Geology of the San Manuel Area Pinal County, Arizona

GEOLOGICAL SURVEY PROFESSIONAL PAPER 471

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By S. C. CREASEY

With a section on ORE DEPOSITS

By J. D. PELLETIER *and* S. C. CREASEY

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A report on the geometry, mineralogy, and origin of the San Manuel porphyry copper deposit and on the distribution, petrology, and structures of the rocks in the adjoining quadrangle

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By S. C. Creasey

ABSTRACT

The San Manuel area is in southeastern Arizona about 30 miles northeast of Tucson. It is covered by the Mammoth 7½-minute quadrangle and includes the San Manuel porphyry copper deposit and the St. Anthony vein deposit, which yielded silver, gold, vanadinite, molybdenite, lead, and zinc. The San Manuel mine began production in 1955, and the St. Anthony mine closed in 1952 after a production of about 2 million tons of ore.

The Black Hills, the chief physiographic feature in the San Manuel area, are a small low-lying fault-block range in the Mountain Region of the Basin and Range province. They are bounded on the east and west by gravels, partly faulted against bedrock. To the northwest they pass into a gently rolling region of low relief, but to the south-southeast they grade into the Santa Catalina Mountains, one of the large rugged ranges in southeastern Arizona.

Precambrian rocks comprise granodiorite, quartz monzonite—Oracle Granite of Peterson (1938)—aplite, alaskite, and some diabase. Crosscutting relations and textural and lithologic similarities indicate that the oldest rock is the granodiorite, followed by the quartz monzonite, aplite, and alaskite; some diabase and aplite have mutual crosscutting relations. In adjacent areas rocks like the granodiorite intrude older Precambrian Pinal Schist.

Granodiorite porphyry, which occurs as small irregularly shaped masses and dikes in the Precambrian quartz monzonite, is the principal host rock for the disseminated copper ores of the San Manuel deposit. The granodiorite porphyry is older than the Cloudburst Formation and some diabase. One lead-alpha age determination made on zircon from the granodiorite porphyry suggests a Cretaceous age for the zircon and, by inference, for the porphyry.

The crosscutting relations of the diabase clearly establish that part of the diabase is Precambrian and that part is Cretaceous(?) or younger.

The Cloudburst Formation, of Late Cretaceous or early Tertiary age, consists of about 6,800 feet of intercalated fanglomerate and propylitized latite flows; neither the top of the section nor the bottom is exposed in the San Manuel area. The formation overlies the Precambrian granitic rocks on a low-angle thrust fault and is unconformably overlain by the Gila Conglomerate.

About two-thirds of the San Manuel area is underlain by Gila Conglomerate, the basin fill for the San Pedro Valley. The Gila ranges from coarse boulder conglomerate to fine marly silt; these deposits represent fanglomerates and playa or lake deposits, respectively. On the basis of differences in lithology and attitude, two members of the Gila Conglomerate, designated lower and upper, are recognized. The lower member, consisting chiefly of indurated conglomerate, dips 25° E. Four bedlike masses and one lens of sedimentary breccia lie conformably within the lower member. The breccia masses and lens comprise one, two, or three rock types. The fragments of the breccias are angular and jumbled, and they, unlike fragments in the surrounding conglomerate, show no indication of water transport or sorting. The breccia deposits are probably due to landslides or mudflows, or both. The upper member of the Gila Conglomerate is chiefly limy silt that dips 5° to 10° E. The two members are separated by an angular unconformity.

Remnants of pediment gravel cap some of the interfluves in the areas underlain by Gila Conglomerate. Apparently, the pediment once covered virtually all the Gila Conglomerate and some of the contiguous bedrock. Unconsolidated recent sand and gravel mantle the floor of the San Pedro River valley and the floors of all the washes except those of the smallest tributaries.

After intrusion and solidification, the Precambrian granodiorite and quartz monzonite were fractured and sheared, and diabase and aplite invaded the ruptures. The next recognizable structures are of Cretaceous age. Whether deformation occurred during the intervening time cannot be determined because the rocks in which the structures would be recorded are missing. The regional distribution of the younger Precambrian Apache Group and the Paleozoic system indicate that these rocks once covered the San Manuel area but that erosion has subsequently removed them; it is possible, however, that some of these rocks might lie beneath the Gila Conglomerate in the San Pedro Valley.

The granodiorite porphyry probably intruded the Precambrian granitic rocks during the Cretaceous, and the San Manuel ore deposit formed before the accumulation of the Cloudburst Formation. Before the Basin and Range deformation, the Cloudburst Formation was thrust over the Precambrian granitic rocks, and rhyolite and rhyodacite intruded it, but whether the rhyolite and rhyodacite were introduced before or after the thrusting was not determined. The thrust is probably a local structure. The Basin and Range deformation produced the San Manuel, Mammoth, and other unnamed high-angle normal and reverse faults. Faulting continued during the accumulation of the basin-fill deposits.

The San Manuel porphyry copper deposit contains combined sulfide and oxide ore that averages about 0.8 percent copper. The altered zone that contains the ore is about 8,000–9,000 feet wide and is more than 9,300 feet long; the long dimension strikes about N. 80° E. The deposit is mined by block-caving.

The ore occurs in quartz monzonite, granodiorite porphyry, and diabase and lies along the contact of granodiorite porphyry (above) and quartz monzonite (below); granodiorite porphyry is, however, the most abundant host rock. The ore may be related in time and source to the granodiorite porphyry. The primary sulfide minerals in the San Manuel deposit are chalcopyrite, pyrite, and molybdenite. Chalcocite is supergene; it occurs in the lower part of the oxidized zone associated with chrysocolla and residual sulfides. Supergene enrichment is slight to undetectable.

Silicate alteration (potassium-enriched rock) associated with copper mineralization produced quartz, potassium feldspar, biotite, and muscovite (sericite). In addition the ore contains residual albite, opaque minerals, rutile, apatite, and kaolinite. Veinlets of quartz, chalcopyrite, and pyrite are common. Quartz-molybdenite or molybdenite veinlets also occur but are not abundant; and a few veinlets of quartz and potassium feldspar, with and without sulfides, were recognized.

A second type of silicate alteration (argillized rock) that is not associated with copper metallization yielded a quartz-muscovite (sericite)-pyrite-kaolinite rock.

INTRODUCTION

LOCATION AND ACCESSIBILITY

The San Manual area lies in southeastern Arizona about 30 miles north-northeast of Tucson (fig. 1). The area includes all the Mammoth quadrangle of the 7½-minute topographic series and is bounded by long 110°37′30″ and 110°45′ W. and lat 32°37′30″ and 32°45′ N. (pl. 1).

The San Manuel mine lies slightly north of the middle of the area, and the St. Anthony mine lies about a mile farther to the north-northeast. Several other prospects and small inactive mines, the largest of which are the Ford, Tar, and Pearl mines, are in the northwest quarter of the area.

Arizona State Route 77 traverses the San Manuel area from the southwest to northeast corners; and a new paved road (not shown on pl. 1) connects the town of San Manuel, which is just south of the mapped area, to State Route 77. Good dirt roads, built and maintained by the local stockmen, are strategically placed to serve the less accessible country. In addition, the larger washes and gulches are natural access roads to the area for vehicles having four-wheel drive. Despite their gentle grades and broad and invitingly smooth beds, the gulches are not passable to two-wheel drive vehicles.

Two roughly parallel lines of the San Manuel Arizona Railroad Co., which is wholly owned by the San Manuel Copper Corp., lie within the area. One line, 8 miles long, connects the mine to the mill and smelter adjacent to the San Manuel townsite. The other, 29 miles long, extends from the mill and smelter to Hayden, where it joins the lines of the Southern Pacific Railroad (fig. 1). The copper anodes and freight outbound from the plant at San Manuel and the limestone, quartzite, and freight inbound to the plant are transported over the line from Hayden. The quarry for the limestone and quartzite used in the smelter lies next to the railroad right-of-way a few miles south of Hayden.

During the time the St. Anthony mine was active, which was prior to the development of the San Manuel deposit, Tiger was the largest town in the area. Its existence, however, depended on the mine. After the St. Anthony mine had closed, many of the residents were forced to seek employment elsewhere, and most of their houses were vacated. The houses were sold for movement elsewhere or for salvage. Many of the transported houses were relocated in Mammoth, and much of the residual population moved there. Today the residuum of Tiger consists of a warehouse, two bunk houses, and a hoist house and headframe for the Mohawk shaft.

Mammoth, along the San Pedro River in the northeastern part of the area, is now the largest town. Originally it was the site of the stamp mill for gold ores mined from the Mammoth mining camp. Old mining camps commonly survive long after logic predicts their end; Mammoth was such a camp. It somehow survived in the years after the mills were moved to the mines, the town apparently being sustained by the scattered residents in the valley and by the stockmen. In recent years Arizona State Route 77, which passes through the town, has been paved, and traffic has increased; the agricultural development of the San Pedro Valley has begun; and many dollars have been spent by the San Manuel Copper Corp. and its employees for supplies, services, and recreation in Mammoth. All these factors have combined to produce a prosperous and growing community which now boasts a suburb called New Mammoth.

Oracle, a small settlement built around a general store and post office, lies about 2 miles southwest of the southwest corner of the map area. Winkelman and Hayden lie in the San Pedro Valley about 20 miles north of the area; they are towns partly supported by the mining, milling, and smelting of ores from the porphyry copper deposit at Ray.

PHYSICAL FEATURES

The San Manuel area (fig. 1) is within the mountain region of the Basin and Range province as defined by Ransome (1903, p. 16). The Mountain Region, according to Ransome, is a zone of short, nearly parallel northwest-trending ranges separated by valleys filled with river and lake deposits. The Mountain Region is bounded on the southwest by the Desert Region of the Basin and Range province and on the northeast by the Colorado Plateau. Although both the Desert and Mountain Regions are made up of ranges and basins, the ranges in the Desert Region have less relief and gentler slopes, and the basins are correspondingly broader and more alluviated. Commonly the ranges are flanked by gently undulating granitic lowlands or pediments, thinly veneered by young gravels.

The Black Hills are a small, low-lying range in the Mountain Region (fig. 2). They are an adjunct to the

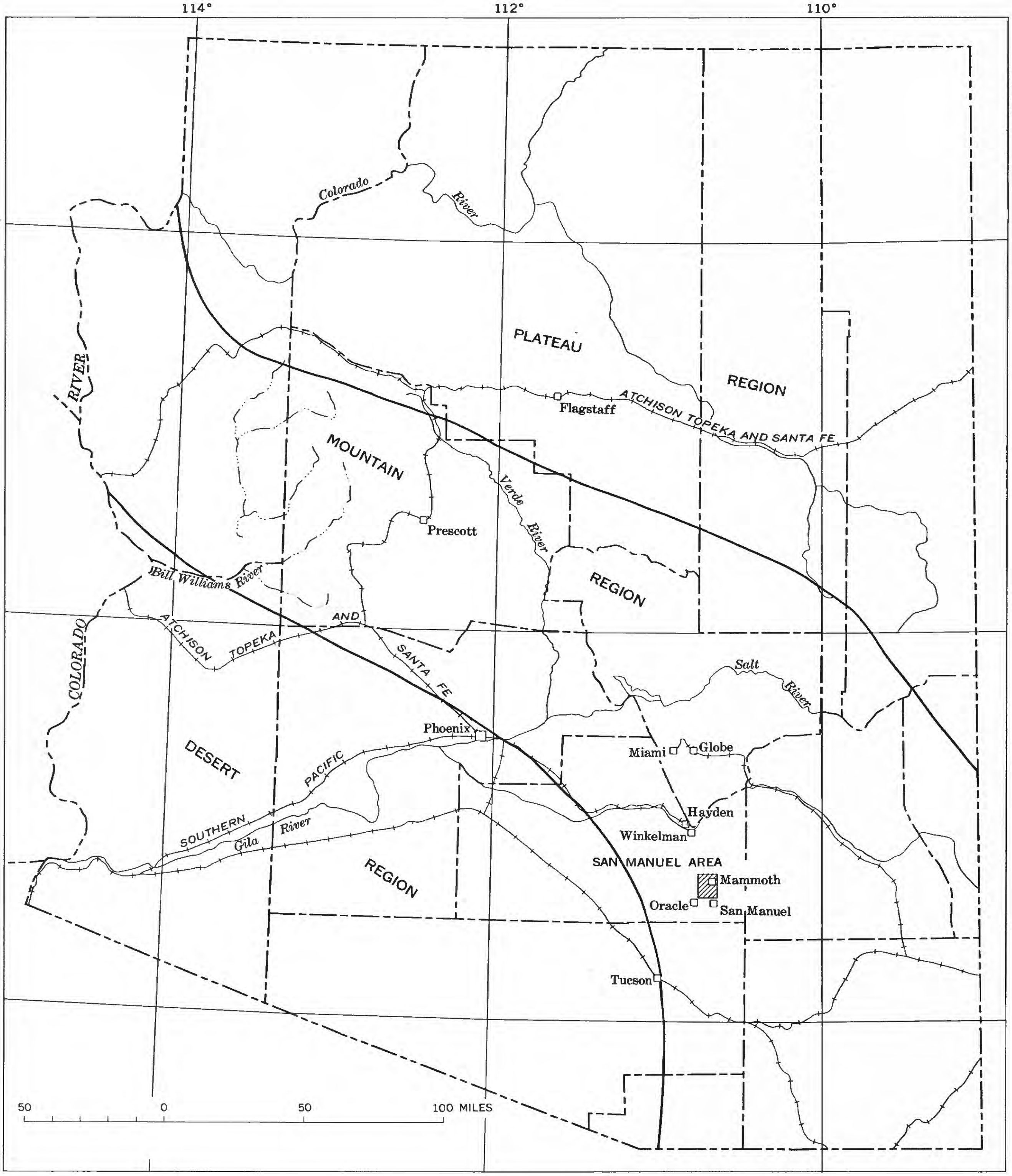


FIGURE 1.—Index map of Arizona showing the location of the San Manuel area.

north end of the Santa Catalina Mountains and appropriately might be considered as a part of that range (fig. 3). To the west and northwest the Black Hills pass into a gently rolling region of low relief whose average elevation is about 3,500–4,000 feet. To the south-southeast the imposing Santa Catalina Mountains rise to elevations of more than 9,000 feet and dwarf the surrounding regions. On the northeast the Black Hills

FIGURE 2.—General view from sec. 32, T. 8 S., R. 16 E., toward the north-northwest. Signal Peak is on the left, and the high peak in sec. 18 is on the skyline in the center.

are flanked by the San Pedro Valley, a well-defined physiographic feature that reaches from northern Mexico northwestward for more than 130 miles to the confluence of the San Pedro and Gila Rivers, about 16 miles north of the San Manuel area.

Elevations increase toward the northwest corner of the area, where the highest point, Signal Peak, attains an elevation of 4,364 feet. The lowest point in the area is where the San Pedro River crosses the north boundary of the quadrangle, and there the elevation is about 2,300 feet. In general, the area slopes and drains northeastward toward the San Pedro River, which runs northwestward through the northeast corner of the area for about 4 miles. Most of the drainage is through five major washes; from south to north they are Smelter, Cottonwood, Mammoth, Tucson, and Tar. Tucson Wash is the largest.

CLIMATE AND VEGETATION

No climatic records are available for the San Manuel area, but a weather station has been maintained for the past 60 years in Oracle (table 1). The Oracle weather station, at an elevation of 4,600 feet, is about 400 feet higher than the nearest parts of the San Manuel area; however, the precipitation and temperatures at Oracle will approximate those at elevations above 4,000 feet in the San Manuel area.

The climate along the San Pedro Valley is significantly hotter and dryer than that in the upper reaches of the San Manuel area, mainly because the average elevation is about 2,000 feet lower in the valley. The climatic records for the Tucson Airport, which, at an elevation of 2,550 feet, is only about 200 feet higher than the valley, are included for comparison with those for Oracle on the assumption that the climate at Tucson is somewhat similar to that in the valley (table 1). The temperatures in the San Pedro Valley probably closely approximate those in Tucson, but the precipitation could differ markedly. Apparently local topography greatly influences precipitation, especially that which falls during summer thunderstorms. There is no doubt, however, that the precipitation in the San Pedro Valley is much less than that at Oracle.

Vegetation in the San Manuel area comprises three general types: creosote bush, desert grasslands, and paloverde-cacti (Nichol, 1952). Creosote bush flourishes on the pediments cut on the Gila Conglomerate just above the flood plain of the San Pedro River. Higher on the pediment slopes the creosote bush yields to jungles of cholla, principally jumping cholla, that are locally underlain by a thin carpet of grass. Washes that cut the pediment support some mesquite and other shrubs whose identities are not known to me. As elevation increases the dense cholla gradually thins and grassy patches become more conspicuous, and the creosote-bush–cholla zone grades into the desert grasslands.

The desert grassland lies at elevations above 3,000–3,500 feet, and it occurs only on the interfluves in areas underlain by Gila Conglomerate, particularly where the pediments have not been stripped by the present erosion cycle. The grassland is dotted here and there with mesquite, clumps of bear grass, cholla, and the picturesque palmilla (yucca). In the washes, mesquite, hackberry, cat's claw, and other bushes abound.

Vegetation on the bedrock is the paloverde-cacti-mesquite type and is entirely different from that on the gravels. The types of cacti are many and varied: among those recognized were saguaro, ocotillo, several species of cholla, several species of prickly pear, barrel, hedgehog, pin cushion, and strawberry cacti. Mesquite is abundant on slopes and is particularly profuse in washes. Cat's-claw and hackberry were also recognized, and other bushes were seen but were not known to me. Grass is sparse in the bedrock areas and occurs only in isolated clumps.

FIELDWORK AND ACKNOWLEDGMENTS

Robert E. Davis and I mapped the San Manuel area (pl. 1) from September 1954 to January 1955. I returned during September and November of 1955 to collect samples from the underground workings of the San Manuel mine and to make minor corrections and additions on the regional geologic map. Mr. John D. Pelletier, chief geologist of the San Manuel Copper Corp., mapped the subsurface workings over a period of several years as development of the mine progressed.

TABLE 1.—*Climatic averages for Oracle*[1] *and for Tucson Airport*[2]

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual	Maximum	Minimum
Average precipitation (inches)															
Oracle	1.96	1.65	1.60	0.84	0.31	0.42	2.82	3.21	1.56	0.92	1.61	2.11	19.01	-------	-------
Tuscon Airport	.64	.92	.65	.47	.16	.22	2.00	2.15	1.26	.60	.68	.94	10.69	-------	-------
Mean temperatures (degrees Fahrenheit)															
Oracle	45.6	48.0	52.3	59.4	67.6	76.8	79.6	77.4	73.7	62.6	53.8	47.3	62.0	108	2
Tucson Airport	50.5	53.6	57.5	65.8	74.0	82.3	86.8	84.6	81.5	71.0	58.8	52.2	68.2	110	16

[1] Sixty-year record. [2] Thirteen-year record.

It is a pleasure to acknowledge the cooperation of the San Manuel Copper Corp., which kindly permitted publication of the geologic maps of the 1475 haulage level and the 1415 Grizzly level as well as three cross sections through the ore deposit. Mr. Pelletier and Mr. Hugh Steele, chief mine engineer, made virtually all the mine facilities available to me; they also gave generously of their time and helped in every way. Other members of the mine staff, chiefly C. L. Pillar, mine superintendent, H. I. Ashby, mine general foreman, and W. W. Savage, mine safety and ventilation engineer, were helpful.

GEOLOGY

PRECAMBRIAN ROCKS

The Precambrian rocks of southeastern Arizona comprise many coarse-grained quartzose granitic rocks as well as low-grade micaceous schist and gneiss. The granitic rocks have only been studied superficially. The Arizona State Geologic Map (Darton and others, 1924) shows that they crop out extensively along the southwest side of the San Pedro Valley in the Huachuca, Whetstone, Santa Catalina, and Tortilla Mountains and in the Black Hills (fig. 3). For some obscure reason, much less Precambrian rock occurs on the northeast side of the valley. Isolated areas of Precambrian rocks, however, occur in the Galiuro Mountains, south of Aravaipa Canyon; in the Dragoon Mountains; and in the Mule Mountains. In addition, Butler and others (1938) and Gilluly (1956) found smaller masses in the Tombstone Hills and in the Little Dragoon Mountains, respectively.

Ransome (1903, 1919), in his studies of the Globe-Miami and Ray areas, described these rocks in detail. He recognized three formations: the Ruin Granite, the Madera Diorite (quartz-mica diorite), and the Solitude Granite. Of these, only the Madera Diorite and the Ruin Granite are widespread; because it is gneissic, the Madera Diorite was presumed to be the older. Ransome recognized that the Madera Diorite extended from the Globe-Miami area southward into the Ray area, which is approximately 17 miles north of the San Manuel area. He described a weathered porphyritic biotite granite from the Ray quadrangle that was virtually identical with the Ruin; but, because the granite was deeply weathered, neither a detailed petrographic description nor a chemical analysis was made.

Even though comparison of Precambrian quartzose granitic rocks from one area to another has little merit, the quartz monzonite (Oracle Granite of Peterson, 1938) of the San Manuel area must be compositionally similar to the Ruin Granite, and the granodiorite, to the Madera Diorite.

GRANODIORITE

The granodiorite crops out over about 4 square miles in the northwest corner of the San Manuel area. It underlies a somewhat larger area but is locally covered by a thrust plate of the Cloudburst Formation. A window in the thrust plate and granitic rocks in fault slivers in the thrust permit a crude approximation of the amount of granodiorite covered by the thrust. I estimate that about 8 square miles of granodiorite occurs within the San Manuel area. To the north and northeast much similar rock occurs, but the relative amounts of quartz monzonite and granodiorite have not been determined.

The granodiorite is a light-colored medium-grained hypidiomorphic-granular rock. The color index is about 13. Locally northeast- and northwest-trending shear planes and joints are conspicuous and are commonly marked by aplitic and diabasic dikes. Other local trends of secondary shear planes and joints were noted, and, where conspicuous, they were recorded by a symbol. The rock, however, is by no means gneissic.

The granodiorite is everywhere so deeply weathered that hand specimens from which thin sections can be made are rare. Relatively fresh granodiorite was obtained from the dump of the Tar Mine and from a few separate outcrops. Most of the granodiorite in surface outcrops is sufficiently rotten that it can be crushed by hand.

Microscopic study reveals that the granodiorite is composed of quartz, plagioclase ($An_{30\pm5}$), feldspar, biotite, and hornblende. Accessory minerals are leucox-

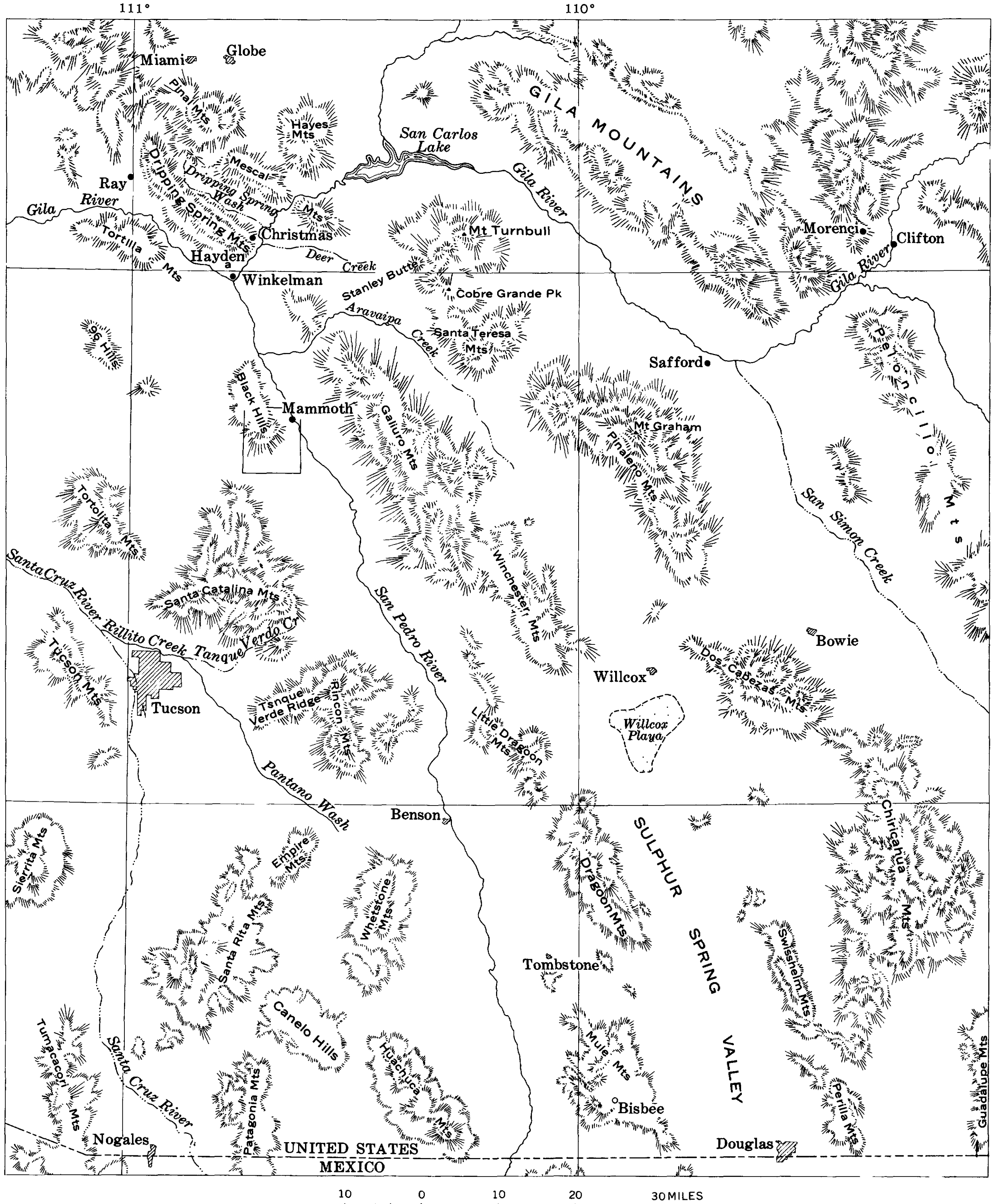


FIGURE 3.—Sketch map showing the principal ranges and valleys in southeastern Arizona.

ene, magnetite, and zircon; and secondary constituents are carbonate, chlorite, and sericite. The plagioclase and mafic minerals are subhedral; the potassium feldspar is anhedral and occurs interstitial to the quartz, plagioclase, and mafic minerals, and as minute blebs included in the plagioclase. The occurrence of potassium feldspar as minute blebs in plagioclase is probably due to exsolution. Much of the plagioclase is argillized. Some crystals are completely altered, whereas others are altered in irregular patches or are differentially altered, the greatest alteration being in the core. The following tabulation gives the average of two modes from the granodiorite and the calculated mineral composition of the Madera Diorite from the Globe area (Ransome, 1903, p. 60) for comparison.

Mode of granodiorite and calculated mineral composition, in volume percent, of Madera diorite from Globe area

	Mode (granodiorite)	Calculated mineral composition (Madera diorite, Globe area [1])
Quartz	23	26.88
Albite		23.22
Anorthite		20.45
An_{30}	51	
Potassium feldspar	10	6.37
Biotite		17.75
Mafic (biotite plus hornblende)	13	
Magnetite		2.84
Accessories	1	1.51
Muscovite		.98
Carbonate	1	
Other	1	
Total	100	100.00

[1] From Ransome (1903, p. 60).

QUARTZ MONZONITE (ORACLE GRANITE OF PETERSON, 1938)

Quartz monzonite probably underlies all the San Manuel area except in the northwest corner where granodiorite occurs for a few square miles. The outcrop area of the quartz monzonite, however, is much smaller than that of the granodiorite because much of the quartz monzonite is covered by Gila Conglomerate and by the thrust plate of Cloudburst Formation. The quartz monzonite crops out (1) in the extreme northwest corner of the area, (2) north of the San Manuel fault from near the west boundary of the quadrangle to south of Cottonwood Wash, (3) in the inlier of bedrock exposed in and around sec. 4, T. 8 S., R. 16 E., and (4) in the southwest corner of the area, where continuous exposures of quartz monzonite extend southward for perhaps 7 miles to the northern front of the Santa Catalina Mountains.

The quartz monzonite is a coarse-grained, porphyritic rock; it has a color index ranging from 5 to 15 and probably averaging about 10. Deformation locally produced joints and sheared zones in the quartz monzonite, as in the granodiorite, but the rock is not gneissic. Most of these structures trend northeast or northwest, and many are occupied by aplitic and diabasic dikes.

Within the San Manuel area the quartz monzonite is deeply weathered, and fresh rock cannot be obtained from surface outcrops. Peterson (1938) found fresh-appearing rock on the 500 and 700 levels in the Mammoth mine, but additional work revealed that the plagioclase was intensely sericitized. To the north the quartzose granitic rocks, which undoubtedly include quartz monzonite, are equally well weathered. To the south in the foothills of the Santa Catalina Mountains, however, erosion has stripped the weathered mantle and exposed fresh rock.

The quartz monzonite consists of phenocrysts of microperthite and potassium-feldspar, as much as 3 inches long parallel to the side pinacoid, set in a medium- to coarsed-grained hypidiomorphic granular matrix. The phenocrysts are pink, whereas the matrix feldspar (both plagioclase and potassium feldspar) is white. The bulk of the potassium feldspar is in the pheoncrysts, but that in the matrix occurs interstitial to the quartz and plagioclase. Accessory minerals are sphene, zircon, and apatite.

In the specimens studied the plagioclase was saussuritized, but whether the saussuritization is characteristic of all the quartz monzonite was not determined.

Table 2 gives the chemical and mineralogic composition of the quartz monzonite.

TABLE 2.—*Chemical, normative, and modal composition, in percent, of the quartz monzonite*

Chemical analysis

	1		1
SiO_2	63.06	H_2O-	0.30
Al_2O_3	14.44	TiO_2	.96
Fe_2O_3	6.57	P_2O_5	.32
MgO	1.41	MnO	.04
CaO	1.49	CO_2	None
Na_2O	2.09	SO_3	.65
K_2O	3.59	FeS_2	2.88
H_2O+	1.83	CuO	.034
		Total	99.66

Norm

Q	28.7	hy	[1] 12.6
or	20.6	C	5.0
ab	17.8	py	2.9
an	5.8	il	2.0
		ap	2.0
		Total	97.40

See footnotes at end of table.

TABLE 2.—*Chemical, normative, and modal composition, in percent, of the quartz monzonite*—Continued

Mode (volume percent)

	2	3	4	Average		2	3	4	Average
Quartz	28	26	26	27	Biotite	5	10	15	10
Microperthite and potassium feldspar	37	31	21	30	Other	2			
Plagioclase ($An_{30\pm5}$)	28	33	38	33	Total	100	100	100	100

[1] Fe_2O_3 recomputed as FeO and combined with MgO to form the normative hypersthene.
1. From churn drill hole 67, San Manuel area (Schwartz, 1953, p. 7).
2. From St. Anthony mine (Peterson, 1938, p. 8–9).
3. From the dump of the Tar mine, Mammoth quadrangle.
4. From near Oracle, Ariz.

The analysis is for an altered sample of quartz monzonite (Schwartz, 1953, p. 7), and the partial norm calculated from it assumes that all the iron not found as iron sulfide is in the mafic silicates and ilmenite rather than in the magnetite. The difficulty in measuring an accurate mode is increased by the porphyritic texture of the quartz monzonite and its coarse grain size. The differences in the modes could be due either to errors in the mode induced by the texture and grain size or to the mineralogic differences in the rock from one locality to another. Nevertheless, both the modes and the norm indicate the rock is a quartz monzonite. The unusual geographic locations of the samples from which the modes were calculated are due to the limited availability of fresh rock.

DIABASE

Diabase dikes occur wherever rocks older than the late Cretaceous or early Tertiary Cloudburst Formation crop out; the longest dike, in the northwestern part of the area, crops out for about 3,500 feet and then continues beneath the thrust plate of Cloudburst Formation. In addition to the dikes, lenticular and irregularly shaped diabase masses also occur. The widest mass, in the southwest corner of the area, is about 400 feet across.

The dikes are found both in swarms and separately. The prevailing trends are northeast and northwest; no age distinction was recognized between the two trends.

The diabase ranges from medium gray to nearly black and has a range in color index from 43 to 75. The diabase is massive. The common texture is diabasic—that is, the mafic constituents are interstitial to the lath-shaped plagioclase. Fine-grained granular textures, however, in which the plagioclase grains are subhedral, characterize some of the larger masses. The diabase was not analyzed chemically, but the variation in its mineralogy is given by the following modes, in volume percent, each from a different dike.

Modes of diabase samples

	Percent	Percent	Percent
Plagioclase	35	39	55
Hornblende	61	[1] 53	26
Chlorite			8
Opaque minerals	4	8	1
Quartz			2
Epidote			8
Total	100	100	100

[1] Includes about 5 percent biotite.

The plagioclase composition in one dike was An_{35-40}. Judged by indices of refraction, the composition of the plagioclase in samples from other dikes is about the same.

Hornblende occurs rather than a pyroxene; in some dikes the hornblende was altered locally to chlorite. About 5 percent biotite, spatially associated with the opaque minerals, largely magnetite, was found in one dike.

The intrusive relations indicate at least two ages of diabase. Some diabase dikes near Red Hill cut the granodiorite porphyry, which is of Cretaceous(?) age; others are cut by the porphyry. Diabase was not found in the Cloudburst Formation, and, for this reason, all the diabase is presumed to be older than the Cloudburst. The older diabase cuts, and is cut by, aplite dikes, which are believed to be satellitic to the quartz monzonite. These intrusive relations suggest a diabase of Precambrian age, and a diabase younger than the granodiorite porphyry but older than the Cloudburst Formation. If diabases of other ages, exist, they were not recognized.

ALASKITE AND APLITE

The distribution of the alaskite and aplite is similar to that of the other Precambrian granitic rocks. Aplite dikes are in the northwest and southwest corners of the quadrangle, just north of the San Manuel deposit; in and adjacent to sec. 4; and in the horst of pre-Gila rocks between the San Manuel and Mammoth faults (pl. 1). Alaskite, however, crops out only in the northwest corner of the area, where it forms an irregularly shaped mass, parts of which are dikelike.

Except for several short dikes in the inlier north of the San Manuel deposit and one short dike south of Smelter Wash, all the aplite dikes strike northwest; this contrasts with the trend of the diabase dikes, which strike either northeast or northwest.

The alaskite and aplite are light cream or buff, and their color index is 1 to 3. They commonly are fractured, jointed and locally sheared; but they did not yield to any pervasive deformation, so that the dominant textures and structures are igneous rather than metamorphic. The aplite is a fine- to medium-grained rock in which the dominant texture is saccharoidal (aplitic). Locally the texture is graphic. The specimen studied under the microscope was composed of albite (59 percent), quartz (40 percent), opaque minerals (1 percent), and a trace (<1 percent) of potassium feldspar. The composition of the albite is An_3. Whether all the aplite is similarly impoverished in potassium feldspar is unknown, but this seems unlikely because the alaskite, which is a related rock, is not.

The alaskite is a medium- to coarse-grained rock. Where the alaskite mass tapers to a dike, the texture of the alaskite is dominantly saccharoidal. Where the mass widens, however, the grain size becomes coarser, and the texture becomes porphyritic; both plagioclase and potassium feldspar phenocrysts are set in a saccharoidal groundmass composed of quartz and potassium feldspar. Virtually all the plagioclase is phenocrystic, and it is argillized. Scattered throughout the alaskite are fibrous hornblende crystals, partly to completely altered to chlorite.

The mode, in volume percent, of the alaskite is 24 percent plagioclase, 43 percent quartz, 31 percent potassium feldspar, 1 percent hornblende, and 1 percent chlorite.

AGE RELATIONS OF THE PRECAMBRIAN GRANITIC ROCKS

Unequivocal evidence for the relative ages of the granodiorite and quartz monzonite was not found. The spatial relations and compositional similarities to and differences from the alaskite and aplite suggest that the granodiorite is older. Using the strontium-rubidium method on biotite, Damon (1959, p. 18) determined the age of the quartz monzonite (Oracle Granite) from near the Campo Bonito mine at Oracle to be 1,450 million years.

The spatial relations of the granodiorite, quartz monzonite, alaskite, and aplite are shown on plate 1. The aplite dikes cut the granodiorite and quartz monzonite indiscriminately; the alaskite, however, is more closely related spatially to the quartz monzonite.

In mineral composition and texture the alaskite is more like the quartz monzonite. The ratios of quartz to alkali feldspar to plagioclase for the granodiorite, quartz monzonite, and alaskite, respectively, are 23:10:51, 27:30:33, and 43:30:24. Although all three rocks contain abundant quartz, the closer ratios of alkali feldspar to plagioclase for the quartz monzonite and alaskite indicates a more similar bulk chemical composition.

Where the alaskite mass is dikelike, it is aplitic. But as the dikelike masses widen into the main body of the alaskite, the texture becomes porphyritic, and the rock grades into a porphyritic alaskite and, locally, into a rock that cannot be distinguished megascopically from the quartz monzonite.

In summary, the alaskite and aplite are closer spatially, chemically, and texturally to the quartz monzonite than to the granodiorite. I assume therefore that they have a close kinship to the quartz monzonite and that they might be late differentiates from the same parent magma. Because the alaskite and aplite cut both the granodiorite and the quartz monzonite, the most probable sequence of intrusion is granodiorite, quartz monzonite, and alaskite and aplite. The mutual contacts between the granodiorite and quartz monzonite, however, are not well exposed, and I saw nothing in their contact relations to suggest their relative ages.

CRETACEOUS(?) AND CRETACEOUS OR TERTIARY ROCKS

The Cretaceous(?) and Cretaceous or Tertiary rocks in the San Manuel area comprise the granodiorite porphyry of Cretaceous(?) age and the Cloudburst Formation of Late Cretaceous or early Tertiary age. Volcanics similar to those found in the Cloudburst and therefore presumed to be Cretaceous or early Tertiary, occur east of this area in the Galiuro Mountains on the opposite side of the San Pedro Valley. Upper Cretaceous sandstones and shales, unconformably overlain by volcanics similar to those of the Cloudburst Formation, are present about 25 miles to the northeast in Reed Basin, east of Christmas, Ariz. (pl. 3).

GRANODIORITE PORPHYRY[2]

The granodiorite porphyry is restricted to the central and southwestern parts of the quadrangle, and it possibly is confined to a wide northeast-trending belt that includes the long axis of the mineralized area in the San Manuel deposit. The granodiorite porphyry occurs as small irregularly shaped masses, lenses, and dikes that intrude the Precambrian quartz monzonite. The underground openings in the San Manuel mine reveal a large amount of porphyry beneath the Pliocene and Pleistocene Gila Conglomerate, whereas the underground openings in the St. Anthony mine, which extend northwest from the St. Anthony mine area, cut little porphyry. Several small additional porphyry masses crop out in the horst lying between the Mammoth and San Manuel faults for about 2 miles southeast of the San Manuel deposit.

The granodiorite porphyry is a gray rock; the color index ranges from 10 to 20 but probably averages near 13. The disseminated mafic constituents in the microcrystalline groundmass darken the rock more than one

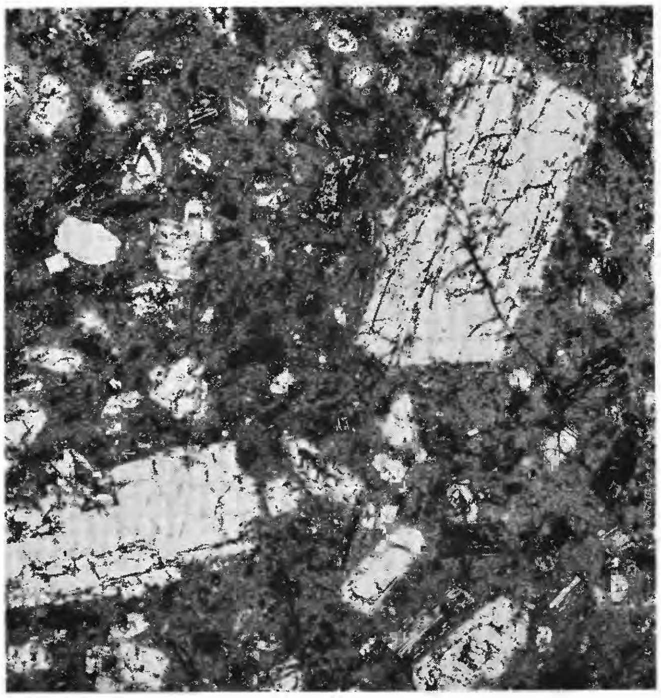
[2] Monzonite porphyry of Schwartz (1953).

would expect from the normative or chemical composition.

The rock is porphyritic. It originally consisted of phenocrysts of plagioclase, biotite, and hornblende in a microgranular groundmass (figs. 4, 5) of plagioclase laths or microlites, granular quartz, potassium feldspar, and mafic constituents. The groundmass in a few specimens tends toward pilotaxitic, owing to abundant plagioclase microlites. Accessory minerals are apatite, zircon, magnetite, and rutile; apatite is most abundant.

Most of the plagioclase is altered, and the intensity of the alteration varies from one porphyry mass to another. The alteration is described more fully in the section on hydrothermal alteration associated with the San Manuel deposit, and the description of altered granodiorite porphyry in the deposit is confined to that section. The alteration products away from the deposit consist of albite and variable amounts of muscovite (sericite), calcite, epidote, kaolinite (or other members of the group), and minor chlorite. The phenocrystic plagioclase has been altered to higher albite content and ranges in composition from An_{0-5} to An_{55}, the An_{55} presumably being the primary composition. Some phenocrysts are zoned, but the range in composition of these was not determined. The two most common alteration assemblages are albite-sericite-kaolinite-calcite, and albite-kaolinite-calcite. In two slides, minor amounts of epidote are associated with calcite. Calcite, however, is much more abundant in the altered porphyry, and it probably is the principal stable calcian mineral.

FIGURE 4.—Least altered granodiorite porphyry in the San Manuel area. It consists of phenocrysts of labradorite (An_{55}) and partly chloritized biotite in a microgranular groundmass of quartz, alkali feldspar, and unidentified materials. Scale in tenths of an inch.



A

B

FIGURE 5.—Photomicrographs of the granodiorite porphyry showing phenocrysts of labradorite (An_{55}) and altered biotite (now chlorite and iron oxide) in a microgranular groundmass. Most of the plagioclase is not zoned. The mass of granodiorite porphyry represented by these photographs is one of the least altered in the area. *A*, Plane-polarized light, × 12; *B*, Crossed nicols, × 12.

About two-thirds of the specimens of granodiorite porphyry studied originally contain both biotite and hornblende, the others contain only biotite. In some of those that contain only biotite, however, secondary minerals appear to pseudomorph the outline of hornblende. The most common alteration assemblage of biotite and hornblende is chlorite-carbonate (mostly calcite)-muscovite. Biotite alters first to a light-green biotite; more intense alteration produces chlorite, calcite (or other carbonate), muscovite, epidote, leucoxene, magnetite, and iron oxide. Hornblende alters to chlorite, carbonate, muscovite, epidote, magnetite, and iron oxide. Hornblende is more susceptible to alteration than biotite; in some specimens where hornblende is completely altered to pseudomorphs of secondary minerals, biotite, although strongly altered, still remains.

Because all the granodiorite porphyry is altered, analyses truly representative of the fresh porphyry are not possible. The analyses in table 3 are for the freshest porphyry available. Sample 1 is from the large mass of porphyry in the central part of sec. 4, T. 9 S., R. 16 E. (pl. 1), and sample 2 is a composite from a churn-drill hole (Schwartz, 1953, p. 10); both samples are altered. Alteration of both rock samples is reflected in the chemical analyses by the presence of CO_2 and H_2O and, for sample 2, by the presence of SO_3 and CuO; in the norms, the alteration is reflected by calcite, corundum, and hematite; and in the calculated composition, alteration is reflected by the calcite and kaolinite.

TABLE 3.—*Chemical, normative, and modal composition of the granodiorite porphyry, in percent*

Chemical analyses

	1	2		1	2
SiO_2	61.8	64.88	P_2O_5	.22	.19
Al_2O_3	16.5	15.01	MnO	------	.04
Fe_2O_3	3.3	1.06	CO_2	1.0	1.35
FeO	1.2	2.42	SO_3	------	1.04
MgO	2.6	1.44	CuO	------	.19
CaO	3.6	2.59			
Na_2O	4.3	3.02	Total	100.04	99.33
K_2O	2.5	3.14			
H_2O+	1.9	2.03	Powder density	------	2.66
H_2O-	.5	.37			
TiO_2	.62	.56	Bulk density	2.625	2.59

Norm

	1	2		1	2
Q	19	31	mt	2	3.3
or	15	18.4	il	1	1
ab	36	25	hm	2	------
an	11	3	ap	.34	.34
C	2.9	4.5	cc	2	3
en	6.5	3.6			
fs	0	2.5	Total	97.74	95.64

Mode (volume percent)

	1	2[1]		1	2[1]
Quartz	------	29	Sericite	------	1
Plagioclase An_{55}	30	------	Calcite	------	3
			Kaolinite	------	10
Albite	------	26	Groundmass	52	------
Potassium feldspar	<1	9	Other	------	11
Biotite Hornblende Chlorite	18	11	Total	100+	100

[1] Approximate composition, given by Schwartz (1953, p. 24) in chart form.

1. Granodiorite porphyry, sec. 4, T. 9 S., R. 16 E., Mammoth quadrangle, Pinal Co., Ariz. Rapid analysis. Analysts: P. L. D. Elmore, K. E. White, and S. D. Botts.
2. Composite sample of least altered monzonite porphyry (granodiorite porphyry of this report). Schwartz (1953, p. 1025).

The modal composition, which is available for sample 1 only, lists the groundmass separately. It is therefore mainly a percentage account of the phenocrystic minerals. Because the groundmass is microcrystalline, I could not distinguish the individual mineral species sufficiently well to obtain a mode; but, as stated earlier, the groundmass contains quartz, potassium feldspar, plagioclase, and mafic minerals. Schwartz (1953) did not publish a mode for sample 2; instead, using the actual minerals and the chemical analysis, he calculated the composition of the porphyry. Table 3 emphasizes the altered nature of even the freshest porphyry and the contrast between the norms and modes. Both quartz and potassium feldspar are abundant normative minerals, yet they are not modal minerals because they are confined to the groundmass.

The granodiorite porphyry intrudes the quartz monzonite, aplite, and some older diabase; but near the San Manuel deposit, it is cut by a younger diabase. In the bedrock horst between the Mammoth and San Manuel faults, about 2,500 feet southeast of State Route 77, fanglomerate of the Cloudburst Formation overlies the porphyry in depositional contact, and altered boulders of the porphyry are part of the fanglomerate. H. W. Jaffe of the U.S. Geological Survey, using the lead-alpha method, determined the age of zircon concentrates from the granodiorite porphyry to be 97–130 million years. This age determination suggests that the porphyry is Cretaceous.

CLOUDBURST FORMATION

The Cloudburst Formation was named from the good exposures in Cloudburst Wash, one of the chief tributaries of Tucson Wash (pl. 1). The Cloudburst Formation includes three major lithologic types: (1) fanglomerate, (2) beds of a distinctive sedimentary breccia, and (3) volcanics comprising intercalated latite flows, flow breccias, and minor intrusive equivalents of the latite. These lithologic types are not considered members because they lack persistent stratigraphic relations to each other.

The Cloudburst Formation underlies most of the northwest third of the San Manuel area. In addition, it forms part of the bedrock horst bounded by the San

Manuel and Mammoth faults southeast of the San Manuel mine. Four dikes—presumably feeders for the lavas of the Cloudburst—cut the quartz monzonite in the southwest corner of the area.

The Cloudburst Formation crops out in the northwest quarter of the quadrangle. Eastward and southward within the quadrangle, it is concealed by Gila Conglomerate. Westward it extends about a mile beyond the quadrangle boundary, where it is in fault contact with the Gila Conglomerate (pl. 3). Northward the Cloudburst has been eroded from the underlying Precambrian granitic rocks.

Some information on the extent of the Cloudburst beneath the Gila is available. In the southwest corner of the quadrangle, Gila rests directly on the quartz monzonite; presumably, the Cloudburst was removed by erosion. To the southeast, the distribution of the Cloudburst Formation chiefly in the bedrock horst between the San Manual and Mammoth faults suggests that the erosional edge may be near the boundary between secs. 7 and 18, T. 9 S., R. 17 E. Eastward from the San Manuel area, no information is available because the Gila extends unbroken, except where it is interrupted by younger alluvium and gravels, for about 10 miles to the foothills of the Galiuro Mountains.

The exposed thickness of the Cloudburst Formation along section *B–B′*, is about 6,000 feet, including both fanglomerates and lavas. But neither the top of the section nor the bottom is exposed. The thickness of fanglomerate south of the San Manuel fault, calculated from an east-west section about 1,000 feet south of the north boundaries of secs. 32 and 33, T. 8 S., R. 16 E., is about 4,800 feet; and the thickness of the lava flows lying to the west within the area, including one bed of fanglomerate about 100 feet thick, is about 2,000 feet. Here also neither the top of the section nor the bottom is exposed.

FANGLOMERATE

The lithology of the fanglomerate in the Cloudburst Formation changes from one series of beds to another and along the strike, but I could not determine whether these changes are due to lenticularity of beds of different composition or to variation of rock types within a single bed or to both. The distribution of the different lithologic types of fanglomerate is shown on plate 2. Where a characteristic lithology is not indicated, either I could not recognize one or no information was obtained.

Fragments in the different types of fanglomerate range in size from 1/16 inch to 10 feet; boulders 10 feet in diameter are rare, but those 5 feet in diameter are common. Sorting ranges from good to crude; the volcanic sandstone is well sorted, the fanglomerate is not. Bedding, which is common, is best shown by beds whose fragments are less than 12 inches in diameter. Induration is moderate, in marked contrast to that of the upper member of the Gila Conglomerate.

Fragments in the fanglomerates include quartz monzonite, granodiorite, mafic volcanics, diabase, aplite, hornblende-biotite andesite, rhyolite, granodiorite porphyry, quartzite, limestone, and gabbro. Of these, the granitic rocks and mafic volcanics are estimated to constitute at least 85 percent of the fragments. The source of the quartzites and limestones could be the younger Precambrian Apache Group and the Paleozoic rocks, respectively, both of which are exposed in the Santa Catalina Mountains about 10 miles southward. Presumably, the gabbro is a phase of the diabase, which is abundant in the Santa Catalina and Galiuro Mountains. Possible sources for the hornblende-biotite andesite and the rhyolite are not known.

The fanglomerate that extends northeastward from the central part of sec. 27, T. 8 S., R. 16 E., into sec. 26 on both sides of Tucson Wash consists chiefly of fragments derived from the lavas in the Cloudburst Formation. Minor beds contain fragments of other rocks, chiefly quartz monzonite, but rhyodacite, quartzite, and possibly aplite were also observed. Peterson (1938, p. 11) called this sequence, "* * * an agglomerate composed chiefly of varicolored basalt fragments together with abundant granitic material."

The fanglomerate beds in Cloudburst Wash (secs. 28 and 29, T. 8 S., R. 16 E.) west of the San Manuel fault consist predominately of crudely bedded brick-red fanglomerate derived almost wholly from the quartz monzonite. The remaining fragments were derived from latite, quartzite, aplite, rhyolite, and probably granodiorite porphyry. The beds contain both sand-sized fragments and boulders, some of which are as much as 1.5 m in diameter; most of the fragments are more than 0.3 m in diameter. Intercalated with these dominantly granitic fanglomerate beds are a few beds which are derived chiefly from the latitic lavas but which also include minor amounts of quartz monzonite and rhyolite. The fanglomerate composed of latitic lava is blue-gray and its color contrasts with the brick-red color of the fanglomerate derived from the quartz monzonite in Cloudburst Wash; the fanglomerate derived from the lava flows, constitutes the bottom 150 feet of the section in the wash and is commonly intercalated with the granitic fanglomerate as far east as McKinney Dam, sec. 29, T. 8 S., R. 16 E. (pl. 1). In addition, in the section at Cloudburst Wash there were (1) a few beds of latitic sandstone as much as 3 feet thick, (2) several beds consisting of mafic volcanic fragments as much as 8 cm in diameter in a sandstone matrix derived from the Precambrian granitic rocks, and (3) one bed of rhyolite tuff as much as 5 feet thick.

The fanglomerate in the north-central part of sec. 27, T. 8 S., R. 16 E. (pl. 2) comprises well-bedded boulder fanglomerates and lesser amounts of intercalated coarse- to medium-grained sandstone. Fragments derived from the quartz monzonite greatly predominate in the fanglomerate, but some beds contain mostly lava fragments. This local sequence is exceptionally well bedded and locally shows water sorting and crossbedding.

The fanglomerate west of the Mammoth fault in the central part of sec. 16, T. 8 S., R. 16 E., contains mostly volcanic fragments; scattered granitic fragments were estimated to make up less than 1 percent of the unit. In contrast, the fanglomerate east of the Mammoth fault contains roughly equal amounts of granitic and volcanic fragments and, in addition, sparse quartzite and limestone cobbles and boulders. Farther east, north of the fault that strikes east and dips 40° S., the fanglomerate, like that west of the Mammoth fault, contains little but volcanic fragments.

Similar lithologic variations occur in Tar Wash east of the Mammoth fault, chiefly in the southwest corner of sec. 15, T. 8 S., R. 16 E. Here the sinuous northwest-dipping fault separates two facies. Only granitic and volcanic fragments—both separated and mixed—occur in the fanglomerate southeast of the fault, whereas numerous conspicuous limestone, quartzite, and sandstone fragments are in the fanglomerate southeast of the fault. Fanglomerate units consisting of sandstone, quartzite, and sandstone fragments are not known west of the Mammoth fault.

The fanglomerate south of the San Manuel fault differs in lithology along the strike of the beds. Most of the materials in the section exposed in Cloudburst Wash were derived from the quartz monzonite. Southward along the strike of the beds in Tucson Wash, boulders derived from the quartz monzonite predominate; but sufficient volcanic material is admixed for the two sections to appear different, and locally beds near Tucson Wash contain more than 90 percent volcanic fragments. Such areas are in the N½ sec. 4 and in the NE¼ sec. 5, T. 9 S., R. 16 E.

The crest of the high peak (elevation 4011 feet) in the southwest corner of sec. 32, T. 8 S., R. 16 E., consists of a breccia composed chiefly of rhyodacite fragments (pl. 2). A similar breccia occurs along the crest of the ridge that joins this peak with a plug of rhyodacite (elevation 3953 feet) in the north-central part of sec. 32. The origin of these two breccia zones is not known. When I mapped them, I thought they were sedimentary because they contained a few foreign fragments and because the zones were parallel to the bedding in the adjacent fanglomerate. If they are sedimentary, the rhyodacite composing them predates the Cloudburst Formation and is unrelated to the rhyodacite plug; furthermore, the close spatial relationship of the breccia zones and the plug is coincidental. Subsequently, I observed breccia dikes in which exotic fragments were abundant and these were related to intrusive rhyolite. I now believe that my observations were too superficial to eliminate the possibility that the breccia zones are a phase of the intrusive rhyodacite.

Sandstone composed of volcanic debris occurs here and there in fanglomerate of the Cloudburst (pl. 2). It consists of medium- to coarse-grained sandstone derived almost wholly from the latite in the Cloudburst. The sandstone is dark gray to black, well bedded and sorted, and commonly crossbedded. Thin sections reveal abundant small lithic fragments of latite and minor amounts of other material, chiefly feldspar and quartz. The thickest section, about 1,000 feet thick, is in Tar Wash, where it begins at a point about 1,400 feet east of the Mammoth fault. Attempts to follow this local section southward were unsuccessful. Beds of sandstone persist locally as far south as Tucson Wash, but apparently they too grade laterally into the typical fanglomerate.

SEDIMENTARY BRECCIA

The sedimentary breccia units occur in secs. 15 and 16, T. 8 S., R. 16 E. The beds range in thickness from about 10 to 175 feet, and in length, from a few hundred feet to about 1 mile. The contacts of the breccia are conformable and sharp. Laterally, however, the breccia grades into typical fanglomerate.

The breccia consists of fragments of Precambrian quartzose granitic rocks, chiefly granodiorite, as much as 1.5 feet in diameter. These fragments are in a comminuted matrix composed of granitic material like that of the fragments. The ratio of fragments to matrix is high, and the majority of the fragments are angular. Sedimentary structures do not exist within breccia beds; the breccia looks more like tectonic breccia than like fanglomerate. Indeed, the first impression suggests brecciated fault slivers. However, the regional geologic map (pl. 1) clearly reveals the conformable bedlike nature of the breccia units.

Here and there the breccia beds are cut by sandstone dikes. The largest dike observed is about 2 feet wide. One dike, exposed in the wall of a gulch, extends downward into the underlying fanglomerate with which it merges, and the composition of the sandstone dike is the same as that of the fine-grained material in the fanglomerate. The relation strongly implies that the fanglomerate was the source of the dike, and that the

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weight of the breccia bed resting on the fanglomerate when it was saturated with water forced the fine-grained material into a fracture in the overlying breccia.

One breccia bed contains remnants of a diabase dike. The dike is segmented, and each segment is askew with respect to the others, yet each segment is close enough to its neighbors that the general continuity of the original dike can readily be recognized. Certainly this breccia bed must have moved largely in mass, and the presumption is strong that it was emplaced through gravity.

There is no problem of source for the breccia. The bedrock for several miles to the west and northwest is Precambrian granitic rock, cut by diabase and aplite dikes.

VOLCANICS

The volcanics in the Cloudburst Formation comprise latite flows, flow breccias, related dikes and small intrusives, and, here and there, intercalated beds of sedimentary material too thin to be mapped separately on the scale of the regional map.

The texture of the latite differs considerably from one flow or fragmental bed to another. Most commonly the texture is porphyritic: phenocrysts are characteristically pyroxene, now intensely altered, and seldom exceed 2 to 3 mm in diameter; phenocrystic plagioclase is uncommon. The phenocrysts are set in a pilotaxitic (felty) groundmass. In addition, the following textures occur in the latite flows: Microcrystalline pilotaxitic, porphyritic with a microcrystalline groundmass, trachytic, and microgranular. The intrusive mass in the NE¼ sec. 17, T. 8 S., R. 16 E., has a fine-grained hypidiomorphic granular texture.

Most of the latite is massive, but some units are fragmental latite or breccia commonly oxidized brick red. The fragments show no signs of an explosive origin; hence, the rock units are presumed to be flow breccias. Locally, sections of massive latite are similarly oxidized. Some of these appear to be the tops of flows, and a similar origin is assumed for the others. Vesicles and amygdules are common. Some of the vesicles are stretched or otherwise distorted by flow. The amygdules consist of chlorite, epidote, quartz, chlorite-epidote, analcite, and analcite-montmorillonite. In the chlorite-epidote amygdules the chlorite surrounds the epidote core. Similarly, in the analcite-montmorillonite amygdules, the montmorillonite encloses the analcite core. The analcite and analcite-montmorillonite amygdules occur in Cloudburst Wash in sec. 30, T 8 S., grained flows tend to be dark gray, and the coarser R. 16 E.

The color of the latite varies from one flow to another. The most common color is medium gray; but the finer grained, light gray. Many of the flows have a purplish or maroon cast, and the oxidized tops of some flows, particularly those that are fragmental, are brick red.

The latite is composed of plagioclase, potassium feldspar, pyroxene, chlorite, biotite, epidote, calcite, magnetite, hematite, leucoxene, apatite, and xenocrystic quartz. Of these, all the chlorite, epidote, calcite, and hematite, and at least part of the potassium feldspar and biotite, are secondary. Most of the pyroxene is altered to chlorite and hematite. Truly fresh pyroxene occurs in a small intrusive latite mass in the NE¼ sec. 17, T. 8 S., R. 16 E., as euhedral crystals about 0.5 mm in maximum dimension. This pyroxene has a $2V$ of about 40°, birefringence of 0.025, and a β index of 1.605; $Z \wedge C$ is about 36°. On the basis of Hess' diagrams relating optical properties to chemical composition of the clinopyroxenes (Hess, 1949, p. 634), the atomic proportion of Mg to Fe to Ca is 43:23:34, which indicates a common augite. Properties of the pyroxene in the latite flows were not determined because of its altered condition and small grain size. In several flows, however, partly altered pyroxene crystals about 0.05 mm in diameter showed a maximum birefringence of 0.022.

Most of the plagioclase occurs in microscopic laths that form the pilotaxitic texture of the flows. Measured compositions ranged from An_{48} to An_5. The composition of the plagioclase reflects a pervasive propylitic alteration; presumably albite was the stable plagioclase under the alteration conditions, and the plagioclase became progressively higher in albite as equilibrium was approached.

The potassium feldspar occurs chiefly as anhedral crystals, mostly less than 0.05 mm in diameter, interstitial to the plagioclase. To a lesser extent, potassium feldspar replaces and rims the plagioclase. In a few slides, potassium feldspar was about as abundant as plagioclase, an abundance predicted by 27 percent normative orthoclase (table 4). In these slides, a little secondary biotite is associated with the potassium feldspar, and the textural relations between potassium feldspar and plagioclase strongly suggests that the potassium feldspar replaced the plagioclase. In several slides, small anhedral crystals of potassium feldspar are disseminated in chlorite pseudomorphs after pyroxene. Such potassium feldspar is presumably secondary.

Chlorite is the dominant mafic constituent of the rock; it is in aggregates pseudomorphic after pyroxene, in disseminated flakes of uncertain origin, and as amygdules. Biotite, which ranges from pale brown to nearly colorless, is sparse; it occurs in small disseminated flakes or shreds. Epidote is common; it is present in disseminated granules, in clots, and as amygdules both separately and associated with chlorite. Calcite, identified through rapid effervescence upon contact with dilute hydrochloric acid, occurs in veinlets, disseminated grains, and aggregates. It is closely associated with epidote but is also independent. One would judge from their occurrence that both are stable calcian alteration products.

To obtain an average composition of the lavas of the Cloudburst, a composite chip sample consisting of about one chip every 75–150 feet was collected throughout the entire section of the volcanics of the Cloudburst in Tar Wash. The analysis of this composite sample along with analyses of Nockolds' average latite (Nockolds, 1954, p. 1017) and Daly's average trachyandesite (Daly, 1933, p. 13) are listed in table 4 for comparison. Alteration products are reflected in the analysis of the latite from the Cloudburst by the CO_2 and by the high Fe_2O_3 with respect to total iron. Because all the volcanics belonging to the Cloudburst are strongly altered, the rock type prior to alteration is unknown. In their altered state, the volcanics are latite or trachyandesite (extrusive equivalents of monzonites), according to the classification of Williams, Turner, and Gilbert (1954, p. 97), who do not distinguish between latites and trachyandesites. In the classification of Williams, Turner, and Gilbert, the potassium feldspar in andesite is less than one-third of the total feldspar, and in trachyandesites, between ⅓ and ⅔ of the total feldspar. In the norm calculated from the analysis of the volcanics in the Cloudburst (table 4), potassium feldspar constitutes 43 percent of the total feldspar; but some, and perhaps much, of the potassium feldspar is secondary. Perhaps prior to alteration the volcanics were andesite.

The latite in secs. 30 and 31, T. 8 S., R. 16 E., consists of a series of porphyritic vesicular and amygdaloidal flows, some of which are 30 to 40 feet thick. The upper few feet of many of the flows is scoriaceous, oxidized brick red, and vesicular; some vesicles are elongated from flowage. The color of the fanglomerate bed intercalated with the latite along the west margin of the quadrangle varies from maroon to brick red. The fanglomerate is composed of boulders and cobbles of latite, quartz monzonite, and minor amounts of quartzite. A few beds of volcanic sandstone are intercalated in the coarse material.

AGE AND CORRELATION

The age and correlation of the Cloudburst Formation have not been unequivocally determined. Its most probable age is Late Cretaceous or early Tertiary; this designation is based upon stratigraphic position and lithologic correlation with the volcanics and a fanglomerate in Reed Basin (pl. 3).

The Cretaceous stratigraphy of central and southeastern Arizona has not been described in detail. Ree-

TABLE 4.—*Chemical and normative composition of the lavas in the Cloudburst Formation, in percent*

Chemical analyses

	1	2	3		1	2	3
SiO_2	53.7	54.02	57.84	H_2O+	2.7	0.78	1.30
Al_2O_3	15.8	17.22	17.24	H_2O-	.7	--	--
Fe_2O_3	6.5	3.83	3.97	TiO_2	.93	1.18	1.11
FeO	.88	3.98	3.18	P_2O_5	.32	.49	.57
MgO	5.4	3.87	1.25	MnO	.16	.12	.05
CaO	4.0	6.76	4.20	CO_2	1.4	--	--
Na_2O	3.2	3.32	5.67				
K_2O	4.6	4.43	3.62	Total	100.29	100.00	100.00

Bulk density 2.50–2.73; Average 2.63

Norm (volume percent)

	1	2	3		1	2	3
Q	5.3	0.5	3.4	mt	--	5.6	7.0
or	27.2	26.1	21.1	il	1.8	2.3	2.1
ab	27.2	27.8	47.7	hm	6.6	--	--
an	8.9	19.2	11.1	ap	.67	1.2	1.34
C	2.2	--	--	cc	3.2	--	--
wo	--	4.5	2.5				
en	13.5	9.7	3.1	Total	96.67	99.3	99.34
fs	.1	2.4	--				
				or × (100)=or+an+ab	43	36	26

1. Composite sample of lavas in Cloudburst Formation. Tar Wash, sec. 21, T. 8 S., R. 16 E. Rapid analysis. Analysts: P. L. D. Elmore, K. E. White, and S. D. Botts.
2. Average of 42 latites. (Nockolds, 1954, p. 1017.)
3. Average of 12 trachyandesites. (Daly, 1933, p. 13.)

side (1944) published a map showing the general character and thickness of the Cretaceous rocks in the western interior of the United States. On this map the southwestern limit of the Upper Cretaceous in Arizona is along a line that lies approximately between Nogales on the southeast and Hoover Dam on the Colorado River on the northwest.

The geologic map of Arizona (Darton and others, 1924) shows that much Upper Cretaceous rock of Colorado age (Dakota, Mancos, and Mesa Verde) extends from the Colorado Plateau in the northeast corner of the State southward part way to the Basin and Range province. Two isolated small patches of these rocks occur near the plateau margin: one in the Pinedale-Showlow area, the other northeast of St. Johns. South of the Mogollon Rim, which marks the southern edge of the Colorado Plateau, Upper Cretaceous rocks of Colorado age were reported from Morenci (Lindgren, 1905, p. 73), from Reed Basin east of Christmas (pl. 3; Ross, 1925a, b), and from the Tucson Mountains west of Tucson (Brown, 1937, p. 719).

The Upper Cretaceous from Reed Basin has been described briefly by Devereux (1881), Walcott (1885), Campbell (1904), and Ross (1925a, b). According to Campbell, Walcott collected some fossil plants when he visited the area in 1885, and they were "* * * doubtfully referred to the Cretaceous * * *" (Campbell, 1904, p. 245). Campbell also collected fossil plants, but, like those in Walcott's collection, they were not sufficiently diagnostic. Fortunately, Campbell also collected invertebrate remains from a conglomerate bed, which were identified by T. W. Stanton as imperfect forms of *Ostrea* and *Exogyra*. These indicated a Cretaceous age, according to Stanton, but the exact horizon could not be identified. Later, Ross (1925a, p. 27) collected fossils from Garden Gulch near Stanley Butte, and these fossils were identified by Stanton as an Upper Cretaceous fauna of Colorado Group age.

The Upper Cretaceous sandstones and shales in Reed Basin are unconformably overlain by a volcanic sequence that contains minor amounts of intercalated fanglomerate and volcanic sedimentary rocks. Ross, Campbell, and others thought that this volcanic sequence intercalated with the terrigenous Upper Cretaceous sedimentary rocks, an erroneous impression probably resulting from complex structures. Although the ratios of the fanglomerate to volcanics in Reed Basin and in the San Manuel area differ markedly, the lithologic similarities are so striking that the correlation of the two sections is proposed. It should be pointed out, however, that porphyries containing phenocrysts of quartz, feldspar, and biotite, and associated equigranular masses intruded the volcanic rocks in Deer Creek and Copper Creek (pl. 3) and that these porphyries and related rocks seem to be related to the ore in the Christmas and Copper Creek ore deposits, respectively; whereas the granodiorite porphyry at the San Manuel deposit is older than the Cloudburst Formation. Some workers believe that most, if not all, the porphyries in southeastern Arizona are the same age, and for this reason they will reject the possibility of correlation of these volcanic rocks on lithology alone.

On the south side of Reed Basin, the Whitetail Conglomerate of Tertiary(?) age and the overlying volcanics in the Galiuro Mountains unconformably overlie the volcanic sequence, which had been folded previous to the deposition of the Whitetail. The Whitetail has not been accurately dated. It is older than the inception of the Basin and Range deformation, which is generally thought to have started in the Miocene. These relations indicate that the youngest possible age for the volcanics in Reed Basin is Miocene. As pointed out in the previous paragraph, however, the volcanics in Reed Basin may be as old as Late Cretaceous.

TERTIARY(?) ROCKS

INTRUSIVE RHYODACITE

Intrusive rhyodacite occurs in small masses in secs. 4, 8, and 9, T. 9 S., R. 16 E., and in secs. 26, 27, 28, 31, and 32, T. 8 S., R. 16 E. In all, I mapped 13 separate intrusions, which ranged in maximum dimension from about 150 to 3,000 feet. Most of the masses are in the Cloudburst Formation, but three are in the quartz monzonite.

The intrusive rhyodacite contains white plagioclase and bronze biotite phenocrysts set in a medium-gray microcrystalline granular groundmass. This rock weathers to medium light gray. The modal composition, by volume (average of three samples), is 92 percent groundmass, 6 percent plagioclase, 1.6 percent biotite, and less than 1 percent magnetite; a few crystals of accessory apatite were noted. The plagioclase, which occurs in laths as much as 5 mm by 2 mm, has an average composition in the freshest rock (sample 1, table 4) of An_{35-40}. Biotite occurs in plates about 1 to 3 mm in diameter in which are included needles and irregularly shaped magnetite crystals.

The groundmass is a microcrystalline aggregate of granular quartz and feldspar. Much of the groundmass feldspar is potassium feldspar. The groundmass plagioclase contains 10 percent or less anorthite.

In altered rhyodacite, albitized plagioclase is partly changed to sericite; and the biotite, to hematite and possibly magnetite. Much fine-grained "dust," which seems to be an alteration product but whose mineralogy is uncertain, occurs in some altered specimens.

Given in table 5 are the chemical and normative compositions of the rhyodacite and, for comparison, the average compositions and norms of Nockolds' (Nockolds, 1954) rhyodacites and dellenites (quartz latite), which are partly similar in composition to the rhyodacite. Whether to call the rock a rhyodacite or dellenite (quartz latite) is immaterial. I used the classification of Williams, Turner, and Gilbert (1954), in which the alkali feldspar in rhyodacites ranges from ⅓ to ⅔ of the total feldspar.

INTRUSIVE RHYOLITE

Intrusive rhyolite occurs in two prominent volcanic plugs in the north-central part of the area and in one large and several small masses near the old town of Tiger in sec. 26, T. 8 S., R. 16 E. (pl. 1). In addition, about 15 small intrusive masses, none of which is more than 300 feet in diameter, occur scattered here and there, chiefly in the Cloudburst Formation. Several of these masses, such as the two large plugs in the north-central part of the area and the two outcrops in Tucson Wash (sec. 24, T. 8 S., R. 16 E.), protrude through the Gila Conglomerate; apparently they stood above the surrounding area and the Gila was deposited around them.

The color of the intrusive rhyolite ranges from grayish orange pink to pinkish gray, according to the Rock Color Chart of the National Research Council; the color index is about 1. Weathered surfaces are lighter hues of the color of freshly fractured rock.

Some of the rhyolite is felsitic, but most of it is porphyritic and has a microcrystalline groundmass. Phenocrysts, which constitute as much as 10 percent of the rhyolite, consist of quartz, albite, potassium feldspar, and minor amounts of biotite. The minerals of the groundmass and of the felsitic rhyolite are partly microcrystalline. Quartz, alkali feldspar, and a few spherulites were recognized.

The texture and structure in the rhyolite vary considerably from place to place. Flow banding is common. In general, the flow bands dip 70° to 80° and strike at random. Intrusive breccias crop out near Tiger, and the rhyolite in the St. Anthony mine was brecciated around the margins of some of the intrusive masses. The superb exposures in the walls of Tucson Wash display a vertical intrusive-breccia dike about 40 feet wide. Near the bottom of the wash the dike consists chiefly of rhyolite fragments; higher on the slopes, more foreign fragments are included (fig. 6), but local patches are nearly all rhyolite. Near the top of the dike, foreign fragments predominate nearly to the exclusion of rhyolite. The wallrocks of the dike consist of fanglomerate of the Cloudburst composed entirely

TABLE 5.—*Chemical and normative composition of the intrusive rhyodacite, in percent*

Chemical analyses

	1	2	3		1	2	3
SiO_2	66.7	66.27	70.15	K_2O	4.4	3.01	4.50
Al_2O_3	16.2	15.39	14.41	H_2O+	1.1	.68	.68
Fe_2O_3	3.2	2.14	1.68	H_2O-	.9	-----	-----
FeO	.11	2.23	1.55	TiO_2	.64	.66	.42
MgO	.60	1.57	.63	P_2O_5	.20	.17	-----
CaO	1.7	3.68	2.15	MnO	.02	.07	.06
Na_2O	4.4	4.13	3.65	CO_2	.09	-----	-----
				Total	100.26	100.00	99.88

Bulk density ---------- 2.511

Norm (volume percent)

	1	2	3		1	2	3
Q	20.3	20.8	26.1	fs	-----	1.3	0.8
or	26.1	17.8	26.7	mt	-----	3.0	2.5
ab	37.2	35.1	30.9	il	0.15	1.4	.8
an	7.0	14.5	9.5	hm	3.2	-----	-----
C	1.63	-----	-----	ap	.7	.3	.3
wo	-----	.2	1.3	cc	.2	-----	-----
en	.6	3.9	1.6	ru	.6	-----	-----
				Total	97.68	98.3	100.5
				or × (100) = or + ab + an	37	26	40

1. Intrusive rhyodacite, NW¼ sec. 9, T. 9 S., R. 16 E., Mammoth quadrangle, Pinal Co., Ariz. Rapid analysis, P. L. D. Elmore, K. E. White, and S. D. Botts, analysts.
2. Average of 115 rhyodacites plus rhyodacite-osbidians. (Nockolds, 1954, p. 1015).
3. Average of 58 dellenites plus dellenite-obsidians. (Nockolds, 1954, p. 1015.) Dellenites are the extrusive equivalents of adamellites.

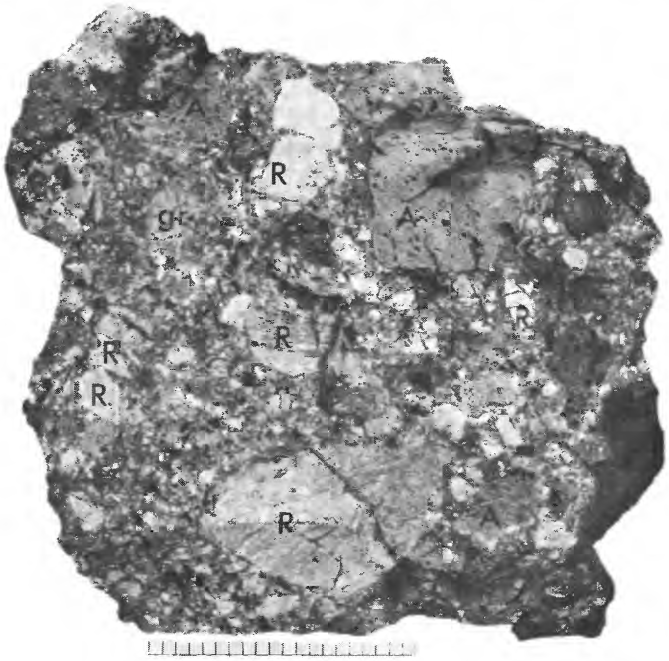

FIGURE 6.—Intrusive-breccia phase of the intrusive rhyolite. Specimen consists of fragments of rhyolite (R), mafic volcanics from the Cloudburst Formation (A), and granitic rock (gr) in a cataclastic matrix derived from all three. Scale in tenths of an inch.

FIGURE 7.—Lapilli tuff from along the east flank of the rhyolite plug in sec. 14, T. 8 S., R. 16 E. The tuff consists of fragments of pumice and crystals of quartz, feldspar, and biotite, all set in a matrix of fine ash. Scale in tenths of an inch.

of volcanic detritus. Most of the foreign fragments in the breccia dike, however, are Precambrian granitic rocks. Mixed with these fragments are minor amounts of other rocks, chiefly quartzite, and this mixture clearly shows that the foreign fragments came from some bed in the Cloudburst Formation lying beneath the floor of Tucson Wash rather than from the Precambrian bedrock itself. Presumably these breccia dikes are a product of vapor or gas transport under high pressures.

Similarly, the two northernmost plugs exhibit explosive phases; both are flanked, particularly on the east, by tuff (fig. 7). Locally, the rhyolite intrudes the tuff, and this indicates that the explosive phase preceded the intrusive. Tar Wash cuts the core of the southernmost of these two northern plugs and exposes a vertical section through a vent breccia. Besides both altered and fresh fragments of rhyolite, the vent breccia includes minor amounts of foreign material, such as quartzite, granitic rocks, and fanglomerate, and blocks about 35 feet across of fanglomerate from the Cloudburst. The altered rhyolite fragments in the vent breccia contain appreciable amounts of montmorillonite.

Table 6 gives the chemical composition of the rhyolite in the southernmost of the two rhyolite plugs along the north border of the quadrangle and the averages of Nockholds' calc-alkali and alkali rhyolites (Nockolds, 1954) for comparison. The rhyolite from the San Manuel area resembles the calc-alkali rhyolites in alkali content and the alkali rhyolites in lime content. The normative plagioclase composition of the three rhyolites is An_6, An_{17}, and An_5, respectively, and the measured composition of the intrusive rhyolite phenocrysts from the San Manuel area is An_{5-10}; if classified by the normative and measured plagioclase compositions, the intrusive ryholite is an alkali rhyolite.

TERTIARY AND QUATERNARY ROCKS

GILA CONGLOMERATE

The Gila Conglomerate of Pliocene and Pleistocene age underlies all but the northwestern quarter of the San Manuel area and is the basin fill of the San Pedro Valley (fig. 3). Within the San Manuel area, the Gila comprises a lower member nonconformably overlain by an upper member; their separation is based primarily on different degrees of tilt and secondarily on lithologic differences. I wish to emphasize, however, that these distinctions are based on observations made near the point where the two members are in contact and that the distinctions are limited to a stratigraphic thickness of not more than 200 feet.

In Copper Creek, which is east of the San Manuel area on the eastern side of the San Pedro Valley, indurated coarse conglomerate similar in appearance to that of the lower member of the Gila in the San Manuel

TABLE 6.—*Chemical and normative composition of the intrusive rhyolite, in percent*

Chemical analyses

	1	2	3		1	2	3
SiO_2	77. 2	73. 66	74. 57	H_2O+	1. 2	. 78	. 66
Al_2O_3	12. 9	13. 45	12. 58	TiO_2	. 10	. 22	. 17
Fe_2O_3	. 56	1. 25	1. 30	P_2O_5	. 02	. 07	. 07
FeO	. 05	. 75	1. 02	MnO	. 04	. 03	. 05
Mg	. 20	. 32	. 11	CO_2	. 13		
CaO	. 46	1. 13	. 61				
Na_2O	2. 7	2. 99	4. 13	Total	100. 66	100. 00	100. 00
K_2O	5. 1	5. 35	4. 73				

Powder density 2.60; Lump density 2.17

Norm (volume percent)

	1	2	3		1	2	3
Q	41. 0	33. 2	31. 1	mt		1. 9	1. 9
or	30. 0	31. 7	27. 8	il	0. 15	. 5	. 3
ab	23. 1	25. 1	35. 1	hm	. 64		
an	1. 4	5. 0	2. 0	ap	Trace	. 2	. 2
C	2. 35	. 9					
wo			. 1	Total	98. 84	99. 3	99. 4
en	. 2	. 8	. 3				
fs			. 6	or × (100) = or+ab+an	55	51	43

1. Intrusive rhyolite. Location: sec. 15, T. 8 S., R. 16 E., Mammoth quadrangle, Pinal Co., Ariz. Rapid analysis. Analysts: P. L. D. Elmore and S. D. Botts.
2. Average of 22 calc-alkali rhyolites plus rhyolite-obsidians. (Nockolds, 1954, p. 1012).
3. Average of 21 alkali rhyolites plus rhyolite-obsidians. (Nockolds, 1954, p. 1012).

area interfingers laterally with poorly consolidated lake deposits composed of limy silt similar to that of the upper member of the Gila in the San Manuel area. In Copper Creek the two types of deposits are clearly time equivalents, and the differences between them resulted from an abrupt facies change. It is likely, therefore, that some fine-grained lake deposits in the central part of the depositional basin are the time equivalent of the conglomeratic lower member of the Gila in the San Manuel area, but whether these lake deposits are also the time equivalent of the upper member of the Gila in the San Manuel area is not known, but the possibility exists. The two members are not everywhere easily separated, and I have no confidence that either of the two members can be recognized in contiguous areas.

LOWER MEMBER

The lower member of the Gila Conglomerate in the San Manuel area consists of overlapping and coalescing alluvial fans that spread eastward and grew vertically by accumulating material from the uplifted Santa Catalina Mountains and Black Hills. Like other typical fans, these display a wide range of fragment size, sorting, crossbedding, and lithology. Differences in lithology from one fan to another presumably reflect differences in source rock from one area to another. Beds of the lower member of the Gila dip 15° to 40° E. and, in general, strike parallel to the San Pedro Valley; these dips reflect both the initial dip of the beds and the subsequent deformation, part of which occurred before the deposition of the upper member of the Gila.

The lower member is well exposed in Tar, Tucson, Mammoth, Cottonwood and Smelter Washes, which are the principal washes tributary to the San Pedro River in the San Manuel area. Owing to the dip and strike of the beds, the washes intersect the beds at high angles, and the character of the member is well displayed. Exclusive of sedimentary breccia, the lower member includes detritus ranging in size from silt to boulders, but most of the member is composed of cobble and boulder conglomerate. Boulders as much as 15 feet in diameter occur in the boulder conglomerate that directly overlies the Precambrian granite rocks. The lower member is well bedded and indurated. Beds range from 1 or 2 inches to about 50 feet in thickness. Material in some beds is well sorted, but in others it is not. The cementing materials are carbonate and silica. In one thin section the grains are cemented by a zeolite.

Because the lithology of each fan depended on the source rock in its drainage area, the composition of the conglomerate varies from bed to bed and from area to area. I did not consistently attempt to divide the Gila Conglomerate, but I did separate conglomerate units that have distinctive lithologies if they occur near sedimentary breccia units (fig. 8). These conglomerate units, described along with the breccia units, perhaps

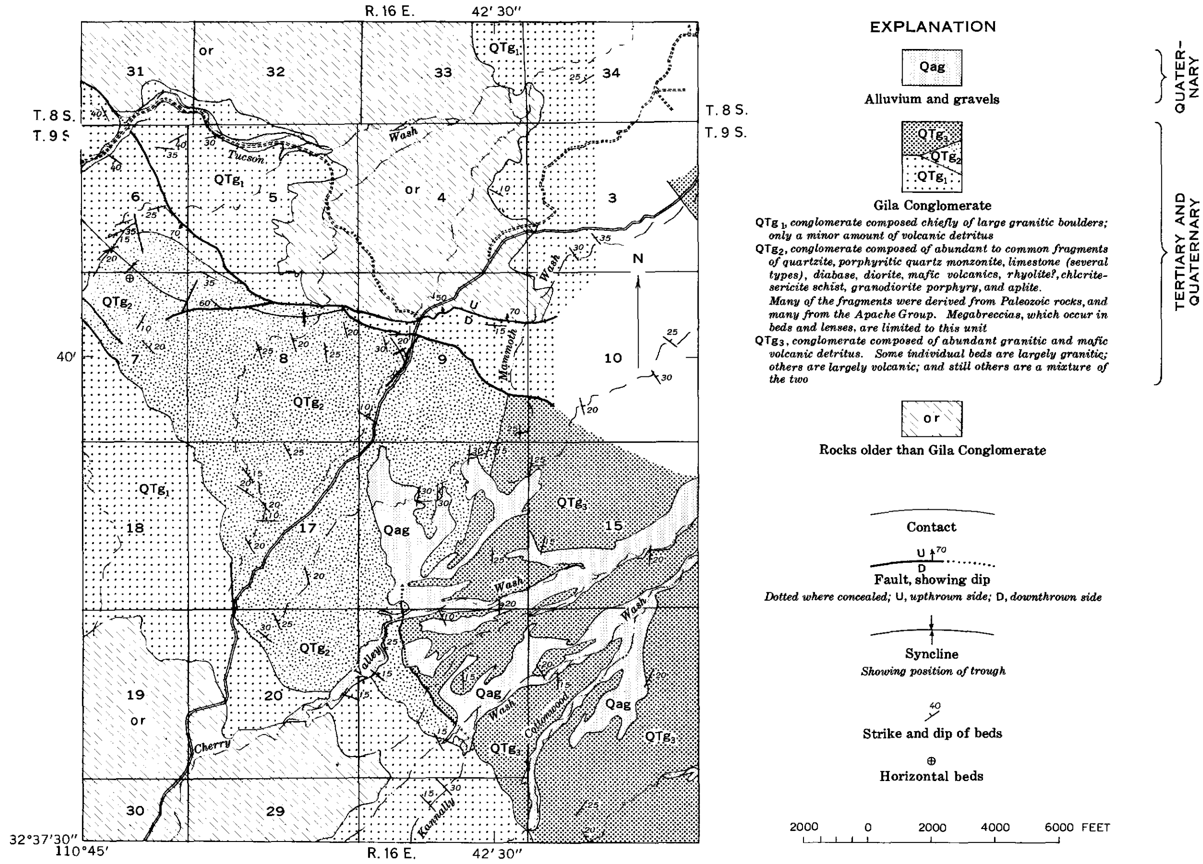

FIGURE 8.—Geologic map showing distribution of lithologic types in the lower member of the Gila Conglomerate near the sedimentary breccia masses in the southwest corner of the San Manuel area.

will give the best insight into the character of the lower member of the Gila. Here it will suffice to point out that the lower member contains more detritus derived from the older Precambrian granitic rocks and the Tertiary volcanics than from the younger Precambrian Apache Group and the Paleozoic rocks. Some individual beds are predominantly one type or another, and others are mixed. Some of the beds are tuffaceous, and several thin predominantly tuffaceous beds were noted.

In secs. 5, 6, 7, 8, and 9, T. 9 S., R. 16 E., the lower member of the Gila includes several beds or lenses of a distinctive sedimentary breccia, and these are shown on the geologic map (pl. 1). In addition, in the areas adjacent to the breccia units, the lower member was subdivided further on the basis of the type and relative abundance of detritus in an effort to determine the origin of the breccia units and their relation to the enclosing conglomerate units.

The sedimentary breccia comprises four bedlike masses, each ranging in thickness from about 25 to 125 feet, and one lenslike mass, ranging in thickness from about 400 to 600 feet, whose strike length is about 4,500 feet (pl. 1). Except where broken by faults, the breccia masses are conformable with the underlying and overlying conglomerate units. The breccia is composed of limestone; quartzite; limestone and quartzite; limestone, quartzite, and diabase; and limestone, quartzite, and hornfels. The ratio of angular fragments to matrix is surprisingly high, and the existing matrix consists of small angular fragments and rock flour of the same rocks that form the fragments. The large lens is a composite breccia mass; it contains lenses or irregularly shaped masses that are monolithologic (fig. 9). Some of these irregularly shaped masses appear to be blocks as large as 50 feet by 20 feet in which the original bedding is consistent throughout, despite a general crackled condition in which no area more than 2 feet across is without a fracture. Such blocks must have been emplaced as a unit (fig. 9).

The large lens is cut by numerous sandstone and pebble dikes. The dikes cut all the breccia types, but chiefly the diabase breccia. They range in width from about 1 inch to 4 feet and were observed to be about 50 feet long. Some dikes are composed of material from the enclosing rocks; others are composed of material that must have traveled upward from the underlying breccia units.

FIGURE 9.—Monolithologic breccia of Paleozoic limestone, possibly Escabrosa Limestone, in the Gila Conglomerate. Original bedding was not recognized in this outcrop.

Fragments as much as 2 feet in diameter were observed in one dike. Much of the dike material is a brick-red rock flour like that in the matrix of the diabase breccia in some of the diabase breccia units; possibly the breccia derived from the diabase supplied much of the material for the dikes.

The four sedimentary breccia beds are composed of limestone, quartzite, diabase, and a diorite, which is probably a facies of the diabase. The longest bed in the central part of sec. 8—the faulted one—is estimated to be 85 percent limestone and 15 percent combined diabase and quartzite.

The large lenslike mass is composite, and although I did not try to separate the different breccia types, it could be done. Four breccia types occur: diabase and diorite, limestone, quartzite, and banded hornfels. The diabase breccia, which is a dark greenish gray, consists of angular diabase fragments in a comminuted matrix of diabase. The finer grained matrix material has been oxidized brick red, presumably by weathering. Megascopic fragments, however, appear fresh under the microscope. A thin section of a fragment shows plagioclase, biotite, chlorite, members of the epidote group, and a small amount of both potassium feldspar and apatite. The texture is typically diabasic. Biotite is partly altered to chlorite.

Limestone breccias (fig. 9) are about as abundant as the diabase breccia, and together they comprise the bulk of the large lens. The limestone breccia units tend to be more coherent than the other breccia units of the lens; original bedding can still be recognized in large blocks that are closely crackled or fractured. Some limestone breccias possibly were derived from the Escabrosa Limestone; others, in which the limestone is impure, probably were derived from the Martin Limestone; and still others, which are impure and slabby, were possibly of Martin derivation. Most of the limestone breccias are monolithologic (fig. 9), but the base of one breccia is composed of limestone fragments set in a matrix of granitic sand and gravel (fig. 10).

Here and there small masses of quartzite breccia occur, but they are not nearly so abundant as the limestone or diabase breccia types. In general, the fragments in the quartzite breccia are much smaller, and the impression is that brecciation was more intense than it was for the other types of breccia. Some of the quartzite is relatively pure and is similar to the Cambrian Troy Quartzite and perhaps to parts of the Dripping Spring Quartzite (Apache Group). Other quartzite is green, owing to chlorite and possibly other micaceous impurities, and probably was derived from the Apache Group. The banded hornfels is a low-grade metasedimentary rock. Thin sections show that the hornfels is granoblastic and consists of quartz, albite, potassium feldspar, members of the epidote group, chlorite, sericite, biotite, and a minor amount of carbonate. The bands, which range in thickness from less than 1 inch to about 6 inches, and in color from white to dark greenish gray (fig. 11), are beds of differing compositions: dark-green layers are rich in chlorite, and some light-yellowish-green layers are essentially albite-epidote hornfels. The Apache Group is the most likely source for this breccia type, but because the alteration of the rock to hornfelses has obscured its original characteristics, I cannot correlate the quartzite breccia type more precisely.

FIGURE 10.—Breccia composed of limestone fragments set in a matrix of granitic sand and gravel.

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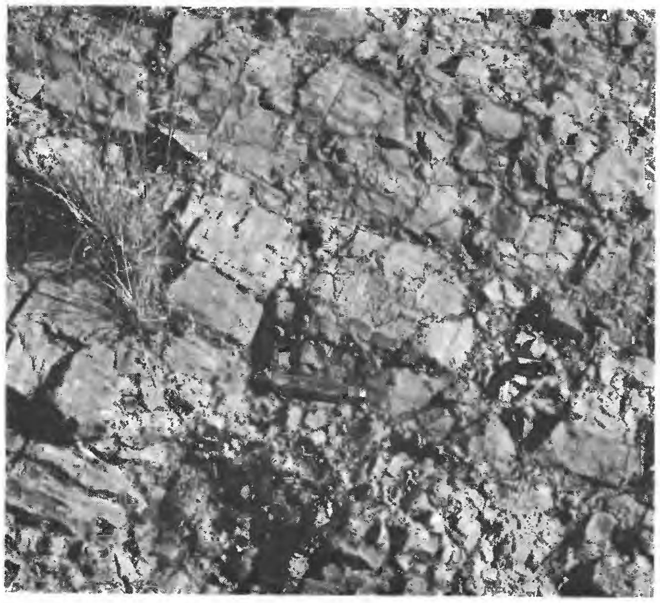


FIGURE 11.—Monolithologic breccia derived from hornfels of the Apache(?) Group. Original bedding dips gently from left to right and is still easily recognized despite general brecciation.

Because most of the lower member of the Gila Conglomerate in the San Manuel area was derived from the Precambrian granitic rocks and the Tertiary volcanics, the lower member and breccias contrast in source material. To try to obtain some concept of the origin of the breccias, I divided the enclosing Gila Conglomerate on the bases of the dominant rock types. The map (fig. 8) shows one highly significant fact: the breccias are included in a thick lens (probably a fan) of Gila Conglomerate in which fragments derived from the same sources as the breccias—that is, from the Apache Group and the Paleozoic rocks—are common, whereas the Gila overlying and underlying this lens or fan has virtually none of these rock types. Obviously the breccias and the related Gila (fig. 8) that encloses them shared the same source areas, and these source areas were essentially different from those of the Gila above and below this lens or fan. Any origin proposed for the breccias must take into account the obvious consanguinity of the enclosing Gila. This relation, in addition to the conformity of the breccias and the enclosing Gila, leads me to believe that the breccias formed as landslides or mudflows. Perhaps a landslide origin is most likely for the lenslike mass of breccia, because the large blocks of limestone retain the original bedding, and this bedding is largely undisturbed; mudflows adequately explain the thinner bedlike masses of mixed breccia.

If the breccias originated as landslides and mudflows, a source must lie nearby at an elevation sufficiently high for gravity to be the moving force. The nearest possible known source is about 8 miles south of the San Manuel area in the northern part of the Santa Catalina Mountains.

Whether the breccias could have originated as landslides and mudflows from a source in the Santa Catalina Mountains can be further evaluated by assuming rates of erosion for the span of time which has elapsed since the breccias accumulated. Gilluly, Waters, and Woodford (1951, p. 135) estimated that the average rate of denudation for the United States is 1 foot per 9,000 years. The erosion rate in the tectonically active Basin and Range province presumably far exceeds the average. Gilluly (1949, p. 573) provided data for the rate of erosion during the Cretaceous, and from these data additional erosion rates can be calculated. Gilluly pointed out that during Early Cretaceous time, which lasted about 25 million years, the source area for Lower Cretaceous rocks was lowered about half a mile; and during Late Cretaceous time, which lasted about 40 million years, the source area for Upper Cretaceous rocks was lowered about 3 miles. These figures yield average erosion rates of 1 foot per 9,500 years and 1 foot per 2,500 years, respectively. The Upper Cretaceous rocks are largely clastic, and this implies rapid erosion of land standing well above sea level. Presumably, the rate of 1 foot per 2,500 years is more applicable to the Basin and Range province, where the conglomeratic basin deposits attest to the rapidity of erosion.

The age of the Gila Conglomerate is Pliocene and Pleistocene, and the oldest age obtained for it in the San Pedro Valley (see p. 23) is early Pleistocene or late Pliocene (Blancan). The breccia beds are in the lower member of the Gila not far above the base and not far from where I found horse teeth also referred to the Blancan. The currently used time scale places the beginning of the Pleistocene about 1 million years ago and the beginning of the Pliocene roughly 10 to 12 million years ago. The breccias, therefore, seems to be at least 1 million years old and probably not more than about 3 million years old; presumably, they are closer to 1 million years old than to 3 million. If one assumes an erosion rate of 1 foot per 2,500 years and for a period of 1 or 3 million years, the Santa Catalina Mountains have been lowered 400 or 1,200 feet, respectively, since the breccias accumulated. These figures added to the difference in elevation (about 3,000 ft) between the level of the possible source area in the Santa Catalina Mountains and the level of the breccias provide a slope of 5° for the 1-million-year erosion period and 6° for the 3-million-year period. Slopes of 5° to 6° are well within the range recorded for mudflows, and the Santa Catalina Mountains seem to be a plausible source.

UPPER MEMBER

The upper member of the Gila Conglomerate in the San Manual area is mainly composed of limy silt and marl but contains subordinate amounts of cobble and boulder conglomerate. North of Tucson Wash, a local basal conglomerate derived almost exclusively from the rhyolite plugs was mapped separately (pl. 1).

South of State Route 77 the upper member of the Gila is dominantly soft unconsolidated limy marl and silt. It is well stratified and dips gently (5° to 10°) toward San Pedro Valley. Presumably, this material was deposited in lakes. Interrupting the lake deposits at irregular intervals are beds of coarse gravel and conglomerate, which are thought to be either channel gravels or the distal edges of fan deposits interbedded with the lake beds. A conglomerate bed of this sort is well exposed near the mouth of Cottowood Wash in secs. 4 and 5, T. 9 S., R. 17 E.

North of State Route 77 the lake beds are gradually displaced by gravel and conglomerate until, from Tucson Wash northward, gravel and conglomerate are more abundant than lake beds. Here the lithology of the upper member of the Gila appears much like that of the lower member. Presumably, the local configuration of the valley, the proximity to bedrock, the stream gradients, and other factors played a part in determining the local lithology. Such observed rapid lateral changes in lithology are good reminders that correlations based on lithology are risky in such basin deposits.

The basal conglomerate in the upper member of the Gila extends from the north edge of the quadrangle southward for about 2 miles to where it either pinches out or is overlapped by younger beds. The maximum thickness is about 300 feet, whereas the average thickness is close to 100 feet. This basal conglomerate is composed of subrounded boulders of rhyolite dike that of the nearby rhyolite plugs that rise about the Gila Conglomerate. The conglomerate occurs only near the rhyolite plugs and is therefore probably derived from the plugs and their associated pyroclastic deposits.

THICKNESS, AGE, AND CORRELATION

The actual thickness of the Gila Conglomerate is not known. Schwartz (1953, p. 14) reported a maximum thickness of 1,208 feet near the San Manuel mine. Undoubtedly the thickness increases toward the valley, and Schwartz reported that east of Tiger, near State Route 77, the Santa Maria Mining Co. drilled through 2,020 feet of alluvium and Gila Conglomerate without penetrating bedrock. The thickness must vary from place to place depending on the configuration of the bedrock surface beneath the San Pedro Valley. Presumably, the general thickness is several thousand feet.

The Gila Conglomerate was named by Gilbert (1875, p. 540–541) from exposures in the Gila Valley above Bonita Creek. The correlation of the Gila Conglomerate in the Gila Valley with similar deposits in the Sulfur Springs and San Pedro Valleys is generally accepted.

Knechtel (1936), while studying the ground-water geology in the Gila Valley, found three vertebrate fossil localities which yielded, in part, fossil vertebrates identified by C. L. Gazin as *Nannippus* sp., *Plesippus* sp., *Platygonus* sp., and undetermined camelid and megalonychid species which at that time were thought to be of late Pliocene age but which are now considered by most authorities to be of early Pleistocene age. Recently Lance (1958) briefly reported the discovery of Pleistocene vertebrates from lake beds in the Gila Valley.

Aided by Kirk Bryan, J. W. Gidley (1923) collected from two vertebrate localities in the Gila Conglomerate in the San Pedro Valley; one locality is about 2 miles south of Benson (Benson locality), and the other is about 12 miles southeast of Benson and 3 miles east of the Curtis School (Curtis Ranch locality). Gidley (1923, p. 119) wrote that there seemed to be no difference in the stratigraphic level of the beds at the two localities, and that they are structurally very similar. Gidley (1923, p. 120) dated the deposition at the two localities as in "* * * a late stage of Pliocene time." These faunas, too, are now considered by most authorities to be of early Pleistocene age.

Gidley noted that the faunas from the Benson and Curtis Ranch localities had no species in common. The reason for the dissimilarity in species is obscure. Although most authorities now consider both localities to be the same age, Gidley (1923, p. 119) thought the Benson locality was slightly older. Gilluly (1956, p. 120), who mapped the area in which the localities occur, pointed out that two distinct sedimentary series may be represented. Both Gilluly (1956, p. 118) and Bryan (1926) recognized that widespread pediment gravels cap the Gila Conglomerate. These pediment gravels occur in the San Manuel area as well as elsewhere throughout the San Pedro Valley. Locally they are difficult to separate from the underlying Gila Conglomerate, mainly because they are locally derived and because their angular discordance to the Gila may be very slight. For these reasons, earlier workers did not attempt to separate the pediment gravel from the Gila, although they recognized the need to do so. Possibly the Curtis Ranch locality is in the pediment deposits, whereas the Benson locality is in the underlying Gila proper. In any event, such possibilities cannot be eliminated unless the collectors clearly establish by maps or other means the relation of the site of collection to the local geology.

I found a few teeth and bone fragments in an isolated small patch of gravel bounded on two sides by faults in the SE¼ sec. 31, T. 8 S., R. 16 E., in the San Manuel area, well above the level of the nearby Gila Conglomerate along Tucson Wash. The teeth were in limy silt, whereas the nearby lower member of the Gila is boulder conglomerate; so I cannot say with certainty that the teeth came from the lower member. For convenience, however, the fossiliferous beds were included in the lower member on plate 1. The fossiliferous beds are nearly horizontal, in sharp contrast to the beds of the adjacent Gila, which dip about 25° to 30°; the fossiliferous beds, however, lie directly on bedrock where the local dip could have been materially affected by the bedrock configuration. G. Edward Lewis of the U.S. Geological Survey identified the teeth as *Equus* (*Plesippus*). Concerning the teeth Lewis said,

> Two of the little-worn lower cheek teeth, on the occlusal surfaces and in section, show a sharp V-shaped groove between the metaconid and metastylid. This character has been widely used to distinguish *Equus* (*Plesippus*) from *Equus* sensu stricto. *Plesippus* is characteristic of early Pleistocene ("Blancan" of authors) time.

Lewis also stated that C. L. Gazin identified similar material from the Benson locality. Although the position of the locality does not preclude the possibility that it is part of the overlying pediment deposits, the lithology—limy silt directly overlying fanglomerate of the Cloudburst Formation—is unlikely for a pediment deposit. In addition, the correlation of the locality with the Benson locality rather than with the Curtis Ranch locality is also suggestive that the locality is in the Gila Conglomerate itself.

QUATERNARY ROCKS

GRAVEL

A pediment formed during an erosional cycle, or cycles, older than the present one is veneered by gravel. In all places this gravel is perched above the level of the adjacent alluvium, and it is this relationship that permits its distinction. The gravel is being eroded and destroyed, but scattered patches remain as erosional remnants of a much larger blanket that at its maximum extent must have covered virtually all the Gila Conglomerate and considerable amounts of the contiguous bedrock. The distribution of the gravel is shown on plate 1.

The pediment gravel is mainly unconsolidated poorly sorted sheets of boulders and cobbles. Some patches are remnants of the gravel veneer that once capped most of the interfluves. Other gravel represents the "roots" of channels that gouged into the underlying Gila and bedrock well below the general level of the base of the pediments. In the channel gravels, crossbedding, cut and fill, and crude bedding can be observed.

No attempt was made to record the thickness of the gravel remaining. To judge from the geologic map (pl. 1), the thickness probably nowhere exceeds 100 feet.

The pediment gravel veneer is not in all places easily distinguished from the underlying Gila Conglomerate. Where underlain by the upper member of the Gila, the angular discordance between the gravel and the conglomerate is small; and unless exposures are good, the difference between Gila and the reworked Gila is subtle. Where erosion has not supplied vertical sections along the walls of gulches, a distinction between the two may not always be possible. For this reason, some gravel may have been overlooked in the southeast corner of the quadrangle where the underlying rock is the upper member of the Gila.

A well-developed dark-red soil formed on top of the pediment. This soil profile, which probably averaged about 2 to 3 feet in thickness, was of great help in the recognition of the pediment; where gulches are sparse or absent, this soil profile was accepted as an indication of the pediment. In the southeast corner of the quadrangle, the dark-red soil occurs only in widely scattered patches on the highest parts of the interfluves. The pediment, therefore, appears to be dissected to a depth of 20 to 30 feet, and the pediment gravel appears to be stripped almost completely; this area was mapped as Gila Conglomerate despite the obvious lack of deep dissection so evident to the north.

ALLUVIUM

Alluvium composed of sand and gravel carpets every streambed—from the smallest gulch to the wide braided flood plain of the San Pedro River. Only the alluvium in the principal streams and gulches can be shown on plate 1 because of the map scale, but the other streams and gulches are alluviated also.

STRUCTURE

GENERAL STATEMENT

The San Manuel area lies in the Basin and Range province, but it is too small to be a representative sample of the province. The area covered by plate 3, about 2,500 square miles of the lower San Pedro Valley, includes the San Manuel area and is representative of the Basin and Range province. It contains major structures of five ages: (1) Precambrian, (2) post-Paleozoic and pre-Cretaceous, (3) Cretaceous, (4) post-Cretaceous and pre-Pliocene, and (5) Pliocene and younger. In addition, disconformities or slight angular unconformities occur between formations in the Precambrian Apache Group and between formations of

Paleozoic age. The types of structures found in each of the five major structural periods are outlined briefly in the following paragraphs.

The old Precambrian rocks in southeastern Arizona—the Pinal Schist—were foliated, sheared, and transformed into low-grade metamorphic mineral assemblages belonging chiefly to the greenschist facies (pl. 3). Anderson (1951) pointed out that metamorphic rocks of this age in Arizona are widespread and that they are similar in metamorphic grade throughout their extent. Although he did not mention the rocks in the lower San Pedro Valley, he described similarly deformed rocks in the Dragoon Mountains, which are about 55 miles to the southeast. The late stages of deformation probably were accompanied by widespread intrusion of quartzose granitic rocks, which were sheared locally but not foliated. The granodiorite, quartz monzonite, alaskite, and aplite in the San Manuel area belong to this intrusive period.

The deformation in the post-Paleozoic and pre-Cretaceous interval produced the angular unconformity between the Paleozoic carbonates and Upper Cretaceous sandstones and shales in Reed Basin (pl. 3). The structural discordance between the Paleozoic rocks and the Upper Cretaceous sandstones and shales is not large within the mapped area on plate 3, for the Upper Cretaceous rocks rest only on the Naco Formation (Pennsylvanian and Permian), except in their southernmost exposures, where they rest on the Mississippian Escabrosa Limestone. Elsewhere the discordance seems to be larger: Gilluly (1956, p. 67) reported that the Lower Cretaceous Bisbee Group rests on the Pinal Schist in the northwest flank of the Mule Mountains, which are about 50 miles southeast of the mapped area of plate 3 (fig. 3). He also found Bisbee Group resting on the Paleozoic rocks, and he concluded that "mountainous topography" existed at the time of the advance of the Comanche seas (Gilluly, 1956, p. 68).

Within the mapped area on plate 3, the Cretaceous deformation is reflected by the discordance between the Upper Cretaceous sandstones and shales and the Cretaceous or Tertiary volcanics; the volcanics not only overlap the Upper Cretaceous rocks but the Paleozoic rocks as well, and they rest unconformably on the Pinal Schist on the western flank of the Galiuro Mountains about 5 miles north of Copper Creek (pl. 3).

The post-Cretaceous and pre-Pliocene deformation was intense, and to a considerable extent it is still reflected in the configuration of the ranges and basins. The structures formed during this deformation cannot always be separated from the younger structures that resulted in the Basin and Range province, and indeed many of the older faults were reactivated during the younger deformation. Among the older structures are the syncline that controls Reed Basin, the strike-fault lying in the south limb of the syncline, the north-northwest-trending faults east of Ray and along the west side of the Black Hills, the west-northwest-trending fault in the Santa Catalina Mountains, and probably the northwest-trending fault along the eastern flank of the Mescal Mountains.

In the mapped area shown on plate 3, known thrust faults are limited to the Black Hills and to a local area in the Dripping Spring Mountains (not shown on plate 3). The thrusts indicate that crustal shortening, presumably through compression, was a part of the post-Cretaceous–pre-Pliocene deformation, and that the crustal shortening probably related this deformation to the period of intense thrusting and folding of the same age in the area to the southeast that includes the Tombstone Hills and the Dragoon, Dos Cabezas, and Mule Mountains (fig. 3).

Another possible structural feature of this age is in that part of the valley of the Gila River extending northwest from Winkelman. There, opposing dips of the Paleozoic and Apache Group rocks on opposite sides of the valley suggest the presence of a syncline. Toward the southeast the westward dip of these rocks flattens in the Galiuro Mountains; so the structural relief between the Galiuro Mountains and the San Pedro Valley probably resulted wholly from a Basin and Range fault. Near the Gila River northeast of Winkelman, the Reed Basin syncline reverses its plunge to form a cross structure presumably of the same age as the folds. The course of the Gila River across the Dripping Spring Mountains seems to be controlled by this structural sag in the fold axes.

The structures of Pliocene and younger age are faults, small folds related to the faults, and homoclinal tilts that commonly resulted from movement along the faults; these structures constitute the Basin and Range period of deformation. The basin fill in the San Pedro and Aravaipa Valleys conceals most of the Basin and Range faults. Therefore, many of the faults are undoubtedly covered; but others, where renewed movement occurred, are undetected because of the uniform lithology of the basin deposits. Recurrent movement during the Basin and Range deformation on older faults locally controlled, or modified, the shape of the basins and ranges. Recurrent movement, detected by reversal of relative movement, occurred along the north-northwest-trending fault near Ray and the fault along the southern limb of the syncline in Reed Basin. Because of its attitude and location, the fault bounding the west side of the Black Hills is suspected to be an older structure that had recurrent movement.

Faults younger than the Gila Conglomerate are known in several places in the San Pedro Valley; some of these faults are shown on plate 3. Detailed mapping in the San Manuel area clearly demonstrates that movement occurred on the faults during accumulation of the Gila Conglomerate, so that a complete separation of pre-Gila from post-Gila deformation is not feasible.

STRUCTURES IN THE SAN MANUEL AREA

Of the five periods of deformation just described for the lower San Pedro Valley, four can be recognized in the San Manuel area. The Precambrian deformation is represented in the granitic rocks. The post-Paleozoic and pre-Cretaceous deformation was not detected, because the Paleozoic is missing. The Cretaceous deformation is represented by the intrusion of the granodiorite porphyry and by its subsequent fracturing, both of which events played major roles in the origin of the San Manuel and other ore deposits. The post-Cretaceous and pre-Pliocene deformation produced the thrust that underlies the Cloudburst Formation as well as most of the high-angle faults that offset the Cloudburst. The deformation of Pliocene and younger age produced the San Manuel and Mammoth fault systems and other faults, some of which cut the Gila Conglomerate. The structures in the San Manuel area are described in more detail in the following paragraphs.

The oldest structures in the San Manuel area are related to the intrusion of the Precambrian granodiorite and quartz monzonite. In Putnam Wash, 6 miles north of the quadrangle, rocks similar to the granodiorite intrude the Pinal Schist, which there comprises well-foliated metamorphic rocks. Because the aplite and diabase dikes occupy old joints or sheared zones in the Precambrian granitic rocks, and because the composition and textures of the aplite and alaskite dikes strongly suggest that they are satellitic to the quartz monzonite, a close time relation seems reasonable between the intrusion of the quartz monzonite, the deformation that produced the fractures and sheared zones in the quartz monzonite, and, by inference, the foliation in the Pinal Schist. The temptation is great, therefore, to relate the intrusion of the granitic rocks and the deformation that foliated the Pinal Schist to a single period of older Precambrian orogeny. Certainly such an explanation is compatible with the known facts, but the meager data permit much latitude in interpretation.

The younger Precambrian Apache Group, the Paleozoic rocks, and possibly the Upper Cretaceous rocks of Colorado age are not exposed in the San Manuel area; their stratigraphic position is in the hiatus between the older Precambrian granitic rocks and the Cloudburst Formation. Part, or all, of this missing sequence may occur beneath the Gila Conglomerate in the San Pedro Valley; for in Putnam Wash, 6 miles north of the area, the entire sequence occurs trending northwest and facing northeast (pl. 3). The sequence also occurs in the Santa Catalina Mountains, about 10 miles south-southeast of the San Manuel area, where it is bounded on the north by the Mogul fault.

The granodiorite porphyry was probably intruded during the Cretaceous. The fracturing of the granodiortite porphyry that provided the open space needed for the mineralizing solutions that formed the San Manuel deposit is presumed to have followed soon after the consolidation of the porphyry. This assumption is based on our concept of the time relations in the processes responsible for the ore deposit. We do know, however, that the fracturing occurred before the accumulation of the Cloudburst Formation, because boulders of fractured and mineralized porphyry occur in the Cloudburst.

The post-Cretaceous and pre-Pliocene deformation is evidenced by the thrust fault that underlies the Cloudburst Formation, probably by related high-angle reverse faults, and by the intrusion of the rhyolite and rhyodacite. In terms of rock units, the deformation is younger than the Cloudburst Formation and older than the youngest rocks involved in the Basin and Range deformation. The youngest rocks have not been dated with certainty, but they must be older than the oldest deposits in the basins formed during the Basin and Range deformation. Chew (1952) reported the identification of a middle Tertiary fossil rhinoceros from folded and faulted sedimentary rocks on the west side of the San Pedro Valley south of Redington (pl. 3). Similar sedimentary rocks on the east side of the San Pedro Valley are overlain unconformably by the volcanics that form most of the Galiuro Mountains, and hence are pre-Basin and Range.

The Cloudburst Formation, which dips east at moderate angles and faces east, is homoclinal and is soled by a thrust. In the area between the San Manuel and Mammoth faults, the thrust fault dips 5° to 10° E., on the basis of its outcrop elevations and elevations on the contact exposed in the St. Anthony mine. Apparently a thrust underlies the Cloudburst south of the San Manuel fault and west of the San Manuel deposit. This thrust, however, was observed only in a small window of granitic rock a short distance west of the San Manuel area (pl. 3). Where exposed, the thrust fault is a sheared zone as much as several feet thick.

The separation of the post-Cretaceous and pre-Pliocene structures from the Basin and Range structures is not always possible. The numerous high-angle faults in the thrust plate cannot always be related to the one period of deformation or to the other. If one judges the faults by their attitude and by their apparent relative movement, the thrust plate is cut by two sets of conjugate reverse faults, one striking northeast and the other, northwest. Presumably the thrust fault and the reverse faults resulted from compression, and both types are therefore related by a common genesis. Northwest-trending normal faults also occur, and many, if not all, of these are probably part of the Basin and Range system.

The intrusion of the rhyolite and rhyodacite and the faulting that localized the veins in the St. Anthony deposit occurred during the post-Cretaceous and pre-Pliocene interval. The veins in the St. Anthony deposit, as well as those that cut the Cloudburst Formation, are younger than the thrust; they are also younger than the intrusive rhyolite and rhyodacite. However, the age relations of the intrusive rhyolite and rhyodacite to the thrust are not known.

Deformation during the Basin and Range period was largely responsible for the present physiography of the Black Hills. The San Pedro Valley is the depressed block; the Black Hills, the elevated block. The Mammoth fault system, the San Manuel fault, probably the Turtle fault, and probably the faults that cut the Gila Conglomerate in secs. 5, 6, 7, 8, and 9, T. 9 S., R. 16 E., were all formed during this period of deformation. Older faults from this period cannot be separated from those that may be younger because faulting and accumulation of sediments in the basins occurred simultaneously. For example, in sec. 1, T. 9 S., R. 16 E., south of State Route 77, the San Manuel fault separates the Cloudburst Formation from the lower member of the Gila Conglomerate, and the Mammoth fault separates the Cloudburst Formation from both the upper and lower members of the Gila. About a mile farther southeast, however, the upper member of the Gila overlaps both faults, but the lower member is still cut by the San Manuel fault.

The Mammoth fault crops out from just three-fourths of a mile north of Cottonwood Wash (sec. 1, T. 9 S., R. 16 E.) northwestward to within 3,000 feet of the northern boundary of the mapped area. The fault is an eastward-dipping high-angle normal fault. From grooves in the fault surface exposed in the St. Anthony mine that were assumed to mark the direction and plunge of the net slip, and from the amount of movement necessary to restore the continuity of the Mammoth and Collins veins, Creasey (1950, p. 72) concluded that the Mammoth is an oblique slip fault, and that the dip-slip component is several times greater than the strike-slip component. The hanging wall (east side) moved down and to the northwest with respect to the footwall; the normal dip-slip component of the fault in the St. Anthony mine was computed to be about 700 feet. Steele and Rubly (1947, p. 5) stated that the vertical displacement on the Mammoth fault (East fault of Steele and Rubly) is about 200 feet near the San Manuel deposit.

The Mammoth fault is composite where it cuts the Cloudburst Formation. From about the latitude of Tiger northward, the Cloudburst Formation forms both walls of the Mammoth fault, and here the fault comprises many strands (pl. 1). In places, principal fault planes are difficult to determine, yet the existence and general location of the northwest-trending fault zone is most evident. From Tiger southward to State Route 77, the Mammoth fault comprises two strands; and from State Route 77 southward, only one. Where the fault consists of only one or two strands, one or both walls are Gila Conglomerate, except for a short distance near where section *D–D′* cuts the fault. This fact probably signifies that the Mammoth fault existed before the deposition of the Gila Conglomerate, and that it was reactivated during the accumulation of the basin deposits.

The San Manuel fault crops out east-southeastward from the north flank of Signal Peak, which is near the west boundary of the San Manuel area, to Smelter Wash in sec. 18, T. 9 S., R. 16 E. In sec. 28, T. 8 S., R. 16 E., it exists as two separate overlapping strands that are not connected on the surface; and in sec. 35, T. 8 S., R. 16 E., it is offset by two high-angle normal faults. The fault dips at angles ranging from 25° to 70° SW. In the San Manuel mine the dip averages about 25° SW., and the average surface dip is estimated to be about 35° SW.; certainly over most of its extent the fault dips less than 45°. During the early exploration and development of the San Manuel deposit, the question of whether or not the low dip of the San Manuel fault might indicate a thrust was commonly raised. Schwartz (1953, p. 17) and Steele and Rubly (1947, p. 5) concluded that the San Manuel fault was a low-angle normal fault. Steele and Rubly attributed the low angle of dip to post-Gila tilting, which decreased the dip from about 60° to 65°. Steele and Rubly's thesis assumed that the San Manuel fault was older than the regional tilting (see p. 29), an assumption which is difficult to prove. Figure 12 shows the effect on the San Manuel fault of removing the regional tilt in the lower member of the Gila Conglomerate. The original dip of the San Manuel fault depends on what one is willing to assume as a reasonable estimate of the initial dip of the Gila. If one assumes that the

Gila initially dipped 15°, one can conclude that the San Manuel fault dipped 45° (fig. 12).

Conversely, after a careful study of the structures in the San Manuel deposit, Wilson (1957, p. 8) concluded that the San Manuel fault was a thrust fault. Wilson found that the fracture pattern in the deposit, including the San Manuel fault, indicated compression, and that the attitude of the San Manuel fault was compatible with a proposed compressional origin. The fault, however, is younger than the fractures in the San Manuel deposit; the age differential is measured by the time required for the accumulation of the Cloudburst Formation. Thus two periods of compression are required: an early period resulting in the fractures, and a later period resulting in the San Manuel fault.

On the basis of the relative displacement of the Cloudburst Formation and the thrust fault that soles the formation, I believe that the San Manuel fault is a normal right-lateral strike-slip fault. Unequivocal proof, however, of the absolute movement on the San Manuel fault, such as the recognition of a point on the hanging wall formerly in juxtaposition to a point on the footwall, has not been found. Plate 3 shows that the San Manuel fault is a right-lateral fault. The geologic map and sections also show that the thrust fault that soles the Cloudburst lies at a lower elevation in the hanging wall of the San Manuel fault than in the footwall. The vertical separation of the thrust at any one point is not known, but a window in the thrust plate south of the San Manuel fault is about 2,000 feet northwest of point *B* on section *B–B′* (pl. 1), and there the thrust is at an elevation of about 3,700 feet. As pointed out on page 26, the thrust fault in the footwall of the San Manuel fault dips 5° to 10° E. If one assumes a general dip of 10° E. for the thrust in the hanging wall of the San Manuel fault, the vertical separation of the plane of the thrust where section *B–B′* cuts the San Manuel fault is about 2,000 feet, a figure probably not underestimated by more than 100 percent. If the Cloudburst Formation dips 45° and strikes at right angles to the San Manuel fault, a normal dip-slip movement having a throw of 2,000 feet would produce an offset of 2,000 feet parallel to the trace of the fault. If the vertical separation on the San Manuel fault is 4,000 feet, the offset would also be 4,000 feet. As shown on plate 1, however, the offset parallel to the trace of the fault exceeds 10,000 feet. It seems probable, therefore, that the displacement had a dominant component of right-lateral strike-slip movement.

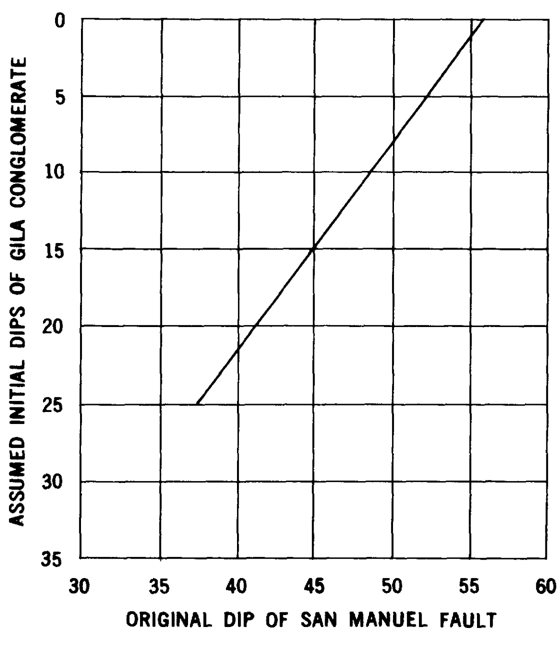


FIGURE 12.—Graph showing the possible original dips of the San Manuel fault as a function of the initial dips in the Gila Conglomerate. The graph assumes that the San Manuel fault is older than the deformation of the Gila Conglomerate. For the construction of the graph, the present attitude of the San Manuel fault was assumed to be N. 80° W. at 30° SW. and the present attitude of the Gila Conglomerate was assumed to be N. 25° W. at 35° NE.

Some data oppose strike-slip movement; the Cloudburst Formation north of the San Manuel fault is composed of interbedded lava and fanglomerate, whereas south of the fault the formation is composed of extensive thicknesses of both lava and fanglomerate that are not appreciably interbedded. Perhaps the difference can best be explained by assuming that the lava and fanglomerate beds are lenticular, but this assumption is made without strong conviction.

The branching network of faults in and around secs. 7, 8, and 9, T. 9 S., R. 16 E., has resulted in the rocks north of the faults being uplifted relative to those south of the faults. I was unable, however, to determine the relative movement on all the individual strands because some of the strands are entirely within the uniform lithology of the Gila Conglomerate. The faults trend from about west to northwest; dips are steep, both to the north and south; some faults are normal faults, whereas others are reverse faults, depending on the direction of dip. These faults are significant chiefly because they uplifted the rocks to the north to such an extent that erosion has exposed the pre-Cloudburst basement rocks, including the granodiorite porphyry. This exposed area lies along the southwest projection of the San Manuel deposit and is, therefore, a welcome surface exposure of an economically promising area. The basement area, chiefly in secs. 4 and 9, T. 9 S., R. 16 E., is locally known as the "Purcell Window" after Martha G. Purcell, who controlled the mineral rights to some of the area.

The faults in this branching network are similar to the San Manuel fault in general strike, approximate age, and relative movement, but they differ markedly in angle of dip and in amount of offset parallel to the trace of the fault. Despite the similarities, I am uncertain as to whether or not they were formed by the same stresses that caused the San Manuel fault, because the suggested strike-slip movement on the San Manuel is not evident in the faults to the south.

One strand of the faults in and around secs. 7, 8, and 9, T. 9 S., R. 16 E., extends northwestward beyond the quadrangle limits. For 1,500 feet southeast of the quadrangle boundary in sec. 31, T. 8 S., R. 16 E., this fault separates the Gila Conglomerate on the southwest from the Cloudburst Formation on the northeast. Either this fault continued northwestward or another one closely related to it is the boundary fault for about 6 miles between the Black Hills on the east and Gila Conglomerate on the west (pl. 3).

The Turtle fault, described by Peterson (1938, p. 22), crops out from the San Manuel fault in the southeast corner of sec. 28, T. 8 S., R. 16 E., east-northeastward at least to where it intersects the Mammoth fault and probably as far as the Gila Conglomerate. It dips 55° to 65° N. Much of its course is marked by a 1- to 2-foot calcite vein containing minor quartz.

If the San Manuel fault offsets the Turtle fault, the segment in the hanging wall of the San Manuel fault lies to the west of the mapped area. It is possible, of course, that the Turtle fault ended against the San Manuel fault. The presumed projection of the Turtle fault east (hanging wall side) of the Mammoth fault shows a left-lateral offset parallel to the trace of the Mammoth fault (two strands here) of only about 300 feet; this small offset is probably due to the near coincidence of the bearings and plunge both of the net movement on the Mammoth fault and of the intersection of the Turtle and Mammoth faults. The displacements of the Cloudburst Formation and of the Collins vein by the Turtle fault seem to be of very different magnitudes, and for this reason two separate periods of movement are likely, the older movement displacing only the Cloudburst Formation. On the footwall of the Turtle fault west of the Mammoth fault, the Cloudburst Formation has been removed by erosion for a distance of about 7,000 feet measured in a southeasterly direction. The throw on the Turtle fault, therefore, was sufficiently large to permit erosion of the Cloudburst Formation on the upthrown side of the fault. In contrast, the horizontal offset of the Collins vein is only about 100 feet. Of course, if the net slip on the Turtle fault was essentially parellel to the intersection of the Collins vein and the Turtle fault, the horizontal offset of the Collins vein would be small despite a large movement on the fault. The chance that the net slip was parallel to the intersection is quite small; and in the absence of information on the direction of net slip on the Turtle fault, two periods of movement are more likely.

The Gila Conglomerate has been tilted. The lower member of the Gila commonly dips at angles as high as 60° well away from known faults, and the consistency in dips of more than 15° strongly suggests regional tilting basinward. The dips in the lower member of the Gila range from 10° to 60°, and the average of 100 randomly selected dips is about 25°. In contrast, the dips in the upper member of the Gila range from 5° to 30°, and the average of the 47 dips shown on the regional map is about 10°. The upper member clearly lies unconformably on the lower; the unconformity is locally exposed in the walls of Cottonwood Wash.

Near Cottonwood and Smelter Washes the upper member of the Gila overlaps the San Manuel fault, whereas the lower member is offset. From near Mammoth Wash northward the Mammoth fault cuts the upper member, but about midway between Mammoth and Cottonwood Washes, the displacement of the upper member seems to die out. These relations suggest that the Mammoth fault is either younger or older than the upper member, depending on which part of the fault is considered, and that deposition and deformation of the Gila were, in part at least, contemporaneous.

A small syncline in the Gila Conglomerate lies in secs. 6, 7, and 8, T. 9 S., R. 16 E., just south of a compound fault (pl. 1; fig. 8). The syncline trends from west to northwest, approximating the trend of the major strands of the fault, and plunges about 15° SE. The axis of the syncline was displaced by some of the branches from the main fault, and this displacement indicates that the fold is not younger than the fault. Because the relative movement on the fault is up on the northeast side, the syncline is a fold that was produced by drag along the fault. This permissive relation, the near parallelism of the fault and syncline axis, and the coincidence, or near coincidence, of folding and faulting strongly suggest that the fault and the fold resulted from the same deformation.

ORE DEPOSITS

By J. D. Pelletier and S. C. Creasey

This description of the San Manuel ore deposit presents a detailed account of information that became available between 1948 and 1955, during which time the deposit was opened for underground study. The information comprises geologic level maps, sections, and additional data on the type and extent of the alteration, including the metallization. An earlier comprehensive report on the San Manuel deposit by Schwartz (1953) included a detailed account of the history, exploration, and development of the deposit from its discovery, in 1943, to 1948. Schwartz also reported the general size, shape, and grade of the deposit, and its general geologic setting, as determined from surface and churn-drill-hole data.

New information has not become available for the St. Anthony deposit since Creasey's work (1950) in 1945, and this deposit will not be considered further except for a brief description of the outcrop of the Mammoth and Collins veins.

Pelletier prepared the underground geologic maps and sections of the San Manuel deposit. He mapped the subsurface openings during the progress of the mine development, and his maps represent a record that cannot be duplicated because most of the mine is now timbered. In a well-timbered mine, competent underground geologic mapping is reduced to peeping through minuscule cracks in lagging and peering up raises or down winzes in a fruitless quest for naked rock. Pelletier is also responsible for the descriptions of the rocks exposed in the mine and for the description of the size, shape, and grade of the ore body. Creasey contributed the information on history, distribution of minor elements, and hydrothermal alteration and assumed the responsibility for a unified presentation.

HISTORY AND PRODUCTION

The early history of the San Manuel deposit probably differs little from that of most of the exposed mineralized outcrops in the southern part of Arizona. The uncompromising hostility of the proud Apaches, who were defending their homelands, effectively deferred prospecting until the late 1870's. The rich silver ores of the Tombstone district were not discovered until Ed Schieffelin risked a prospecting trip into the Tombstone Hills in 1877. The first claims were staked on the St. Anthony deposit in 1879, but one can reasonably assume that the mineralized rock of Red Hill may have attracted the attention of earlier prospectors. The reports that claims were located on Red Hill in or about 1870 (Chapman, 1947, p. 5; Knoerr, 1956, p. 75) seem reasonable.

The mineralized area around Red Hill aroused little interest until 1916 (1917 according to Knoerr, 1956, p. 76), when three churn-drill holes were dug to probe for what is now the San Manuel deposit. According to Chapman (1947, p. 5), logs or assay records of these holes are not available, but Knoerr (1956, p. 76) reported that the holes were unproductive. Schwartz (1953, p. 42) reported that the holes were drilled in 1917 and he listed the number drilled as two rather than three. According to Schwartz, one of the holes, whose site was recovered, penetrated the pyritic footwall of the deposit. After this unsuccessful but commendable attempt at discovery, the San Manuel deposit lay dormant until the series of events that led to its discovery in 1943.

According to Knoerr (1956, p. 76), Anseline Laguna took over the claims around Red Hill in 1925 and later included Burns Giffin of Superior, Ariz., as a partner. Following Laguna's death, Giffin formed a partnership with James Douglas; later Victor Erickson obtained an interest in the mine in exchange for assessment work. The deposit was then optioned to Mr. Piffin, who let his option expire in 1942. In April 1942, to aid in the sale of the property, the partners gave an interest to Henry W. Nichols, who was employed by the Magma Copper Co. Mr. Nichols worked either to sell or to develop the property with a zeal that could only have stemmed from a conviction of its merits, but he apparently was unsuccessful. Finally, in October 1942, Nichols applied to the Phoenix office of the Reconstruction Finance Corp. for a $20,000 loan to drill the deposit in the hope of finding enough ore to warrant a mill, and this application was the first link in the chain of events that led to the discovery and development of the deposit. The sequence of events and the significant dates were listed in detail Schwartz (1953, p. 42–43). It will suffice here to point out that the U.S. Geological Survey recognized the possibility of hidden ore beneath the blanket of Gila Conglomerate; the U.S. Bureau of Mines concurred in this judgment and drilled a part of the deposit. The successful negotiations of the Magma Copper Co. in acquiring the deposit were lucidly set forth by Knoerr (1956).

Production from the San Manuel deposit is given in table 7.

TABLE 7.—*Production from the San Manuel deposit, 1956–59*

[Production figures obtained from the 1957, 1958, and 1959 Annual Reports of the Magma Copper Co., of which the San Manuel Copper Corp. is a wholly owned subsidiary]

	1956	1957	1958	1959
Copper____pounds__	78, 152, 140	119, 797, 769	149, 401, 672	92, 340, 444
Molybdenum sulfide____do____	591, 970	1, 452, 080	1, 872, 450	1, 435, 613
Silver____ounces__	136, 074	200, 301	253, 858	158, 594
Gold____do____	9, 719	13, 578	16, 868	10, 232
Total ore____tons__	5, 539, 581	8, 825, 130	11, 486, 300	7, 595, 867
Total copper content____percent__	.771	.818	----------	----------
Sulfide copper content____do____	.754	.755	.716	.719

The St. Anthony deposit has a long and colorful past, which was described by Peterson (1938, p. 25–28). The deposit was developed as three separate properties: (1) the Collins mine, developed on the Collins vein, which is in the footwall of the Mammoth fault; (2) the Mammoth mine, developed on the Mammoth vein, which is in the hanging wall of the Mammoth fault; and (3) the Mohawk mine, developed on the Mammoth vein on the Mohawk claim south of the Mammoth mine (pl. 1).

The first claims were located on the Collins vein by Frank Shultz in 1879, and additional claims were located in 1881 and 1882 on the Mammoth vein. After a few years Shultz sold the Mammoth mine to George Fletcher, who blocked out gold ore and built a 30-stamp amalgamation mill on the San Pedro River a few miles to the east of the mine and, thereby, established the town of Mammoth.

In 1889 the Mammoth property was acquired by the Mammoth Gold Mines, Ltd., an English company. The mill was enlarged, and gold was profitably extracted from ore mined from the upper levels of the Mammoth vein. In 1893 the mine caved between the 200 and 400 levels. In 1896 the Mammoth Gold Mining Co. acquired the property and constructed a cyanide plant to increase the gold recovery and to rework the tailings, which still contained a good part of the original gold. Mining continued until 1901, when the Mammoth vein caved from the 750 level to the surface. Shortly thereafter the mine was closed, and it was not reopened for 12 years.

In 1913 the Great Western Copper Co. leased the property but did not operate the mine. In 1915 the Mammoth Development Co. took over both the Mammoth and Collins mines. During the early part of World War I, the tailings were successfully treated by the Arizona Rare Metals Mining Co. to extract wulfenite by gravity methods. In 1918 the St. Anthony Mining and Development Co. acquired the property and successfully mined high-grade wulfenite ore in response to the demand for molybdenum induced by World War I. Following the armistice, the price of molybdenum fell, and mining of the wulfenite ore ceased.

In 1892 Frank Shultz sold the Mohawk Claim, which joins the Mammoth on the south, to the Mohawk Gold Mining Co., which mined and treated gold ore in a 10-ton stamp mill until 1897. In 1906 the company was refinanced, and the stamp mill was enlarged to 30 tons. New ore bodies were found, and production continued until 1916.

Stimulated by the increase in the price of gold in 1933, the Molybdenum Gold Mining Co., a subsidiary of the Molybdenum Corp. of America, acquired the Mohawk mine and the New Year property, which lay just east of the Mohawk Claim. The company successfully developed ore bodies containing gold, lead, vanadium, and molybdenum.

In 1934 the Mammoth and Collins properties were obtained by Mammoth St. Anthony, Ltd., later known as St. Anthony Mining and Development Co., Ltd. Production of gold-vanadium-molybdenum ores from the oxidized parts of the veins started in 1934. Production continued until 1943, when the decrease in reserves of these ores and the demand created by World War II for base metals stimulated the development of lead-zinc sulfide ore bodies in the unoxidized parts of the Collins vein below the 650 level; galena and sphalerite were the chief ore minerals. With increasing depth, the lead-zinc content of the ores decreased, and in 1952 the mine was closed because the company was hard pressed by the depleted reserves and a large influx of water on the lower levels of the Collins vein.

In 1953 the Magma Copper Co., the owner of the San Manuel Copper Corp., acquired the St. Anthony deposit in exchange for Magma stock.

Production at the Mammoth Mining camp is given in table 8.

AGE OF THE ORE DEPOSITS

Some of the ore deposits cannot be dated closely with respect to the associated rocks because of the incomplete geologic section exposed in the San Manuel area. Rocks

TABLE 8.—*Production at the Mammoth Mining camp*

[Production from 1881–1936 after Peterson (1938); production from 1937–47 after Creasey (1950); production from 1948–52 not available]

Year	Location	Ore mined (tons)	Gold (ounces)	Silver (ounces)	Copper (pounds)	Lead (pounds)	Zinc (pounds)	MoO_3 (pounds)	V_2O_5 (pounds)
1881–1901	Mammoth–Collins	350,000	150,000	----	----	----	----	----	----
1896–1912	Mohawk–New Year	----	[1] 20,000	----	----	----	----	----	----
1916–19	Mammoth–Collins	49,764	10,450	----	----	----	----	447,876	----
1934	Mohawk–New Year	24,784	2,691	----	----	----	----	70,546	103,937
1935	Mammoth–Collins	18,267	2,174	8,604	----	379,954	----	49,869	40,918
1935	Mohawk–New Year	17,468	1,892	3,305	----	334,657	----	93,649	63,849
1936	Mammoth–Collins	40,115	7,100	33,456	----	742,128	----	109,915	108,712
1936	Mohawk–New Year	34,036	3,522	7,675	----	786,375	----	137,889	132,570
1937	Mammoth (production only)	54,540	10,477	47,649	----	1,605,122	----	245,042	193,126
1938	Total production (all mines)	165,465	24,352	87,398	----	5,511,385	----	840,900	433,015
1939	do	191,892	32,357	93,009	----	5,702,466	----	820,169	447,419
1940	do	186,110	33,762	95,549	----	5,750,650	----	946,300	312,491
1941	do	178,018	33,800	83,700	----	5,690,000	----	890,000	302,500
1942	do	151,141	27,905	80,347	----	3,529,940	----	624,144	255,890
1943	do	132,396	17,868	98,304	693,969	8,840,685	7,589,272	743,025	117,734
1944	do	39,135	5,647	27,137	161,970	2,741,801	2,042,737	295,488	28,681
1945	do	76,075	807	114,294	1,044,397	11,763,439	13,857,872	None	None
1946	do	86,049	622	97,804	764,458	10,428,135	12,867,773	None	None
1947	do	94,120	1,275	105,687	790,787	10,923,552	11,915,000	None	None
	Total	1,889,375	386,701	983,918	3,456,121	74,730,289	48,272,654	6,314,812	2,540,842

[1] Approximate.

representing the interval between the older Precambrian and the Cretaceous either are not exposed or do not exist; the small vein deposits that cut only Precambrian rocks cannot be dated except, by inference, where they are similar to veins that elsewhere cut the Cloudburst Formation, which is Cretaceous or Tertiary in age.

The ages of the San Manuel and the St. Anthony deposits are reasonably well known. Zircons from the granodiorite porphyry have been dated by the lead-alpha method as 97 to 130 million years (Cretaceous(?)). The San Manuel deposit is younger than the porphyry and older than the Cloudburst Formation. Rocks believed to be correlative to the Cloudburst Formation south of the Gila River between Christmas and Winkelman (pl. 3) unconformably overlie Upper Cretaceous rocks of Colorado age and unconformably underlie the Whitetail Conglomerate, which is the conglomerate below the Tertiary volcanic sequence in central Arizona. Thus the most probable age for the San Manuel deposit is Cretaceous; however, the possibility of an early Tertiary age cannot be eliminated, because of the lack of a precise age for the Cloudburst Formation.

The St. Anthony deposit is younger than the intrusive rhyolite that cuts the Cloudburst Formation, so both the rhyolite and the related mineralization are presumed to be Tertiary. The rhyolite and the mineralization, are however, older than the Whitetail Conglomerate and the overlying volcanics, as shown by the general absence of mineral deposits, like the St. Anthony deposit, in the younger Tertiary volcanics. The veins in secs. 20, 21, and 28, T. 8 S., R. 16 E., are similar in their surface appearance and attitude to the Mammoth and Collins veins; and because these veins also cut the Cloudburst Formation, it seems reasonable to assume they are the same age as the Mammoth and Collins veins, at least until some indication to the contrary is found. The veins in and near the Pearl mine (secs. 17, 18, and 20, T. 8 S., R. 16 E.) cut only Precambrian rocks; however, because they have a similar attitude and appearance, they are presumed to be Tertiary also.

SAN MANUEL ORE DEPOSIT

MINE DEVELOPMENT

By 1948, churn drilling had indicated the size, attitude, and depth of sulfide ore, and consideration of the depth of overburden indicated that block caving would be the best mining method.

No. 1 shaft was collared March 17, 1948, well to the north of the ore zone, to serve as a supply and ventilation shaft and for possible future use in hoisting ore. No. 2 shaft was collared in October 1948 over the southeast limb of the ore body to allow immediate access to the ore and to permit exploration and development to proceed at an early date.

In December 1950, drifting was begun on the 1285 exploration level off No. 2 shaft to explore the central part of the southeast limb of the ore body. Diamond drilling, concurrent with drifting on the 1285 level, further outlined the ore in the first area to be mined, and explored ground not previously churn drilled. Drifting was started on the 1475 haulage level in May 1952 and on the 1415 Grizzly level in November 1952. In July 1953, No. 4 shaft, a service and supply shaft, was collared near No. 1 shaft. Two hoisting shafts, No. 3A shaft and No. 3B shaft, were collared southwest of the ore zone in September of the same year (fig. 13).

Methods used in sinking the shafts were described by Pillar (1954), and drifting methods, rates of progress, and ground support were described by Ashby (1954).

At the end of 1955 the development necessary for production, exclusive of stope development, totaled 8,708 feet of shaft, 97,463 feet of drift, and 116,998 feet of diamond-drill hole. The first ore, which was mined during development, was sent to the mill on September 15, 1955. The undercut of the first caving block was started November 24, 1955, and ore from the first stope dropped into the chutes shortly thereafter. Smelter production began with the casting of the first anodes on January 8, 1956.

ROCK DESCRIPTIONS

QUARTZ MONZONITE AND APLITE

Precambrian quartz monzonite is the main rock exposed in an area including No. 1 and No. 4 shafts and extending about 2,400 feet southeast of No. 1 shaft on the 1475 and 1415 levels (pls. 4, 5). The quartz monzonite is also exposed in the bottom of No. 2 shaft and in a zone extending roughly 600 to 1,200 feet southeast of No. 2 shaft in an elongate mass whose axis trends northeast. The aplite facies of the quartz monzonite occurs in a small dike that drops out in the Clear Water sump of No. 1 shaft, 1475 haulage level.

GRANODIORITE PORPHYRY

Granodiorite porphyry constitutes the bulk of the rock remaining below the San Manuel fault in No. 2 shaft, on the 1415 Grizzly level, and east of the San Manuel fault on the 1285 and 1475 levels (figs. 18, 19, 20, 21, 22). In general, granodiorite porphyry occurs in two large eastward-converging masses separated by the projection of quartz monzonite southeast of No. 2 shaft. The north mass of granodiorite porphyry has been de-

FIGURE 13.—Principal surface installations at the San Manuel mine. The two ore hoisting shafts, 3A (left) and 3B (right), are in the foreground. No. 4 shaft is beyond the left edge of No. 3A shaft in the middle distance. No. 1 shaft is to the left of No. 4 shaft. Red Hill, in the middle distance, is viewed between No. 3A and 3B shafts. The Collins vein in the St. Anthony deposit crops out in the saddle between the twin peaks to the left of No. 1 shaft in the middle distance.

scribed as a sheetlike mass lying above quartz monzonite (Schwartz, 1953, p. 9). The bottom of the south mass has not been determined by drilling south of the ore body. Churn-drill holes 108 and 109, 1,210 feet and 2,170 feet deep, respectively, southwest of No. 2 shaft, penetrated granodiorite porphyry after passing through some quartz monzonite in their upper sections. This information indicates that the north edge of this mass of granodiorite porphyry plunges to the north, which adds weight to Schwartz's suggestion (1953, p. 9) that a stock of porphyry lies to the south.

Granodiorite porphyry also occurs as northeast-trending dikes cutting quartz monzonite. These dikes become more numerous near the larger masses of granodiorite porphyry. In some places, contacts of the porphyry with the quartz monzonite are gradational and are represented by a zone of intricately mixed quartz monzonite and porphyry in which it is not possible to recognize exact contacts. More often, however, there is a reasonably sharp contact between the two rocks: close to the contact the grain size of the quartz monzonite is unchanged, but the porphyry shows fewer phenocrysts.

DIABASE

A dike of diabase 11 feet thick was cut by No. 1 shaft at a depth of 100 feet, and small irregular injections were cut at 340 feet and at 450 feet. A dike 7 feet wide was mapped in the Clear Water sump of No. 1 shaft, 1475 level. Several irregular coarse-grained diabase dikes were exposed in the South haulage drifts, southwest of No. 2 shaft, on the 1475 level (pl. 4).

CLOUDBURST FORMATION

The Cloudburst Formation in the San Manuel mine comprises both fanglomerate and mafic dikes; the mafic dikes are believed to be the intrusive equivalent of the latite flows, as Schwartz suggested (1953, p. 12). Mafic dikes were cut at a depth of 1,050 feet to 1,055 feet in No. 2 shaft and at 495 feet in No. 4 shaft. The dike in No. 4 shaft was 3 to 6 feet thick and nearly horizontal. Several similar dikes were exposed in the main crosscuts between No. 1 shaft and No. 2 shaft on the 1415 and 1475 levels. A small dike, approximately 12 inches wide, was cut by the North haulage drift of the 1475 level, 1,670 feet northeast of the main crosscut.

A fanglomerate facies of the Cloudburst Formation was cut by No. 3A and No. 3B shafts and by drifts in the westernmost part of the 1475 level. No. 3A shaft, which offers the thickest section, cut fanglomerate in the Cloudburst between a depth of 1,335 feet and 1,564 feet below the collar of the shaft and cut flows and flow breccias belonging to the Cloudburst from 1,564 to 1,708 feet, which is at present the bottom of the shaft. The fanglomerate consists mainly of quartz monzonite fragments but contains fragments of all the older rocks in the area. The matrix consists of granitic sand and gravel. The fanglomerate is poorly cemented but relatively well sorted compared with the overlying Gila Conglomerate; beds of sand and gravel alternate with beds of larger boulders. Slickensides on bedding planes are common. Tuff beds occur in the fanglomerate and in the underlying flows and flow breccias. Where not distorted by drag adjacent to the San Manuel fault, the average strike in the underground exposures is approximately N. 5° W., and the average dip is about 30° E.

The latite flows generally are vesicular, and calcite either fills or lines the vesicles; the flows are aphanitic, except for one 30-foot section of flow breccia which contains extremely altered, elongated mafic phenocrysts that are presumed to have been hornblende.

As seen in No. 3A shaft, the Gila Conglomerate unconformably overlies the Cloudburst. The contact is marked by an irregular tuff bed in No. 3B shaft. There, and in the exposures of this contact on the 1475 haulage level, the bedding of the two formations is nearly parallel. On the 1475 haulage level, however, the tuff bed was not recognized, and the contact was not located accurately because of the similarity of the formations.

INTRUSIVE RHYOLITE

Rhyolite dikes are cut in No. 2 shaft and in several places on all levels in the central and western areas of the mine (pl. 4). These dikes generally have sharp contacts with the rocks they intrude, and most of the dikes are flow banded along their outer margins. A few dikes have brecciated margins: the outer 4 feet on either side of a dike exposed about midway in the main crosscuts consists of a breccia of quartz monzonite and angular rhyolite fragments, and a rhyolite dike near the west end of the 1285 level consists mainly of angular rhyolite fragments in a rhyolite matrix.

GILA CONGLOMERATE

Gila Conglomerate is cut in the upper parts of No. 2, 3A, and 3B shafts and on the 1475 haulage level southwest of No. 2 shaft. The Gila is poorly sorted, and, in the small exposures in the mine, bedding is not always readily apparent. The fragments in the upper part of the Gila Conglomerate exposed in the hanging wall of the San Manuel fault in No. 2 shaft are predominantly mafic volcanics, whereas those in the lower part, seen in No. 3A and No. 3B shafts, are mainly granitic rocks. Fragments of tuff and conglomerate derived from the Cloudburst Formation commonly serve as the best marker for the base of the Gila, for the unconformity between the two formations is not apparent. The attitude of the Gila Conglomerate varies considerably within the mine area: east of the Hangover fault, the attitude of the bedding exposed on the 1475 haulage level averages N. 50° W., 35° NE., whereas west of the Hangover fault the attitude is about N. 17° W., 35° NE.

STRUCTURE

Faults and fractures are the dominant structures in the San Manuel deposit. The San Manuel, East (Mammoth), West, Hangover, and Vent Raise faults are younger than the ore deposit. They displace either the ore deposit or other faults that in turn displace the ore deposit. The deposit was fractured during two periods of deformation: the post-Cretaceous and pre-Pliocene, and the Pliocene or post-Pliocene. In addition, the attitude of the lower member of the Gila Conglomerate suggests that the region was tilted in the Pliocene or post-Pliocene period. As a result, the fracture pattern is so complex that we have not been able to interpret it satisfactorily.

SAN MANUEL FAULT

The San Manuel fault is the oldest of the postmineralization faults exposed in the mine; it is cut by No. 2 shaft at a depth of 702 feet, by the 1285 exploration level southwest of No. 2 shaft, and in seven different places by drifts on the 1475 level between No. 2 shaft and Nos. 3A and 3B shafts. It is also intersected in many of the diamond-drill holes. The average attitude of the fault in the mine area is N. 66° W., 26° SW. The strike and dip vary widely in individual exposures, and this indicates an uneven surface, probably cut in many places by later faults. A segment of the San Manuel fault exposed between two branches of the Hangover fault in the South haulage drift No. 1 of the 1475 level about midway between No. 2 shaft and Nos. 3A and 3B shafts is nearly horizontal and is displaced by numerous small faults related to the Hangover fault.

Typically, slickensides and from 1 to 3 feet of red gouge mark the San Manuel fault. Immediately beneath the red slickensides in the footwall of the fault, a layer of gray gouge from 5 to 15 feet thick is alined about parallel to the fault. The gray gouge is marked by irregular slickensided surfaces and includes slightly rounded hard fragments. Beneath the gouge the underlying rock is intensely fractured but grades into normal rock about 50 to 100 feet vertically below the fault surface. Smaller faults, nearly parallel to the San Manuel fault, are common in this broken zone.

The Gila Conglomerate in the hanging wall of the San Manuel fault east of the Hangover fault is disturbed a little and contains a few small slips close to the fault surface. West of the Hangover fault the zone in which the Gila and Cloudburst Formations are disturbed by drag, and in which small offsets occur adjacent to the San Manuel fault, extends approximately 300 feet vertically above the fault plane. This deformation flattened and nearly reversed the dips of the beds to form a trough plunging to the southeast. This drag and the comparison of the formations mapped in the hanging wall and footwall on the surface clearly suggest that the San Manuel fault is a normal fault, regardless of whether movement occurred before or after tilting of the conglomerates.

EAST (MAMMOTH) FAULT

The East fault, recognized on the surface northeast of No. 2 shaft by Schwartz (1953, pl. 1) and by Steele and Rubly (1947, p. 5), is undoubtedly part of the Mammoth fault zone. It strikes N. 20° W. and dips 58° to 80° NE. Locally at least, the East fault is multiple; other nearby conspicuous faults are parallel to the East fault and are therefore considered to be related to it. Underground the East fault was tentatively identified in four places on the 1415 Grizzly level and in six places on the 1475 haulage level; in one place on the 1285 level the fault was identified as a gouge and breccia zone ½ to 4 feet thick. All these localities lie on a reasonably uniform plane, but the East fault was not recognized in several drifts that cut this plane. At the points where the projection of the East fault cuts these drifts, the rock is only fractured; conceivably either the movement was taken up along these fractures, or the drifts pass through zones where the East fault is cut out by other faults.

Estimates of the displacement on the East fault were obtained from displaced intersections of assay boundaries, with the San Manuel fault. Using these intersections, one finds that the vertical separation in the vicinity of the North ore body is about 200 feet, as determined by churn-drill logs and assays, and in the vicinity of the South ore body, only about 40 feet, as determined by diamond-drill logs and assays. These intersections are not entirely reliable, but they do suggest that the direction of relative movement is nearly down the dip, the east side thrown down relative to the west side.

WEST FAULT

The West fault, which has been described by Schwartz (1953, p. 17) as a northwest-striking fault dipping 60° to 80° E., was not definitely located underground. The 1285 exploration level cut a brecciated fault about 3 feet wide some 440 feet southwest of No. 2 shaft; possibly this may be the West fault. This fault strikes N. 22° W. and dips 76° NE. Fault gouge penetrated in diamond-drill holes on both sides of the drift suggest that the average strike of this fault may be nearly north.

HANGOVER FAULT

Two faults 70 feet apart cross the South haulage drifts on the 1475 haulage level, and a fault zone about 130 feet wide and containing a pronounced fault in the west margin crosses the North haulage drifts on the 1475 haulage level about midway between No. 2 and No. 3 shafts. This faulted zone is the Hangover fault; the strike averages N. 24° W., and the dip varies from 40° to 76° NE. An indistinct fault in the north bank of Mammoth Wash is presumed to be the Hangover. If the fault is projected from the surface to the 1475 haulage level, it dips about 57° N. Displaced points by which the true displacement of the Hangover fault could be measured were not found, but the Hangover fault displaces the San Manuel fault, and the relative movement indicates that the Hangover is a normal fault. The vertical separation, measured on the displaced San Manuel fault on the 1475 haulage level, is about 260 feet on the east branch of the Hangover fault and 150 feet on the west branch.

VENT RAISE FAULT

A major fault called the Vent Raise fault is exposed in the ventilation raise from the 1475 haulage level to the 1415 Grizzly level, in the North haulage drifts on the 1475 haulage level, in the ventilation crosscut on the 1415 Grizzly level, and in the main crosscuts on both levels. The strike of the fault averages about N. 59° E., and the dip varies from vertical to about 70° SE. By projection, the intersection of the San Manuel, East, and Vent Raise faults can be located on both the footwall and the hanging wall of the Vent Raise fault. Although these two points cannot be located accurately, their approximate positions suggest a reverse dip-slip movement of about 400 feet and a strike-slip movement of about 100 feet on the Vent Raise fault; the south block is displaced upward and to the southwest in relation to the north block.

FRACTURES IN THE SAN MANUEL DEPOSIT

Wilson (1957) made a comprehensive study of the structures in the San Manuel deposit to help determine whether the deposit was suitable for mining by block caving. He concluded that the fractures were systematic, and that this indicated a tectonic origin; he recognized eight separate strike trends: north, N. 30° E., N. 45° E., N. 60° E., east, N. 60° W., N. 45° W., and N 30° W. Wilson found sulfide minerals in the fractures lying in all eight directions. He concluded that the north-striking and the east-striking fractures were the same age, and that they cut all other steeply dipping fractures except possibly those that strike N. 30° to 60° W. (Wilson, 1957, p. 76).

The fractures must have resulted from at least two periods of deformation: one post-Cretaceous and pre-Pliocene, the other Pliocene or younger (Basin and Range). In addition, the area around the deposit seems to have been tilted about 10° to 20° E., if one judges by the attitude of the lower member of the Gila Conglomerate. To help distinguish the Pliocene or younger fractures from those older, Wilson mapped the fractures in 950 feet of drainage ditch that was entirely in Gila Conglomerate which could have been involved only in the Pliocene and post-Pliocene deformation. He found that N. 45° W., N. 30° W., and north-trending fractures are most common; but he also observed a few fractures trending east and N. 30° E. The set trending N. 45° W. seemed to cut all the others.

To help evaluate the relative significance of the fractures of each trend, we measured from Wilson's maps the attitude of 568 fractures in granodiorite porphyry on part of the 1415 level (Wilson, 1957, p. 28–32, 42–43, 45). This area was chosen because the drifts strike at right angles to each other, so that a representative sampling of fractures could be made. Poles of the fracture planes were plotted on an equal-area net and contoured on the basis of percentages of the total number of points (fig. 14).

The predominant trends of fractures on the 1415 level as indicated by figure 14 agree only in part with the predominant trends of faults and fractures at the surface. The attitudes of post-Gila fractures measured on the surface and the attitudes of those on the 1415 level only partly coincide: the abundant north-striking fractures on the surface are concentrated 4 to 8 percent underground (fig. 14), whereas the N. 30° W.-striking surface fractures are concentrated only 2 to 4 percent underground; and the N. 45° W.-striking surface fractures are not present in abnormal concentrations. The more numerous fracture trends in the granodiorite porphyry presumably include fractures formed during the earlier post-Cretaceous and pre-Pliocene deformation. The Cloudburst Formation, which is underlain by a thrust of the earlier deformation, might be expected to exhibit the dominant fracture trends of this earlier period. The dominant fault trends in the Cloudburst Formation, however, which are northeast and northwest, do not coincide with the dominant east and north trends of fractures in granodiorite porphyry on the 1415 level. Despite this lack of coincidence, some of the fractures in the granodiorite porphyry must have resulted from the earlier deformation. Our regional data on the two periods of deformation are too incomplete to permit an analysis of what deformation each period comprised. For this reason we were unable to distinguish between structures of the two periods, and whether such a distinction can be made after good regional data are available remains to be determined.

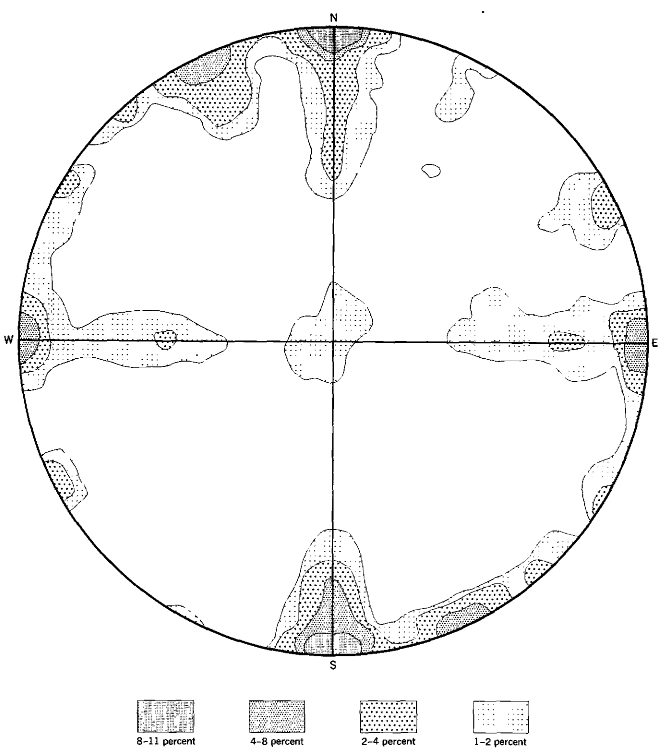


FIGURE 14.—Contour diagram of poles to planes of 568 fractures, 1415 level, San Manuel mine. Lower hemisphere projected. Data from Wilson (1957).

SIZE AND SHAPE

The mineralized zone, which includes the ore deposit, is about 8,000 to 9,000 feet wide and more than 9,300 feet long; it trends east-northeast. The part of this zone classed as ore is arbitrarily determined by using a cutoff in copper content—that is, all mineralized rock assaying above this arbitrarily determined copper content is classed as ore, all below is classed as waste. The ore boundaries along the sides and bottom of the ore deposit are therefore assay boundaries; the top, however, is determined by the overlying Gila Conglomerate or Cloudburst Formation, both of which were laid down after formation of the ore. The deposit is reported to contain about 500 million tons of ore containing about 0.8 percent copper (Knoerr, 1956, p. 75).

The upper and western parts of the ore body are separated by a lean zone in which the host rock is similar to that of the ore areas but which has less sulfides. At depth the lean zone disappears and the two richer parts converge, so that the cross-sectional shape of the ore body is like a U or V tilted to the northwest (pl. 5). The northwestern limb of ore is known as the North ore body, and the southeastern limb, as the South ore body.

The North ore body strikes about N. 60° E. and dips approximately 50° SE. The western part of the South ore body also strikes N. 60° E., parallel to the North ore body, but eastward the strike of the South ore body gradually swings to about N. 45° E. The dip of the South ore body is variable: in the upper part the dip is southeast, but with increasing depth the dip changes from southeast to vertical and then to northwest before the body finally joins the North ore body. To the east, the central area of lean material gradually diminishes and disappears, and the two limbs join to form a single mass of ore.

At the east end of the mine, the top of the ore, which was determined by assays, plunges approximately 10° NE.; but the bottom of the ore and the notch formed by the junction of the North and South ore bodies plunge southwestward to a point east of No. 2 shaft, where the plunge flattens. From there westward the ore body is nearly horizontal as far as it has been explored.

HYPOGENE MINERAL ZONES

The chief primary ore and gangue minerals in the San Manuel deposit are chalcopyrite, pyrite, quartz, muscovite (sericite), kaolinite, biotite, and potassium feldspar. Three zones can be distinguished on the basis of the relative distribution of these minerals: (1) the ore zone, (2) the central lean zone, which lies between the North and South ore bodies, and (3) the outer pyritic zone, which surrounds the ore body and the central lean zone.

The ore zone, which averages approximately 0.80 percent copper, contains most of the chalcopyrite, quartz veinlets, molybdenite, biotite, and secondary potassium feldspar; sericite is also common. Pyrite is about as abundant as chalcopyrite. Most of the yellow sulfides are finely disseminated through the rock, but some occur as veinlets or, more often, as a sprinkling on fractures. Molybdenite commonly forms a slickensided coating on fractures or accompanies quartz veinlets.

The rock in the central lean zone is similar to ore-zone rock except that it contains less primary sulfide minerals. The abundance of sulfide minerals decreases gradually from the ore zone toward the lean zone, so that the boundary is not sharply defined.

The outer pyritic zone, which surrounds the ore and lean zones, consists essentially of granular quartz, sericite, pyrite, and kaolinite. It differs, therefore, from the ore and lean zones by containing more quartz, pyrite, and kaolinite, and less chalcopyrite, biotite, and potassium feldspar. In the outer pyritic zone, pyrite is most abundant south of the South ore body, where it comprises 10 to 20 percent of the rock by weight. The pyrite content north of the North ore body gradually decreases over a distance of at least 1,500 feet to a very small amount. Chalcopyrite is rarely, if ever, seen in the outer zone, quartz veinlets are very rare, and molybdenite does not occur in visible amounts.

RELATION OF ORE TO ROCK TYPE

Ore occurs in quartz monzonite, granodiorite porphyry, and diabase. In a general way, the ore body lies along the contact of the sheetlike mass of granodiorite porphyry (above) and the quartz monzonite (below). The east end of the ore body is entirely in granodiorite porphyry, but there the cross-sectional area of the ore body is smaller. The ore is not directly related to the granodiorite porphyry because the ore is included in several rock types, and some of the granodiorite porphyry is barren. The coincidence in large part of the ore body and the sheetlike mass of granodiorite porphyry, and the coincidence of the ore body and younger chloritic alteration along fractures (discussed on p. 53), suggests that the primary localization of intrusion and mineralization may be structural.

The Cloudburst Formation is unmineralized except for some dikes that cut the deposit; these dikes contain a minor amount of sulfide minerals acquired from the host rock. The dike in No. 2 shaft was unmineralized, according to H. J. Steele (oral communication), as was that in the North haulage drift of the 1475 level. All the other dikes showed small amounts of pyrite, notably less than in the intruded rock. A 5-foot sample of dike taken from a diamond-drill hole in the ore body assayed 0.10 percent copper. Chlorite, and perhaps serpentine, was the only alteration mineral noted in this rock.

At a depth of 1,638 feet, No. 3A shaft cuts a tuff bed from 1 to 4 feet thick that is strongly mineralized with disseminated pyrite; this bed assays 0.05 percent copper. The pyrite is presumed to be younger than the ore minerals because the Cloudburst Formation is not mineralized where it overlies mineralized granodiorite porphyry at the surface 3,300 feet east of No. 2 shaft.

The rhyolite dikes do not contain hypogene copper minerals; they are stained locally by chrysocolla where they are in, or close to, the zone of oxidation. Chlorite coats joint faces of two rhyolite dikes, one in No. 2 shaft and the other in the east drift of the 1285 level.

OXIDATION AND SECONDARY ENRICHMENT

The upper part of the ore body, except at its west end and in much of the central lean zone, is oxidized or partly oxidized. The bottom of the oxidized zone is irregular and is gradational into unoxidized rock. In most places the lower several hundred feet is a zone of mixed oxides, chalcocite, and primary sulfides and does not show much enrichment. Oxidation penetrated much deeper between the two limbs of ore than in the ore itself, so that, in cross section, the bottom of the oxidized zone is trough shaped (pl. 5).

The principal minerals formed during oxidation are chrysocolla, chalcocite, and iron oxides. Smaller amounts of cuprite, especially the variety chalcotrichite, native copper, and black copper oxides occur where rock rich in oxide copper minerals grades into rock enriched in chalcocite. Copper carbonates are very rare; only one small specimen of malachite was found.

Oxidized rock can be separated into two types on the basis of the color that the iron oxides impart to the rock. The first type, characterized by a deep red or reddish-brown color, occurs at the surface, in the upper parts of No. 1 and No. 4 shafts, and in diamond-drill holes extending above the top of the sulfide ore at the east end of the South ore body. Oxidation of the sulfides is nearly complete, and the contact with the underlying sulfides is sharp. An irregularly thick chalcocite zone commonly marks the base of this "red" type oxidation.

A yellow to tan limonite- and goethite-rich rock that represents the second type of oxidized rock was reported by Schwartz (1953, p. 37, 57) as being abundant in the deep parts of drill holes, and it is now exposed in drifts on the 1285, 1415, and 1475 levels. Complete oxidation of sulfides is not everywhere attained, and large volumes of unaltered rock are enclosed (pl. 5) by oxidized rock. The fringes of oxidized rock generally contain chalcocite, primary sulfides, and much iron oxide stain but very few copper oxide minerals. Secondary enrichment of copper is very slight or negligible, and occasionally the copper content is lower than in the primary ore. Chalcocite and, in some places, native copper and cuprite, occur along the top and sides of tongues of this "yellow" oxidized rock. This relation produces an inversion of the normal sequence of oxidation: primary ore lies above secondary sulfide ore, which in turn overlies oxidized ore. The average copper content of such tongues also indicates no overall enrichment.

The drift on the 1285 level west of No. 2 shaft cut through a large area in which there are many tongues of "yellow" oxidized rock. This drift, together with rather closely spaced diamond-drill holes, outline the distribution of the oxidized rock. The oxidized zone tends to parallel certain dikes and structures, such as rhyolite dikes, the San Manuel fault, and a large north-striking fault that may be an extension of the West fault. In some places, no structural control was recognized; presumably oxidation was controlled by local differences in permeability.

Lovering (1948) measured the geothermal gradients in 11 churn-drill holes at San Manuel before mining began to determine whether the oxidation of the sulfides yielded detectable amounts of heat. In addition to those temperature inflections ascribed to climatic changes, a temperature inflection was detected where sulfides are at or above the water table, and this inflection was related to oxidation of pyrite. The temperature gradient calculated from this inflection was from 0.4° to 0.6° F. per 100 feet. Using this temperature gradient and other data, Lovering (1948, p. 14) calculated that all the pyrite would oxidize in about 40,000 years.

Ground water in the mine is not uniformly distributed, and this fact may partly explain the trough-shaped distribution of oxidized rock. A perched water table exists in the conglomerate above the San Manuel fault; the saturated zone was 382 feet thick where the San Manuel fault was cut on the 1475 haulage level. Beneath the San Manuel fault and below the water table, the quartz monzonite and certain zones in the granodiorite porphyry yield water, but other zones in the porphyry are dry.

The top of the water table is somewhat irregular. In the No. 1 shaft, it was at an elevation of 2,230 feet. During the early exploration of the deposit, Steele and Rubly (1947, p. 5) found that the average elevation of the water table was about 2,575 feet. Later, Lovering and others (1950, p. 508) found that the elevation of the top of the water table in some of the churn-drill holes ranged from 2,547 to 2,698 feet. In the St. Anthony mine, a mile north of the San Manuel deposit, the water table was penetrated 33 to 46 feet below the 700 level, or at an average elevation of about 2,510 feet. From the San Manuel deposit, the water table, sloping gently toward the San Pedro River, drops about 250 feet in a horizontal distance of about 3 miles, or from an average elevation of about 2,550 feet at the deposit to about 2,300 feet at the river. The water table is only a few feet below the surface in the flood plain of the San Pedro River.

None of the water found in the mine shows a relationship to the bottom of the oxidized zone; however, the saturated quartz monzonite in the area of the North ore body corresponds roughly to the north wall of the deep trough-shaped oxidized zone.

At the east end of the South ore body, the base of the oxidized zone is a somewhat planar surface that dips to the north and is subparallel to the base of the Gila and Cloudburst Formations. Most drill holes that cut this contact of the oxide and sulfide cut a chalcocite zone.

Northwest of the ore zone the bottom of the oxidized zone parallels the present ground surface, although it is not at or parallel to the present water table. Oxidation is thorough, and a thin zone of chalcocite occurs at the base of the oxidized zone.

In places, Gila Conglomerate rests directly on mineralized igneous rock and, in other places, on remnants of the Cloudburst Formation, which in turn rests on the ore body. The ore body therefore was subjected to at least two periods of erosion prior to the present one: one before deposition of the Cloudburst Formation, and the other after the deposition of the Cloudburst but before deposition of the Gila Conglomerate.

Lovering, Huff, and Almond (1950) analyzed samples of soil, alluvium, ground water, and vegetation from the San Manuel deposit and its environs to determine the copper-dispersion pattern in desert climates. They found that little copper is taken up by plants or is dissolved in the ground water. Chrysocolla, however, was eroded from the outcrops of the deposit and was mechanically distributed in washes that drained the outcrop area. They concluded that studies of copper dispersion in soils and alluvium is the best geochemical approach to mineralized zones like that at San Manuel.

ALTERATION OF THE GRANODIORITE PORPHYRY

The study of the alteration of the granodiorite porphyry is largely the study of the San Manuel ore deposit. The alteration includes the metallization that formed the ore, the formation of certain secondary silicates, the destruction of other silicates, and the supergene alteration due to oxidation of sulfide minerals on and near the ground surface.

To a large extent, this study of the alteration at San Manuel supplements the earlier work of Schwartz (1953); none of his efforts were duplicated other than those necessary for our guidance and orientation. Schwartz's work included a thorough study of the surface and of churn-drill cuttings taken during the exploration that outlined the deposit; we studied the alteration in a horizontal plane, defined by the 1475 haulage level, through the ore body. A few samples of altered surface rock were studied to help determine the similarities and differences of the altered granodiorite porphyry away from the deposit as compared to that in and near the deposit.

The purpose of our study was to obtain additional information on the nature of the alteration itself; and to simplify our problem, only the granodiorite porphyry was sampled. We assumed that, prior to alteration, the different masses of granodiorite porphyry had the same bulk composition.

All the granodiorite porphyry is altered, and the alteration is of three types: propylitic, potassium silicate, and argillic. The propylitized porphyry occurs in the areas peripheral to the San Manuel deposit, and the potassium-enriched and argillized porphyries occur in the deposit. The characteristic mineral assemblage of the propylitized porphyry comprises chlorite, epidote, and calcite (or another carbonate); that of the potassium-enriched porphyry comprises biotite, potassium feldspar, and sericite; that of the argillized porphyry comprises sericite and kaolinite. In addition, in surface outcrops near the deposit, either the argillic alteration or a type of alteration very similar to it produced abundant alunite. The relationship of the mineral assemblages characteristic of the potassium silicate and argillic alterations is illustrated in figure 15.

We did not distinguish between individual members of the kaolinite group in any of the alteration assemblages. The group was readily identified by X-ray diffraction methods and was observed microscopically, but the clay in all the assemblages occurs finely mixed with other minerals, and the identification of the individual kaolinite members was uncertain. Also, no attempt was made to distinguish between well-crystallized secondary muscovite, sericite after plagioclase, and mixed-layer or poorly crystallized material. Under the microscope the sericitelike minerals were observed to range in birefringence from about 0.030 to 0.010, and a wide range in indices of refraction was noted. The 001 X-ray diffraction peak is broad and poorly defined, and in some specimens the peak is spread as it would be if mixed layering occurred. The material elsewhere called illite and (or) hydromica is almost certainly well represented in the alteration products of the plagioclase. Schwartz (1953, p. 20–22) found abundant sericite and hydromica in all types of alteration zones at San Manuel.

Based on their mutual relations, the assemblages from both the potassium-enriched porphyry and the argillized porphyry could have formed about the same time, or the sericite-kaolinite assemblage could have formed later. Biotite and potassium feldspar relicts are absent in the sericite-kaolinite assemblage except in the contact zone with the biotite-potassium feldspar-sericite assemblage. This absence of relicts suggests that biotite and

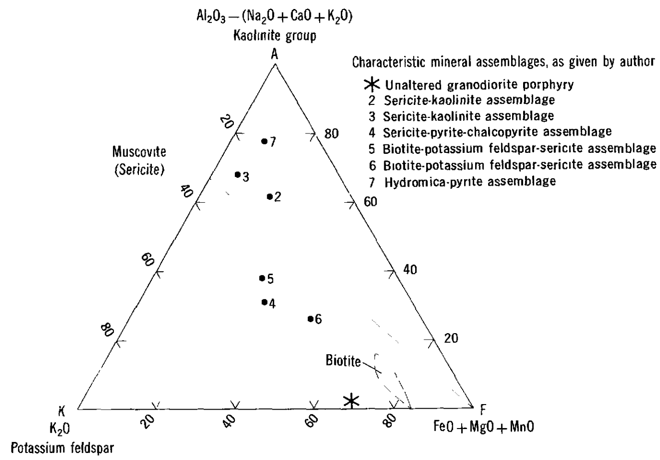


FIGURE 15.—AKF diagram for mineral assemblages resulting from hydrothermal alteration at San Manuel, Ariz. SiO_2 and H_2O in excess. Analyses for the samples plotted are listed in table 9. Sample 1 from table 9 cannot be plotted in this figure because only the total iron was determined. Molecular percentages plotted. Data for all samples except 4 and 7 from this report; data for 4 and 7 from Schwartz (1953).

potassium feldspar were never present, and, therefore, that both assemblages formed essentially contemporaneously. However, veinlets of quartz, sericite, and pyrite bounded by selvages of argillized rock cut the potassium-enriched rock in a few places. Where these veinlets occur, the texture is completely destroyed. These veinlets, however, are neither common nor widespread.

PROPYLITIZED PORPHYRY

All the porphyry except that in the San Manuel deposit and that in surface outcrops immediately adjacent to the deposit, as on Red Hill, is propylitized. Outcrops of propylitized porphyry occur (1) northwestward from the San Manuel deposit, (2) between the Mammoth and San Manuel faults southeast of the San Manuel deposit, (3) in sec. 4, T. 9 S., R. 16 E. and sections adjacent thereto, and (4) in the southwest corner of the mapped area.

Samples from all the granodiorite porphyry masses were studied. Most of the information on the alteration was derived from examination of the phenocrysts, which comprised biotite, hornblende, and plagioclase. The alteration products of the microcrystalline groundmass were commonly too fine grained and intergrown for identification and description.

Relict minerals from the propylitized porphyry occur in both the potassium-enriched and the argillized porphyry. Most common among these relict minerals is chlorite, partly replaced by biotite and sericite. The propylitic alteration, therefore, preceded the alteration that produced the potassium-enriched and argillized porphyry in the deposit and may represent an earlier, weaker phase of the alteration. Such an interpretation is compatible with the alteration sequence seen in the deposit.

The mineral phases found in the propylitized porphyry are chlorite, albite, epidote, calcite, sericite, clay minerals, apatite, zircon, sphene, and iron oxide minerals. All these except the accessory minerals and perhaps some of the iron oxide minerals are secondary after the mafic mineral and plagioclase. The propylitic alteration of the porphyry is somewhat similar to that described by Turner (1948, p. 96) for the muscovite-chlorite subfacies of the greenschist facies in regional metamorphic terranes, or to that in the marginal zone of propylitic alteration around the Castle Dome porphyry copper deposit (Peterson and others, 1951, p. 71–73). In general, hornblende is the most susceptible to alteration; biotite, less; and plagioclase, least.

No unaltered hornblende occurs in the mapped area. In some outcrops where biotite is partly altered, the hornblende is altered to chlorite, epidote, calcite, sericite, and possibly iron oxide.

Biotite alters first to a light-brownish-green mica that is distinguished from the original biotite by a lighter color and by a more fibrous appearance in sections cut perpendicular to 001. The mineral becomes progressively lighter in color until it passes imperceptibly into a white mica; the brown tone disappears first, leaving a bright light-green mica, which in turn grades into the white mica. Formation of chlorite is contemporaneous with the progressive alteration of biotite to sericite. To some extent at least, the iron and magnesium lost during the alteration of the biotite became fixed in the chlorite. When the last vestige of biotite disappears, the common assemblage is chlorite, sericite, perhaps a little calcite, granular rutile, leucoxene, and iron oxide; this assemblage is characteristic of the propylitic alteration.

To determine the relation of the propylitic alteration of the biotite to the alteration responsible for the San Manuel deposit, the degree or extent of alteration of biotite from each porphyry mass is plotted in figure 16. The masses of granodiorite porphyry are too few to indicate for certain that a progressive transformation toward the deposit of biotite through the light-brownish-green mica to chlorite took place, but they do suggest this progressive transformation.

The progressive alteration of the plagioclase yields an albite-rich residuum that contains varying amounts of clay minerals, sericite, calcite, chlorite, and epidote. Calcite is much more abundant than epidote, and clay minerals are commonly associated with the calcite, whether or not sericite is present. Alteration to clay begins along fractures. As alteration progresses, patches of clay form at intersections of fractures and, by selective alteration, in the cores of some plagioclase grains and on rims of others.

In weakly altered specimens, the type of clay mineral formed could not be determined, but indices of refraction indicate that there are at least two types or species. In specimens where the alteration to clay was strong, the kaolinite group was recognized by X-ray diffraction methods and by microscopic study. Such specimens came from the strip of bedrock between the Mammoth and San Manuel faults southeast of the deposit and from the porphyry masses in the inlier of bedrock in sec. 4, T. 9 S., R. 16 E., southwest of the deposit. This clay persists into the ore zone and is only destroyed by the more intense alteration that produced a biotite-potassium feldspar-sericite assemblage.

Albitization of plagioclase occurs through loss of lime and alumina. If the alteration is centered on the San Manuel deposit, the albite content of the plagioclase

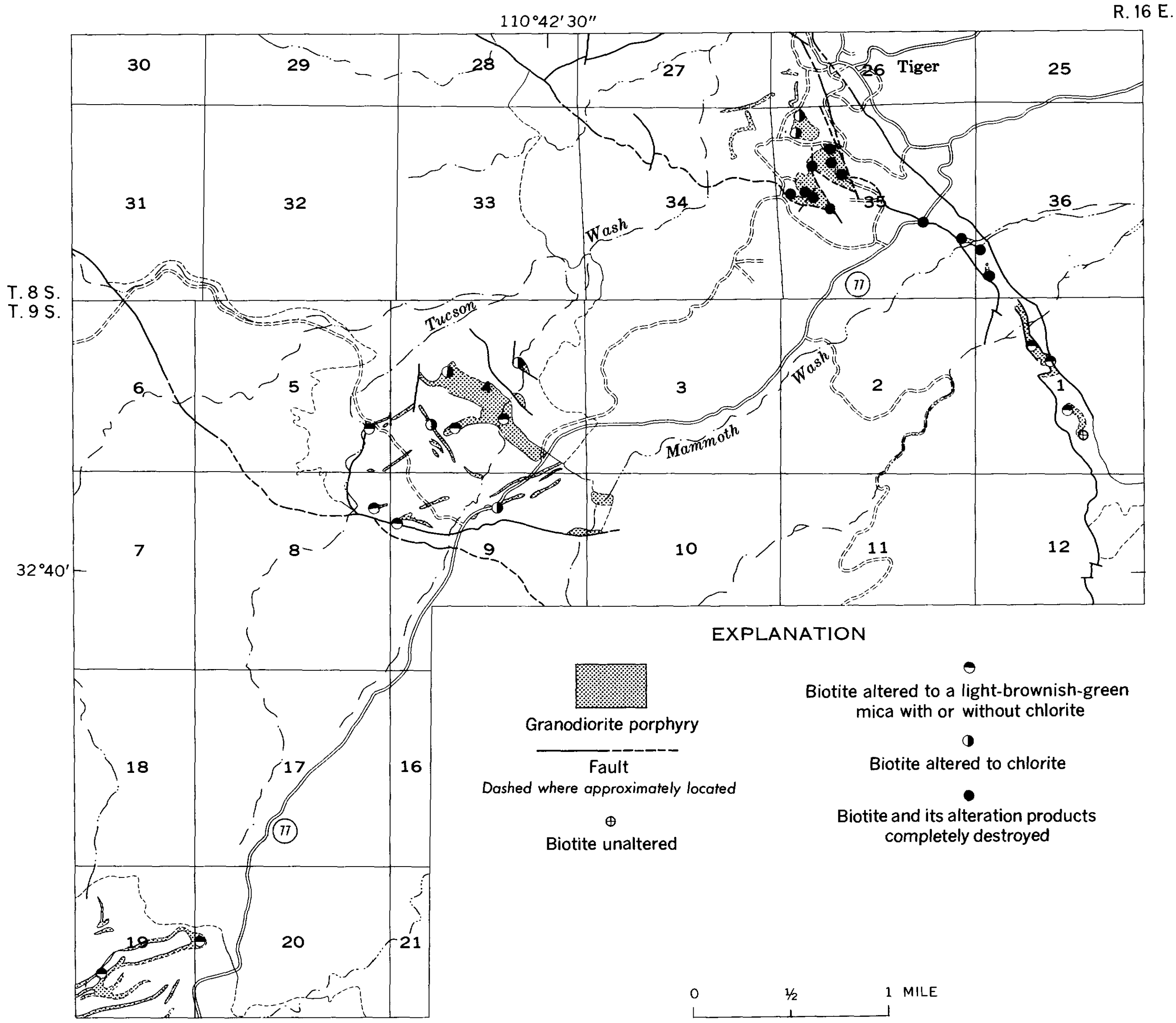


FIGURE 16.—Degree of alteration of the biotite in the surface outcrops of the granodiorite porphyry.

might increase towards it. However, the degree of albitization shows no consistent relation to proximity to the San Manuel deposit (fig. 17). The anorthite content progressively increases southeastward from the deposit, but in the area around sec. 4, the anorthite content is erratic and seems to change from one porphyry mass to another without any apparent relation to distance from the deposit. Size of the porphyry mass correlates with the anorthite content to a large extent; the largest mass has the most anorthitic plagioclase. It is significant to note that the albitization of the plagioclase is more complete in the porphyry in the southwest corner of the area than in many of the masses around sec. 4. Certainly there is no clear-cut simple spatial relation between the San Manuel deposit and the albitization of the plagioclase.

POTASSIUM-ENRICHED PORPHYRY (BIOTITE-POTASSIUM FELDSPAR-SERICITE ASSEMBLAGE)

The distribution of the potassium-enriched porphyry is the same as that of the copper metallization. Most of the potassium-enriched rock is overlain by Gila Conglomerate; only about an acre of the potassium-enriched rock is exposed on the surface, and this acre lies between the San Manuel fault and one of the strands of the Mammoth fault southeast of No. 4 shaft (pl. 1). The distribution on the 1475 haulage level of the potassium-enriched rock and of the argillized rock with which the potassium-enriched rock is in contact is shown in figure 20. The boundary between the two coincides essentially with the southern limit of ore; the argillized rock forms the outer pyritic zone.

The mineral phases found in the potassium-enriched

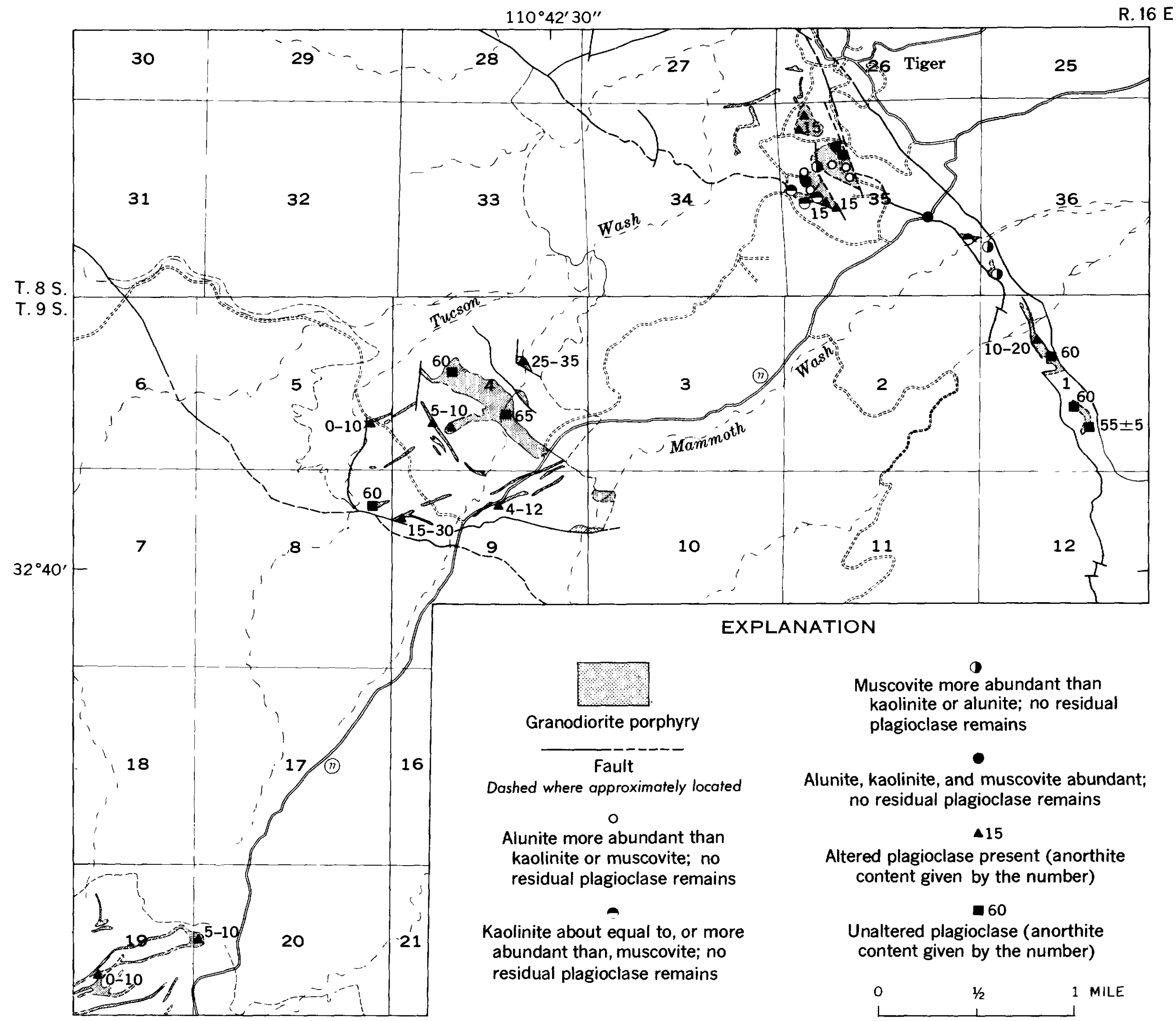


FIGURE 17. Anorthite content of the altered plagioclase in the surface outcrops of the granodiorite porphyry, and major alteration products where no residual plagioclase remains.

porphyry are albitic plagioclase, potassium feldspar, quartz, biotite, sericite, kaolinite, chlorite, calcite, rutile, leucoxene, apatite, zircon, magnetite, pyrite, and chalcopyrite. Of these, chlorite, calcite, kaolinite, and perhaps leucoxene are unstable and are chiefly relicts from the propylitic alteration. Apatite and zircon are residual from the original rock, although apatite has recrystallized. New minerals which are stable (or metastable) phases are albitic plagioclase, biotite, potassium feldspar, sericite, granular rutile, magnetite, pyrite, and chalcopyrite. Quartz is a stable mineral and forms during the alteration, but it is not a new mineral.

The potassium-enriched porphyry has a relict porphyritic texture similar in general appearance to that of the unaltered rock. The phenocrystic plagioclase, which is the most conspicuous mineral in the fresh rock, maintains its approximate outline in the potassium-enriched porphyry despite general intense alteration (fig. 18). Enough book biotite also occurs to give the same general textured effect as is seen in the unaltered porphyry. The general appearance of this biotite does not reveal that it is regenerated from chlorite, which was itself a propylitic alteration of the original biotite. The groundmass has recrystallized (fig. 19), but it remains aphanitic, and to the unaided eye it is similar to that in the unaltered rock. The casual observer therefore might fail to recognize that the porphyry was profoundly altered and has largely recrystallized. Anderson and others (1955, p. 52) pointed out this spurious similarity of fresh quartz monzonite

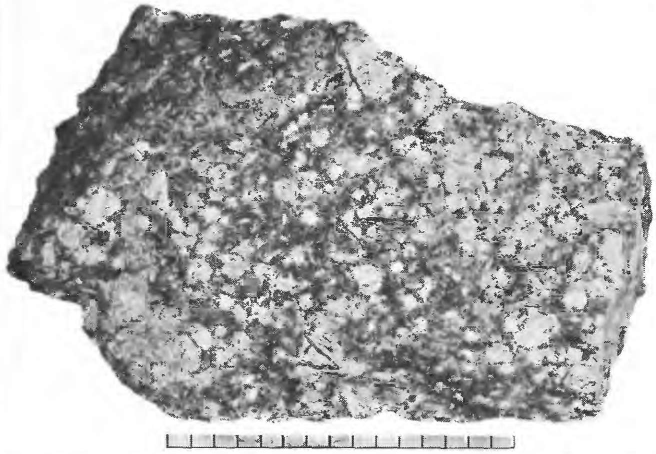


FIGURE 18.—Typical specimen of copper ore. The relict plagioclase phenocrysts are a dull greenish gray and consist of a mixture of argillic alteration products and albite. The matrix has recrystallized; it consists of about equal amounts of quartz and alkali feldspar, chiefly potassium feldspar. The veinlets consist of quartz, pyrite, and chalcopyrite. Sulfides are also disseminated through the rock; they show in the photograph as tiny white specks, owing to the reflection of light. Scale in tenths of an inch.

to altered quartz monzonite (biotite-albite-orthoclase assemblage) in the Bagdad porphyry copper deposit.

In most of the potassium-enriched porphyry, the original plagioclase is altered to albite, sericite, calcite, kaolinite, or minor chlorite. The appearance of the altered plagioclase shown by figure 18 and the distribution of the types of altered plagioclase on the 1475 haulage level is shown in figure 20. The composition of the residual plagioclase is about An_{5-15}, and the more intense the alteration, the more albitic the residual feldspar. Common associations among these alteration products are kaolinite-calcite, kaolinite-sericite, and kaolinite-calcite-chlorite. The alteration of plagioclase to kaolinite and calcite but not to sericite is so common that it cannot be by chance; actually, about half the thin sections of the potassium-enriched porphyry show a kaolinitic alteration of the plagioclase, and of these, most had associated calcite. In the most intensely altered rocks, potassium feldspar partly replaces the altered plagioclase and its included kaolinite. In these places calcite is no longer present, and this suggests that it is less stable than the kaolinite. Apparently neither is a stable phase in the potassium-enriched porphyry. Albite is partly replaced by potassium feldspar locally but is rarely, if ever, completely eliminated; locally, at least, it is a metastable phase.

In a few places along the footwall of the deposit, the plagioclase is relatively unaltered (An_{30-35}) despite much secondary biotite and potassium feldspar (fig. 20). Such occurrences tend to confirm the suggestion above, that the albitization of the plagioclase and the concomitant replacement of plagioclase by kaolinite, sericite, calcite, and minor chlorite is not a part of the

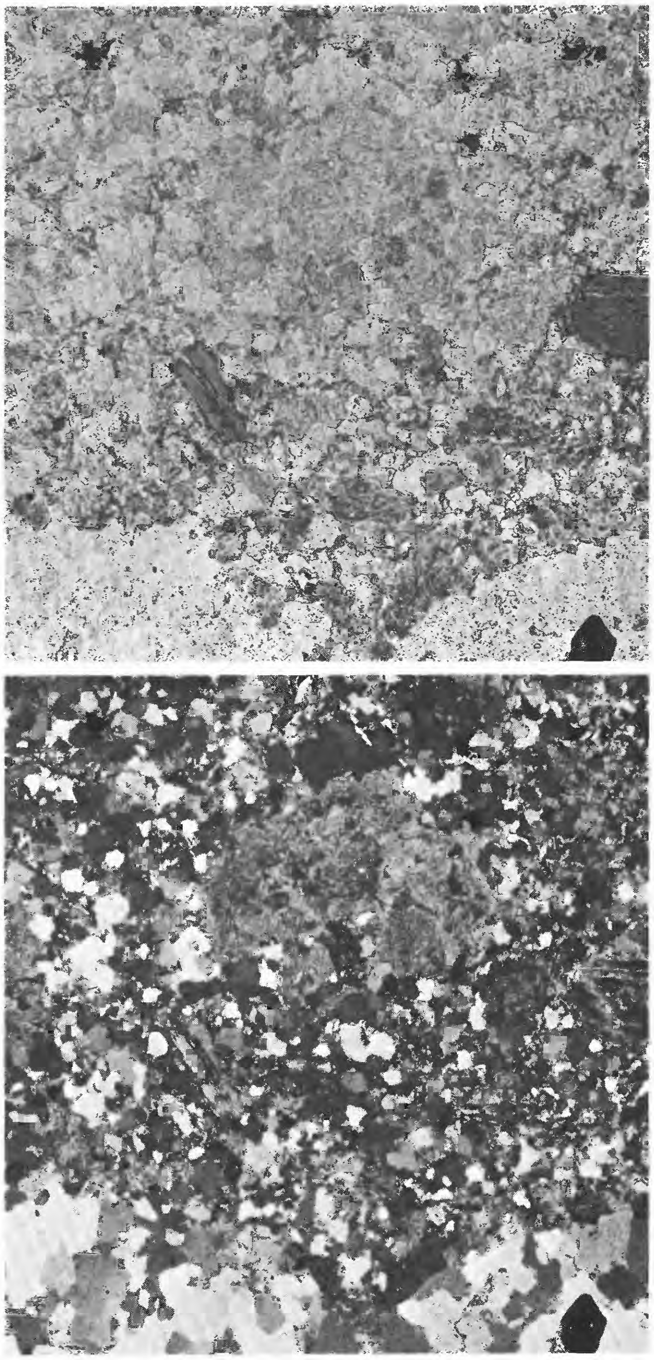


FIGURE 19.—Photomicrographs of typical specimen of potassium-enriched porphyry (biotite-potassium feldspar-sericite assemblage). Quartz occurs in veinlet along bottom of photograph and in anhedral crystals throughout groundmass. Leafy secondary biotite occurs in two large ragged flakes and in numerous smaller flakes interstitial to the groundmass quartz and feldspar. A relict plagioclase phenocryst (now albite) in central part of photograph is faintly discernible in plane-polarized light and is easily seen under crossed nicols. The feldspar, chiefly potassium feldspar, is intergrown with quartz to form the groundmass, a combined product of the recrystallized original groundmass of the granodiorite porphyry plus some new material, chiefly potassium feldspar. The potassium feldspar (upper) is slightly darker than the quartz and has a negative relief against it. Albite and potassium feldspar cannot be distinguished separately. Opaque mineral is pyrite. Upper photograph, Plane-polarized light, × 23. Lower photograph, Crossed nicols, × 23.

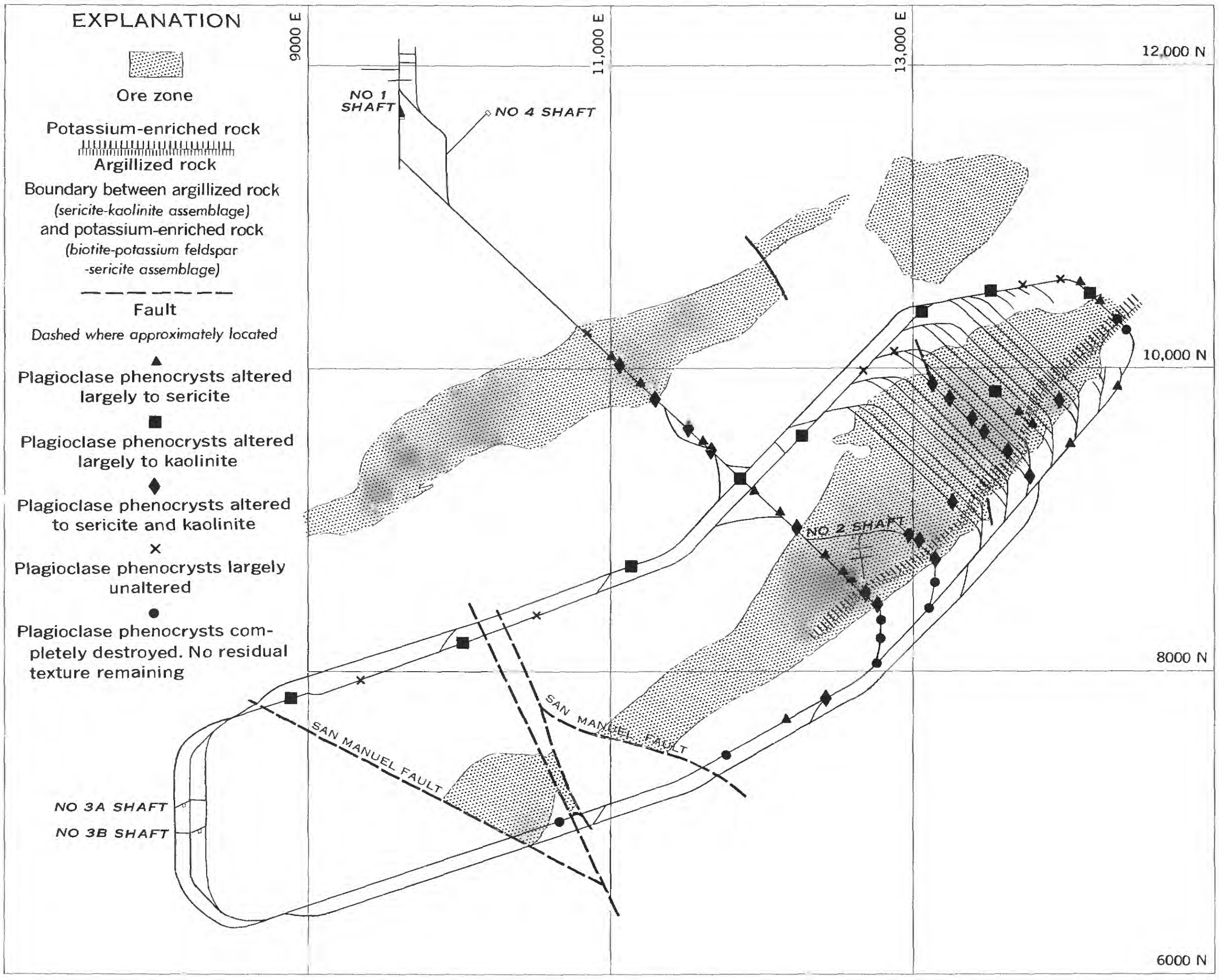


FIGURE 20.—Distribution of types of altered plagioclase phenocrysts in the granodiorite porphyry on the 1475 haulage level, San Manuel mine, Arizona.

alteration of the granodiorite porphyry to the biotite-potassium feldspar-sericite rock.

A few phenocrysts of the albitized plagioclase have overgrowths of alkali feldspar, most of which is albite but some of which appears to be potassium feldspar. The overgrowth rims are readily apparent in hand specimen because the new feldspar is bright and clear and has good cleavage, whereas the core is dull and clouded by alteration. Clear albite also occurs in the groundmass; it undoubtedly has recrystallized.

Biotite is a characteristic constituent of the potassium-enriched rock. It occurs in every specimen examined but one (fig. 21). The habit of the secondary biotite ranges from small disseminated leaves to well-formed books pseudomorphic after chlorite that had replaced the primary biotite. Leaf biotite also occurs in randomly oriented aggregates that mark the former site of chlorite but do not retain the exact crystal shape of the chlorite or its orientation (fig. 22). Anderson and others (1955, p. 52) noted at Bagdad, Ariz., that secondary biotite is only in leaves, whereas the primary biotite occurs in books.

Chlorite altering to biotite was noted in several thin sections. In some crystals the biotite replaced the chlorite along cleavage (fig. 23); in others, a biotite rim formed around a core of residual chlorite. Occasionally, chlorite, partly altered to biotite, can be recognized as an alteration product of primary biotite because it has included rutile granules that separated from the primary biotite. A few large euhedral plates of biotite had cores of granular quartz and potassium feldspar; apparently such crystals grew in place.

The study of the occurrence and distribution of the potassium feldspar was greatly aided by the use of

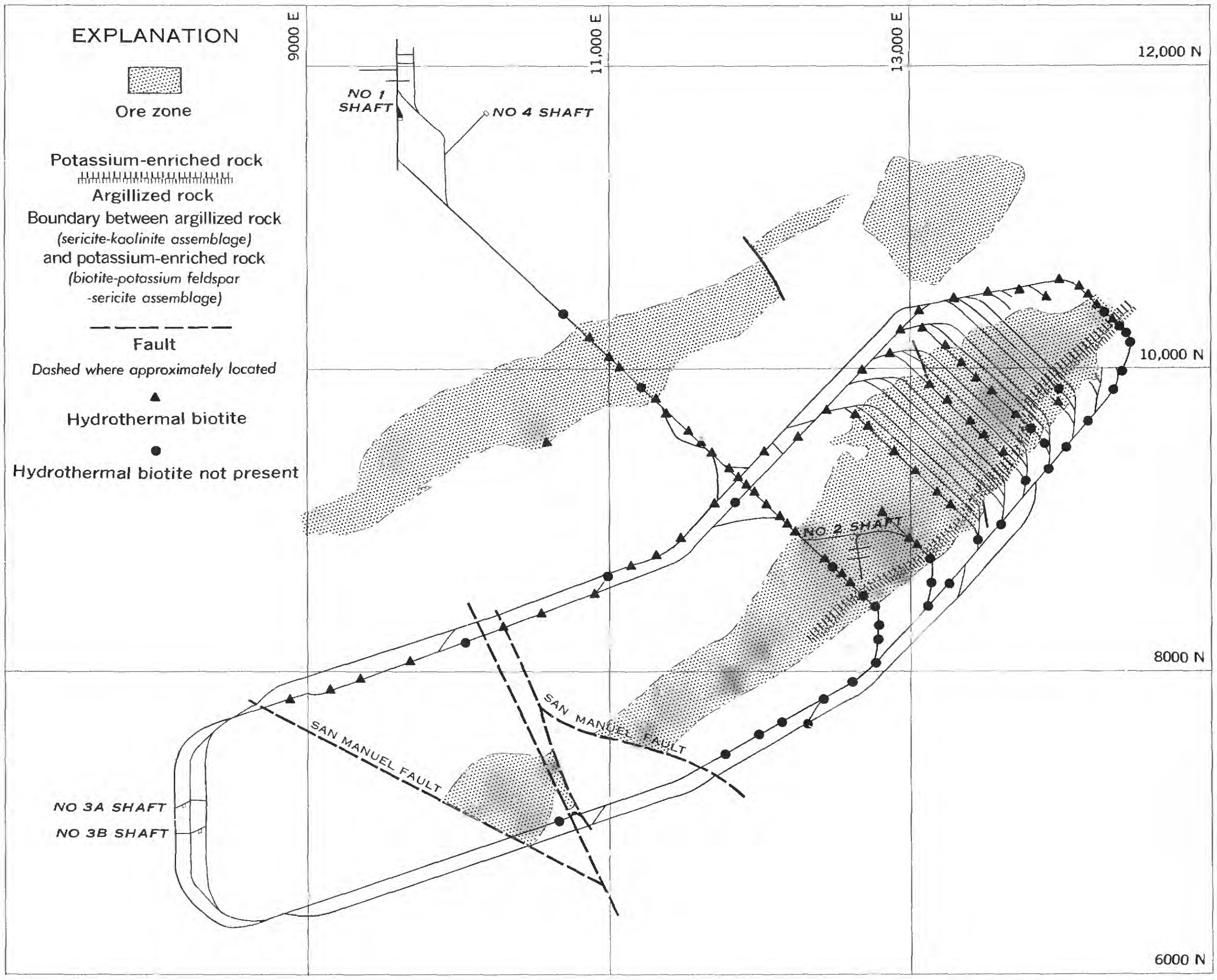
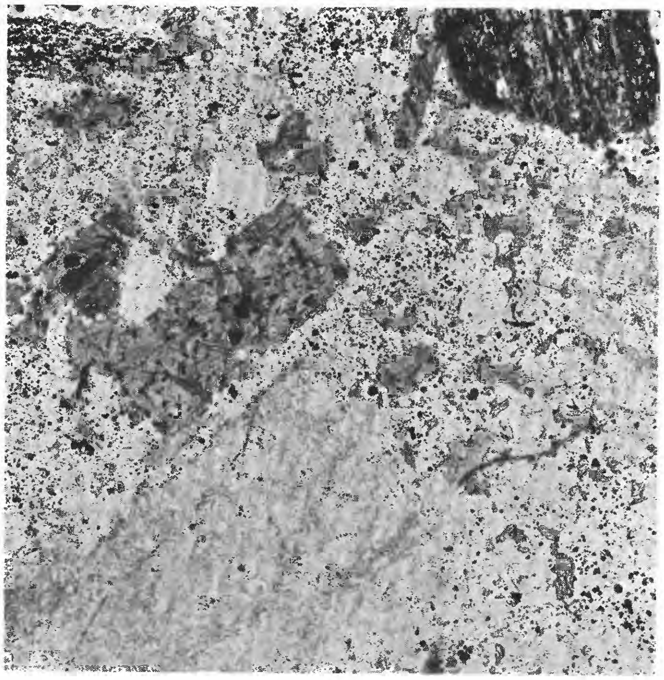


FIGURE 21.—Distribution of hydrothermal biotite in the granodiorite porphyry on the 1475 haulage level, San Manuel mine, Arizona.

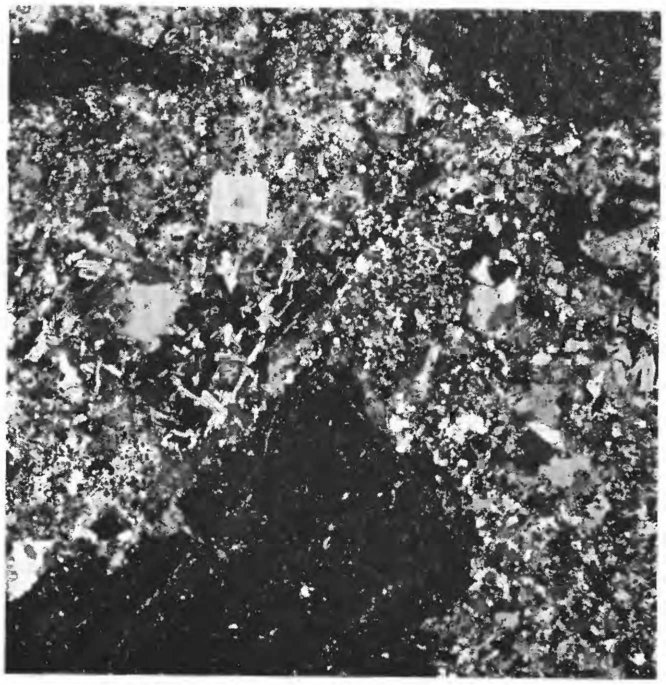
sodium cobaltinitrite. Small rock chips were sawed and polished, dipped or fumed in hydrofluoric acid for 15 to 30 seconds, and stained in a saturated solution of sodium cobaltinitrite in distilled water. Potassium feldspar takes on a canary-yellow stain from this procedure. This technique is most helpful in distinguishing between groundmass albite and potassium feldspar.

Introduced potassium feldspar, which occurs throughout the potassium-enriched rock (fig. 24), ranges in individual hand specimens from less than 5 percent to as much as 30 to 50 percent of the rock. The secondary potassium feldspar has several distinctive occurrences: (1) in veinlets, associated with pyrite or quartz, or both (fig. 25), (2) concentrated in small anhedral crystals adjacent to quartz veinlets, (3) disseminated in the groundmass of the porphyry interstitial to the quartz, (4) as a replacement of biotite and argillized plagioclase, or (5) as clear overgrowths on albitized plagioclase.

The potassium feldspar in the veinlets occurs as small anhedral crystals. It is similar to that in the groundmass and is indistinguishable, except for location, from the potassium feldspar found just outside the physical limits of the veinlet yet spatially related to the veinlet. Veinlets containing potassium feldspar cut phenocrysts of quartz and altered plagioclase and the groundmass of the porphyry (fig. 25). About a gram of pure quartz and potassium feldspar was hand picked from a small quartz-potassium feldspar veinlet. The powder X-ray diffraction pattern of this material revealed that the potassium feldspar is monoclinic, or very nearly so. The position of the 201 reflection at about 21°20′ (Cu K_α filtered Ni radiation) indicates that virtually no sodium is held in solid solution in the potassium feldspar (Bowen and Tuttle, 1950, p. 493).



A



B

FIGURE 22.—Photomicrographs of an aggregate of biotite flakes pseudomorphic after the original igneous biotite. Probably the original biotite was first altered to chlorite during the earlier period of propylitic alteration and then altered back to a leafy secondary biotite. The dark phenocryst in the upper right is a partly biotitized chlorite crystal. In the lower central part of the photograph is a partly altered plagioclase phenocryst, the margin of which seems to be corroded. The corrosion probably occurred during the recrystallization of the groundmass, which now consists of an aggregate of granular quartz and alkali feldspar (chiefly potassium feldspar) and leafy biotite. *A*, Plane-polarized light, × 23; *B*, Crossed nicols, × 23.

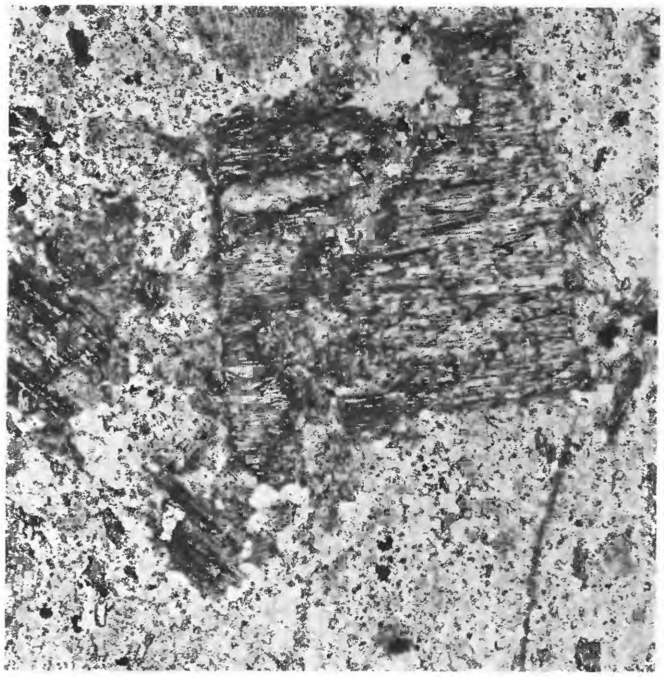


FIGURE 23.—Photomicrograph showing partly biotitized chlorite in the potassium-enriched porphyry (biotite-potassium feldspar-sericite assemblage). The bulk of the phenocryst is still chlorite. The biotitized parts are the irregular dark areas with the hairlike margins. The light-colored augen are calcite. The groundmass has recrystallized (compare with fig. 7); it is a granular aggregate of quartz and alkali feldspar. Plane-polarized light, × 36.

Commonly, the potassium feldspar replaces the plagioclase along cleavages; to a small extent, it appears to replace book biotite and altered plagioclase phenocrysts in irregularly shaped patches. In addition, the book biotite commonly includes small granules of potassium feldspar of uncertain origin; these granules may be a byproduct of the original alteration of biotite to chlorite. Chayes (1955) pointed out that this transformation could yield potassium feldspar.

In ordinary light the potassium feldspar in the groundmass appears to be in tiny veinlets that anastomose around the granular quartz and other minerals. Under crossed nicols, however, the potassium feldspar appears to be in many small anhedral crystals interstitial to the quartz, and the veinlike aspect is not evident. The grain size of the feldspar is two to three times smaller by estimate than that of the quartz, and groundmass areas devoid of potassium feldspar are noticeably coarse grained.

In the unaltered granodiorite porphyry, the quartz occurs chiefly in the microcrystalline groundmass and, rarely, as phenocrysts. In the potassium-enriched rock, quartz is abundant, comprising over half of the microcrystalline groundmass aggregate. Phenocrystic quartz persists through the alteration without change. Much of the silica released from the destruction of silicates and from recrystallization of the groundmass, and

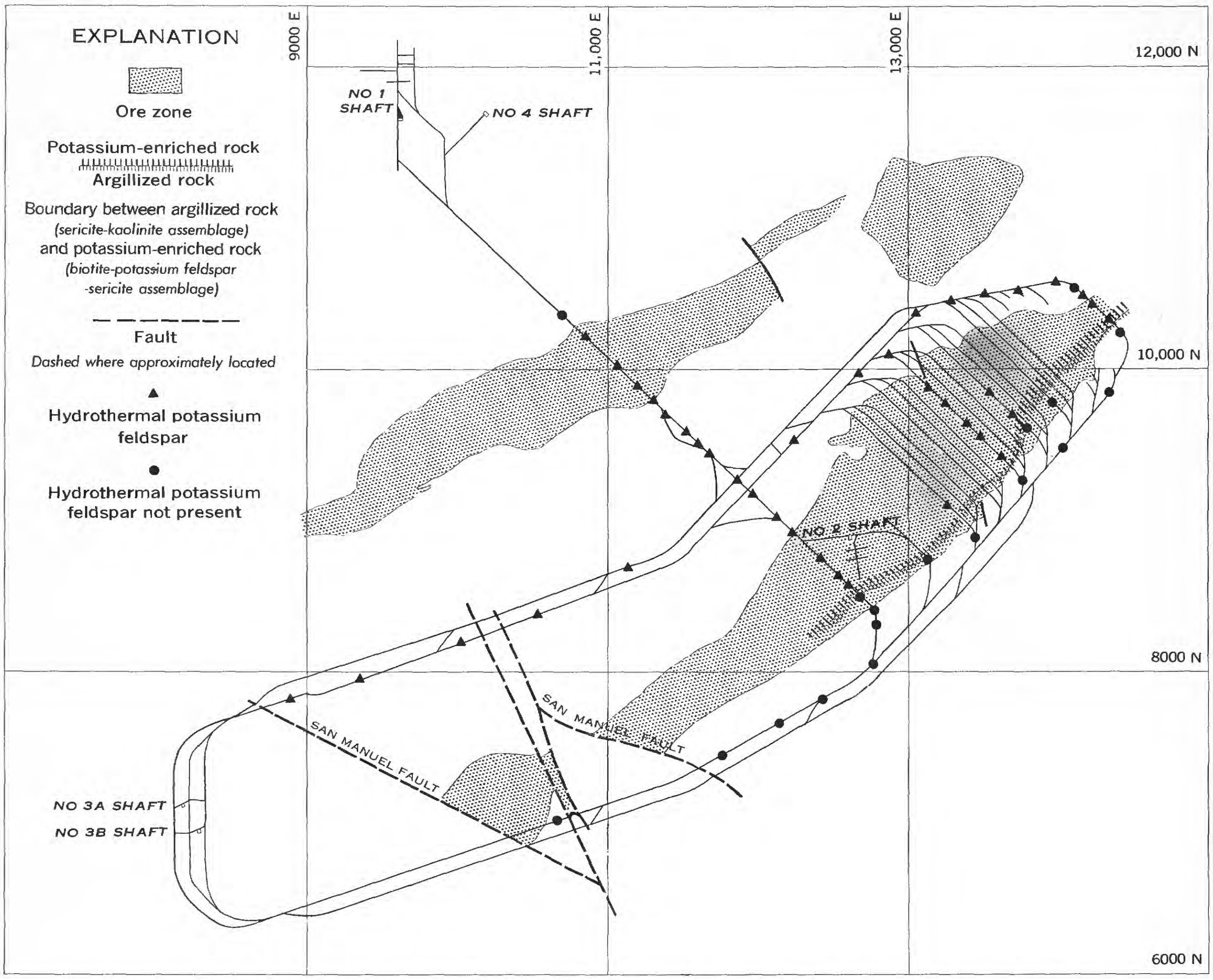


FIGURE 24.—Distribution of the hydrothermal potassium feldspar in the granodiorite porphyry on the 1475 haulage level, San Manual mine, Arizona.

perhaps silica from external sources, combined to form the granular quartz-rich aggregate that proxies for the original groundmass. Whether the quartz in the quartz veinlets was locally derived or whether it was introduced is not known. Some introduction of silica is shown by the increase of SiO_2 in the altered porphyry (fig. 33), and some introduction of quartz is shown by the increase of normative quartz from 20 percent for the unaltered porphyry to as much as 38 percent for the potassium-enriched rock.

Rutile occurs in granular aggregates in both the potassium-enriched and the argillized rock. Some rutile is associated with biotite and probably represents titanium oxide released upon the propylitic alteration of the original biotite. In a few places, granular rutile forms diamond-shaped pseudomorphs after sphene; elsewhere its occurrence is not suggestive of its source.

ARGILLIZED PORPHYRY (SERICITE-KAOLINITE ASSEMBLAGE)

Near the San Manuel deposit the intensity of the alteration increased, and the minerals of the propylitized rock became unstable and recrystallized into those characteristic of argillized rock. During this change, appreciable potassium, sulfur, and water were added to the rock; calcium, sodium, aluminum, iron, and magnesium were leached; and the bulk specific gravity decreased. All gradations exist between propylitized rocks in which the original texture is still discernible and those in which all traces of original minerals, textures, and structures are destroyed.

The argillized porphyry crops out on the surface between the San Manuel fault and the various branches of the Mammoth fault. According to Schwartz (1953, pl. 8), argillized porphyry (hydromica-pyrite and kaolinite-alunite alterations of Schwartz) extends from

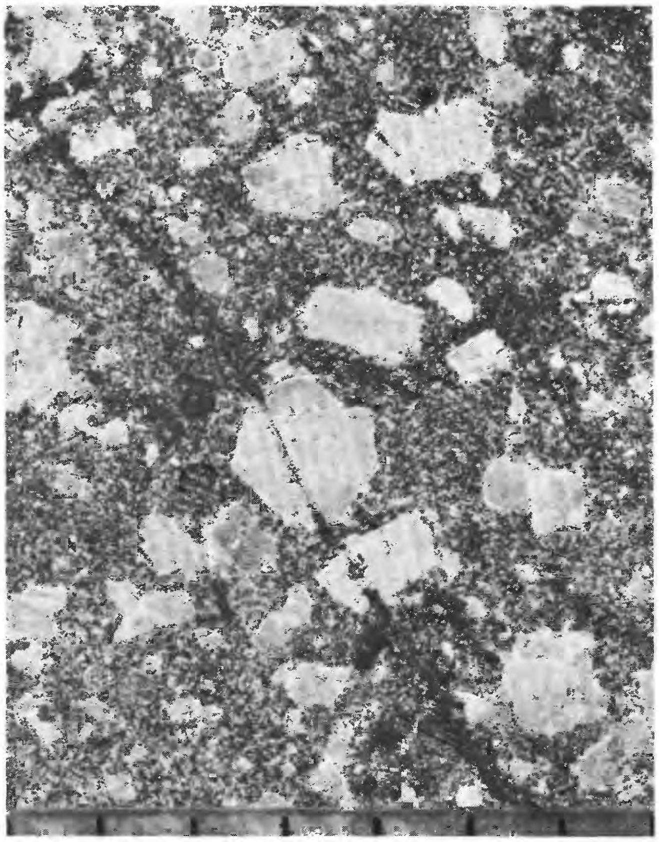


FIGURE 25.—Veinlets of potassium feldspar (dark) cutting potassium-enriched granodiorite porphyry. Potassium feldspar is stained with sodium cobaltinitrite and appears dark in the photograph. The potassium feldspar occurs disseminated in the groundmass as well as in the veinlets. Scale in tenths of an inch.

FIGURE 26.—Granodiorite porphyry from the argillized rock (sericite-kaolinite assemblage) in the San Manuel deposit. The porphyry consists essentially of quartz, muscovite (sericite), pyrite, and kaolinite. The original texture is completely destroyed. Scale in tenths of an inch.

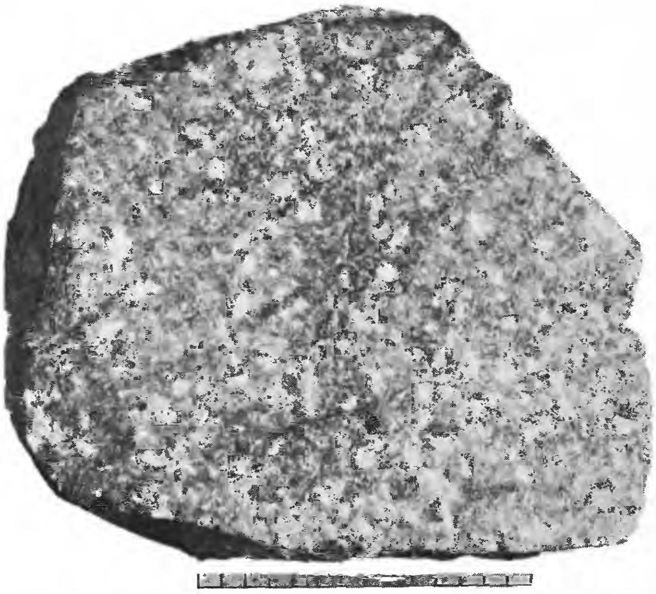


FIGURE 27.—Granodiorite porphyry similar to that shown in figure 26, but having a vague porphyritic texture. The relict phenocrysts are composed of mixtures of kaolinite and sericite. The original outlines of the phenocrysts were not preserved when the albite was replaced. Scale in tenths of an inch.

No. 1 shaft on the west to about 800 feet north of No. 1 shaft on the north, to the Mammoth fault on the east, and to the San Manuel fault on the south. The altered zone continues to the east and south beneath the cover of Gila Conglomerate. Most of the surface indications of the San Manuel deposit, including Red Hill, are within the argillized rock north of the ore zone (potassium-enriched rock).

In the San Manuel deposit, argillized rock forms the outer pyritic zone; it lies both north and south of the ore (potassium-enriched rock), and the presumption is strong that, in part at least, the argillized rock underlies the ore. Schwartz (1953, p. 25 and pl. 8) pointed out that argillized rock (hydromica-pyrite of Schwartz) occurs east, north, and south (both walls) of the San Manuel deposit, and that exploration did not locate either the eastern or the southern limits.

The major mineral phases in the argillized porphyry, listed in order of abundance, are quartz, sericite, pyrite, and kaolinite. In addition, there are minor amounts of granular rutile, leucoxene, apatite, and zircon. Both the rutile and the apatite have recrystallized. The transition from the potassium-enriched porphyry to the argillized porphyry takes place within a few feet. Within this narrow zone, however, biotite appears to be altering to sericite and, to a minor extent, to kaolinite, pyrite, and leucoxene. The residual plagioclase appears to be further altered to sericite and, to a lesser extent, to kaolinite. These relations could be interpreted as indicating that the argillized rock formed at the expense of the potassium-enriched rock. But as was pointed out elsewhere, the indications are neither widespread nor abundant, and we are not certain that extrapolation of local time relations over wide zones is warranted.

The alteration to argillic rock produced the most profound change in the appearance of the granodiorite porphyry. Locally a faint relict texture is suggested by clots of argillic minerals that mark the former sites of plagioclase and rarely by a sericite pseudomorph after biotite. Commonly, however, there is no recognizable vestige of the original rock. Thus, the original porphyritic texture was destroyed (figs. 26, 27).

Quartz is the most abundant mineral. It occurs chiefly as interlocking granular aggregates, but some also occurs in veinlets where it is either alone or is associated with pyrite and, rarely, with sericite. Much of the quartz is new, the silica having been released by the alteration of the original silicates and then formed into argillic products whose silica content is lower than that of the original silicates. The new quartz thus formed raised the normative quartz content from 20 percent for the unaltered porphyry to 30 to 35 percent for the argillized porphyry.

Sericite is next to quartz in abundance. It occurs in disseminated flakes associated with granular quartz, in clots or patches that mark the former sites of plagioclase phenocrysts, and in quartz and pyrite veinlets. Sericite-kaolinite combination is also a stable alteration of the plagioclase. A few sericite pseudomorphs after biotite were noted, and some of these contained systematically arranged rutile needles.

Kaolinite is not as abundant as sericite but is present in all the samples of argillized porphyry (fig. 28). It occurs in patches as an alteration product of plagioclase and is disseminated in the altered porphyry. It occurs both alone and associated with sericite. In one section, kaolinite was rimmed by sericite flakes and cut by sericite veinlets.

Pyrite, accompanied by only very minor amounts of chalcopyrite, is disseminated throughout the argillized porphyry. It also occurs in veinlets, both alone and associated with quartz and, rarely, with sericite. Pyrite forms from 10 to 20 percent by weight of the argillized rock. However, it appears to be less abundant than quartz, sericite, or kaolinite.

Accessory minerals are granular rutile, apatite, and zircon. Some of the granular rutile is pseudomorphous after sphene. Both the apatite and the zircon were inherited from the unaltered porphyry. The zircon appears to be unaffected by the argillic alteration, but the apatite has recrystallized.

The argillized porphyry at and near the surface is sprinkled with iron-stained cavities and is cut by iron oxide veinlets, both of which mark the former sites of pyrite. To what extent the mineralogy of the surface rocks is due to the acid solutions derived from the oxidation of the pyrite cannot be determined accurately. Schwartz (1953, p. 23) recognized that some of the kaolinite and alunite might be supergene, but he believed that the well-developed alunite crystals were hydrothermal. The writers found alunite veinlets cutting a mat of sericite and kaolinite in one specimen, but we found no other indication of age relations. Neither Schwartz nor we recognized alunite from subsurface samples. The zone underlying the surface area of high alunite described by Schwartz, however, has not been opened for inspection. Figure 29 shows the relative abundance of alunite in samples collected from the surface near the San Manuel deposit. The samples confirm the area of abundant alunite reported by Schwartz but also show alunite locally outside the area. Schwartz listed alunite as one of the sparse constituents formed in the hydromica-pyrite alteration. Except for the presence of alunite in the surface rocks, the surface and subsurface rocks are alike; and if one will accept the generation of alunite by acid solutions derived from the oxidation of pyrite, the surface and subsurface rocks were originally the same.

Kaolinite is abundant locally in surface samples near the deposit, (fig. 30). It is also an alteration product from plagioclase in the propylitized rock away from the deposit, and it persists into the ore zone on the 1475 haulage level of the San Manuel deposit well below the oxidation level. Clearly this subsurface kaolinite is hydrothermal. The kaolinite in the surface rocks that formerly contained sulfides is an alteration product of plagioclase, but we know of no criteria whereby supergene kaolinite can be separated from hypogene. The environment was one of oxidation and was favorable for the formation of supergene kaolinite, and one might expect to find it.

Sericite is the ubiquitous alteration product. Away from the deposit it occurs in the propylitized rock; near the deposit it occurs in the altered rocks in and below the zone of oxidation. Although sericite is more abundant in the altered rocks in and near the deposit, it differs in amount from place to place (fig. 31). Apparently it is a stable phase in all the altered rocks

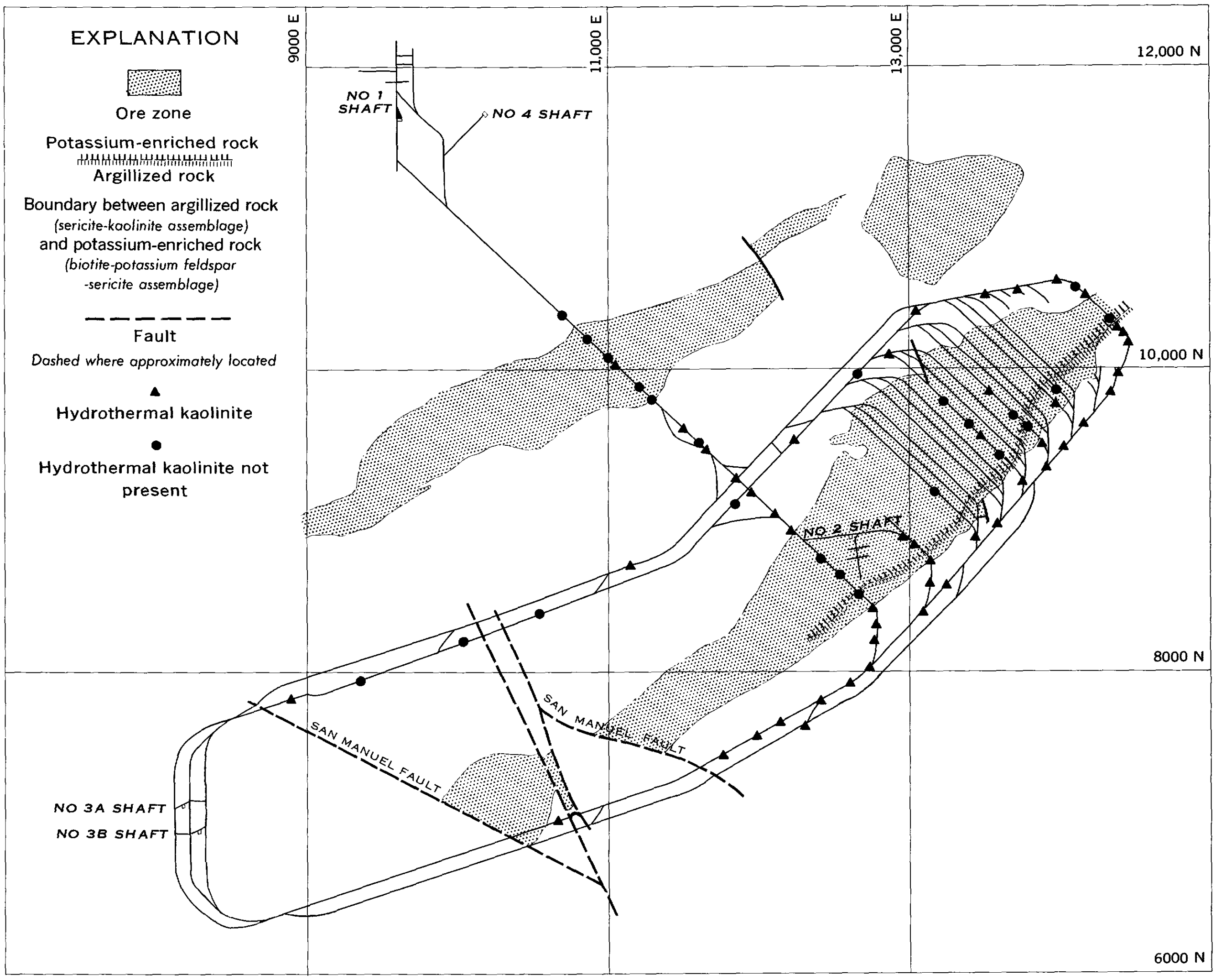


FIGURE 28.—Distribution of hydrothermal kaolinite in the granodiorite porphyry on the 1475 haulage level, San Manuel mine, Arizona.

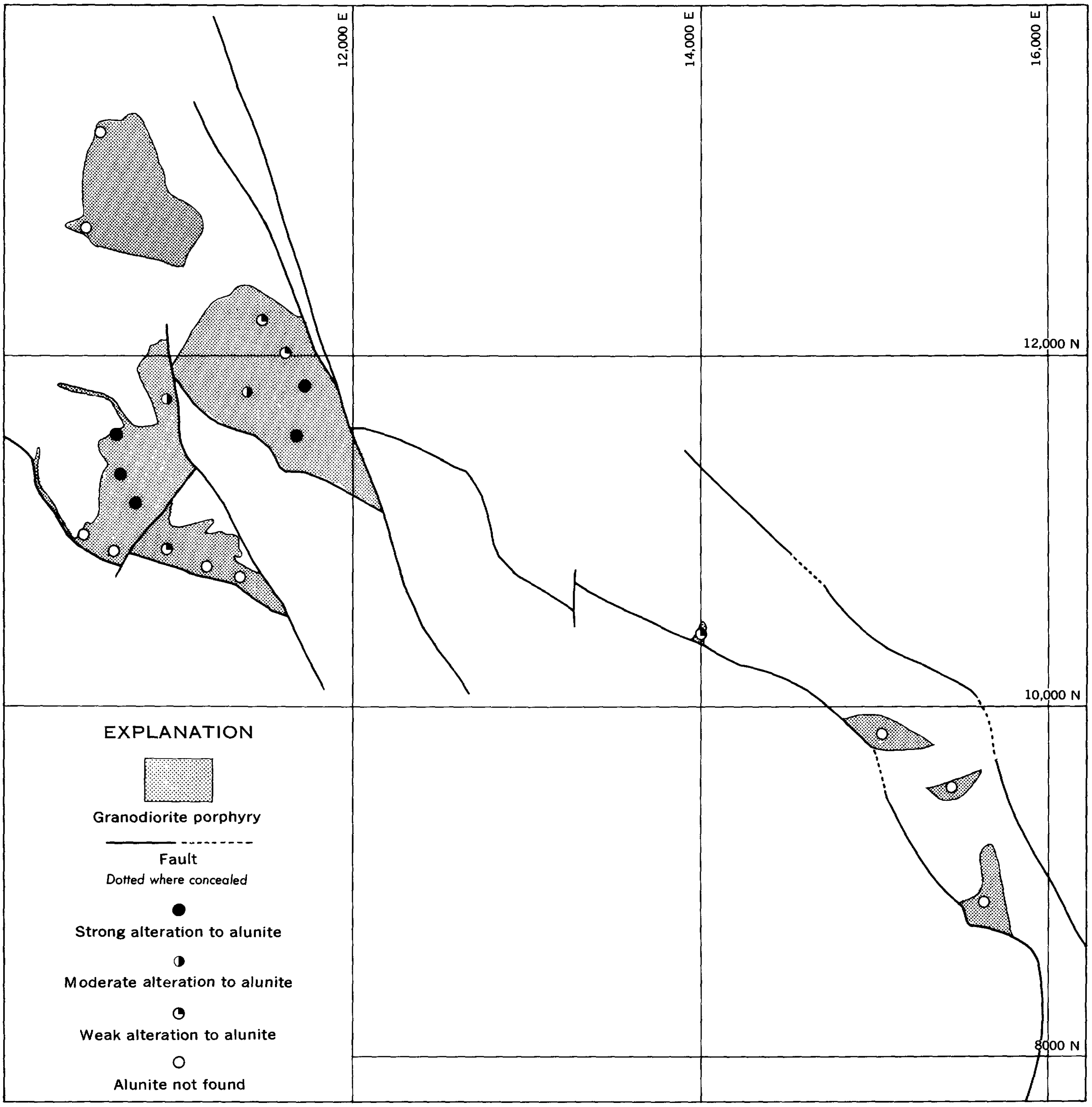


FIGURE 29.—Distribution and intensity of alteration of rock to alunite in surface samples of granodiorite porphyry near the San Manuel mine, Arizona.

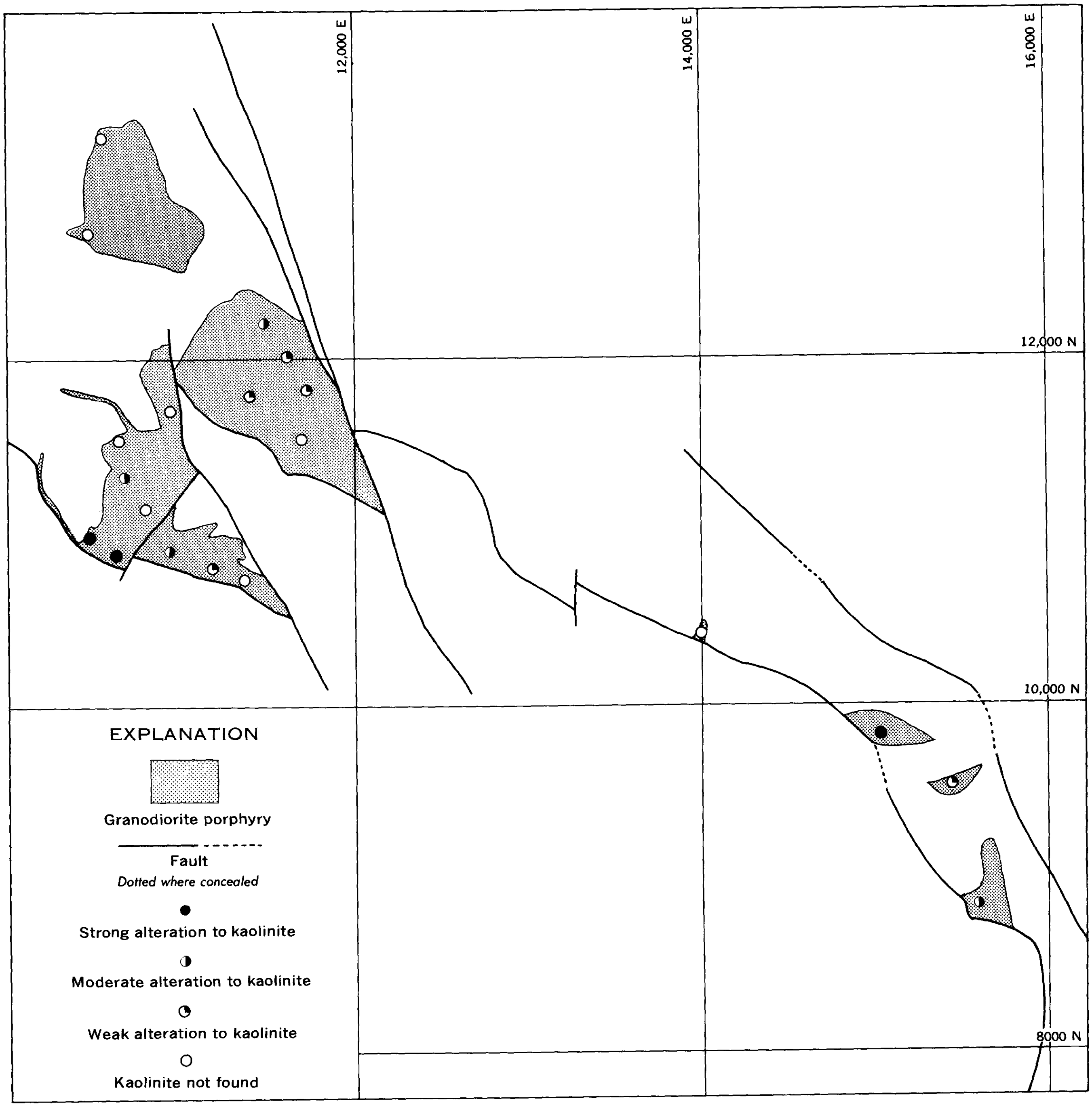


FIGURE 30.—Distribution and intensity of alteration of rock to kaolinite in surface samples of granodiorite porphyry near the San Manuel mine, Arizona.

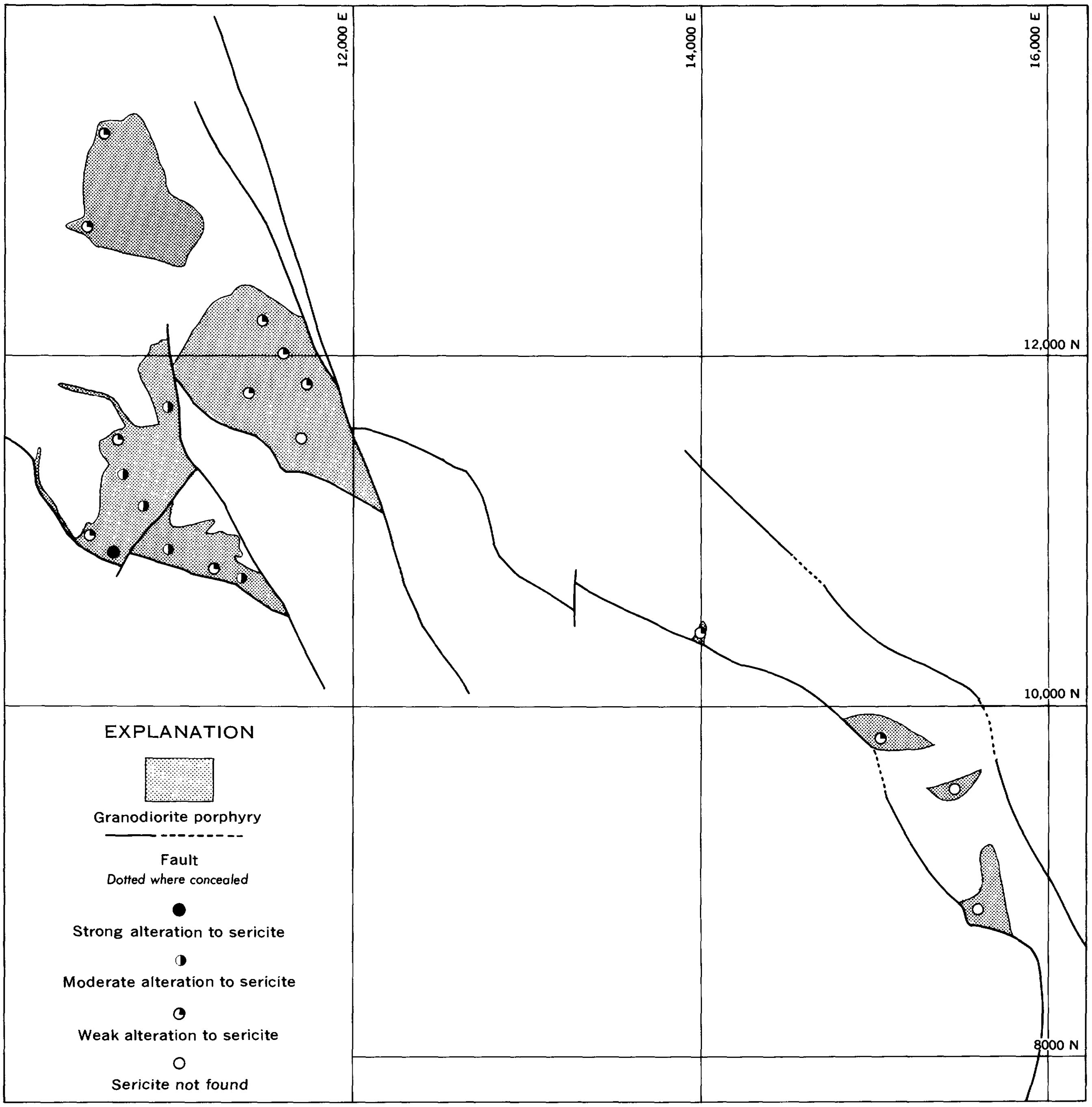


FIGURE 31.—Distribution and intensity of alteration of rock to sericite in surface samples of granodiorite porphyry near the San Manuel mine, Arizona.

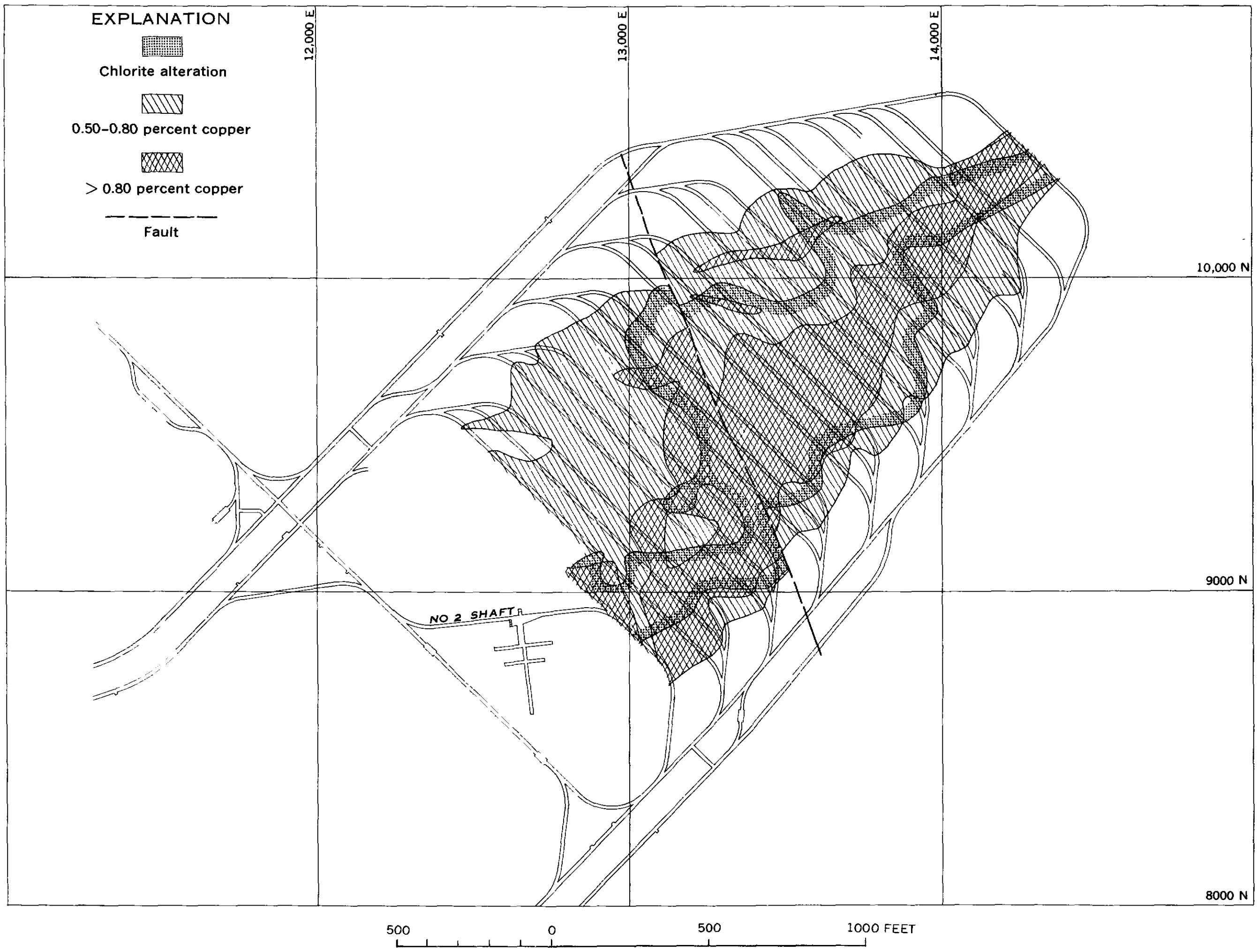


FIGURE 32.—Distribution of secondary chlorite in fractures on the 1475 haulage level of the San Manuel mine.

associated with the deposit, and variations in amount may be merely a measure of the completeness of the alteration.

LATE CHLORITIC ALTERATION

A weak chloritic alteration was superimposed on the more intense argillic and potassic alterations in the San Manuel deposit. The extent of this alteration on the 1475 haulage level of the San Manuel deposit is shown in figure 32.

The source of this chloritic alteration is speculative, but the chlorite most likely formed during the same period of mineralization as did the St. Anthony deposit. Chlorite is one of the chief alteration products of this period, which is younger than the period of mineralization responsible for the San Manuel deposit. (See p. 32.)

CHEMICAL CHANGES DURING HYDROTHERMAL ALTERATION

The gains and losses of individual elements that occurred during the hydrothermal alteration of the granodiorite porphyry are shown graphically by figure 33, and the chemical analyses from which the gain and loss chart was constructed are tabulated in table 9. Figure 33 indicates that the alteration at San Manuel resulted in a gain in silicon, potassium, hydroxyl ion, and sulfur, and in a loss in aluminum, magnesium, calcium, and sodium. No significant gain or loss in total iron is apparent, but the increase in ferrous iron is about commensurate with the decrease in ferric iron. Presumably the difference is due to reduction of some of the ferric iron rather than to simultaneous leaching of ferric iron and introduction of ferrous iron.

Anderson (1950) compared the chemical gains and losses of the Bagdad (Arizona) porphyry copper depos-

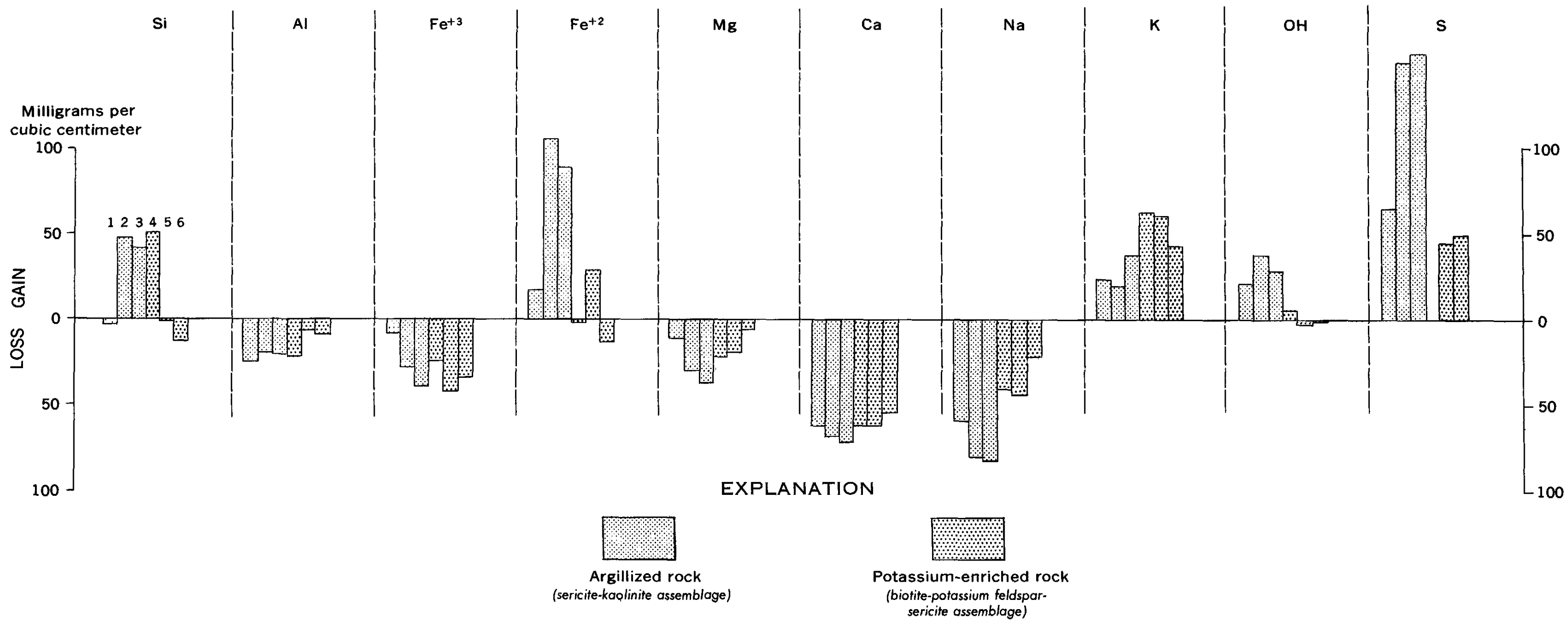


FIGURE 33.—Graph showing gain and loss of the principal rock constituents through rock alterations at San Manuel. Numbers on individual graphs refer to corresponding analysis in table 9. No. 7 from table 9 could not be plotted because the bulk specific gravity was not determined.

TABLE 9.—*Chemical and spectrographic analyses of unaltered and altered granodiorite porphyry from San Manuel*

	(*)	1	2	3	4	5	6	7
Chemical analysis [Analyses 1, 4, 7 after Schwartz (1953); analysts for*: P. L. D. Elmore, K. E. White and S. D. Botts; analysts for 2, 3, 5, and 6: P. L. D. Elmore and S. D. Botts]								
SiO_2	61.8	64.09	62.7	63.6	66.98	64.8	62.6	65.64
Al_2O_3	16.5	15.50	15.2	16.8	15.32	17.0	16.4	15.95
Fe_2O_3	3.3	2.98	1.4	.63	1.87	.54	1.0	6.61
FeO	1.2	--------	1.1	.1	1.13	.8	1.2	.48
MgO	2.6	2.03	.68	.41	1.33	1.4	2.4	.28
CaO	3.6	.53	.22	.10	.50	.57	1.0	.27
Na_2O	4.3	1.36	.24	.19	2.33	2.2	3.2	.72
K_2O	2.5	3.69	3.2	4.1	5.29	5.4	4.5	1.95
H_2O+	1.9	2.76	3.2	3.0	2.15	1.9	1.9	4.58
H_2O-	.5	.49	--------	--------	.46	.57	--------	.34
TiO_2	.65	.73	.71	.48	.60	.25	.61	.48
P_2O_5	.22	.28	.24	.17	.20	--------	.24	.22
CO_2	1.0	0	--------	--------	0	--------	--------	0
MnO	.10	.02	--------	0	.04	0	0	.008
CuO	--------	.33	--------	--------	1.10	--------	--------	.038
SO_3	--------	--------	--------	--------	.04	--------	--------	2.00
FeS_2	--------	4.62	9.9	10.3	--------	3.2	3.56	--------
Total	100.17	99.41	98.79	99.88	99.34	98.63	98.61	99.56
Bulk specific gravity	2.625	2.52	2.74	2.69	2.58	2.50	2.55	--------
Powder specific gravity	--------	2.76	2.84	2.84	2.65	2.70	2.78	2.71
Semiquantitative spectrographic analyses [Spectrographic analyses for 1, 4, and 7 after Schwartz (1953); analyst for*: U. Oda; analyst for 2, 3, and 5: K. V. Hazel]								
Cu	0.002	--------	0.03	0.03	--------	1.0	1.0	--------
Mo	<.001	0.01	.01	.001	0.009	.001	.01	--------
Ag	<.0001	--------	--------	--------	--------	.00001	.00003	--------
Ni	.001	.007	.001	.001	.003	.001	.001	--------
Co	.001	.01	.003	.001	.002	.003	.003	--------
Be	--------	Trace	.00003	.00003	Trace	.00003	.00003	--------
V	.015	.01	.01	.01	.01	.01	.01	.007
Cr	.005	.01	.003	.003	.01	.003	.003	.007
Zr	--------	.008	.003	.003	.01	.01	.01	.02
Sn	<.001	Trace	.001	.001	Trace	.001	.001	--------
Pb	.0015	.02	--------	--------	Trace	.001	.001	Trace
B	--------	--------	--------	--------	--------	--------	--------	.0005
Sr	.2	.01	.03	.03	.01	.01	.01	.04
Y	--------	.002	.001	--------	.003	.001	.001	.003
Ga	--------	--------	.001	.001	--------	.001	.001	--------
Sc	--------	--------	.001	.001	--------	.001	.001	--------
Ba	.2	.02	.03	.03	.03	.03	.03	.04
Quantitative spectrographic analyses [Analyst: K. V. Hazel]								
Cu	--------	--------	0.03	0.03	--------	0.7	0.7	--------
Mo	--------	--------	.009	.001	--------	.001	.009	--------

* Unaltered granodiorite porphyry.
1. Argillized porphyry (hydromica-pyrite assemblage).
2. Argillized porphyry (sericite-kaolinite assemblage).
3. Argillized porphyry (sericite-kaolinite assemblage).
4. Potassium-enriched porphyry (sericite-pyrite-chalcopyrite assemblage).
5. Potassium-enriched porphyry (biotite-potassium feldspar-sericite assemblage).
6. Potassium-enriched porphyry (biotite-potassium feldspar-sericite assemblage).
7. Potassium-enriched porphyry (biotite-potassium feldspar-sericite assemblage).

Corresponding numbers in figures 15 and 33 and in table 9 indicate the same sample of granodiorite porphyry.

it with those at Ajo (Arizona), Castle Dome (Arizona), and Ely (Nevada). He summarized the comparison as follows:

> If any general statements can be made about the porphyry copper deposits for which there are chemical data, it would be that lime is more readily leached than soda during alteration; potash is usually added; magnesia may be added or slightly leached in some facies, but it is definitely leached in other facies. The iron content does not increase, except locally, and in general, iron is leached even in sulfide ore. Silica and alumina are not appreciably changed during alteration. Perhaps the increase in quartz content in the altered rocks is due to release of silica from other minerals during alteration.

Creasey (1959) compared the hydrothermal alteration in eight porphyry copper deposits: San Manuel, Morenci, Ajo, Bagdad, and Castle Dome, all in Arizona; Santa Rita, in New Mexico; Ely, in Nevada; and Bingham, in Utah. He found no significant loss in silicon, a small but persistent loss in aluminum, a moderate loss in iron and magnesium, heavy losses in sodium and particularly calcium, and gains in potassium, sulfur, and hydroxyl ion (water).

The increase in potassium is greater in the potassium-enriched rock than in the argillized rock (fig. 33). Creasey (1959) found that the argillized rocks gained an average of 8 mg per cc, or 15 percent, K_2O, whereas the potassium-enriched rocks gained an average of 51 mg per cc, or 76 percent, K_2O. In the San Manuel deposit, for example, the increase in K_2O in the argillized rock is 20 mg per cc, or 30 percent, and in the potassium-enriched rock, 60 mg per cc, or 90 percent.

In the San Manuel deposit, appreciably more sulfur is added in the argillized rock. The sulfur is in pyrite, which also contains the iron. In contrast, in the potassium-enriched rock, the sulfur is in both chalcopyrite and pyrite, and much of the iron is in silicates, chiefly biotite. Mafic minerals were unstable during the reconstitution to the argillized rock; presumably the iron released by their breakdown was sulfidized to form pyrite.

MINOR ELEMENTS IN THE SAN MANUEL DEPOSIT

Semiquantitative spectrographic analyses of 39 samples of the granodiorite porphyry largely from the underground workings of the San Manuel deposit were run for 14 minor elements (Mo, Pb, Zn, Ni, Co, Mn, V, Cr, Sr, Ba, Sn, Ag, Cd, and Bi) and for copper to try to detect any significant variation in minor-element content within the ore deposit. In addition, 18 samples of altered rock collected from the outcrops of the deposit were run for the same elements. The results of analyses of nine of these elements are summarized in table 10. Analyses for the other six elements did not show sufficient variation to warrant inclusion in the table. The concentration of these elements, in parts per million (ppm), are as follows: Pb, <10; Zn, <500; Sn, <10; Ag, 10–<1; Cd, <50; and Bi, <10. Analyses for the ore zone, the potassium-enriched rock, the zone of argillized rock, the surface rocks near the deposit, and the surface rocks away from the deposit are reported separately to show the variations. Vinogradov's averages (1956) for "acid rocks" and Goldschmidt's averages (1954) for the earth's crust are included for comparison.

The ore deposit, including the adjacent argillized rock, is impoverished in manganese, in comparison to

Vinogradov's average for acid rocks, and is enriched in copper and molybdenum (table 10). The limits of the ore zone are defined by a 5,000 ppm Cu cutoff, and the average grade of the ore, which was determined by many assays, is about 8,000 ppm Cu. It is significant to note that the average copper content from the semiquantitative spectrographic analyses is 5,200 ppm as compared to 8,000 ppm from the wet analyses, a difference of only 35 percent.

All the granodiorite porphyry, including both the mineralized and unmineralized porphyry, is rich in strontium in comparison with Vinogradov's average. The propylitized porphyry away from the ore deposit contains the most strontium. In the San Manuel deposit and in the adjacent argillized rock, the strontium content varies systematically, but we are not certain that the variation has any relation to the different types of hydrothermally altered rocks (fig. 34). The zone of potassium-enriched rock is higher in strontium than is the zone of argillized rock; within the ore zone, however, the strontium content is relatively low in an irregular zone along the south side of the South ore body, but the reason for this is not apparent to us. If the copper metallization and related silicate alteration resulted in the removal of strontium, the entire ore zone should be low in strontium, but it is not. A relatively high strontium content peripheral to the zone of low strontium would strongly suggest leaching, but figure 34 shows no such peripheral concentration—only that the adjacent rocks are somewhat higher in strontium.

The variation in relative amounts of molybdenum on the 1475 haulage level of the San Manuel deposit is shown by figure 35. The zone of higher molybdenum coincides closely with that of the copper. It was known, of course, that the ore zone contained concentrations of molybdenum; but because the limits of the zone sampled were determined by the copper content, we did not know whether the zone of higher molybdenite was smaller, larger, overlapping but offset, or essentially coincident with the copper-rich zone. Apparently the zone of higher molybdenite is coincident with the copper-rich zone.

OTHER MINES AND PROSPECTS

ST. ANTHONY MINE

The St. Anthony mine closed before the present investigation of the San Manuel deposit started, and it was inaccessible during the entire period of our work in the district. The St. Anthony deposit, however, has been described by Peterson (1938) and by Creasey (1950). As part of the geologic mapping of the San Manuel area, the Mammoth and Collins veins were traced on the surface (pl. 1). The veins, however, could not be traced continuously in the area south of Tucson Wash near the mine, partly because they do not crop out well, and partly because the surface installations of the mine—houses, roads, and so on—have obliterated the natural exposures. North of Tucson Wash the Collins vein crops out for about 4,000 feet.

The outcrop of the Collins vein is not overly impressive. It ranges in width from about 2 to perhaps 6 feet and is marked by a sheared and brecciated zone well stained with iron oxide. Vein quartz is common

TABLE 10.—*Semiquantitative spectrographic analyses of granodiorite porphyry, in parts per million*

[U. Oda analyst]

	Mo	Co	Ni	Mn	V	Sr	Ba	Cr	Cu
Ore zone	100	20	10	100	1,000	<50	750	100	1,000
	<10	50	20	50	350	350	750	35	10,000
	10	<10	5	50	500	150	1,000	20	10,000
	<10	<10	5	50	200	200	750	20	3,500
	35	<10	5	50	200	150	500	20	7,500
	200	15	10	20	350	750	750	50	5,000
	1,000	35	15	20	200	200	750	20	7,500
	35	15	5	10	200	500	500	35	10,000
	10	15	10	<10	200	350	500	20	750
	500	35	10	20	200	500	750	35	2,000
	10	50	10	10	150	200	750	20	3,500
	200	15	5	200	350	750	1,000	20	10,000
	35	10	5	50	350	750	1,500	35	5,000
	75	<10	<5	20	350	500	1,500	20	5,000
	50	35	20	150	350	500	750	35	3,500
	<10	35	5	75	350	350	750	20	5,000
	35	50	75	10	500	100	750	35	3,500
	10	15	10	<10	350	75	750	35	750
Potassium-silicate alteration zone	<10	10	<5	200	200	500	750	35	1,000
	20	10	5	200	350	750	750	20	1,500
	<10	<10	<5	350	100	750	3,500	10	350
	10	10	5	150	350	750	1,500	35	1,000
	<10	10	<5	50	200	1,000	750	20	750
	<10	10	<5	100	150	750	500	35	1,000
	<10	10	7	75	500	750	750	35	7,500
	1,500	<10	5	100	500	750	750	20	1,500
	<10	10	5	100	500	750	750	20	1,000
	<10	<10	5	50	500	750	1,000	15	1,000
	<10	10	5	100	500	100	750	15	2,000
	<10	10	5	75	35	750	3,500	100	100
	<10	10	10	<10	500	1,000	2,000	20	1,000
	<10	10	10	750	500	1,000	1,500	20	350
Argillic alteration zone	<10	15	5	<10	200	1,000	500	35	200
	10	15	<5	10	150	200	750	20	2,000
	<10	35	20	<10	500	200	1,000	50	200
	100	35	35	10	200	350	500	35	5,000
	20	35	5	<10	350	500	750	20	1,000
	20	20	50	20	1,000	3,500	3,500	100	1,000
	20	75	10	100	500	150	750	20	2,000
Surface near ore deposit	<10	<10	<5	<10	100	350	75	35	75
	<10	<10	<5	75	200	500	750	20	100
	<10	<10	<5	<10	200	150	750	20	20
	150	----	----	----	----	750	----	----	5,000
	20	<10	<5	20	200	350	1,000	35	750
	50	----	----	----	----	1,000	----	----	150
	<10	<10	<5	<10	10	200	150	10	20
	<10	<10	<5	<10	100	75	750	75	20
	<10	<10	<5	100	100	75	750	50	35
	<10	<10	<5	50	75	50	750	35	200
	<10	----	----	----	----	500	----	----	150
	<10	----	----	----	----	200	----	----	20
	35	<10	<5	<10	100	350	750	50	50
	35	<10	<5	<10	100	350	750	50	50
	50	<10	<5	75	150	75	1,000	35	7,500
	<10	<10	<5	<10	100	500	500	35	200
Surface away from ore deposit	<10	<10	<5	750	150	500	750	20	100
	<10	<10	<5	750	200	500	1,500	10	15
	<10	10	<5	500	200	1,000	1,500	20	15
	<10	15	10	500	350	1,500	1,500	35	10
	<10	15	5	500	200	1,500	1,500	35	15
	<10	15	15	1,000	200	1,500	2,000	75	20
	<10	10	10	1,000	150	2,000	2,000	550	20
	<10	10	5	350	150	1,000	1,000	35	15
	50	10	<5	1,000	100	150	350	20	15
	<10	15	5	750	200	750	1,500	50	20
	<10	15	10	750	350	1,000	750	150	50
	<10	10	7	750	100	350	750	50	20
	<10	10	<5	750	100	200	150	20	10
	<10	15	5	350	100	1,500	2,000	50	15
Average in earth's crust:									
Goldschmidt (1954)	2.3	40	100	1,000	150	150	430	200	70
Vinogradov (1956)	1.9	5	8	610	400	300	830	25	30

but not abundant. Much of this quartz is cavernous or vuggy, owing to the oxidation of sulfides. In a few prospect pits a few crystals of wulfenite were seen. None of the observed outcrops of the vein contain high-grade sulfide ores, such as those found between the 700 and 1,000 levels on the Collins vein.

TAR MINE

The Tar mine, located in Tar Wash, sec. 21, T. 8 S., R. 16 E., was developed through a vertical shaft reported to be several hundreds of feet deep. The mine was inaccessible at the time of our work.

The dump is so large as to suggest that there were considerable lateral workings in addition to the shaft. The dump consists largely of rocks from the Cloudburst Formation but includes a minor amount of quartz monzonite. A small pile of rock stained with oxidized copper minerals lies near the collar of the shaft, and similar material can be found in Tar Wash below the mine; presumably this float was derived from erosion of the dump during the infrequent times Tar Wash was in flood.

FORD MINE

The Ford mine is in the bottom of Tucson Wash in the SE¼ sec. 27, T. 8 S., R. 16 E. It consists of a vertical shaft, which at the time of our work was covered and locked. Surface exposures show that the shaft is on a fault whose attitude is N. 25° W., 85° SW. The depth of the shaft and the type and extent of mineralized rock are not known to us.

VEINS IN SECS. 20, 21, AND 28

Three northwest-trending veins, all similar in nature, crop out in secs. 20, 21, and 28, T. 8 S., R. 16 E. (pl. 1). The longest vein was traced as a continuous structure for about 5,000 feet.

These veins consist of well-defined sheared zones composed of as much as 5 feet of oxidized gouge bounded by crackled zones that locally extend outward as much as 50 feet from the vein. Vein minerals are sparse, although no sulfides were seen, the abundance of iron oxide suggests that some pyrite must be present. The most impressive indication of mineralized rocks is given by the numerous prospect pits. If these pits had not been so numerous, we probably would have mapped the structure as a small fault.

PEARL MINE AND NEARBY VEINS

A group of veins, including those that compose the Pearl mine, trend northwestward from sec. 17, T. 8 S., R. 16 E., to the northwest corner of the quadrangle.

The veins consist of a family of shear zones in quartz monzonite trending from north to N. 35° W. and dipping 25° to 75° W. Prospect pits on the veins reveal oxidized copper minerals in thin seams and as stain on the walls of the fractures. The granodiorite adjacent to the veins is not strongly altered, and vein quartz is sparse.

TABLE 10—Continued

Summary

[Number of samples: ore zone, 18 samples; potassium-silicate alteration zone, 14 samples; argillic alteration zone, 7 samples; surface near deposit, 16 samples; surface away from deposit, 14 samples]

	Nickel			Cobalt			Manganese		
	Range	Median	Mode	Range	Median	Mode	Range	Median	Mode
Ore zone	<5-75	10	5	<10-50	15	15	<10-200	35	50
Potassium-silicate alteration zone	<5-10	5	5	<10-10	10	10	<10-750	100	100
Argillic alteration zone	<5-50	10	5	15-75	35	35	<10-100	10	<10
Surface near deposit	<5	<5	<5	<10	<10	<10	<10-100	<10	<10
Surface away from deposit	<5-15	5	<5	<10-15	10	12.5	350-1,000	750	750

	Molybdenum			Vanadium			Chromium		
	Range	Median	Mode	Range	Median	Mode	Range	Median	Mode
Ore zone	<10-1,000	35	22.5	150-1,000	350	350	20-100	27.5	20
Potassium-silicate alteration zone	<10-1,500	<10	<10	35-500	425	500	10-100	20	20
Argillic alteration zone	<10-100	20	20	150-1,000	350	350	20-100	35	20
Surface near deposit	<10-150	<10	<10	10-200	100	100	10-75	35	35
Surface away from deposit	<10-50	<10	<10	100-350	175	200	<10-550	35	20

	Strontium			Barium			Copper		
	Range	Median	Mode	Range	Median	Mode	Range	Median	Mode
Ore zone	<50-750	350	500	500-1,500	750	750	750-10,000	5,000	5,000
Potassium-silicate alteration zone	100-1,000	750	750	500-3,500	750	750	100-7,500	1,000	1,000
Argillic alteration zone	150-3,500	350	200	500-3,500	750	750	200-5,000	1,000	1,000
Near surface deposit	50-1,000	350	350	75-1,000	750	750	20-7,500	87.5	20
Surface away from deposit	150-2,000	1,000	1,500	150-2,000	1,500	1,500	10-100	15	15

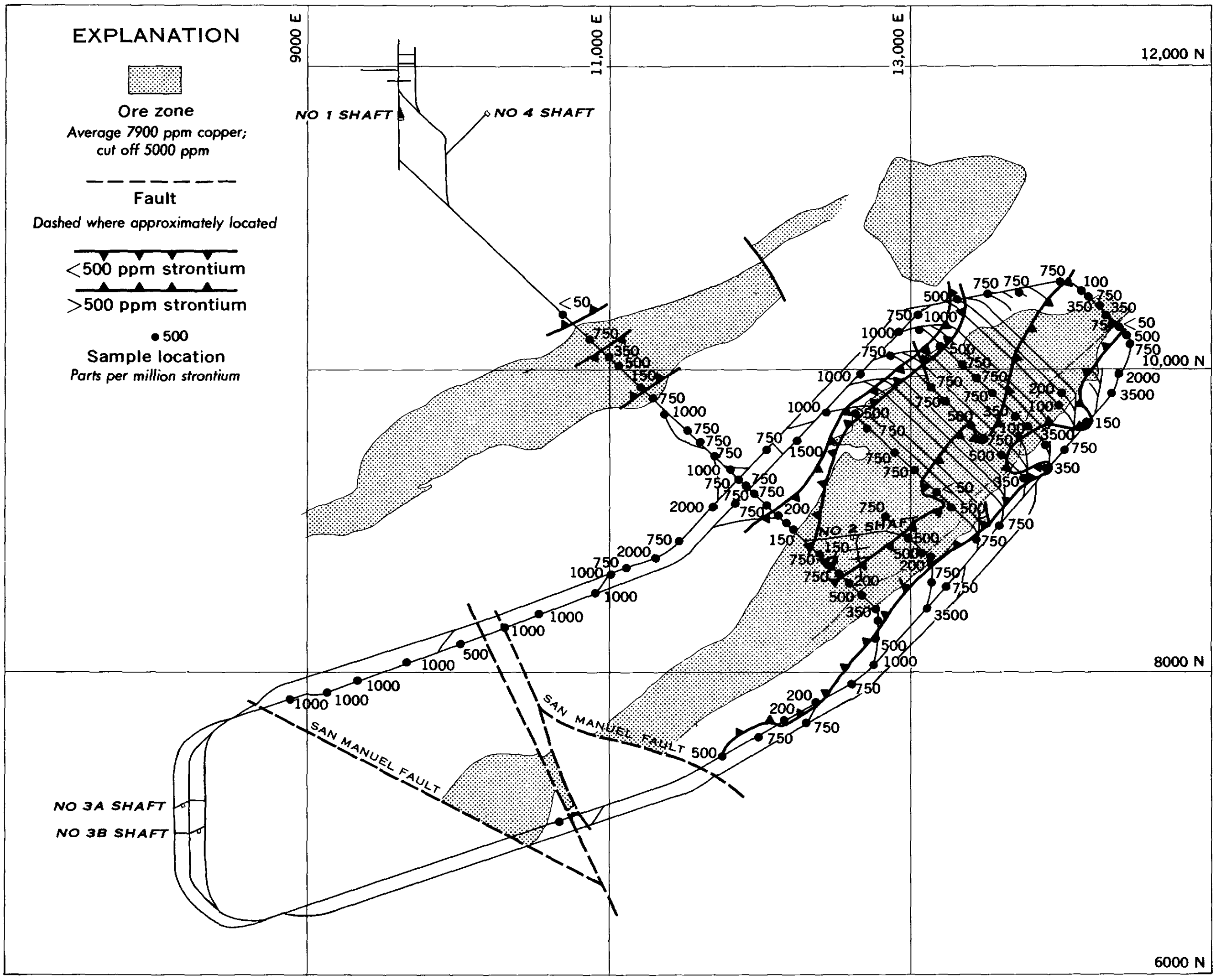


FIGURE 34.—Distribution of strontium on the 1475 haulage level, San Manuel mine, Arizona. Semiquantitative spectrographic analyses in parts per million.

The Pearl mine was inaccessible during the period of our fieldwork.

OTHER PROSPECTS

In the NW¼ sec. 29, T. 8 S., R. 16 E. (pl. 1), a small prospect pit exposes an east-trending carbonate vein ranging in width from 4 to 10 feet. The vein could not be traced beyond the vicinity of the pit. Although there was no manganese ore exposed in the pit, the dump contained about 2 tons of hand-sorted psilomelane-type manganese ore. The ore mineral was hard, botryoidal, and free of visible impurities.

About 300 feet north of the San Manuel fault in the central part of sec. 29, T. 8 S., R. 16 E., a prospect exposes a quartz vein, partly stained with iron oxide probably derived from pyrite. The vein strikes about N. 70° W. and dips 80° S.; it could not be traced more than a few feet away from the pit.

About 2,500 feet west-northwest of the quartz vein, and next to the San Manuel fault, a prospect pit in the quartz monzonite exposes a northwest-trending sheared zone coated with chrysocolla.

In the central part of sec. 17, T. 8 S., R. 16 E., the east-striking right-lateral fault that offsets the thrust fault appears to be intruded by felsite and mineralized with secondary quartz. Sulfide minerals are absent, but iron oxide is plentiful. Several prospect pits and shallow shafts explored the fault without apparent success.

In the NW¼ of sec. 9, T. 9 S., R. 16 E., several prospect pits exposed fractured and sheared zones that strike N. 40° to 60° E. and dip 65° S. Some of the

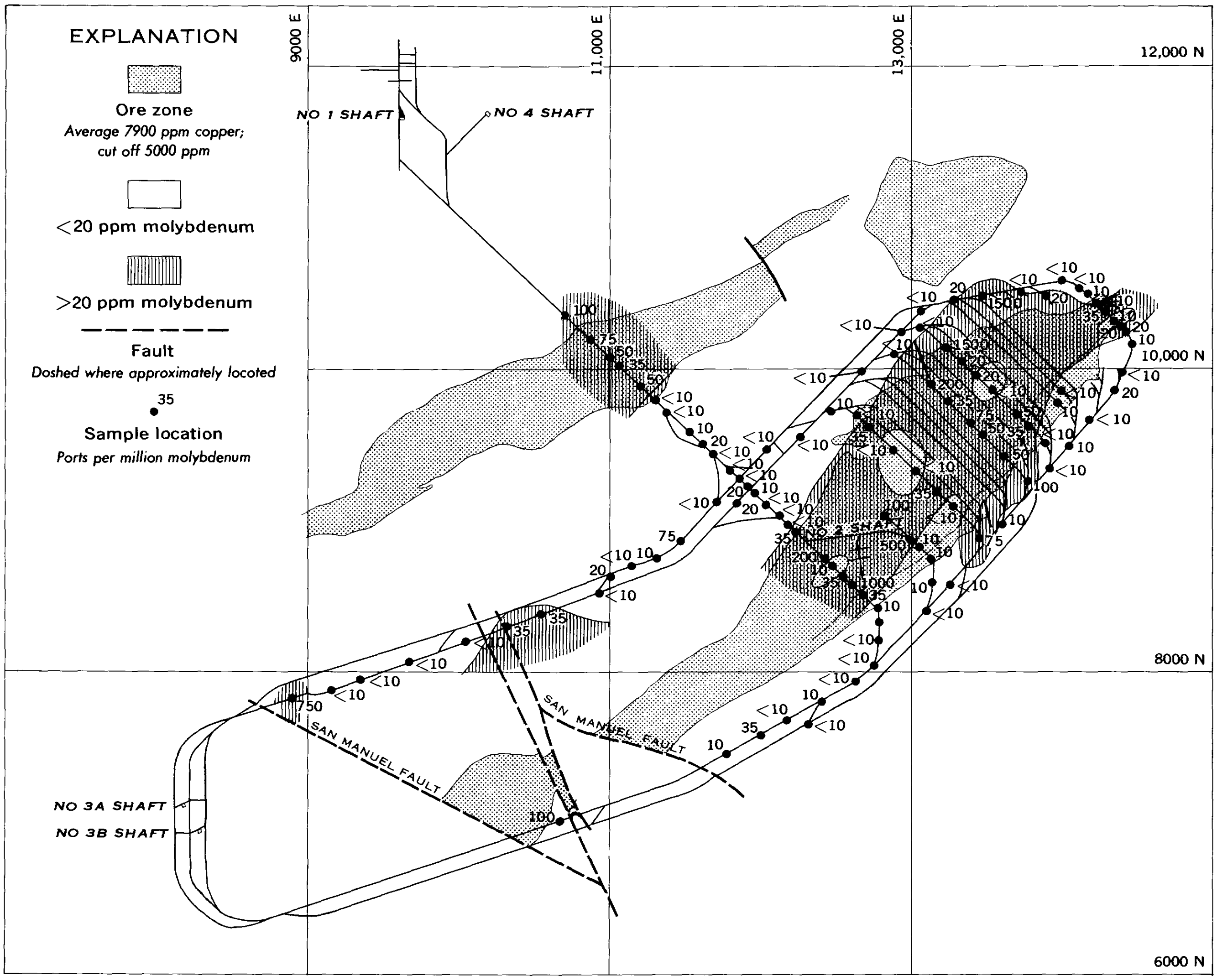


FIGURE 35.—Distribution of molybdenum on the 1475 haulage level, San Manuel mine, Arizona. Semiquantitative spectrographic analyses, in parts per million.

sheared zones are along the contacts of diabase dikes. The dumps of some of the pits contain a few pounds of hand-sorted oxidized copper ore, and the walls of some of the fractures are weakly stained with secondary copper minerals.

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