeast at an excellent exposure of the Whipple Fault about a mile west of Whipple Wash. Note that crushed zone is composed mostly of basement material while the soft sediments on the left are only slightly altered.

those on the south side. To the north Copper Basin sediments and volcanics strike into the Whipple Fault and dip generally southwestward. Even the basement rocks of the north hills are different, as they are made up mostly of contorted gneiss penetrated by many dikes, while to the south the basement is schist which dips evenly northwestward.

About a half mile north of the "three-fingered" ridge the Whipple Fault swings eastward and heads toward B.M. 405 south of Murray Flat. (Plate 16.) Some of the best exposures of the fault are in this area, for Copper Basin gravels are found in fault contact with the basement rocks. The actual fault is exposed best about a quarter of a mile west of Whipple Wash and an average dip on the rather clean cut hanging wall is about 65 northeast. (Figs. 25, 26 and 27.) The Copper Basin beds strike into the fault in this area. Also a slight depression follows the line of faulting. Across Whipple Wash the fault is covered by younger alluvial deposits, but it is seen on both banks of the wash. East of Whipple Wash the fault is actually exposed in the deeper ravines but the intervening areas are covered by outwash material and older river gravels. However, here Copper Basin volcanics occur north of the fault, while to the south is basement material. (Plate 17.)

At B.M. 405 the Whipple Fault swings southward to assume a northwest-southeast strike, closely following the course of the Colorado River at this point. That the fault exists here is clear, for basement rocks are on the southwest side of the river while all along the northeast side of the river as far as and beyond the Williams River are southwest dipping Copper Basin beds. About 1 1/2 miles up the Williams River from its mouth the fault is again actually exposed in a side canyon on the south side. Here the fault dips northeast at an angle of 65 .

The zone of brecciation along the fault is mostly composed of crushed basement material. It is significant to note that the Tertiary rocks show little mutilation, on either a large or small scale.

Minor features within the fault zone which might present proof of the direction of movement are lacking. The direct evidence of areal distribution of the rocks points toward the fault being normal; the plane dips away from the mountains at about 65 wherever the actual fracture is exposed; Tertiary beds strike into the fault and basement rocks from the hanging wall side on the north limb of the arc;

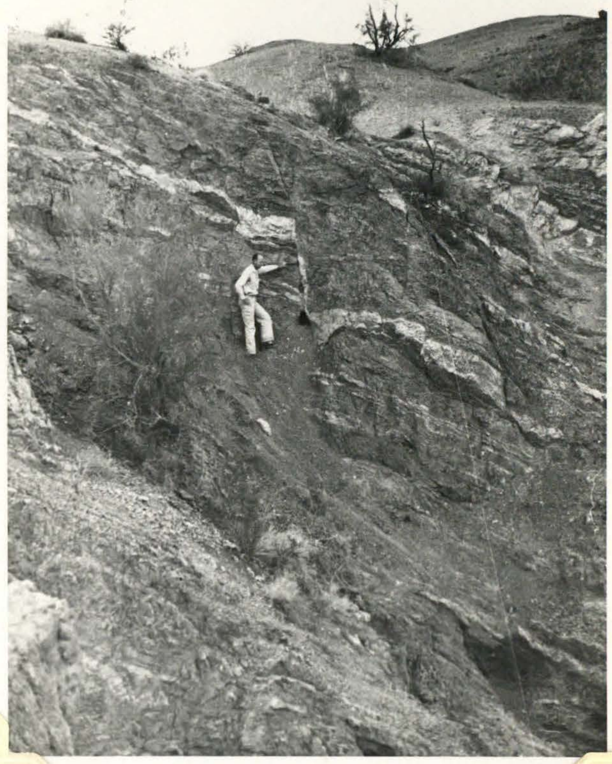


Figure 28

Minor normal faulting in the Basement rocks adjacent to the Whipple Fault. View looking northwest.

Figure 29

Exposure of Basement Complex in North Hills, showing lack of arrangement of dark dikes.

they dip into the fault and basement rocks on the east limb of the arc; minor faults within the basement rocks of a few feet displacement in the immediate vicinity of the Whipple Fault are clearly normal and roughly parallel to the major fault. (Fig. 28.)

Assuming displacement parallel to the dip, and projecting the Copper Basin beds to extend across the mountains, the total displacement on the Whipple Fault would be at least 4000 feet. However, certain features in association with the Whipple Fault point to a horizontal component: there is indication of drag to the east in the fault pattern of the north hills; the streams from the mountains have been offset to the east in the fault trough area.

The North Hills. The North Hills is that group of lower hills lying north of the Whipple Fault in the area of curvature on that fault. They cover an area of about ten square miles. The rocks of these hills are Copper Basin volcanics and sediments and Basement Complex, all in a very complex association. The basement rocks are gneiss and contorted schists shot through with many dark dikes. (Fig. 29.) The Copper Basin formation in the eastern part of the hills is composed of coarse sandstone and gravels consistently dipping southwest and striking into the Whipple Fault. In the central and eastern part, the Tertiary is not

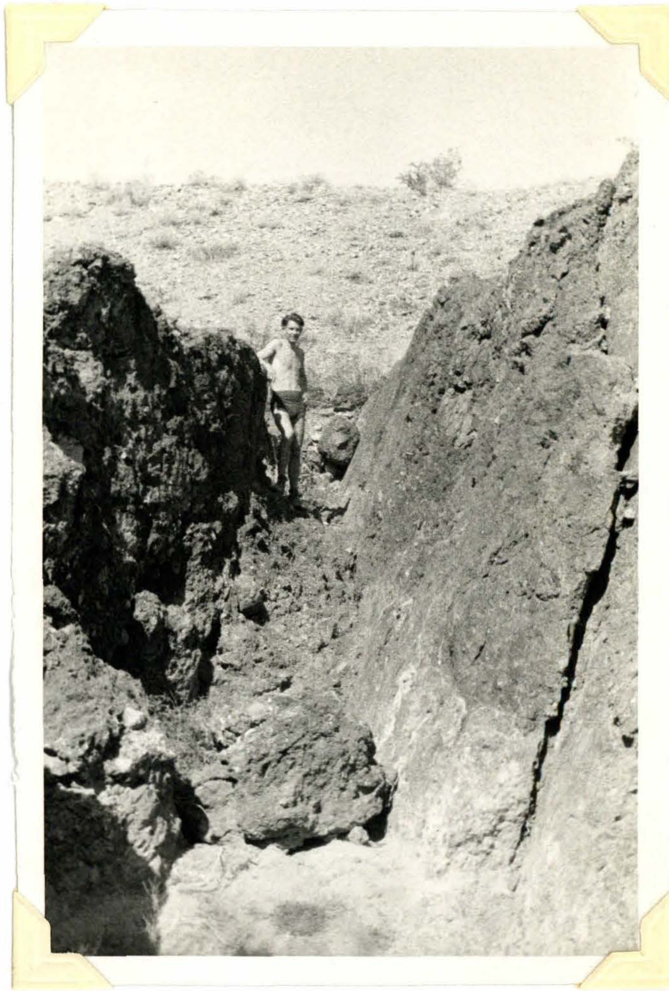


Figure 30

Steep fault in the North Hills. Both walls of the fracture zone are composed of Copper Basin volcanics.

consistent either in lithology or structure. There is a complex jumble of volcanic rocks with occasional apparently interbedded sediments. The whole block is so faulted that accurate interpretation is impossible on the scale of mapping used. The structure is enigmatic and the generalities concerning this part of the area well may be wrong.

Many faults are well exposed in the North Hills, and those mapped are considered to be the most important and characteristic. (Fig. 30.) There is a general northwest trend to most of the faults and they show an interconnection so that the pattern over the whole area is braided. The movement along the faults has been such that a complex arrangement of upthrown and down dropped blocks has resulted. Cross-section A-A', northeast-southwest through the hills, is more schematic than actual.

The north side of the North Hills is a rather steep front which follows a general east-west alignment. This physiographic feature may be the expression of a concealed fault (not mapped) which is similar to and parallel with the Whipple Fault. If such a fault exists, then the structural complexity of the North Hills could be explained by their being part of a squeezed block between two major faults, but possibly of regional significance.

Unless there is sufficient proof, it is dangerous to make any statement regarding a possible source of the volcanic material. No proof of the actual source of the Copper Basin lavas was found, but in the northwest part of the North Hills there is such a varied mass of volcanic rocks with vague concentric arrangement that a possible source in this area is suggested. More detailed work in this area may lead to a conclusive idea on this subject.

Mechanics of Deformation

General Results of the Movements. Features significant in the interpretation of the deformation in the Whipple Mountains are well exposed. Attitudes of the sedimentary strata are readily observed; contacts are quite distinct and easily followed; and the position and dip of the major fault surfaces bounding the individual blocks are known from good exposures on the surface and underground in the several aqueduct tunnels. The nature of the movements can therefore be expressed with confidence. However, as previously pointed out, lack of stratigraphic marker beds precludes accurate quantitative estimates of movement. Even though the excellent exposures afford much reliable data, opinions regarding the results of movement are qualitative.

Two major systems of faults have been discussed: the arcuate fault which outlines the mountains on the northern and northeastern limits, and the interior faults which trend generally northwest and bound tilted segments of the mountain mass. In every case the faults are normal. The Whipple Fault dips away from the mountains which are relatively uplifted. Most of the interior faults dip northeast and the blocks which they outline are tilted to the southwest. It is significant that these latter fractures are grouped somewhat in the northeastern part of the area and that the displacement along each one increases toward the southeast. The general result of the uplift is a broad arching of the area to form an elongated dome, now broken by the block faulting in the northeastern portion.

Relative Ages of Major Fault Systems. It is impossible to date the time of inception of faulting accurately. This is true of the interior faults as well as of the Whipple Fault. The opinion has been stated that the major faults probably were active prior to Copper Basin time, then followed a period of quiescence during the deposition of the Copper Basin formation after which the faults underwent renewed movement. The activity of the faults ceased prior to the deposition of the Pleistocene and recent sediments.

There is no actual proof that the interior faults are either younger or older than the Whipple Fault. The interior faults end before they reach the Whipple Fault, so either case might be satisfied. The interior faults outline blocks tilted to the southwest, and the east limb of the Whipple Fault is the boundary of a similarly tilted block northeast of the Colorado River. Inasmuch as the movement on that part of the Whipple Fault is the same as that of the northeast dipping faults in the interior and the strike of all the faults is similar, it is reasonable to presume that the faulting is contemporaneous, at least in the period of renewed activity.

Deformation of the North Hills is regarded as secondary to that of the Whipple Mountains. The faulting is complex and defies solution on the small scale map used and from the data obtainable. The northwest faults of this area are generally steeper, closer spaced, and less consistent in their attitude than those within the Whipple Mountains. These features in the North Hills may be older than the Whipple Fault, but it seems more likely that they also are closely related to this major fault. A possible break parallel with and similar to the Whipple Fault is suggested along the north flank of the North Hills. If this be true, the faulting within the North Hills could be due to complex deformation in a block bounded by two parallel major faults. There is no proof of that idea, however, but this situation would be in accord with the braided fault pattern, the apparent eastward swing of the larger faults, and the time of faulting.

Relative Ages of Tilting and Faulting. It has been shown that tilting and faulting has occurred in the northeast part of the Whipple Mountains. The blocks have been tilted as high as 45°, and the faults, which are normal, dip as low as 40°. I have no explanation at the present time why the tilting should be so high and why the dip of the normal faults should be so low. It is believed, however, that the fracture planes were tilted as well as the blocks. Also, the stratified rocks which demonstrate the tilting are merely passengers on a much deeper block; the Tertiary mantle, even the softer portions, is remarkably intact while the basement is broken by faults. Apparently most of the adjustment necessary in such tilting was taken up in the basement rocks.

It is possible that the tilting of the Tertiary beds occurred before or after they were faulted or else the two processes went on together. An analysis of a similar case was made by Ransome, Emmons and Garrey in their study of the Bullfrog District.[1] They concluded that in that district the tilting and faulting probably operated at the same time, for the following reasons: (1) "The absence of faulted but untilted rocks of later age than the lavas points toward the conclusions that the lavas were not tilted very long before they were faulted"; (2) the absence of tilted but unfaulted sediments of a later age points to the conclusions that faulting and tilting went on together; (3) "there is little variation of dip within single blocks", which "fact further suggests the interdependence and contemporaneity of the faulting and tilting." Conditions in the Whipple Mountains are in accord with these conclusions.

Fault Movements and Displacements. There are insufficient data from which to draw conclusions concerning a horizontal component on the faulting in the Whipple Mountains. Possibly extension of field observations and further study may yield material for determination of the importance of this movement. The character of the data obtained made it advisable to consider only the more apparent vertical displacement. Even these estimates are inaccurate and should be considered relative.

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1. Ransome, F. L., Emmons, W. H., and Garrey, G. H., Geology and ore deposits of the Bullfrog District, Nevada. U.S.G.S. Bulletin 407, pp. 82-89. 1910.

The northeast-southwest cross-sections show the several blocks in the northeastern portion of the mountains tilted to a similar degree. It is also evident that the blocks become more depressed toward the northeast. The block northeast of the Whipple Fault and the Colorado River shows the greatest amount of sinking, while the Monument Block has been tilted only slightly and depressed relatively a small amount. It should be recalled that the interior faults have had a rotary movement with the displacement increasing from zero in the central area to as much as 3000 feet to the southeast. This rotary effect is especially evident on the Gene, Spring and Copper Faults.

<u>Doming.</u> The broad structural feature of the Whipple Mountains is a faulted dome, extending roughly east-west. Cross-sections taken in any direction through the higher part of the range indicate this condition. (See cross-sections B-B' and E-E' and Plates 2, 3, 4, 5-6, 7, 8, 9 and 11.) The major part of the range consists of Basement Complex, but patches of Tertiary rocks remain. It is likely that the Tertiary mantle at one time covered the entire area, for the correlation of the remnant pieces strongly suggest such a distribution. Moreover, the attitudes of the beds indicate warping rather than faulting to account for the main differences of elevation in the

widely separated patches.

Along the southern and southeastern borders of the mountains the Tertiary beds dip gently away from the mountains and their bases can be projected to join with interior remnants. Faulting which is found in this part has had slight movement in post-Copper Basin time and evidence of doming has not been obliterated.

Along the northwest face of the range the metamorphic rocks dip regularly northwest toward the Whipple Fault with no pronounced faulting within the slope. This slope might be deemed to reflect the doming in the basement rocks. In other localities the warping is shown in the relationships of the Tertiary beds. (See Plates 2, 3, 15 and 16.)

In spite of the apparent connection with the various tilted blocks an alignment of the capping rocks clearly shows a warped slope to the north in the area northwest of Whipple Wash. (Plates 11 and 16.)

The evidence of warping in the Monument Peak Block is discussed under that heading. It is stated that Cross-section E-E', taken in a northwest-southeast direction, shows a monoclinal structure immediately southeast of Monument Peak. Northwest of the monocline the formations are broadly warped and to the southeast they are gently folded.

The dome of the Whipple Mountains is outlined on the north and east flanks by the arcuate Whipple Fault which dips away from the mountains. The northeast area is cut by a series of northwest trending normal faults roughly parallel to the eastern portion of the Whipple Fault. The time of the inception of faulting cannot be determined definitely, but both sets of faults are no doubt relics of earlier activity, with renewed movement in late Tertiary. In every case of major faulting the associated brecciation is composed of basement material, while the softer Tertiary beds show little mutilation. Inasmuch as no evidence of great compressional force exists, the doming is attributed to vertical forces acting over a broad east-west area, but most effective near the northern central part of the mountains. Failure of the rocks under the vertical forces created the Whipple Fault as well as the interior faults on the eastern flank of the dome. The uplift is elongate in an east-west direction but decreases westward. Westward, outside of the area mapped and south of and in alignment with the projection of the Whipple Fault, are low hills and isolated peaks of Copper Basin volcanics. (See Plate 21.) The elevation of these features corresponds roughly to that of similar patches along the southern border. It is concluded that the amount of doming and uplift south of the Whipples decreases westward.

<u>Negative Conclusions.</u> Several negative conclusions are summarily presented.

1. The block faulting within the Whipple Mountains is not of regional extent. The blocks are not of the so-called Basin-Range type. The northwest trending normal faults outline minor tilted blocks within a larger structural unit. These fractures do not extend through the mountains, but generally terminate near the central part of the larger mass giving a rotational character to the movement. However, the steep escarpment and the Whipple Fault along the north side of the range give an east-west orientation to the mountains practically at right angles to that of the basin ranges.

2. Evidencesof large compressional forces are not present, and it is considered unlikely that the doming is the result of such action. Thrust faulting which might have involved the Tertiary mantle as an over-riding block on the Basement Complex has been considered and is regarded as untenable. Without resorting to fanciful associations the deformation suggested by the direct evidence cannot be explained by thrust action which might have involved a block of basement material.

3. Deformation has not occurred in this area since pre-Pleistocene time. The post-Tertiary beds within the district apparently are not faulted or folded.

4. No direct evidence is found by which the uplift and faulting in the mountains could be attributed to the intrusion of magma.

Possible Cause of Deformation. The foregoing discussion is more or less factual, with the idea of reserving inferential statements for these later sections of the paper, especially those ideas regarding the possible cause of deformation and the origin of the Whipple Mountains, as well as the regional relationships. Geologic studies in adjacent areas are cursory explorations, made for the most part during the period of early national surveys, with a decided lack of detail. None of the surrounding ranges has been mapped; so any statement regarding a relationship with the Whipple Mountains is tentative and subject to revision in the light of new information. The region is isolated with regard to other detailed studies, so little aid can be obtained from any previous work. It is not difficult to determine what has happened in the area worked, and these conclusions have been expressed with some confidence. On the other hand, it is felt that the examination of a much more extended region is needed in order to determine with any degree of certainty the causes of deformation.

The opinion is stated that the normal faulting is the result of failure of the rocks under vertical forces. The movements are relative and may be due to the mountain mass rising or adjoining areas, principally to the north and east, subsiding. The arching effect evident in the mountains indicates uplift in that region. This condition is in line with the previous history, for it is possible that the Whipple Mountains represent a positive block which has undergone periodic vertical changes. The intrusion of a granitic magma into pre-Cambrian sediments probably represents one period of uplift; the metamorphism of this series indicates a later time of subsidence. No Paleozoic or Mesozoic rocks exist in the mountains although formations of these ages are known to be present in some of the surrounding ranges. Such formations may have been deposited and later eroded, or the block possibly stood high during these times and received no deposition. The former case would illustrate the fluctuation up and down of the area, and the later case would indicate the tendency for the block to retain an elevated position.

The patch of "new granite" in Copper Basin may represent a Mesozoic intrusion; at least it is later than the granite gneisses of the basement. This evidence of later intrusion together with the accumulation of Tertiary volcanics in the Whipple Mountains and the still younger, possibly Quaternary, lavas in the adjoining area to the east perhaps signify that the region is one of magmatic activity. The rise of the block and the warping of the surface formations may then be due to the intrusion of magma in post-Copper Basin time, albeit no proof of this idea is known.

East and northeast of the Whipple Mountains in the so-called Bill Williams country, the formations equivalent to the Copper Basin formation are overlain by a considerable thickness of flat-lying lavas. These later volcanics probably extended over many tens of square miles. The Copper Basin sediments likely accumulated in a low-lying basin surrounding the Whipple Mountains area. The load of sediments in the basins may have opposed the uplift of the Whipple Mountains and intensified the tension faults near the borders of the uplifted block. The rotational effect observed on the normal faults in the northeastern part of the area may be due to relatively greater sinking of the Bill Williams country under load.

It is also possible that the doming is only apparent and that the Whipple Mountains represent a large block, tilted to the southwest. The Whipple Fault would then be a boundary fault along which the greatest amount of movement took place, and the interior faults would be adjustment faults near the northeastern end of the larger unit. The southern border areas would represent a region of relative depression. If this be the case, the probabilities are that the Whipple block is just one piece in a great mosaic of structural blocks in a much more extended region.

The writer feels the inadequacy of these possible causes of deformation, but he recognizes the need of widening the scope of observation. It is also believed that the deformation is not due to local causes but is the result of regional tectonics.

Regional Relationships

One of the geologic provinces of Southern California is that of the Transverse Ranges, "distinguished by complex ranges and valleys with a general east-west trend."[1] Although Reed considers this province in the light of evidence in the coastal area he further states, "Some of the desert ranges in the southern Mohave desert region should probably be included." This concession was made in view of the earlier statements by Hill.[2] Hill wrote, "There are physiographic

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1. Reed, Ralph D., Geology of California. A.A.P.G. Bulletin. 1933.
2. Hill, R. T., Southern California and Los Angeles Earthquakes, p. 86. Los Angeles, 1928.

complexities on the Desert Side [of the San Andreas fault] which we do not as yet venture to interpret. These are produced by the meeting and, at times, crossing of Great Basin, Transverse Belt and Northwest-Southeast trends in that region. The East-West fault lines of the Transverse Belt continue through the region with undiminished displacement..." In another part of his paper[1] Hill further states: "No more interesting geologic features exist in California than the faults and folds of the great Transverse Belt which, as previously mentioned, extend in irregular sequence and sometimes indefinite expression from the westernmost end of the Channel Islands eastward to and beyond the Colorado River into Arizona, where they are associated with the southward discontinuation of the Colorado Plateau. These features are reflected in the relief of both sea and land, and on both the Pacific and Desert sides. Among the highlands which are delineated in part by the east-west structures are the Santa Ynez, Santa Monica, San Gabriel, San Bernardino, Little San Bernardino, Eagle, Pinto and others, and more or less the Anacapa group of islands. The Santa Barbara Channel, the Foothill Valley, Rabbit Springs, Dole and Chuchwalla Valleys are some of the

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1. Hill, R. T., _op. cit._, pp. 136-137.

lowland features which accompany these Transverse structures." Added acceptance of Hill's ideas is made by Noble who stated:[1] "The recognition by R. T. Hill of a great series of approximately east-west faults, which are cut across by northwest-southeast faults of the San Andreas system, seems to be well founded in fact."

The Whipple Mountains appear to belong to the province of Transverse Ranges. The mountains themselves are oriented, in a broad way, east-west; the oval dome structure also extends in that direction and the major fault feature of the area, the Whipple Fault, strikes east-west. The Whipple Fault appears to extend westward across the lowland area toward the southern part of the Turtle Mountains.

Doming is not unusual along the Transverse Belt, for a similar feature was described by Harder[2] in the Eagle Mountains. Harder stated: "The broad structural feature of the northern third of the Eagle Mountain -- that is, of the portion consisting of sediments and intrusive granites -- is an oval dome, extending in a general east-west direction." He further mentions that the doming of the Eagle Mountains

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1. Noble, L. F., The San Andreas rift in the desert region of southern California. Carnegie Institute of Washington, Year Book 31, 1932, p. 360.
2. Harder, Edmund C., Iron ore deposits of the Eagle Mountains, California. U.S.G.S. Bulletin 503, p. 22. 1912.

was accompanied by great faulting. Harder's findings were later corroberated by Scharf[1] who described the north front of the Eagle Mountains as "a steep rectilinear east-west scarp, interrupted by only a few canyons of any size" and extending for about ten miles. The time of doming and faulting in this latter range agrees with that of the Whipple Mountain structures.

If the age of the Tertiary formations in the Whipple Mountains be correct -- that is, Oligocene or Miocene -- it is not surprising that the overthrusting is not found, at least that which might be connected with the belt of overthrusting extending from southern Alberta to southern Nevada. To quote Hewett:[2] "Also the evidence is increasing that there is an extensive belt of overthrust faults that extends from northern Montana southeastward into Wyoming and eastern Idaho and Utah. In some places these have been proved to be early Eocene and in others later Eocene. The belt of overthrusts of southern Nevada appears to be the southern extension of those known farther north and may have the same age. At present the writer favors this interpretation."

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1. Scharf, David, The Quaternary history of the Pinto Basin, Southwest Museum Papers N. 9, p. 13. March 1935.
2. Hewett, D. F., Geology and ore deposits of the Goodsprings Quadrangle, Nevada. U.S.G.S. Prof. paper 162, p. 55. 1931.

A regional physiographic map shows the adjacent ranges to the north and east to be oriented northwest-southeast, more nearly in agreement with the orthodox Basin Range type. The Whipple Mountains probably are a border range in the Transverse Belt at the southern end of the Basin Range Province. Just what the position of the Whipple Mountains is relative to the extension of the Transverse Belt eastward will depend on more extensive examination of the desert ranges along this belt. It would be unsafe to make any statement of opinion in this regard at the present time.

GEOMORPHOLOGY

General Features

In the preceding chapters of this paper data are given on the topography, stratigraphy and structure of the Whipple Mountains. An explanation of the landforms requires an understanding of the relief, distribution and character of the rocks and the deformation of the district as well as the nature of the erosional agencies active in the region. The reader is referred to the chapters on these several subjects for details, but in this consideration of the physiographic forms a summary is given.

Most of the mountain ranges of the Basin and Range Province are elongate and trend nearly north and south. In this respect the Whipple Mountains are not characteristic of "basin-range" type for the mass is not elongate but practically equidimensional. However, structural lines are reflected in the topography and the relief shows distinct orientation. A relatively steep escarpment along the northwest side with a comparatively gentle slope to the southeast gives an impression of an east-west strike almost at right angles to that of the basin-ranges. However, the grain of the topography is compatable with the normal basin-range pattern for the internal ridges and depressions are mostly aligned in a northwest-southeast direction, even though the transverse structures have governed the mountains as a unit.

Lithology, Distribution and Relief

The main part of the Whipple Mountains is highly dissected to a remarkably even degree. Differences in form and strength of relief are due principally to the distribution and the nature of the rocks acted upon. The pattern of the relief for the most part is governed by the deformation. The area of basement rocks is most intricately and deeply dissected, but a structural control is suggested by the general northwest-southeast direction to the ridges and channels. This control is especially noticeable in the extreme western portion near Chambers Well (Plate 3). The basement rocks are a heterogeneous mixture of metamorphic rocks, highly fractured, which yield easily to erosive forces. Moreover, the ridge tops are sharp, and the area of basement rocks with the exception of a single minor instance contains no surfaces which might suggest previous erosion cycles. The eastern half of the mountains includes a series of Tertiary volcanics and sediments which vary in hardness both vertically and horizontally. On the whole, the Tertiary rocks, especially the volcanics and the more highly indurated sediments, are more resistant to erosion than the basement rocks. Much of the Tertiary mantle has been eroded, but patches of volcanics and harder portions of the sediments still remain capping the basement rocks in several localities. The orientation of ridges and channels is likewise northwest-southeast, also suggestive of structure. (Plates 8, 9, 11 and 13.)

Structure

The broad structural feature of the mountains is a faulted dome, elongated roughly east-west. Cross-sections taken in any direction indicate this condition. (See cross-section B-B' and E-E' and Plates 2, 5-6, 8, 9 and 11.) It is likely that the Tertiary formations at one time covered the entire range for correlation of the remnant patches suggests such a distribution. The dome is outlined on the north and northeast flanks by an arcuate fault which dips away from the mountains. The northeast area of the mountains is broken into southwest-tilted blocks, bounded by northeast-dipping normal faults, roughly parallel to the southeast-trending portion of the arcuate fault. Most of the fracturing within the mountains trends northwest-southeast, a fact which is true even in the cases where the age of activity is uncertain.

Specific Data

Interior Area. It is apparent from the prevailing course of the drainage that channels were instigated in zones of weakness created by fault movement. In many cases the present streams do not actually follow the fracture zones, but veer one way or another dependent on the hardness of the rocks. In the cases of Gene Basin and Copper Basin, these broad areas are cut for the most part in the softer portions of the sedimentary formations. The constricted parts of these basin-like areas are due to lateral variation in the hardness of sedimentary beds.

It is stated that the Tertiary volcanics in the interior portions of the range are broken and not tilted as much as some of the other areas. This area contains flat topped or gently sloping topped promontories which might be presumed to be old land surfaces. These are, however, remnant portions of Tertiary volcanics which have been more resistant to erosion, and have acted as a protecting covering to the more easily eroded basement complex.

Whipple Fault. A notable trough is developed along the strike of the Whipple Fault on the north side of the mountains where the zone of fracturing is narrowed considerably. Here the eroded escarpment along the north side closely follows the direction of the Whipple Fault, but farther west the escarpment retreats some distance southwest. This is due to the broader fault zone and the weakening of the basement complex by the movement, making these rocks more susceptible to erosion. Near the central part of the north side of the mountains the drainage from the steep slope appears to be offset to the east. This might indicate recency of movement along the Whipple Fault but, inasmuch as no other signs of late movement are observed, it is probable that these cases are due to a selective action by the streams.

<u>Border Areas.</u> Surrounding the mountains are alluvial fans and outwash planes which do exhibit stages in deposition and down cutting. Several terraces can be traced, but these are attributed to changes in the development of the Colorado River. At the present time all of the streams emerging from the Whipple Mountains are down-cutting. No signs of recent faulting are present. The general down-cutting of the streams may be due to an upwarping of the entire area, but no proof of this was observed.

<u>Colorado River.</u> It is difficult to state with any feeling of certainty just what part the Colorado River has played in the building of the Whipple Mountains. The Colorado River extends for such a long distance and flows through regions which have had such varied geologic history that changes in one district no doubt have affected other districts either directly or indirectly. To differentiate between

outside influences and those peculiar to the district in question would entail consideration of practically the entire course of the Colorado River. This is outside the scope of this paper.

Certain inferences regarding the course of the river within the Parker sheet can be drawn from its relationship to the areal geology and the structural trends. Near the southern end of Chemehuevi Valley between Pittsburg Flat and B. M. 438 the river has an east-west course for about 2½ miles, which may coincide with possible fractures parallel to the Whipple Fault. Between Pittsburg Flat and the mouth of the Williams River the Colorado River flows southeast, roughly parallel to the faults in the North Hills and the eastern portion of the Whipple Fault. In fact, between Murray Flat and the Williams River the course directly follows the fracture zone of this latter fault. The course of the Colorado River in the northern half of the quadrangle was no doubt determined by the position of the fracture zones, with the meanders influenced by the rock types. At the mouth of the Williams River the Colorado River makes an abrupt turn to the south for about three miles, whence it flows southwestward for the remainder of its course in the Parker area. In the southern part of the quadrangle the river flows across the structure, but the direction of flow roughly coincides with the regional dip of the Tertiary sediments and the tilt of the structural blocks. It is possible that the course of the river in this section was determined by the general regional slope prior to the block faulting. The steep-walled gorge in the vicinity of the Parker Dam site, together with the lacustrine deposits in the Chemehuevi Valley, suggests that a barrier once existed just below that mouth of the Williams River. A number of north-south minor faults are present in the Parker Dam area which may have afforded a zone of weakness for the river to cut through the tilted Gene Block at this point.

Present Erosion Cycle

In the Whipple Mountains the present erosion cycle has progressed to a stage of maturity in the arid cycle. Apparently nothing has happened to arrest this cycle since its inception in post-Copper Basin time. Within the mountains are no stream terraces which might indicate renewed uplift or faulting. No doubt during this period climatic changes or alteration of base level may have invigorated or enfeebled the forces of erosion, but evidences of these changes are not seen in the mountain area.

Earlier Erosion Cycles

Landforms which might be interpreted as indicative of earlier cycles of erosion are lacking. However, the surface upon which the Copper Basin formation was deposited is so even that it is safe to postulate a stage of peneplanation prior to the accumulation of these strata. At one locality in the interior the volcanics have been stripped from a long narrow area revealing an even surface on the basement rocks. This is a single case, however, and very minor. Several cycles of erosion have been indicated in the chapter on geologic history, but aside from the one case mentioned they are not indicated by the landforms.

GEOLOGIC HISTORY

Paleontological evidence for establishing the age of developments in the Whipple Mountains is meager and uncertain. The fossil material found in some of the sediments was determined to be early Tertiary in age, and was used in constructing a general sequence of events. The major criteria, however, are based on structural and stratigraphic relationships. A chronological list, constructed in accordance with the data presented in the preceding sections of this paper, follows:

1. Sedimentation and Vulcanism. The earliest record is contained in the Basement Complex and shows a period of sedimentation and volcanic activity.

2. Intrusion and Metamorphism. These early sediments were intruded by a granitic mass after which extensive metamorphism altered the original character of sediments and extrusive rocks as well as the intrusive rocks into mainly schists and gneisses. This primary period of the history is considered pre-Cambrian in age.

3. Uplift and Erosion (Great Interval). After the metamorphism of the basement rocks a long interval of time passed and there remain no direct clues to the events which must have ensued. It is certain, however, that uplift and erosion took place,

probably in early Tertiary prior to the deposition of the Gene Canyon beds. Erosion during this time probably proceeded until peneplanation, although an area of low mountains must have existed nearby.

4. Subsidence and Sedimentation. The completion of the erosion cycle of the previous period was interrupted by subsidence which resulted in the accumulation of the Gene Canyon formation. These sediments are generally coarse with angular and subangular particles, and are deposited in discontinuous beds. Their character suggests a nearness to source, and although the structural evidence is not clear the sedimentation may have been due to differential subsidence or block faulting. A single lava bed at the top of the Gene Canyon formation indicates limited volcanic activity near the close of this period. The age of this period is indicated as Oligocene or very early Miocene, from artiodactyl hoof prints found.

5. Diastrophism, Uplift. Following the deposition of the Gene Canyon beds deformation took place by uplift and tilting and faulting. Folding was apparently minor. Although the evidence also is not clear the faulting probably followed a northwest trend and the beds were probably tilted as much as 25° to the southwest.

6. Erosion and Peneplanation. Widespread erosion followed the uplift and this cycle must have reached a peneplane stage before interruption. The peneplane surface is clearly seen at the depositional contact with the next overlying sediments and in places where present day erosion has uncovered this old land surface. During this period of erosion much of the Gene Canyon formation was stripped, for this formation now remains only as occasional patches.

7. Vulcanism, Subsidence and Sedimentation. Peneplanation of the area was interrupted by subsidence and extensive volcanic activity. The volcanic flows occurred in the Whipple Mountains and sedimentation apparently took place in the basins surrounding the area of vulcanism. Subsidence must have continued, resulting in what is now called the Copper Basin formation, during and following the outpouring of the lavas, for the indications are that sediments of Copper Basin formation at one time extended over a large part of the present Whipple Mountains. The age of this activity is placed at Miocene, judged from a few artiodactyl tracks found.

8. Uplift and Diastrophism. Following the accumulation of volcanic material and basin sediments the entire area was uplifted or domed. During or closely following this uplift the region was completely

faulted in the manner already described. Folding was minor. Faulting probably followed along lines established in a previous period of diastrophism. The time of this period is possibly late Tertiary or early Pleistocene, and represents the latest period of deformation in the area.

9. Erosion; Sedimentation in the Flanking Areas. As a consequence to the last uplift and diastrophism all of the formations were subjected to erosion. The material eroded was deposited on the flanks of the mountains as alluvial fans and outwash plains or basins. These sediments graded into and commingled with material brought down by the Colorado River. It is probable that in Pleistocene time the Colorado River was impounded near the mouth of the Bill Williams River which established in temporary base levels around the mountains. Rather extensive lake deposits accumulated in the Chemehuevi Valley on the north side of the mountains until changes in the Colorado River caused this stream to break through the barriers in the neighborhood of the present Parker Dam site.

10. Renewed Erosion. At the present time the streams from the mountains are down cutting. This This apparently has been the condition since the renewed activity of the Colorado River, for in the area of Chemehuevi Wash several stages exist. It is possible

that the down-cutting may be due to continued doming or uplift of the Whipple Mountains, but proof of this is not apparent. It seems more likely, in the writer's opinion, that the renewed erosion is due to changes during the development of the Colorado River.

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PLATES

Oblique Aerial Photographs

Plate 1

Looking northwest at the Turtle Mountains. The road shown is the Needles-Vidal road, Needles being about 30 miles north from the right hand side of the picture. The Metropolitan Water District aqueduct construction can be seen in the lower left hand corner. The Whipple Mountains lie immediately to the east (right), and the low hills in the right center lie along the westward projection of the Whipple Fault. Even in this area, away from the Colorado River the fan dissection can be seen.

Plate 2

Looking northeast across the main mass of the Whipple Mountains near the point of highest elevation. The Colorado River flows from left to right at a slight diagonal across the upper center of the picture. The dark patch near the center is the mesquite flats of Chemehuevi Valley, and left of this area near the edge of the picture are the low rhyolite hills (West Hills).

The intricate dissection and the steep rugged character of the topography can be seen. In the lower left hand quarter the rather vague alignment of ridges and depressions is northwest and southeast. The presence of the steep northwest face can be surmised by the sharp crest of the master ridge, especially near the right hand side of the picture. The rocks composing the main mass shown here are Basement Complex, and on the northwest slope in the center of the picture the sedimentary-like attitude indicates the northwest dip of the foliation.

Plate 3

Looking northwest across the western portion of the Whipple Mountains. The Colorado River can be seen in the upper right hand corner; the West Hills lie just above Whipple Peak between the Whipple Mountains and the Chemehuevi Mountains in the middle distance.

The main mass shown here is composed of Basement Complex, but the dark patches in the lower left hand quarter are Copper Basin sedimentaries and volcanics. Although most of the main washes in this view flow southwest the predominant topographic grain is northwest-southeast -- compatable to the interior fault system. However, the broken character of the Basement Complex makes it precarious to project faults through this formation on topographic evidence alone. This fine directional agreement leads to the inference that the basement rocks have suffered a very complete shattering oriented with the determinable faults. The northwest escarpment is again indicated by the sharp crest of the master ridge, while the more gradual southeastern slope is apparent. The foliation banding is also evident near the crest of the master ridge.

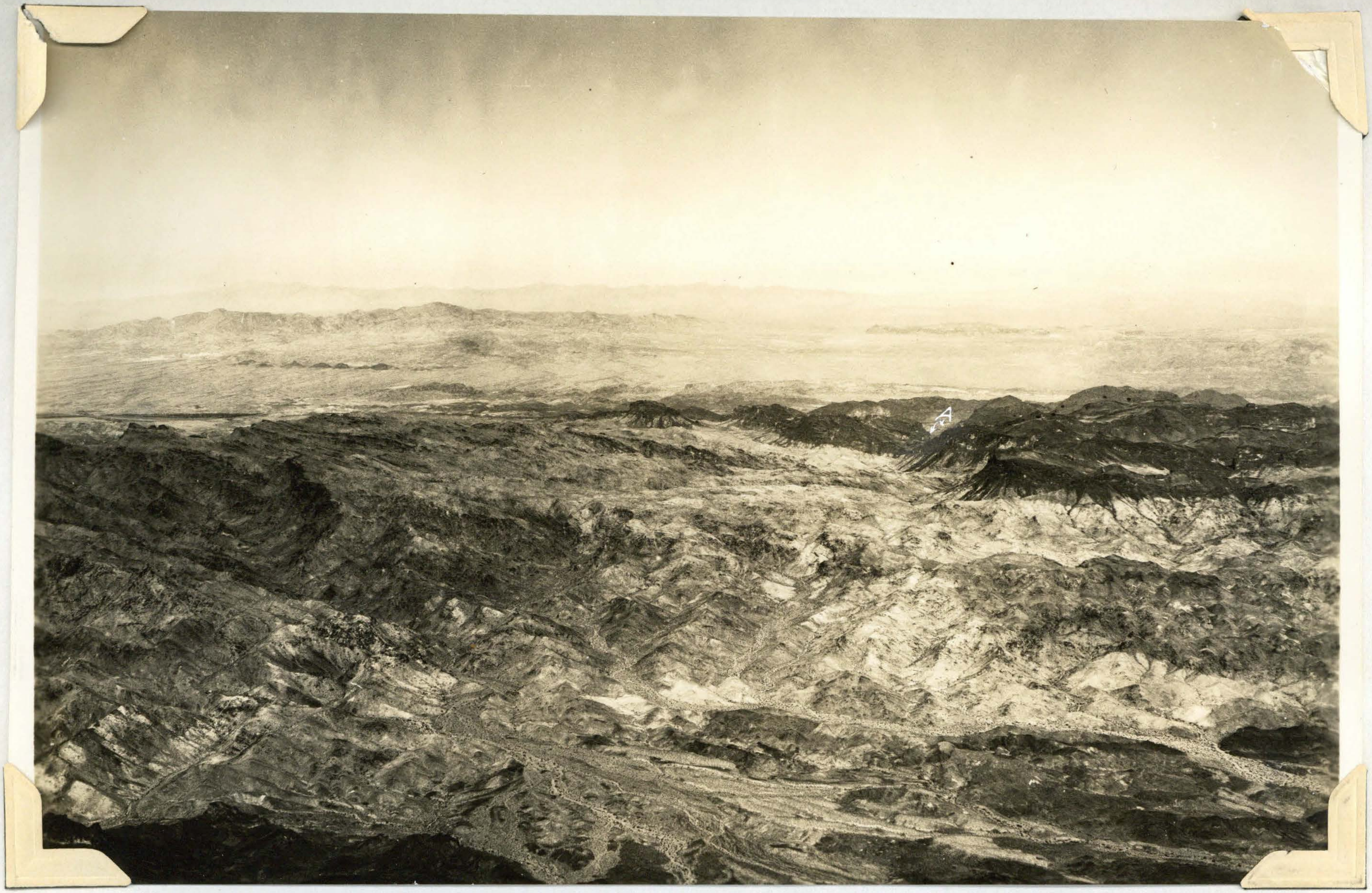
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Plate 4

Looking northeast across the central portion of the Whipple Mountains toward Whipple Wash which is the depression (A) shown to the right center. The gradual slope of the southeastern side of the mountains can be noted. The lighter colored rocks are Basement Complex while the wedge of dark material coming in from the right is Copper Basin formation, here made up mostly of volcanic material. The fringe-like contact is due to talus, but the contact can be seen to be dipping slightly to the right (southeast) on the ridge immediately to the left of Whipple Wash. It is presumed that erosion has eliminated much of the Tertiary formations, and it can be seen how the Copper Basin formation might be projected to have covered much if not all the Basement Complex.

Plates 5 and 6

Looking almost due east and showing most of the area covered by Tertiary rocks. The lighter colored and more intricately dissected areas are Basement Complex while the darker patches are Tertiary volcanics and sedimentaries. Little structural detail is apparent in this view, but the topographic difference between the Tertiary and pre-Cambrian is evident. In the foreground the tilted Tertiary beds lie on basement rocks. Physiographically there appears to be a fault between the two series, but on the contrary in the field the evidence indicates normal deposition with much of the Tertiary having been eroded. This is true also of the area to the lower right where Tertiary beds can be discerned dipping to the southwest. Farther east the Copper Basin beds, nearly flat-lying and very slightly folded, lap up northwestward over the basement rocks with increasing dip until the area of Monument Peak, after which the beds again flatten as they proceed westward.


A
B

Plate 7

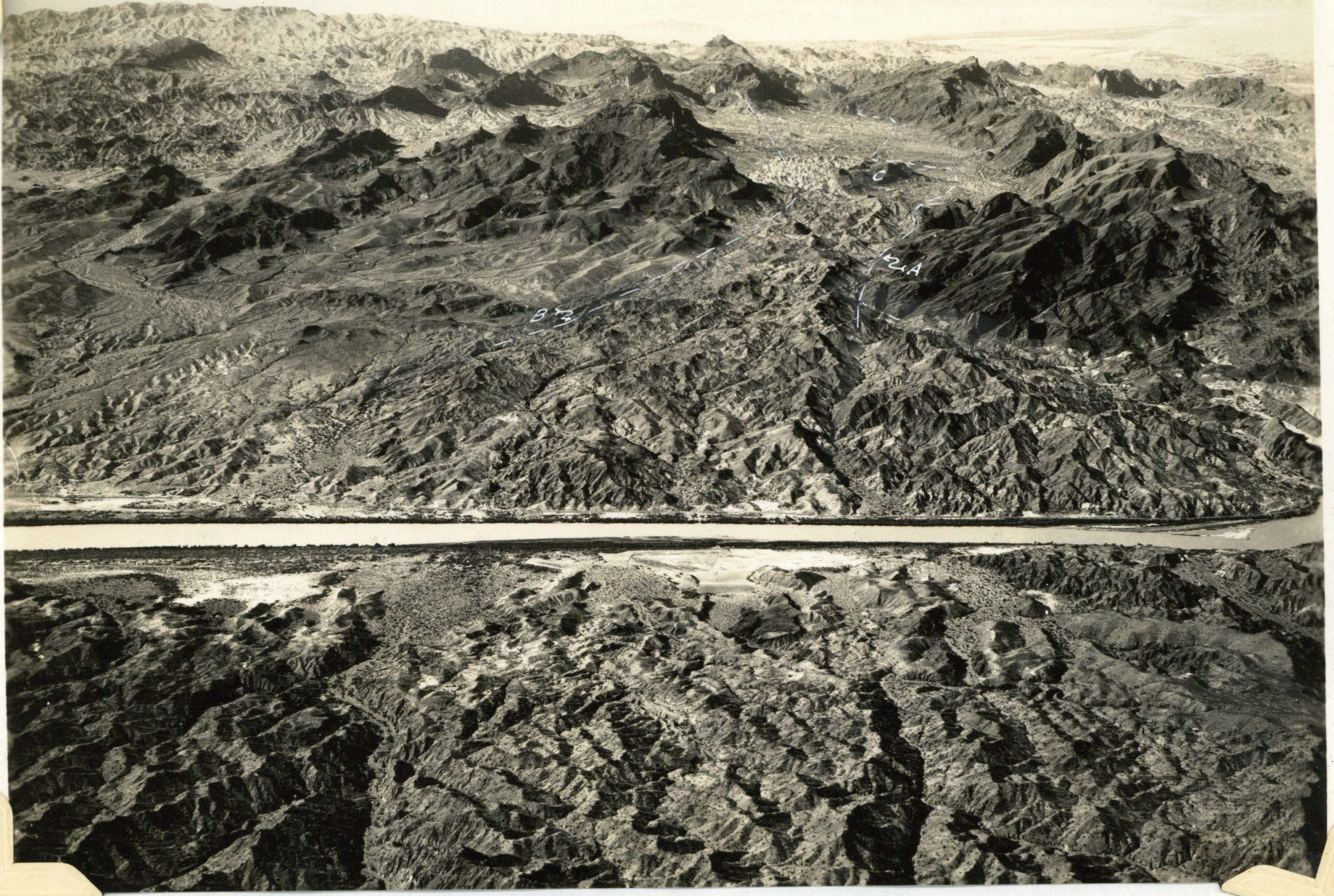
Looking north toward the Colorado River from about Bennett Wash, showing topographic detail and some structure in the western portion of the area covered by Tertiary volcanics and sediments. The light colored material is Basement Complex while the dark material is Copper Basin formation. Where the fringe of talus has not obscured it entirely, the contact between the lavas and the basement can be seen to be rather flat. This is especially well exemplified in the upper central portion of the picture. The area is broken into tilted blocks, so this contact is not apparent everywhere, but the diminishing effect of the faults is indicated by the nearly flat-lying Copper Basin formation in the upper part of the picture as well as the continuity of the basement around this concentrated mass of Tertiary material by which it is overlain.

Note the construction camp and the dump from the Whipple adit in the center foreground.

(A) Camp Fault.
(B) Barometer Fault.

Plate 8

Looking northwest across the Tertiary covered area of the Monument Peak Block. toward the Chemehuevi Valley from Bennett Wash. The whitish patch in the Copper Basin (A) area is the new granite intruded into the older basement rocks. Monument Peak is the spire to the left of the new granite. Tilted Copper Basin beds can be seen in the upper right hand quarter, but the Copper Fault (B) near their base is only vaguely discernible. The Copper Basin volcanics in the upper left hand quarter are tilted somewhat, but it can be seen that relatively the deformation is not great. Barometer Fault (C) and Camp Fault (D) are identifiable at the left center. The less rugged hills in the foreground and lower right are Copper Basin sedimentaries which, though slightly folded, dip generally southeast. Toward the Monument Peak area these sedimentaries overlie the volcanics. Also toward Monument Peak the dip increases, but actually in the areaof true volcanics the beds are more or less flat-lying, giving the impression of a slightly tilted monocline.



C
A
B

Plate 9

Looking northwest across Copper Basin toward the Chemehuevi Mountains is the distance from approximately Eagle Landing on the Colorado River. In the upper right hand quarter can be seen the tilted Copper Basin beds of the Copper Block, which is cut off to the southwest by the northeat dipping Copper Fault.(A). The aligned drainage channels (right center) are an expression of a branch of the Copper Fault in basement rocks. Left center is the trace of the west dipping Monument Fault (B). Slightly left in the middle distance the general agreement of the volcanic cappings can be noted. In the central area of Copper Basin is a small down-dropped block of Copper Basin formation (C).


A

Plate 10

Looking northwest across Copper Basin (A) and the Monument Peak Block toward Whipple Peak. In the upper portion of the picture the general continuity of the volcanic cappings to indicate a broad warp is apparent. Just above the Colorado River, which flows from right to left in this picture, the tilting of the Copper Block and the Monument Peak Block is seen. The trace of the Monument Fault, the Copper Fault, and portions of some of the minor faults are discernable.


A

Plate 11

Looking northwest across the middle and west segments of the Copper Block from Bandit Pass. The southwest tilt to Copper Block is clearly to be seen, and the curving path of the Copper Fault (A) is apparent. Note the anticlinal fold of the Copper Basin volcanics in the west segment and the steep face on the northeast side of the Copper ridge which marks the vertical fault zone. Note also that the continuity of the volcanic cappings in the upper portion of the picture indicates a broad upwarp. The dark material in the upper right hand quarter is part of the Spring Block.

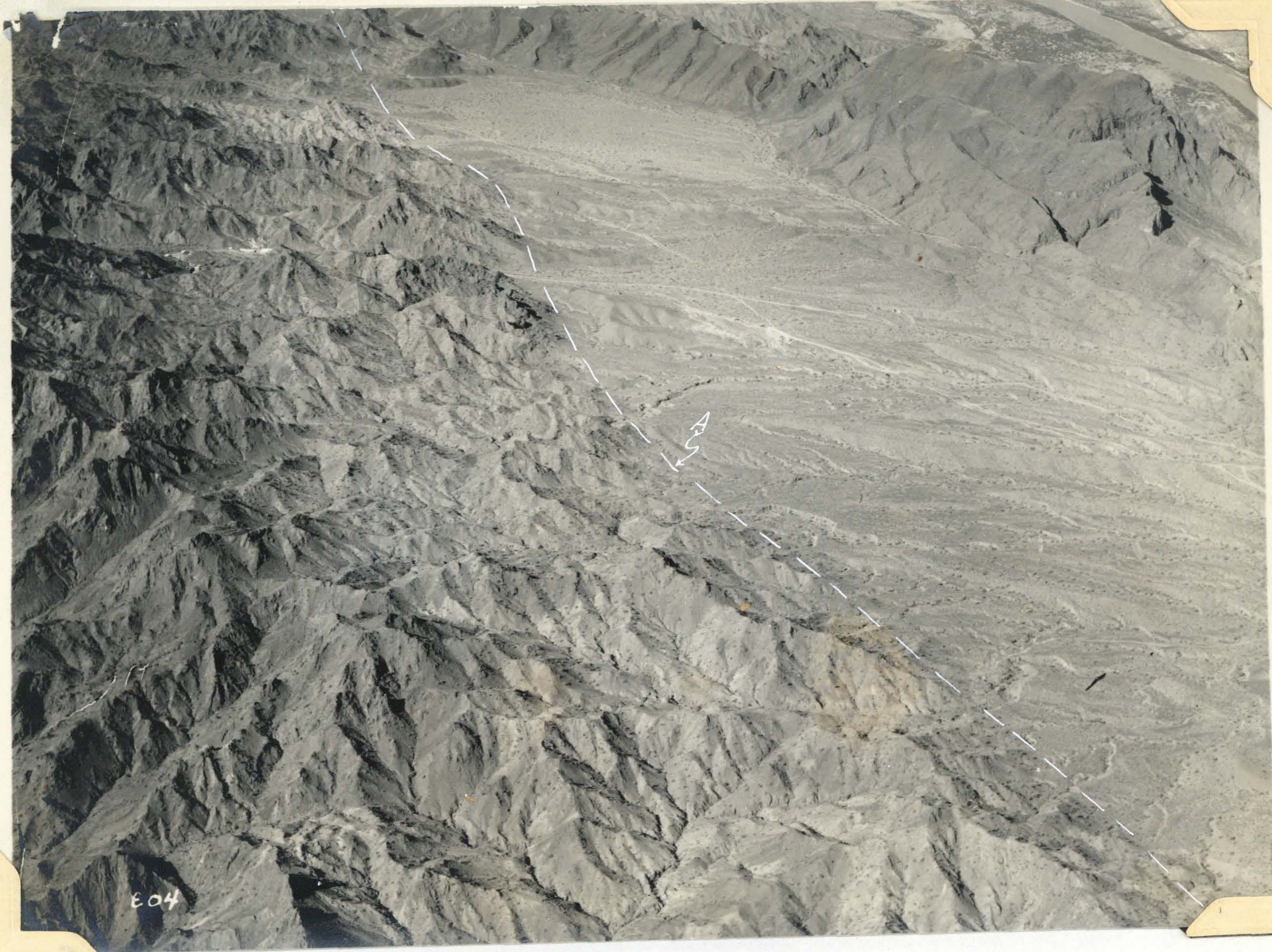

A
E04

Plate 12

Looking northwest across the upper end of Gene Basin, showing the trace of the Gene Fault (A). Note the general northwest grain in the dissected area, in spite of general northeast drainage. The smooth appearing area is underlain by softer Copper Basin sediments dipping toward the fault.


SB
A

Plate 13

Looking northwest across the upper end of Gene Basin toward Little Chemehuevi Valley. The Gene Fault (A) and the tilted Copper Basin beds of the Gene Block are shown. In the upper left hand quarter is the Spring Block. The trace of the Whipple Fault (B) is shown diagonally in the upper portion of the picture. The lower hills on the far side of the river in the upper right hand quarter are Copper Basin beds dipping toward the river and into the basement rocks.


A

Plate 14

Looking northwest across the Gene Block showing the tilted Copper Basin formation and its contact with the Basement Complex high up on the northeast side of the ridge. Note the northwest-southeast grain of the basement area. The lower hills on the far side of the Colorado River are Copper Basin beds dipping toward the river. The Whipple Fault (A) is shown roughly paralleling the river.

Plate 15

Looking northwest across the trough of the Whipple Fault. The consistent dip of the basement schists is clearly shown in the area below the fault and the unbroken character is apparent. It is evident that the northwest trending interior faults do not continue through the mountains. The lower hills above the fault are the North Hills which are completely deformed by northwest trending faults which end at the Whipple Fault. A drag effect is indicated at the Whipple Fault. In the left center of the picture the dark patches of Copper Basin sediments can be seen dipping southwest and striking into the Whipple Fault. In the middle distance are the West Hills, composed of rhyolite mainly.


A

Plate 16

Looking northwest across the upper end of the Spring Block. The trace of the Whipple Fault is clearly seen and the curve of the fault to the right of the picture is evident. The Spring Fault (A) is shown and its bifurcation at "three-fingered" ridge is indicated. Note the regular dip of the metamorphics in the area of basement rocks below the Whipple Fault. Note also the northwest grain within the North Hills.


S B
A

Plate 17

Looking north along Whipple Wash (A) and Little Chemehuevi Valley. The dark ridge in the lower left hand corner is made up of Copper Basin volcanics and in front of the steep cliff the more finely dissected area is made up of basement rocks. The limit of this dissection marks the trace of the Whipple Fault (B). Some of the best exposures of the actual fault are to be found in the area to the left of Whipple Wash.


A
A
C
B

Plate 18

Looking southwest along the Colorado River (A) from the junction of the Williams River (B). Note nearby flat-lying lavas (C) in the area southeast (left) of the Colorado River.

Plate 19

Looking northwest across the area between the North Hills and the West Hills, showing the recent dissection of the Pleistocene and the younger sediments. The white bed in the upper right hand quarter is the Lake Series.

Plate 20

Looking northwest across the Chemehuevi Valley showing the recent dissection of the nearly flat-lying Chemehuevi formation and the younger alluvium. The white lake series is evident.


B
S A

Plate 21

Looking northwest across the western extension of the Whipple Mountains, outside of the area included in the Parker Quadrangle. The low dark hills in the left center are patches of Copper Basin volcanics. The Whipple Fault (A) apparently extends westward along a line just north of these toward the Turtle Mountains (B).