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THE AJO MINING DISTRICT ARIZONA

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PREFACE

By G. F. Loughlin

Although the Ajo mining district is known mainly because of its importance as a producer of copper, the district and its immediate surroundings in the Ajo quadrangle present so many unusual features of petrology, metamorphism, geologic structure, and physiography that it is likely to be of interest to specialists in all these branches of geology, as well as to those interested in mining geology. The author's keen interest in these different subjects has led to a thorough treatment of each one. The last third of the text deals with ore deposits and directly related features; that third, if preceded by the abstract of the whole report, should serve the reader who is concerned only with ore deposits. Other sections of the report may serve in a similar way.

The work upon which this report is based was done during the years 1932-34, and the statistics and descriptions are for that period.

THE AJO MINING DISTRICT, ARIZONA

By James Gilluly

ABSTRACT

The Ajo quadrangle embraces the area bounded by the meridians 112°45′ and 113° W. and the parallels 32°15′ and 32°30′ N. in the Papago country of western Pima County, Ariz. It is in the Sonoran Desert section of the Basin and Range province. The climate is arid, with average rainfall about 10 inches and very low humidity. Consequently there are no permanent streams, although the drainage is external.

The area contains several small mountain masses, but much of it is occupied by desert plains, the largest of which is the Valley of the Ajo. Altitude ranges from 1,150 to 3,200 feet. The local relief is moderate and is only exceptionally as much as 1,000 feet within a square mile.

The rocks of the area range in age from probable pre-Cambrian to Recent. As the only fossils found were in transported boulders and as none of the formations recognized can be dated closely, the ages assigned to the different formations are all tentative. Inasmuch as the area is distant from any previously studied in detail, all the formations named have their type localities within it.

The oldest formation, presumably pre-Cambrian, is the Cardigan gneiss, which occupies much of the south and west parts of the Little Ajo Mountains. This is a quartz-albite-chlorite injection gneiss whose composition, relict structures, and minerals give evidence of low-grade metamorphism superposed on an earlier high grade metamorphism.

The formation is intruded by hornblendite, in very small masses of rounded outline, also regarded as probably pre-Cambrian, and by large, probably composite, masses of quartz monzonitic and related rocks called the Chico Shunie quartz monzonite.

The Chico Shunie quartz monzonite is largely brecciated and is chloritized and somewhat saussuritized practically throughout. It contains many inclusions that range in size from masses more than a mile long to aggregates less than 1 millimeter in diameter. Many of the inclusions are of Cardigan gneiss; others are highly altered sandstone, shale, and lava, and may be of Paleozoic age. The Chico Shunie quartz monzonite is accordingly regarded as possibly Mesozoic. Its crushing is presumed to be simultaneous with the low-grade metamorphism of the Cardigan gneiss.

The Concentrator volcanics, although not in depositional contact with any of these formations, are believed to be next younger than the Chico Shunie intrusion and may be Cretaceous. They include chiefly rhyolitic and andesitic pyroclastic rocks that have been albitized to keratophyres and quartz keratophyres.

The Concentrator volcanics are cut by a stock of Tertiary (?) quartz monzonite called the Cornelia quartz monzonite, which makes up most of the higher part of the Little Ajo Mountains. A smaller offshoot, probably the displaced apex of this stock, contains the ore deposit of the New Cornelia (Phelps Dodge) mine at Ajo. The Cornelia quartz monzonite has a discontinuous quartz dioritic border. Mineral parallelism is weak or absent throughout the stock; there is little suggestion of motion in the mass after crystals were formed in notable quantity, and no positive evidence was detected showing either forcible injection or stoping. The porphyritic facies of the Cornelia quartz monzonite contain orthoclase phenocrysts that show definite association with pegmatic veins and are believed to have formed late in the magmatic history.

The Locomotive fanglomerate (middle (?) Tertiary) rests on an irregular erosion surface that cuts all the previously described rocks. It is a continental deposit many thousands of feet thick and contains large, rolled boulders of fossiliferous limestones referable to the Devonian (Martin limestone), Mississippian (?), and Pennsylvanian. As these boulders can hardly have been transported far, they indicate former extension of the Paleozoic of Arizona farther southwestward than has previously been supposed. The accumulation of so thick a mass of coarse sediments must imply active growth of mountains nearby during the period of deposition. Perhaps interior drainage is also implied by this great thickness.

The Ajo volcanics, which consist of several thousand feet of andesitic breccia, tuff, and lava flows of probable middle Tertiary age, interfinger with and overlie the Locomotive fanglomerate. A second andesitic series, the Sneed andesite, is similar to the Ajo volcanics but is believed, on admittedly uncertain grounds, to be younger. The two are not present in the same area, however.

The Daniels conglomerate, consisting of about 200 feet of poorly consolidated stream gravels, rests on the Sneed andesite and is in turn overlain by about 700 feet of coarsely porphyritic latite, the Childs latite. The Childs latite is of possible Pliocene age. It is succeeded by the Batamote andesite, a series of basaltic andesite flows at least 1,500 feet thick that makes up most of Black Mountain, Childs Mountain and the Batamote Mountains. Some volcanic breccias and minor dikes in this formation, together with vent structures, mark the location of old volcanoes. Batamote Peak is the most conspicuous and largest of these. The Batamote andesite is probably Pliocene. Quaternary alluvium is widespread and occupies most of the quadrangle.

The area comprises a mosaic of diversely tilted fault blocks, many of whose bounding faults are clearly exposed, whereas others are obscured or concealed by the widespread alluvium and are only indirectly known or inferred.

Faults that trend north-northeast are most common. Some are pre-Concentrator in age, and others have been active in two post-Concentrator epochs. The largest single fault, the Little Ajo Mountain fault, trends about N. 60° W., and bounds the Little Ajos on the north. It is demonstrable on stratigraphic grounds that its displacement may exceed 10,000 feet, but it is not directly expressed topographically. The entire mountain block has been relatively elevated and steeply tilted about 50° southward from this fault. Movement on the fault is probably later than the Ajo volcanics. Most of it is probably Pliocene, pre-Sneed, but some of it may even be post-Batamote.

The Little Ajo block is cut off on the east by a north-northeast fault, exposed on the west flank of Black Mountain. This Black Mountain fault, though downthrown on the east, is marked by a westward-facing scarp, testifying to its considerable age. Similar faults bound Childs Mountain on the west and others of the higher blocks of the area. Some may be Quaternary but most are probably Pliocene.

Physiographically the area is divisible into three parts—the mountains, the rock plains (pediments), and the alluvial plains (bajadas). The mountains are of two classes; sierras (maturely dissected with sharp crested ridges and peaks), and mesas and cuestas (young, with flat interfluves and canyons). The sierras are cut on massive formations or those with steeply inclined division planes. Black Mountain is the only sharp-crested lava ridge, and its anomalous dissection is attributed to its being a narrow fault block. The mesas and cuestas are all gently inclined blocks of massive lava. Their topographic contrast with the sierras is directly referable to the contrasts in their lithology and attitudes.

The pediments have been developed on all the rocks except the massive lavas. They represent mature stages in the arid erosion cycle and are not developed fronting "young" types of mountains. The pediments with one exception are concave and not fan-shaped in cross section, and nearly all are concave upward in profile. All are slightly dissected, probably in part because of some climatic change, for there is no evidence of lowered baselevel; however, it is suggested that part of this "dissection" may have developed simultaneously with the formation of the pediment. The rounded divides, the fine texture, and dendritic pattern of the drainage high on the pediments suggest that much of the planation of the surface is by normal slope wash, and the restricted distribution of gravel on the interfluves (even near the bajadas) suggests that not all the pediment has ever been traversed by laterally migrating streams.

The bajadas are even, slightly dissected alluvial slopes. They are slopes of transportation, only subordinately of deposition, as the drainage of the region is integrated and the streams are essentially at grade. There is no evidence of current down-sinking of the bajada blocks.

The only productive mine in the Little Ajo area is the New Cornelia mine, of the Phelps Dodge Corporation, south of Ajo. A little prospecting has been done near Cardigan, south of Locomotive Rock, in Gibson Arroyo, and near Salt well, but thus far without promising results.

Although the presence of copper ore at Ajo was known at least as early as 1750, there was no considerable mining activity until shortly after the Gadsden Purchase transferred the land to the jurisdiction of the United States in 1853. Owing to the low grade of the ores and the cost of transportation, there was very little production at this time, although a good deal of work was done. A renewed attempt to exploit the deposits in 1894 was also a failure.

The active development of the deposit dates from 1911, when the Calumet & Arizona Mining Co., of Bisbee, under the leadership of John C. Greenway, general manager, undertook the testing of the ground. After an intensive drilling campaign had established the existence of a large body of low-grade ore, experiments were undertaken to develop a leaching process applicable to the carbonate ores. These experiments led to the design of a leaching plant, which was constructed in 1916, a railroad having been built from Gila Bend in 1915. Production of high-grade shipping ore began in 1916, and in May 1917 the leaching of the carbonate ore began. The concentrator for handling the underlying sulfide ore was completed in 1924, and both carbonate and sulfide ores were treated until 1930, when most of the oxidized ore had been exhausted and the leaching plant was closed. In 1928 and 1929 the concentrator was enlarged to a capacity of 16,000 tons a day and in 1936 to a capacity of 20,000 tons a day.

In 1929 the New Cornelia Copper Co. was absorbed by the Calumet & Arizona Mining Co., and in 1931 this company was consolidated with the Phelps Dodge Corporation.

The production of copper prior to 1917 was probably less than 1,700,000 pounds. The production from 1917 to 1934, both inclusive, was about 805,000,000 pounds. Although copper is overwhelmingly the most valuable product, gold and silver recovered with it in the sulfide ores have netted about five-sixths of a cent per pound of copper. The developed reserves are adequate for a life of 30 or 40 years at a rate of production in excess of 50,000,000 pounds a year.

The New Cornelia mine exploits a large body of disseminated copper ore by open-cut methods. Most of the ore is in the normal facies of the Cornelia quartz monzonite, but some is contained in the dioritic border facies and some in the Concentrator volcanics. The ore body is roughly elliptical, about 3,600 feet long by 2,500 feet across. Its average thickness is 425 feet and the maximum about 1,000 feet. Most of the ore is in a rather flat lens, with a deeper, northwestward-trending keel, but at the south end a tongue dips steeply southward to great depths.

The primary ore consists chiefly of chalcopyrite with some bornite and a little pyrite. The gangue consists of quartz and orthoclase, and the sulfides are distributed both in veinlets and in discrete grains through the altered monzonite. A little tennantite, considerable magnetite and specularite, and a little sphalerite and molybdenite also accompany the ore. The rock is so highly impregnated with orthoclase as to be practically pegmatized along two main north-northwest trending zones, and the richest ore accompanies this more intensely altered rock. Chlorite and sericite that have replaced plagioclase are widespread, but the rock contains so much orthoclase and quartz that it is extremely hard and resembles fresh rock physically, contrasting markedly with soft, chalky-appearing ores of most of the "porphyry coppers."

The ore body was oxidized to a surprisingly level plane, which lies near the water table, beneath both hill and valley, at an altitude of about 1,800 feet. There were local variations of as much as 50 feet, but for the most part the transition from sulfide to the oxidized zone was so sharp that it could be closely followed by steam shovel. The depth of oxidized ore thus ranged from 20 to 190 feet, with an average of about 55 feet. The minerals of the oxidized ore were malachite, with a little azurite, cuprite, tenorite, chrysocolla, hematite, and limonite. A little chalcocite was found just beneath the bottom of the oxidized zone.

The fact that in most of the ore body the tenor of ore was essentially the same in oxidized and subjacent sulfide ore seems to show, in connection with the rather insignificant quantity of chalcocite, that there was little migration of copper during weathering. In this respect the Ajo ore body differs from most of the other great disseminated deposits of the Southwest, for in most of them supergene chalcocite is an essential constituent of the commercial ore.

The supergene chalcocite of the Ajo deposit is found in insignificant amounts over most of the area of the pit at about the original ground-water level, but at the south end of the ore body there is a crescentic outcrop of a chalcocitic ore shoot. This shoot pitches 60° S., parallel to the dip of the overlying fanglomerate, and has been followed by the diamond drill to depths of more than 2,000 feet, to a point 200 feet below sea level. This chalcocite zone is overlain by a reddish weathered zone containing cuprite, native copper, and hematite and obviously represents an old zone of supergene enrichment formed prior to the deformation of the fanglomerate and probably prior to its deposition. The oxidized and enriched zones have been deformed in this region and dislocated by faults of several hundred feet displacement, as shown by diamond drilling.

The close association of the ore with the pegmatized quartz monzonite porphyry is sufficiently indicative, in conjunction with the content of magnetite and specular hematite, of its magmatic source. The emplacement was largely effected by metasomatic processes and was guided by widespread fissure zones along dominantly north-northwest lines.

The regional geologic setting of the Ajo deposit is not yet well enough known to furnish clear-cut data as to its age. No fossiliferous rocks are involved in the nearby structures. The present erosion surface has been masked by volcanic flows, now largely removed. This surface is carved across the steeply tilted fanglomerate, and that in turn rests on a surface of mineralized monzonite that presumably has been deeply eroded. Thus if the deposit is of Tertiary age, its formation has been succeeded by a long and rather involved history. On the other hand, intense contact metamorphism of Carboniferous (?) limestones in the Growler Mountains, to the south, merely suggests that the major intrusives were post-Carboniferous. As far as direct data go, then, nothing can yet be said with certainty as to its age; the probabilities lie between Permian and early Tertiary, though analogy with other deposits of the region would favor an early Tertiary age.

The deposit is mined by the open-cut method, with steam shovels operating on benches at vertical intervals of 30 feet. Inasmuch as the oxidized part of the ore body was practically as productive as the sulfide part, there was here no stripping problem of the sort confronting most of the disseminated deposits of the Southwest. To January 1931, less than 7,000,000 tons of waste had been moved in the mining of 32,400,000 tons of ore, a ratio of 0.22 ton of waste to 1 ton of ore. Much of this waste was within the ore body and was not overburden. As the depth of the pit increases, a larger proportion of waste will have to be moved in order to maintain a safe angle of slope.

INTRODUCTION

LOCATION, CULTURE, AND ACCESSIBILITY

The Ajo quadrangle, Ariz., embraces the area bounded by the meridians 112°45′ and 113° W. and the parallels 32°15′ and 32°30′ N., in western Pima County. It includes a representative part of the "Papago country" of southwestern Arizona, about 20 miles from the Mexican boundary. (See fig. 1.)

The only town of any size in the area and, indeed, in the entire Papago country, is Ajo, a "company town" controlled by the Phelps Dodge Corporation, owner of the large copper mine and mill at that point. Ajo is adjoined on the east by the hamlet of Clarkstown (Rowood post office) and on the west by the scattered settlement called Gibson. The small group of houses clustered about the Phelps Dodge well at the "water mine" by Childs siding, 6 miles north of Ajo, and a few scattered ranch houses are the only other white habitations in the quadrangle. There are a few semipermanent Indian settlements near wells.

The town of Ajo is connected by the standard-gage Tucson, Cornelia & Gila Bend R. R., owned by Phelps Dodge Corporation, with the main line of the Southern Pacific R. R. at Gila Bend, a station about half way between Tucson and Yuma. An excellent motor highway, about 44 miles long, connects Ajo with Gila Bend, where it joins a fine transcontinental highway, U. S. No. 80. A somewhat inferior, though good road, extends from Ajo to Tucson by way of Covered Wells and Indian Oasis, a distance of about 135 miles. From near Ajo a good road branches southward from the Tucson road to the village of Sonoita, a few miles south of the international boundary, in Sonora, Mexico.

PHYSICAL FEATURES

The Ajo quadrangle lies in the "desert region" of Arizona, as defined by Ransome,[1] and the "Sonoran desert" section of the Basin and Range province, as outlined by Fenneman.[2] It is fairly representative of that physiographic subdivision, which is characterized by short ranges separated by wide desert plains.

One of the larger of the desert plains of the Papago country is the Valley of the Ajo (see fig. 2), so named because of the prevalence of the wild onion (Spanish, ajo) in it. The Valley of the Ajo is roughly meridional, about 30 miles long by 10 miles wide, and is practically hemmed in on all sides by hills and mountains. Of these, the highest are the Ajo Mountains, locally called the "Big Ajos," which trend southward along the southern part of the east side of the valley. The low Gunsight Hills lie north of the Ajo Mountains and are separated by a small valley from the south end of the Pozo Redondo Mountains, which form the east wall of the Valley of the Ajo for about 12 miles to its northeast corner where they are divided by a narrow canyon from the Batamote Mountains. A long westerly spur descends from the central mass of the Batamote Mountains and forms the north wall of the valley. A flat-bottomed gap about 1½ miles wide at the northwest extremity of the valley, through which its northern part drains to Childs Valley and thence toward the Gila River, separates the Batamote Mountains from Childs Mountain.

Childs Mountain is a roughly equilateral triangular mass, and its eastern border extends south-southwest from this gap for about 6 miles. Here a gently sloping plain, dotted with low hills, separates it from the Little Ajo Mountains. This plain is a pediment carved on bedrock and covered by only a thin veneer of gravel. It and the low hills to the south and southwest form the western border of the Valley of the Ajo for about 8 miles. (See pl. 1, *A*.) There is no clear separation between these southwestern foothills of the Little Ajos and the eastern foothills of the much larger Growler Mountains, although toward the north and northwest the two ranges diverge, and a rather large valley, occupied by alluvium, intervenes between them. South of this hilly zone the west border of the Valley of the Ajo is formed by the Growler Mountains and the lower Bates Mountains, which are separated from the Growler Mountains by the narrow Growler Pass. The southern end of the Valley is closed by the low transverse hills called the Puerto Blanco Mountains.

The Ajo quadrangle embraces the northwestern part of the district whose salient topographic features have just been mentioned. The Little Ajo Mountains, forming a typical sierra mass, with sharp ridges and serrate peaks, occupy the central and southwestern parts of the quad-

[1] Ransome, F. L., Geology of the Globe copper district, Ariz.; U. S. Geol. Survey Prof. Paper 12, p. 16, 1903.

[2] Fenneman, N. M., Physiographic divisions of the United States: Assoc. Am. Geographers Annals vol. 18, p. 346, 1928.

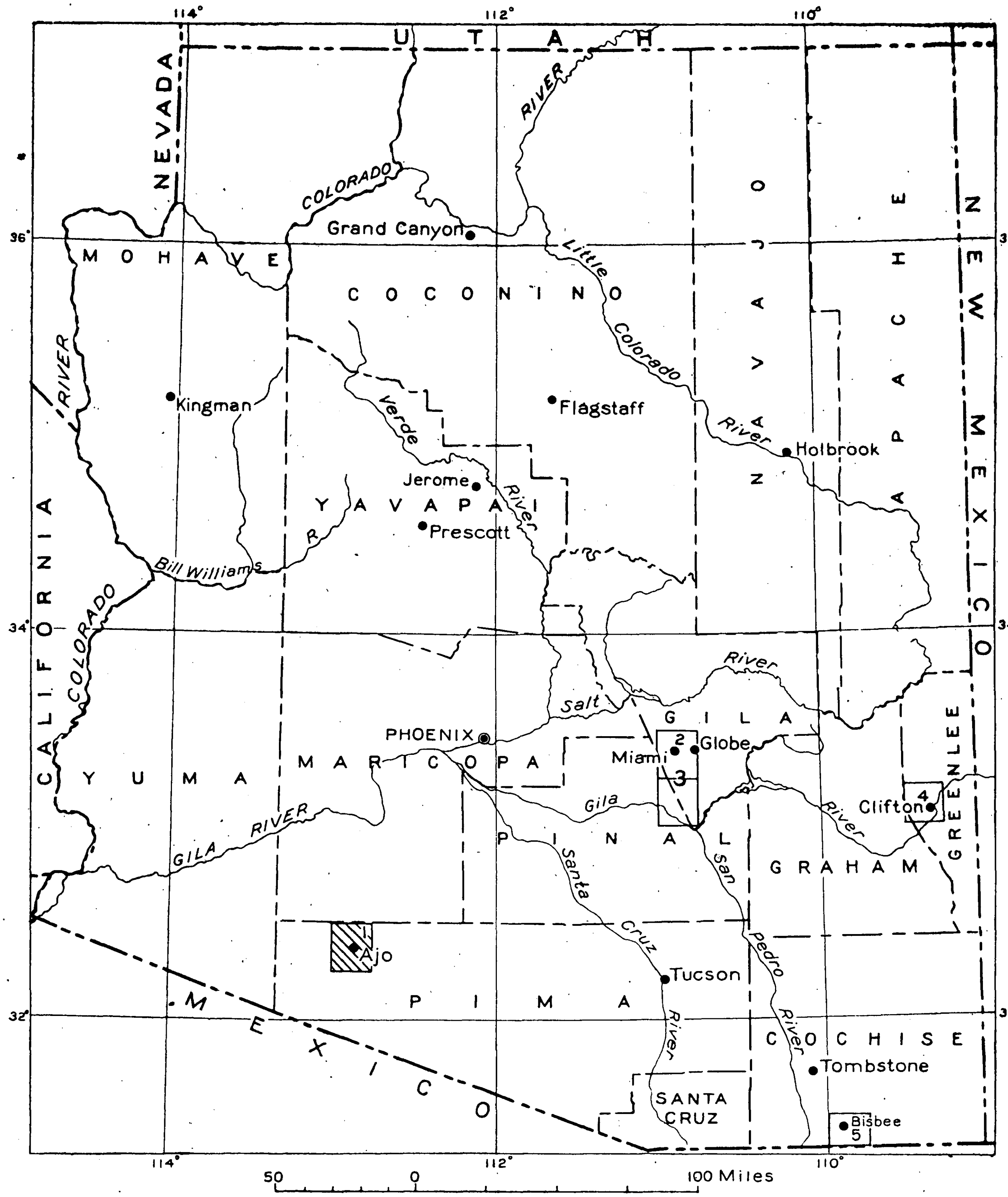


FIGURE 1.—Index map of Arizona showing location of the Ajo quadrangle and other metalliferous districts described in detailed reports of the Geological Survey. 1, Ajo; 2, Globe; 3, Ray and Miami; 4, Clifton-Morenci; 5, Bisbee.

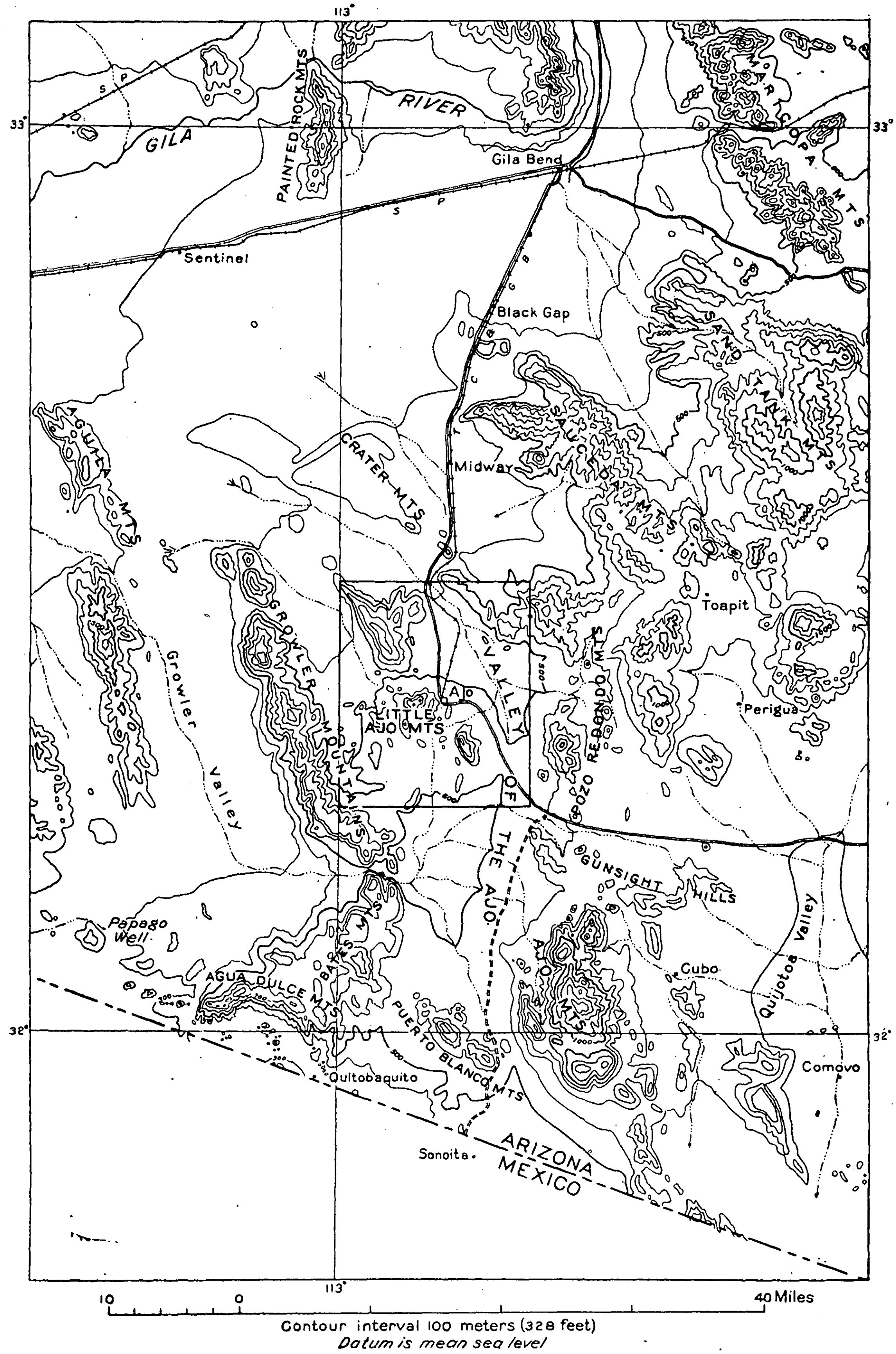


Figure 2.—Generalized topographic map of the Ajo quadrangle and contiguous areas in southwestern Arizona.

rangle and rise abruptly from a broad pediment that slopes gently and evenly away in all directions. Toward the north, east, and south this rock-floored pediment merges imperceptibly with the broad alluvial flat of the Valley of the Ajo (see pl. 1, *B*); toward the southwest and south it merges with the alluvial fill of the valley that divides the Little Ajos from the much higher Growler Mountains. (See pls. 6, *F*, and 2, *A*.) Northwest of the Little Ajos and in the northwest part of the quadrangle, is Childs Mountain. The northeastern corner of the area is occupied by a westward-trending spur of the Batamote Mountains.

Altitudes in the quadrangle range from less than 1,150 feet in Childs Valley, near the northwest corner of the quadrangle, to 3,016 feet at the summit of Black Mountain, the practically detached ridge southeast of the main mass of the Little Ajos. (See pls. 1, *C*, 2, *A*, and 6, *E*, *F*.) The highest point in the main mass of the Little Ajo Mountains is the unnamed peak with an altitude of 2,980 feet on the divide west of Gibson Arroyo and half a mile east of Cardigan Peak. (See pl. 2, *A*.) The summit of Childs Mountain is 2,910 feet in altitude. The highest point of the Batamote Mountains, 3,198 feet, is just east of the quadrangle, but the long spur that extends westward across the northern part of the area approaches 3,000 feet at the boundary of the quadrangle. The total relief in the area is thus more than 1,860 feet, but the long gentle grades of the alluvial and pediment slopes that intervene between the valley bottoms and the abrupt, commonly cliffy slopes of the mountains make the local relief only in a few places as great as 1,000 feet in a square mile.

Despite this moderate local relief, the mountains are rugged and present numerous precipices, although there are few points that cannot be readily scaled from one direction or another. The most spectacular of the rugged peaks are doubtless the twin pinnacles just south of the main mass of the Little Ajos, Ajo Peak and North Ajo Peak, landmarks for many miles toward the south and east. (See pl. 2, *A*.)

The wide, rock-floored plains or pediments surround the main mountains and pass smoothly outward into the alluvial valleys. Their headward extensions into the mountain mass divide the Little Ajo Mountains into three smaller groups. The largest of these, about 2 by 5 miles in area, extends nearly due westward from the town of Ajo and is dominated by Cardigan Peak and peaks nearby. It is nearly cut through by the Gibson and Cornelia Arroyos. Separated from this mass by the practically continuous pediments of Copper Canyon and Darby Arroyo, a sprawling group of lower hills and peaks, of which the Ajo Peaks are the most conspicuous, forms the southwestern part of the mountains. (See pl. 1,*A*.) Still lower hills, which may be regarded as part of this group, occupy perhaps 10 square miles south of Chico Shunie well. I have called them the Chico Shunie Hills. The third group includes Black Mountain and the lower hills southwest of it and lies southeast of the Cardigan mass and east-southeast of the Ajo Peaks. (See pls. 2, *A*, and 6, *F*.) Black Mountain trends nearly south and is about 4 miles long by 1½ miles wide. Between it and the Ajo Peaks are some much lower hills and isolated rocks along the divide between Darby Arroyo and the southward drainage, the most conspicuous, and a well-known landmark, being Locomotive Rock.

There are no permanent streams in the area. The runoff from the occasional torrential rains has nevertheless carved and moulded the topography in characteristic fashion. The northern end of the Valley of the Ajo drains to Childs Valley by way of the Rio Cornez, which receives the drainage from as far south as Black Mountain. The principal streams from the Little Ajo Mountains that are tributary to the Rio Cornez are Gibson, Cornelia, and Darby Arroyos. There is a low, hardly recognizable divide in the Valley of the Ajo just southeast of Black Mountain, and drainage from more southerly points and from the country near Locomotive Rock passes southwestward to Growler Pass and Growler Valley, west of the Growler Range, by way of the arroyo called the Cuerdo de Lena. The southwestern part of the quadrangle and the west slope of the Little Ajo mass drain through Daniels and Chico Shunie Arroyos and Copper Canyon to the valley between Childs Mountain and the Growler Range, thence to Childs Valley. All the runoff passes eventually to the Gila River drainage, though it is rarely, indeed, that more than a few of the streams are flowing simultaneously.

None of these streams can be depended upon to furnish water for man or beast, although there is a little water in plunge pools and channel holes for a few days after rain. All the water for the use of the town and the concentrating mill at Ajo and for the few cattle ranches and Indian villages is derived from wells. Ajo is supplied from well No. 1, at Childs siding, near the north end of the Valley of the Ajo, where the New Cornelia mine has developed a very large supply of potable water by means of two shafts and several thousand feet of tunnels and crosscuts at a depth of 600 feet below the surface. The shafts pass through about 170 feet of alluvium into bedrock of Batamote andesite. The water is pumped by electrically driven pumps through two pipe lines to the reservoir at Ajo, 6 miles away and 1,200 feet higher than the water surface in the "watermine." This so-called watermine is a remarkable monument to the ingenuity and engineering skill of the men who developed the Ajo mine and built here a modern city in the midst of a desert.

The water from the watermine has a content of 2.4 parts per million of fluorine,[3] a quantity sufficient to cause "mottled teeth" in the children who drink it regularly, but adults can drink it without ill effects. Many of the towns-

[3] Smith, H. V., Determination of fluorine in drinking water: Ind. and Eng. Chem., vol. 7, p. 23, 1935.

people of Ajo import water for their children; others obtain their supply from Sneed Ranch, where the water is free, or essentially free, of fluorine.

Smaller supplies of water, adequate for the stock range tributary to them, have been developed at much shallower depths at Batamote well, Dunn's well, Chico Shunie well, Tule well, and Salt well, and by wells at Cardigan, Childs Ranch, Sneed Ranch, and the villages of Gibson and Clarkstown. A single charco, or alluvial depression along a stream course was seen at the south border of the quadrangle, at the west edge of range 7 W. It was about 3 feet deep, 100 feet long, and 10 to 30 feet wide (see pl. 1, *F*) and held water for several weeks after a rain.

CLIMATE AND VEGETATION

The climate of the Ajo country is that of the Sonoran Desert. The temperature range in 1932 was from 113° F. to 28° F., with 100° a very common occurrence. Rain is rare and very irregularly distributed both in time and place. The annual rainfall has averaged about 10 inches during the 20 years in which records have been kept. The altitude range in the quadrangle is so little that the rainfall records at Ajo are probably reasonably representative of conditions throughout the quadrangle. July and August are the months with the greatest moisture, and there is a second moist period in December and January. February and March have the least precipitation.

According to the classification of Merriam,[4] the vegetation belongs to the Lower Sonoran zone. Despite the aridity, trees are widely distributed. The commonest, the palo fierro or ironwood, flourishes over most of the pediments but is not so widely present on the alluvium of the valleys. It is commonly a few inches in diameter and as much as 30 feet high. The mesquite, a tree of much the same form and size, seems to prevail in the alluvial valleys but is not common on the rocky soils of the mountains. The palo verde, a bizarre tree with bright green trunk and branches, is very common and is ordinarily 6 inches to a foot thick and 20 to 30 feet high. All these trees are thorny legumes. The ocotillo, a very striking tree, consists of a group of long, slender, gracefully curving branches that rise and diverge from a central clump near the ground. Other trees, generally found along the watercourses, are catsclaw and desert willow.

The commonest cacti are the cholla (several varieties), the sahuaro or giant, the bisnaga (barrel), and the organpipe. The creosote bush is very widely distributed over all the valleys and is probably the most characteristic plant of the region.

PREVIOUS WORK

Aside from brief notes on the early reconnaissance in the Papago country and incidental mention in the mining press of the geology immediately around the mine at Ajo, the first systematic paper to deal with the area was published in 1914 by Ira B. Joralemon,[5] at that time geologist of the New Cornelia Mining Co. This paper, though written at an early stage in the development of the mine, is an excellent account of the mining geology. Joralemon recorded the occurrence of "rhyolites" (Concentrator volcanics of this paper) as the country rock of the monzonite mass, which he regarded as a laccolith. The "conglomerate" to the east and south of the mine (Locomotive fanglomerate of this piper) he recognized as post mineral, but he reached no conclusion as to its age with reference to the andesite and basalt flows of the surrounding region (Batamote andesite of this report). The sulfide ore of the New Cornelia mine was recognized as primary, and the absence of leaching of the oxidized zone was attributed to the poverty of the ore in pyrite.

Bryan[6] made a reconnaissance of the entire Papago country in 1917. He regarded the lavas of Black Mountain (Batamote andesite) as conformably overlying the conglomerate of the Ajo Peaks (Locomotive fanglomerate) and recognized that Black Mountain is faulted down with respect to the country to the west. He also described in some detail the pediments around the Little Ajo Mountains and incidentally mentioned that they are in part cut on gneiss (Cardigan gneiss of this report). His attention was primarily directed toward ground-water problems and physiography, and neither he nor Joralemon attempted a systematic study of the geology of the district.

An excellent concise description of the geology of the New Cornelia ore body and the mining methods there employed appeared in 1932.[7] The diorite along the east side of the ore body was stated to be an earlier intrusive than the monzonite. In other respects the paper follows the interpretations of Joralemon in its essentials.

A brief digest of the geology of the New Cornelia mine, based on the present work, was published in 1935,[8] and a more extended summary was published in 1937.[9] All other papers that discuss the Ajo district treat of the many outstanding technical accomplishments at Ajo rather than the nature of the ore deposit.

FIELD WORK AND ACKNOWLEDGMENTS

The field work upon which this report is based was begun in April 1932 and continued to June 1932. During this season attention was concentrated upon the area em-

[4] Merriam, C. H., The geographic distribution of life in North America: Biol. Soc. Washington Proc., vol. 7, pp. 1-64, pl. at end of paper, 1892.

[5] Joralemon, I. B., The Ajo copper-mining district; Am. Inst, Min. Eng. Trans., vol. 49, pp. 593-610, 1914.

[6] Byran, Kirk, The Papago country, Arizona; U. S. Geol. Survey, Water-Supply Paper 499, pp. 208-210, 1925.

[7] Ingham, G. R., and Barr, A. T., Mining methods and costs at the New Cornelia Branch, Phelps Dodge Corporation, Ajo, Ariz.; U. S. Bur. Mines Inf. Circ. 6666, 1932.

[8] Gilluly, James, The Ajo district, Arizona: 16th Internat. Geol. Cong., Copper Resources of the World, vol. 1, pp. 228-233, 1935.

[9] Gilluly, James, Geology and ore deposits of the Ajo quadrangle, Ariz.: Arizona Bur. Mines Bull. vol. 8, No. 1, 1937.

bracing and immediately surrounding the New Cornelia mine at Ajo, shown on plate 21. Because it was hoped that a study of the regional geology of a larger area might throw helpful light upon the local problems, it was the original plan that this detailed study might be expanded to embrace the entire quadrangle. However, owing to decreased funds, the Geological Survey was unable to continue the project as planned, and further work was delayed until, in the autumn of 1933, the Geological Society of America, through the Penrose Fund, made a generous grant that made possible the extension of the study to the larger area originally planned for. I wish to record my appreciation of the grant, which enabled me to complete the mapping of the quadrangle between October 1933 and April 1934.

It is a pleasure to acknowledge the cordial cooperation of the Phelps Dodge Corporation, through Mr. Michael Curley, at that time manager of the New Cornelia Branch, in making available much of their material on the ore deposit. Mr. Alfred T. Barr, Chief Engineer of the operation, cordially cooperated in many ways.

During the field season of 1932 Lincoln A. Stewart served as assistant and during the following winter did considerable work on the mineralogy of the New Cornelia ores, the summary results of which are incorporated in this report. Mr. Edward Sandberg, who had been for several years a member of the engineering staff of the New Cornelia mine, aided greatly in a study of the drill cores in the possession of the company. W. T. Schaller, J. J. Glass, C. F. Park, Jr., and C. S. Ross contributed to the mineralogic sections of the report, and G. H. Girty and Edwin Kirk made the paleontologic determinations. K. E. Lohman made many of the photomicrographs. I am indebted to my colleagues W. W. Rubey, W. H. Bradley, and C. H. Dane for helpful discussions of some sections of the report and especially to T. B. Nolan, also of the Survey, for a stimulating 2-day visit in the field and for frequent discussions during the preparation of the manuscript.

DESCRIPTIVE GEOLOGY

GENERAL FEATURES

The rocks of the Ajo quadrangle range in age from probable pre-Cambrian to Recent. Owing to the absence of indigenous fossils in any of the formations, the ages are largely problematic and can only be inferred indirectly.

The formations recognized include: injection gneiss and hornblendite, both regarded as pre-Cambrian; hornfelsed lavas and sedimentary rocks of possible Paleozoic age; sheared quartz monzonite, perhaps of Mesozoic age; siliceous to intermediate volcanics, tentatively regarded as Cretaceous; quartz monzonite and its quartz dioritic border facies, perhaps of early Tertiary age; fanglomerate and two varieties of andesite, referred to the middle Tertiary; conglomerate, latite, basaltic andesite, and basaltic breccia, of perhaps Pliocene age; and alluvium, Pleistocene and Recent. The thicknesses are practically all uncertain. They are shown schematically in figure 3. The regional correlation of these rocks is entirely speculative, as no detailed mapping has been done for many miles in all directions.

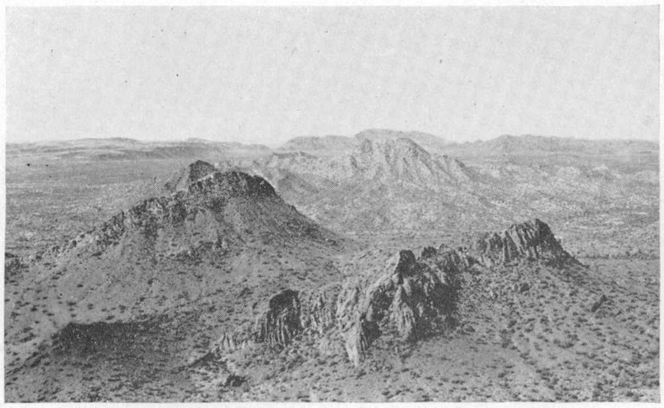
The structure of the pre-Cretaceous rocks is obscure and not directly to be read from their distribution. They were affected during several pre-Cretaceous periods of metamorphism, the most outstanding of which were a presumably pre-Cambrian period of widespread injection metamorphism and a later, perhaps Mesozoic, period of pervasive shearing.

The structural features that control the present distribution of the formations and directly or indirectly the present distribution of the mountain masses and valley blocks are post-Cretaceous normal faults. These are of at least three ages. The earliest of these faults, north-northeasterly in trend, is younger than the early Tertiary (?) quartz monzonite and older than the fanglomerate. A second fault is of west-northwesterly trend and separates the middle Tertiary andesitic formations. A third group of faults is probably Pliocene in age and includes faults that trend north-northeast, north, and north-northwest. This set appears to control, in large part, the present topography.

The surface features of the area are the result of desert erosion of the fault-block mosaic that was left after the Pliocene faulting. They include mountains of two sorts, wide rock-floored plains or pediments and alluvial slopes that compose the "valley" areas. The older more massive or heterogeneously oriented rocks are carved into sierra-type mountains, with sharp ridges and needle peaks. The more gently inclined basaltic andesite flows, on the other hand, form mesa-and-cuesta topography and are bordered by huge talus piles. Their peaks are not sharp, except where they occur in narrow blocks. The rock-floored sloping plains or pediments border the sierra-type mountains and merge outward into the alluvial slopes. The mesa-type mountains are bordered directly by alluvium.

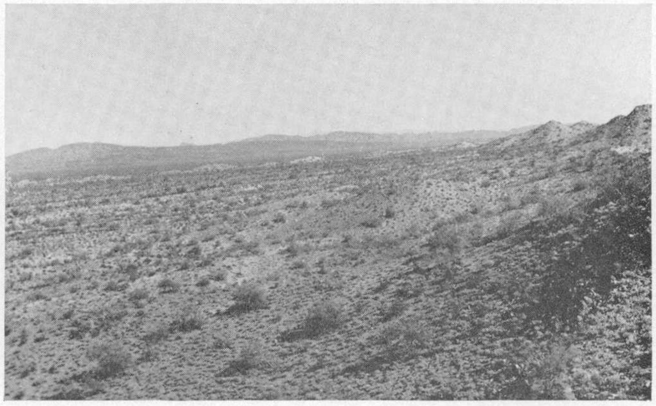
The great copper mine at Ajo is opened in a low-grade deposit of chalcopyrite and bornite disseminated in a mass of the quartz monzonite that is here tentatively referred to the early Tertiary.

The rock formations of the Ajo quadrangle are shown on the geologic map, plate 3, and their relations and character are indicated in figure 3 and the accompanying table. It will be noted that there are strong angular unconformities beneath the Concentrator volcanics, Locomotive fanglomerate, Sneed andesite, Daniels conglomerate, and Batamote andesite, as well as the Quaternary alluvium. Since none of the formations have yielded fossils, except the Paleozoic boulders found in the Locomotive fanglomerate, correlation and geologic dating of the formations are uncertain.



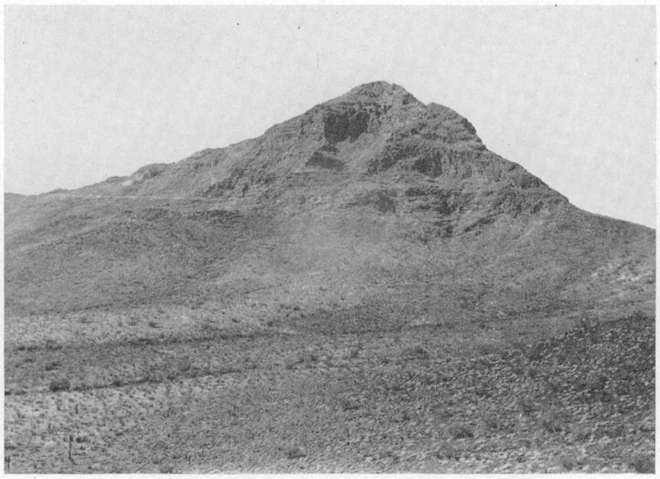
A. VIEW WEST FROM AJO PEAK.

Hogback ridges in the foreground, light-colored western hills of the Little Ajos in the middle ground, and Growler Mountains on the sky line. The hogbacks are Locomotive fanglomerate capped by Ajo volcanics. The lighter hills are Chico Shunie quartz monzonite, with Cardigan gneiss on the lower right-hand slopes. Pediment along Chico Shunie Arroyo at extreme left middle ground.



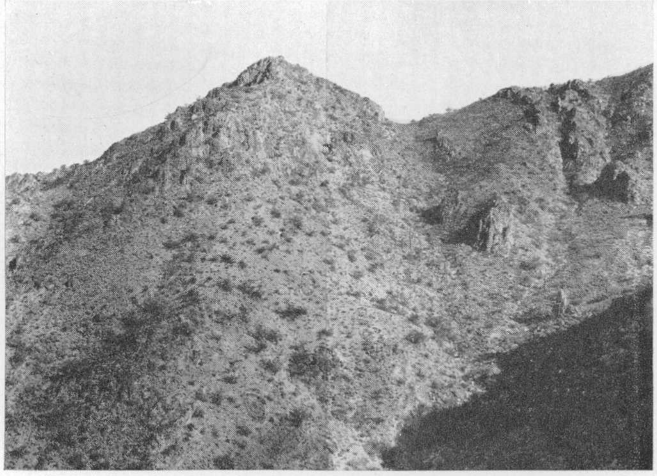
B. NORTH BASE OF LITTLE AJO MOUNTAINS AND THE PEDIMENT FRONTING IT, LOOKING NORTHEASTWARD FROM NORTHWEST SPUR OF THE LITTLE AJOS.

Batamote Mountain on sky line at left and Pozo Redondo Mountains in the middle sky line. These are lava hills. The light-colored hillocks standing above the pediment in the left middle ground are residua of Cornelia quartz monzonite, above the pediment. The valley of the Ajo lies between them and Batamote Mountain.



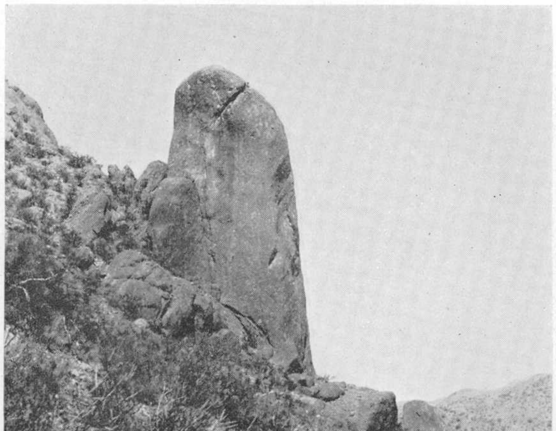
C. BLACK MOUNTAIN FROM THE NORTHEAST.

Composed of Batamote andesite. Note steep debris slopes below the cliffs and the uneven topography at the base in contrast with the smooth pediment carved on quartz monzonite, shown on *B*.



D. APLITE DIKES ON ONE OF THE HIGHER SPURS IN THE NORTHWESTERN PART OF THE LITTLE AJO MOUNTAINS, VIEWED FROM THE WEST.

The smooth hill slopes are equigranular Cornelia quartz monzonite. The craggy outcrops are aplite, commonly with blending contacts against the coarser-grained rock. The dikes dip steeply to the left (north).

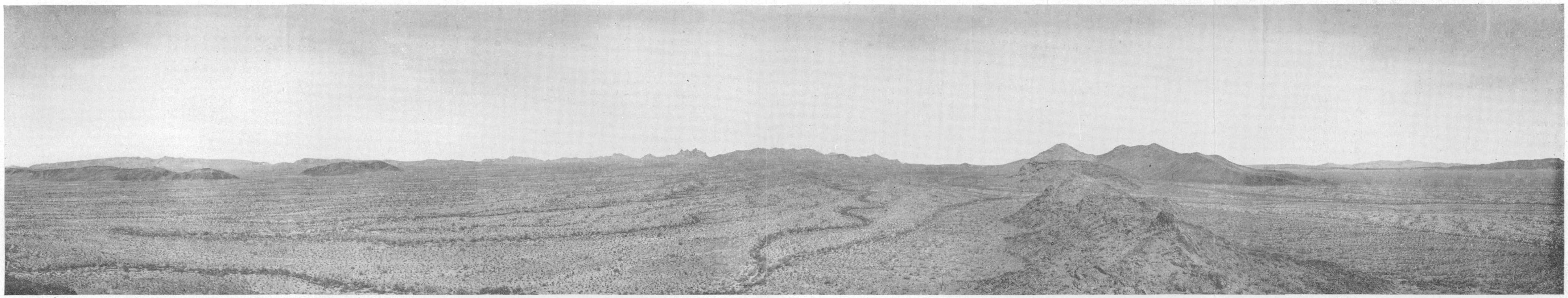


E. MASSIVE MONOLITH OF LOCOMOTIVE FANGLOMERATE FORMING A BOLD CRAG ON THE NORTHEAST FACE OF NORTH AJO PEAK.

The formation dips into the peak at about 50°, as shown by gash near top.

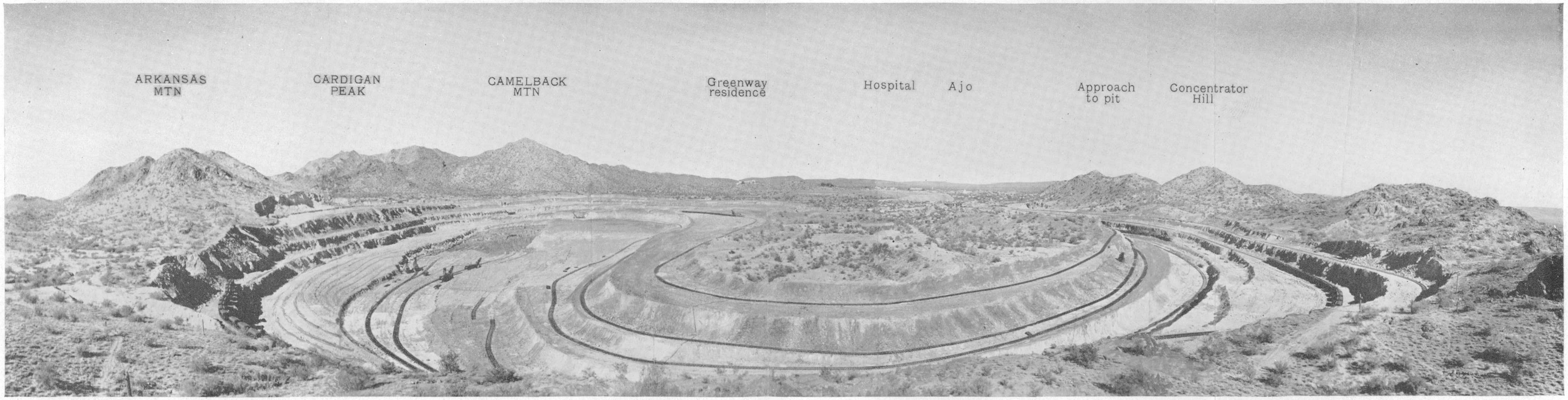
F. CHARCO AT WEST SIDE OF SEC. 31, T. 13 S., R. 6 W., NEAR SOUTH EDGE OF QUADRANGLE.

The cattle-trampled water hole had received no rain for several weeks prior to the time of photographing. Alluvial banks about 2 feet above water. Mesquite trees on both sides.



A. PANORAMA FROM 2,172-FOOT HILL SOUTHWEST OF BLACK MOUNTAIN.

Extreme left is west. Shows pediment and alluvial slope in foreground, hill of Cardigan gneiss and Daniels conglomerate overlain by Batamote andesite in middle ground, Growler Mountains on sky line at left. Butte in left center is of Batamote andesite. Pinnacles in left center are the Ajo Peaks, with the main mass of the Little Ajos on the sky line to their right. Black Mountain on right center. The ragged hills in the foreground leading toward the high peak of Black Mountain are of Childs latite. Valley of the Ajo on right, with Pozo Redondo Mountains at extreme right.



B. PANORAMA OF NEW CORNELIA MINE FROM THE SOUTH, FEBRUARY 1934.

Hills at extreme right hide waste dumps and valley of the Ajo.

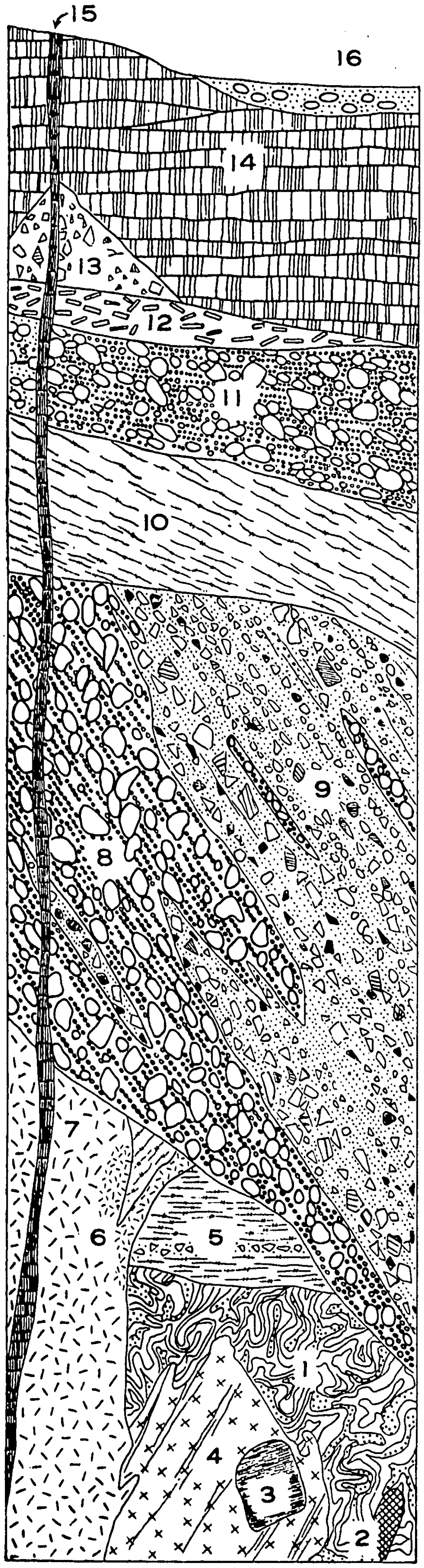


FIGURE 3.—Generalized diagrammatic section illustrating the principal rock formations and their age relations in the Ajo quadrangle.

Sequence and character of rocks in the Ajo quadrangle

No. on fig. 3	Formation	Thickness (feet)	Lithology and remarks	Age
16	Alluvium.	800+	Stream gravels, sand, and silt, largely unconsolidated but locally cemented with caliche.	Pleistocene and Recent
	Unconformity			
15	Batamote andesite. Basalt.	(?)	Dense to coarsely crystalline hypersthene olivine basalt forming dikes associated with old volcanoes. Includes some olivine andesite in the Childs Mountains.	Pliocene (?)
14	Batamote andesite. Basaltic andesite.	1,500+	Basaltic olivine-andesite, augite andesite, and some hornblende andesite in flows 20 to 60 feet thick. Constitutes Black Mountain, Batamote Mountain, and most of Childs Mountain.	Pliocene (?)
13	Batamote andesite. Basaltic breccia.	300+	Scoriaceous red basalt and andesite breccia forming what is probably the throat of a volcano (Batamote Peak) and cinder cones (Childs Mountain). Some older and some younger than 14 and 15 but probably little age difference between them.	Pliocene (?)
	Unconformity?			
12	Childs latite	700±	Augite latite, coarsely porphyritic, in thick flows of aa and block lava. May be intercalated in Batamote andesite. Probably related to Hospital porphyry dikes.	Pliocene (?)
11	Daniels conglomerate	200+	Coarse stream gravels, partly cemented. Includes a little interbedded quartz latite.	Middle (?) Tertiary.
	Unconformity			
10	Sneed andesite.	3,000?	Hornblende andesites, commonly much altered. Largely flows but some breccias.	Middle (?) Tertiary.
	Unconformity			
9	Ajo volcanics.	3,500-5,000+	Biotite and hornblende andesite tuffs and breccias passing upward into flows. Interfingers with Locomotive fanglomerate.	Middle (?) Tertiary.
8	Locomotive fanglomerate.	6,000-12,000	Chiefly coarse alluvial fan deposits, poorly sorted and interbedded with tuff and breccia. Some sandstone and shale toward the top and in southeasterly exposures. Interfingers with Ajo volcanics.	Middle (?) Tertiary.
	Unconformity			
7	Cornelia quartz monzonite (main facies).	(?)	Porphyritic to equigranular quartz monzonite, cut by aplite dikes and a few small pegmatites. Forms stock with crosscutting contacts. Carries ore of New Cornelia mine.	Early Tertiary (?)
6	Cornelia quartz monzonite (dioritic border facies).	(?)	Fine-grained equigranular diorite, locally with poikilitic orthoclase. Forms discontinuous slightly older border around 7.	Early Tertiary (?)
5	Concentrator volcanics.	Several hundred to perhaps 3,000+	Andesite, keratophyre, and quartz keratophyre flows, breccias, and tuffs, highly altered and of complex structure.	Cretaceous (?)
	Unconformity			
4	Chico Shunie quartz monzonite.	(?)	Quartz monzonites, mostly sheared, some partly or wholly recrystallized. As mapped on plate 3, includes some potash granite, albite granite, quartz diorite, and trondhjemite, which may be of several ages.	Mesozoic (?)
3	Hornfels.	1,000±	Altered sandstone, shale, andesite, and rhyolite, hornfelsed by Chico Shunie quartz monzonite, in which they occur as inclusions.	Paleozoic (?)
	Unconformity			
2	Hornblendite.	(?)	Massive to foliated dark-green rocks in small rounded masses in Cardigan gneiss.	Pre-Cambrian (?)
1	Cardigan gneiss.	(?)	Contorted gneiss, showing injection features and refoliation, possibly of two ages. Probably chiefly of igneous (quartz dioritic) origin.	Pre-Cambrian (?)

CARDIGAN GNEISS

DISTRIBUTION AND TOPOGRAPHIC EXPRESSION

The Cardigan gneiss is exposed over about 8 square miles of the Ajo quadrangle.[10] The principal area of outcrop extends from Gibson Arroyo and the prospect called Cardigan, from which the formation is named, westward along the lower southern slopes of Cardigan Peak and occupies most of the range of hills between Copper Canyon and Chico Shunie Arroyo. Smaller exposures are found in the long northwestern spur of the Little Ajos, which extends to the pass just west of Salt well; in the low hills between Tule well and the west edge of the area; and scattered over the Chico Shunie Hills, where there are many large and small inclusions of gneiss in the Chico Shunie quartz monzonite. As pointed out on pages 16 and 17, all of these inclusions are not properly referred to this formation, although many undoubtedly are.

The Cardigan gneiss characteristically forms somber, brownish-gray rolling hills, with subdued irregularities and few sharp peaks or cliffs. It is perhaps the least resistant to erosion of the bedrock formations and, on the whole, is the least well-exposed.

RELATIONS TO OTHER FORMATIONS

The Cardigan gneiss is the oldest formation in the quadrangle and serves as the basement upon which the supracrustal rocks were deposited and as the country rock into which the subcrustal rocks were intruded.

PETROGRAPHY

The Cardigan gneiss includes rocks of many varieties. Different facies range in color from dark brownish-gray through greenish-gray to very light silvery-gray and in texture from almost massive granitic through crudely foliated gneissic to extremely fissile schistose. Despite this diversity in the appearance of the rocks, their mineral composition is astonishingly uniform. With few exceptions the several rock varieties that constitute the gneiss are distinguished by the proportions of their constituent minerals and their textural and structural relations rather than by the mineral species occurring in them.

MEDIUM-GRAINED, IRREGULARLY BANDED GNEISS

Perhaps the commonest variety of the gneiss is the banded, irregularly foliated variety shown in plate 4, *A*, *B*, and *D*. This variety is dark to medium gray on fresh fracture, with commonly a slightly greenish cast ascribable to chlorite. On weathering the rock becomes brown or dark brownish gray. Conspicuous banding is due to layers 0.5 millimeter to 3 centimeters thick of almost dead-white feldspar and subordinate quartz alternating with layers of greenish-brown biotite, with or without chlorite. This banding is commonly highly irregular even in hand specimens and is cut by dikelets and veins of more massive and porphyritic dioritic rock, forming a typical injection gneiss. (See pls. 4, *C*, *E*, and 5, *A*.) Locally small nests of pink feldspar are common, and in places quartz forms irregular masses and veins. (See pl. 5, *B*.)

The minerals seen in hand specimens are white feldspar in crystals 0.5 millimeter to 2 millimeters long; quartz, rarely exceeding 1 millimeter in size; muscovite, chiefly in small flakes but in places as much as 2 centimeters across; and chlorite in crystal forms as much as 1 millimeter in diameter that represent original biotite or hornblende.

The dominant minerals of this variety are plagioclase, quartz, chlorite, biotite, and muscovite. The plagioclase is commonly altered in whole or in part to aggregates consisting of sericite, with a little zoisite or epidote, set in a base whose optical properties, where determinable, correspond with those of albite. In some specimens andesine near An_{35} is residual in the cores of such saussuritic aggregates or lies centrally in lenses between foliation surfaces lined with chlorite, along which sericitization or saussuritization has been intense. Near the border of the Cornelia quartz monzonite, andesine, or oligoclase-andesine, is more common than sericitic and saussuritic feldspars and in some rocks occurs to the exclusion of such aggregates. Such feldspars are also found at a few other localities apparently capriciously distributed through the gneiss.

Quartz is much more prominent in thin section than in hand specimens. Even the rather dark varieties of gneiss commonly contain at least 35 percent of quartz by volume, and some, in which veining is more conspicuous, contain more than 50 percent despite their rather dark-gray color.

A little microcline (and possibly orthoclase) occurs in some specimens of this variety. It rarely exceeds 5 percent of the rock by volume. Most of it is quite unaltered, although it locally contains a few wisps of muscovite. Most specimens rich in microcline are readily recognized by their pinkish hue; some, however, are gray and indistinguishable in hand specimen from the gray plagioclase-quartz-chlorite rock just described.

Chlorite is the commonest dark mineral but rarely exceeds 15 percent of the rock by volume. Some of it forms pseudomorphs after amphibole, but most of it is an alteration product of biotite, remnants of which are very common.

Biotite is common and, in part, oriented in the foliation, owing to mineral banding, but there is much biotite oriented apparently at random, both as respects grain shape and crystal lattice. The larger muscovite crystals are apparently only slightly, if at all, governed by the foliation, although the smaller crystals are crudely oriented parallel to it. Some muscovite is in parallel intergrowth with chlor-

[10] Gilluly, James, Geology and ore deposits of the Ajo quadrangle, Ariz.: Arizona Bur. Mines Bull., vol. 8, No. 1, p. 14, 1937.

ite; in these specimens both doubtless represent replaced biotite. Sericite has its usual habit. Hornblende was found only near younger intrusive bodies and there only in small amount.

Pistacite and carbonate are locally present but are not characteristic of this facies. Where they occur they are usually in cracks cutting the foliation. Magnetite, which in some specimens is strung out along the schistosity, locally makes up several percent of the rock but is chiefly accessory, with zircon, apatite, sphene, leucoxene, and locally tourmaline.

The textures of the commonest varieties are dominantly crystalloblastic (with completely recrystallized minerals), with some suggestion, locally rather pronounced, of cataclastic (brecciated) texture. Quartz in some specimens appears to vein the other minerals; in others it forms a mosaic enclosing them. The foliation seems to be more a result of alternation of bands of different mineral composition than of a parallel arrangement of the individual grains. (See pl. 5, *C*.) Nevertheless, there is generally a very crude parallelism of the long dimensions of the grains of feldspar, quartz, and mica, and in some specimens chlorite forms thin curving sheaths (phyllonitic skins) along the foliation. Some of the chlorite, however, also occurs in rosettes. Aside from the thin chlorite sheaths there is no pronounced crystallographic parallelism of any minerals, even of biotite, although in the absence of statistical analysis this apparent lack may be overemphasized.

There is a wide variation in composition of superficially similar rocks of this facies. Two representative specimens have been analyzed, Nos. 1 and 2, table 1, page 12, and their composition and origin are further discussed in connection with those of other facies of the gneiss.

FINER-GRAINED GNEISS

Finer-grained facies are subordinate but common in the formation. As a rule they are less siliceous and feldspathic and hence darker than the average gneiss. (See the dark ground of pl. 4, *D*, *E*, and the darker margin of pl. 5, *C*.) Near contacts of the Cornelia quartz monzonite this variety is hornblendic and contains unaltered feldspar, generally less than 0.2 millimeter in diameter, with little chlorite or epidote except along cracks younger than the foliation. Representative specimens contain approximately 35 percent of hornblende, 45 percent of andesine near An_{40}, 10 percent of quartz, 5 percent of orthoclase, and minor amounts of ilmenite, magnetite, apatite, epidote, and chlorite. Other less common facies are mottled hornfels and carry a little augite and biotite with or without microline. They show granulitic or sieve textures, and many show feldspars clouded by opaque, metallic-appearing inclusions, such as are common in contact-altered igneous rocks.

Still others are relatively coarse-grained rocks of apparently similar original composition but so silicified that they have become quartz-biotite-chlorite granulites. Some show replacement by microline also. Away from the intrusive contact of the Cornelia quartz monzonite the finer-grained dark gneiss is almost everywhere a confused mat of chlorite, saussurite, sericite, and subordinate quartz, with minor quantities of magnetite, leucoxene, and locally hematite. Radiating "mat" textures resulting from hydrothermal alteration are characteristic.

AUGEN GNEISS

A rather common variant of the gneiss contains white lens-shaped masses or augen of feldspar or less commonly of quartz, 5 millimeters or less in diameter. These augen are set in a dark streaky chloritic base which also contains sporadic biotite and muscovite flakes about half a millimeter wide. Under the microscope the augen are found to be andesine (An_{35}), oligoclase (near An_{20}) or, in some specimens, sericitic or zoisitic aggregates in an albitic base. They are round, ellipsoidal, or lens-shaped, doubtless from crushing, but are now almost wholly recrystallized. The groundmass features are like those of the more equigranular varieties described. A specimen of this small-augen gneiss has been analyzed (No. 3, table 1), and its composition is further discussed on page 13.

SCHIST

A few albite-chlorite-sericite-quartz schists with marked parallel-scaly (lepidoblastic) texture are present in the Cardigan gneiss. They are not regularly distributed and do not seem separable from the main body. Although extreme examples contain as much as 50 percent of sericite and others 25 percent of chlorite with considerable carbonate, they do not differ mineralogically from the gneisses, except in the proportions of their minerals. Some contain "micro-augen" like the larger ones just described. A few rocks, apparently of this character originally, have been thoroughly silicified along crush zones and are now more than two-thirds quartz, although superficially they resemble the chlorite schists just mentioned.

QUARTZ-DIORITE GNEISS

A widespread component of the Cardigan gneiss is a crudely foliated to practically massive variety. It is very light-gray, porphyritic, and occurs intimately interbanded with and transecting the darker equigranular gneisses, and forms injected bands and highly contorted (ptygmatic) folds in that rock. Such masses are rarely more than 20 or 30 feet wide and are commonly very much narrower. Locally these injected bands are so numerous that the rock has become a true injection gneiss. Such gneisses are especially common northwest of Cardigan and near Tule well, but they apparently are not derived from the large intrusive masses (the Chico Shunie and Cornelia intrusives) now exposed in the quadrangle, as these intrusives transect the banding of the gneisses. The gneiss clearly has been altered to hornfels by the Cornelia quartz monzonite, but such definite evidence of age difference has not been noted along the contacts of the Chico Shunie quartz monzonite. The nearly massive facies is illustrated on plate 5, *C,* the injection facies on plate 4, *B, E,* and the ptygmatic layers on plate 4, *E, F.*

For the most part this rock is conspicuously porphyritic, with white feldspar and subordinate quartz phenocrysts ordinarily ranging in size from 0.5 millimeter to 1 centimeter but with sporadic subhedral crystals as much as 4 centimeters across, set in a finer groundmass of pinkish or greenish-gray cast. Some of these massive facies are equigranular (1 to 3 millimeter grains) throughout. In some specimens muscovite forms large flakes. Crystals originally of hornblende or biotite but now replaced by chlorite are locally present. The largest are more than 3 millimeters long.

In thin section this porphyritic rock shows dominant plagioclase and quartz, with a little microline (exceptionally up to 20 percent), sericite or muscovite, chlorite (exceptionally a little biotite), some epidote, and accessory apatite, zircon, magnetite, and sphene. A few specimens show normally zoned andesine feldspar (An_{50} to An_{30}), but in most the plagioclase is represented by sericitic aggregates in an albitic base. Other specimens have clear oligoclase or even albite border zones around central cores. These cores are dominantly sericitic; some are in part zoisitic. Microcline seems more plentiful in the equigranular varieties of this more massive facies, but not uniformly so. It constitutes as much as 40 percent of some specimens but is absent from others. Its relations suggest strongly that some of it has formed by replacement of plagioclase, but it is impossible to be sure how much is of this origin. Tourmaline, dichroic in green, is a common accessory.

Two specimens of this porphyritic injection gneiss have been analyzed—columns 4 and 5, table 1. They were selected to show coarse-grained and fine-grained facies.

Narrow seams of quartz and feldspar having a composition essentially similar to these more massive facies form thin veins with ptygmatic folding in the darker gneiss. (See pl. 4, *F.*)

MINOR VARIETIES

Some pegmatitic facies of the gneiss also occur, with pink microline, white oligoclase, and quartz in crystals as much as 3 or 4 centimeters on a side and a little interstitial muscovite, sericite, and chlorite.

Many very large and innumerable small bodies of Cardigan gneiss occur as inclusions in the Chico Shunie quartz monzonite. These commonly preserve some suggestion of their original gneissic structure but are flecked with poikilitic crystals of mica and chlorite that are oriented at random and enclose the original minerals of the gneiss. In thin section they commonly show remnants of the older foliation, but it is contained as ghostlike (helicitic) remnants in the enlarged crystals (poikiloblasts) of biotite or is largely obliterated by the development of rounded granules of quartz and plagioclase at random throughout the rock. The smaller inclusions become merely scattered darker clots in the enclosing rock, which is obviously greatly contaminated.

COMPOSITION

The following five specimens, representing the most diverse of the common facies of the gneiss, were selected for analysis.

TABLE 1.—*Analyses of specimens of Cardigan gneiss*
[Charles Milton, analyst]

	1	2	3	4	5
SiO_2	70.78	77.23	68.21	62.13	65.48
Al_2O_3	14.15	8.61	15.15	18.59	16.39
Fe_2O_3	3.19	4.25	3.14	2.09	1.31
FeO	2.00	1.97	2.26	3.24	2.32
MgO	1.60	1.11	1.88	1.72	1.56
CaO	.71	1.57	2.57	3.10	2.93
Na_2O	2.16	2.20	3.47	4.09	3.63
K_2O	2.95	.81	1.44	2.36	3.14
H_2O+	1.33	.81	1.32	1.67	1.40
H_2O-	.14	.07	.17	.29	.20
CO_2	.15	.05	.12	.13	.54
TiO_2	1.08	1.19	.90	.79	.80
ZrO_2	.03	.07	.02	.04	Trace
P_2O_5	.04	.04	.06	.04	.10
S	.06	.01	.05	.12	.12
MnO	.02	.03	.03	.04	.01
BaO	.03	.02	.06	.07	.07
	100.42	100.04	100.85	100.51	100.00

1. Fine-grained (½ mm. maximum), medium gray, irregularly foliated gneiss, composed of quartz, sericite, albite, chlorite, and accessories. Crystalloblastic texture. From NE¼ sec. 29, T. 12 S., R. 6 W.

2. Millimeter-grained pinkish gray irregularly foliated gneiss. Very quartzose, with andesine, biotite partly altered to chlorite, muscovite, and accessories. Crystalloblastic texture. From NE¼ sec. 29, T. 12 S., R 6 W.

3. Millimeter-grained crudely foliated gneiss with augen of saussuritic feldspar as much as 4 mm. long. Quartz, albite, epidote, sericite, chlorite, muscovite, hornblende (little), and accessories. Cataclastic texture. From SW¼ sec. 28, T. 12 W., R. 6 W.

4. Poorly foliated millimeter-grained gneiss. Contains roundish andesine crystals averaging 1 mm. in diameter in a dark mass of quartz, orthoclase, muscovite, sericite, chlorite, biotite (little), epidote, and accessories. Feldspars sericitic only along cataclastic zones. Mortar texture and crystalloblastic texture both present. Forms matrix for No. 5. From NE¼ sec. 29, T. 12 S., R. 6 W.

5. Coarse light-colored nearly massive veins injecting No. 4. Plagioclase as much as 1 cm. in diameter in finer groundmass. Minerals are same as in No. 4, except that the andesine is saussuritized throughout and is veined by clear albite. Crystalloblastic-cataclastic texture. From NE¼ sec. 29, T. 12 S., R. 6 W.

The norms of these rocks, computed according to the classification of Cross, Iddings, Pirsson, and Washington are as follows:

TABLE 2.—*Norms of specimens of Cardigan gneiss*

	1	2	3	4	5
Quartz	43.02	56.34	33.56	18.84	24.36
Orthoclase .	17.79	5.00	8.34	14.46	18.35
Albite	18.34	18.34	29.34	34.58	30.92
Anorthite ..	2.78	7.78	11.95	14.46	11.12
Corundum .	6.32	1.22	3.47	3.88	2.96
ΣSalic ...	88.25	88.68	86.66	86.22	87.71
Hypersthene	4.00	2.80	4.96	7.20	5.75
Magnetite .	3.25	3.02	4.41	3.02	1.86
Ilmenite ...	2.13	2.28	1.67	1.52	1.52
Apatite	....	....	....	....	.34
Hematite ..	.96	2.24	....	....	....
ΣFemic ..	10.34	10.34	11.04	11.74	9.47
Calcite	.30	.10	.30	.30	1.20
Symbol	I(II).3.3(4).3	I(II).2(3).(2)3.4	I(II).3(4).(2)3.4	I(II).4.2(3).4	I(II).4.2.(3)4

None of these rocks are well adapted to Rosiwal measurements of the actual mineral composition. Accordingly, the chemical analyses, which were made from large specimens, have been used in connection with microscopic study to compute, approximately, the modal composition given in the following table:

TABLE 3.—*Approximate modal mineral composition of Cardigan gneiss*

	1	2	3	4	5
Quartz	48	56.5	36.5	20	26.5
Albite	An_{10} 18.5	An_{30} 18.5	An_{10} 29	An_{30} 34.5	An_{15} 31
Anorthite	1.5	7.5	3	13.5	5.5
Sericite and muscovite	21	5.5	12	9.5	8.5
Orthoclase	—	—	—	7.5	11.5
Hornblende	—	—	1	—	—
Biotite	—	3	—	1	—
Chlorite	5.5	7	7	10	8.5
Epidote	—	—	7	2	4
Sphene	1	—	—	—	1
Ilmenite and magnetite	4	2	4	1.5	2
Calcite	.5	—	.5	.5	1
Apatite	—	—	—	—	.5

Although these estimates are somewhat arbitrary, it is believed that the composition of the formation is so variable that precise determinations would have little value in any event. No reasonable number of analyses can give a basis for an accurate estimate of the composition of the formation as a whole. Nevertheless it is worthy of note that the ratios of salic to femic minerals in the five analyses are all closely similar and that the rocks all fall in subrangs represented in Washington's tables by quartz diorites and soda-rich granites. The low ratio of alumina and alkalies to silica in No. 2, and to a less extent in No. 1, throws some doubt on an interpretation of the rocks as normal igneous intrusions and suggests that they may be in part sedimentary. It should also be pointed out that pyroclastic rocks or sediments of the graywacke type might also have compositions of normal intrusive rocks; furthermore, in areas of injection metamorphism there is a common convergence of the composition of even normal sedimentary rocks with those of igneous rocks. Too much stress should, accordingly, not be laid on bulk composition as showing the origin of rocks so highly metamorphic as these. These features are discussed further in connection with the origin of the formation.

The chemical analyses in table 1 furnish the basis for computation of the parameters of the rocks according to the scheme of classification devised by Niggli.[11] The Niggli values are as follows:

	1	2	3	4	5
al	42	32	39	41	42
c	4	11	12	12	13
fm	33	40	31	26	22
alk	21	17	18	21	23
si	361	488	297	234	279

By reference to Niggli's graphs it is seen that every one of these analyses falls just on the border of the field of igneous rock analyses. Not one is definitely outside of the range of composition of igneous rocks, yet they are all so close to the border that they could be regarded as intermediate, chemically, between "normal" igneous rocks and sedimentary rocks.

ORIGIN AND HISTORY

Mineralogically, certain facies of the gneiss resemble quartz diorite very closely, although most are more or less chloritized, and only exceptionally is the microtexture that of a normal igneous rock. Most commonly the texture is crystalloblastic or more or less cataclastic, so that no unequivocal textural evidence remains to show the character of the original rock from which the gneiss was developed.

The structural features of the Cardigan gneiss, whether microscopic or large, are extremely irregular. It is difficult to measure the predominant attitude of the foliation, as it changes greatly and without apparent system in almost every outcrop. If there is a dominant strike of the foliation it is perhaps northwesterly, but this is by no means certain. (See pl. 3.)

The oldest foliation recognizable is the mineral banding of the dark variety that is extremely contorted by later folding. (See pls. 4, *C, D, E*, and 5, *A*.) As shown both by the microscope and the chemical analyses, this banding of the dark rock by conspicuous feldspathic layers does not reflect such marked chemical contrasts as might be inferred from study of hand specimens.

[11] Grubenmann, U., and Niggli, Paul, Die Gesteinesmetamorphose, vol 1, pp. 27-42, Berlin, 1924.

The oldest recognizable stage in the history of the gneiss seems to be represented by banded gneisses of wide variety, but of which Nos. 1, 2, and 3, table 1, are representative. There is no assurance that the present chemical composition of these rocks is closely similar to their original composition, for evidences of injection and metasomatism are widespread, even in them. However, it is probable that the rocks like No. 1 and No. 3 were in large part quartz dioritic igneous rocks rather than well-sorted sediments. Rocks like No. 2, which closely resemble those like No. 1, may be ultrametamorphic injected sediments, but they seem to be subordinate and cannot be separately mapped from the others. The foliation of all these rocks, although later much deformed, seems to have been originally planar rather than contorted. In part, it may be primary injection banding, but it more probably records orogenic deformation and metamorphism at considerable depth of a quartz dioritic injection complex of predominantly intrusive origin. (See pl. 5, *C,* upper half.)

The next stage was the injection and intimate contortion of the rocks represented by Nos. 1, 2, and 3 by feldspathic intrusions, such as are represented by analyses 4 and 5 of table 1. (See pls. 4, *A, B, C, E, F,* and 5, *C.*) That this injection affected a previously foliated rock is very evident from the transection of foliation in the invaded rock. During this period the rocks were doubtless thoroughly softened and deformed. The type of folding shown in plate 4, *C, E, F,* to which Sederholm[12] has given the name "ptygmatic folding", seems to require a plasticity in the matrix approaching that of a magma. The retention of detailed banding and folding shows, however, that true fluidity was not attained, and there was clearly a difference in the viscosity of the vein material and its matrix.

The question might be raised as to whether these ptygmatic veins represent material in process of ejection from, rather than injection into, the matrix gneiss; that is, whether they are not "lateral-secretion venites" rather than "arterites."[13] The lateral-secretion theory does not seem acceptable for several reasons. Many of the veins are more feldspathic and less siliceous than their matrix and hence are less likely to be soluble or fusible at low temperatures, as would be required were they veins derived from the surrounding rock.[14] The veins are highly contorted in a manner suggesting that the pressure within them actively deformed the country rock rather than that differential pressure on the country rock deformed or opened way for the veins. Finally, the veins do not appear to be localized along zones of deformation that were active during their formation. The rocks are therefore classed as arteritic migmatites,[15] that is, mixed rocks into which the veins have been injected from an external source.

Arteritic or injection gneisses as shown by Sederholm,[16] are products of deep-seated metamorphism under conditions approaching those appropriate to magmas. Their characteristic minerals are hornblende, biotite, microline, plagioclase (not usually albite), and quartz. All these rocks are rather coarsely crystalline and distinct from the "alpine" metamorphic rocks that commonly contain such minerals as carbonates, chlorite, chloritoid, talc, sericite, serpentine, albite, and quartz in fine-grained aggregates. It is likely, therefore, that the present mineral facies of these rocks, that is, the chlorite, sericite, epidote, and albite so widespread in them, does not represent the metamorphic assemblage existent at the time of injection but is a later assemblage, stable under less intense temperature and probably under dynamometamorphic or hydrothermal conditions. It has frequently been pointed out that the "hydrothermal" minerals as a group are largely also those appropriate to dynamic metamorphism under relatively light load. Furthermore, as many of the rocks show cataclastic features related to the most prominent foliation and smeared out (phyllonitic) sheaths of chlorite along the foliation surfaces, a part of the foliation is clearly not of ptygmatic origin but is due to orogenic deformation. In some specimens the alteration of plagioclase to sericite, epidote, and albite is apparently localized along these chlorite seams. These rocks are thus products of regressive metamorphism, a low-rank metamorphism having been superposed on an originally higher-rank metamorphic series; they are therefore diaphthorites.

It is impossible to determine the relative ages of these two aspects of the regressive metamorphism, that is (1) the cataclastic reworking of the older injection foliation into a new transverse foliation (Umfaltungsclivage, see pl. 5, *D, E*) and (2) the mineral alteration to an association representative of hydrothermal rather than magmatic conditions. It might be thought that the widespread occurrence of cataclastic textures is evidence of the later superposition of mechanical deformation on the chemically altered rocks, but it is more likely that the two proceeded more or less simultaneously, as there is commonly little difference in coarseness of crystallinity between the cataclastic and crystalloblastic layers in the rock, and there is apparently a direct relation in some places between shear surfaces and chloritization and saus-

[12] Sederholm, J. J., Ueber ptygmatische Faltungen: Neues Jahrb. für Min. Geol. und Paläont., Beilage-Band 36, pp. 491-512, 1913.

[13] Holmquist, P. J., Typen und Nomenklatur der Adergesteine: Geol. Fören. Stockholm Förh. Band 43, pp. 612-613, 1921. This view has also been advocated by Eskola, Pentti, On the principles of metamorphic differentiation, Comm. géol. Finlande, Bull. No. 97, pp. 68-77, 1932, and somewhat less sweepingly by McCallien, W. J., Metamorphic diffusion, Comm. géol. Finlande, Bull. No. 104, pp. 11-27, 1934.

[14] Goranson, R. W., Some notes on the melting of granite: Am. Jour. Sci., 5th ser., vol. 23, pp. 227-236, 1932.

[15] Sederholm, J. J., On migmatites and associated pre-Cambrian rocks of southwest Finland: Comm. géol. Finlande Bull. 58, pp. 1-153, 1923; idem, Bull. 71, pp. 1-143, 1926.

[16] Sederholm, J. J., Faltung und Metamorphose im Grundgebirge und in alpinen Gebieten: Geol. fören. Stockholm Förh., Band 41, p. 249, 1919.

suritization. Furthermore, some specimens with mortar structure are cut by veins of albite with some replacement along them. The deformation was probably paracrystalline in the sense in which the term is used by Sander;[17] that is, the recrystallization of the rocks proceeded simultaneously with their deformation.

The hydrothermal impregnation was of uncertain source. It affects the Chico Shunie quartz monzonite to an extent comparable to that in the Cardigan gneiss, so is younger than the consolidation of that mass, though it is possible that both rocks owe their alteration to solutions originating in the deep-seated chamber of the Chico Shunie intrusive. During the dynamic disturbances recorded in the pervasive cataclastic structure of the Chico Shunie quartz monzonite (see pp. 19-20) these hydrothermal solutions permeated wide areas of the country to considerable depths. This alteration antedates the Cornelia quartz monzonite, because, near the Cornelia masses, the chlorite-albite-epidote facies of the Cardigan gneiss has changed toward a hornblende-andesine facies, that is, to a product of higher-grade metamorphism, accompanied by a change to a granulitic texture. Furthermore, tourmaline was developed along later joints in the Cardigan gneiss for a long distance from the Cornelia stock, and locally nests of epidote and hematite like those found in the Cornelia stock itself, were also found in the Cardigan gneiss in points that show complete independence from the features that guided these more widespread alterations.

In summary, the history of the Cardigan gneiss appears to include the following stages:

1. Intrusion of a quartz dioritic rock into an unknown country rock.
2. Shearing of the plutonic mass by orogenic movement, producing a marked foliation. This stage and the first may have been more or less contemporaneous.
3. Injection metamorphism of this gneissic quartz diorite, veining and impregnation by quartz diorite magma and related pegmatitic juices, with a little orthoclasization. The age of this injection metamorphism with respect to the intrusion of the Chico Shunie quartz monzonite is uncertain. It is very probably older than the Chico Shunie, because many inclusions in that intrusive show alteration to hornfels rather than to injection gneiss, and there is no injection but rather clean-cut transection of the Cardigan gneiss at the contact of the two rocks.
4. Cataclastic refoliation of this gneiss, with accompanying hydrothermal alteration to chlorite-albite-sericite-epidote facies. This metamorphism is thought to be younger than the intrusion of the Chico Shunie quartz monzonite.
5. Local contact-metamorphism to andesine-hornblende facies along the contact of the Cornelia quartz monzonite, with formation of some tourmaline on joints for a mile or more from the contact.
6. Epidote-hematite mineralization along a few joints, later than the Cornelia quartz monzonite.

Several other episodes, such as the local formation of hornblendites (see p. 16) and pegmatization, cannot be placed in this sequence for lack of evidence.

AGE AND CORRELATION

No direct evidence is available with which to date the Cardigan gneiss. The lithology of a formation is a notoriously untrustworthy guide to correlation. Especially is this true in southern Arizona, where, in the Santa Catalina Mountains, injection gneisses comparable in every essential detail with the Cardigan gneiss have been formed during post-Cretaceous time.[18] Similar alteration in the Dragoon Mountains, Cochise County, is also post-Cretaceous and has changed the Comanche sedimentary rocks into injection gneisses. However, the highly complex history of the Cardigan gneiss antecedent to the emplacement of the Cornelia quartz monzonite, which is itself probably not younger than early Tertiary (see p. 33), enders it unlikely that this gneiss is younger than early Mesozoic. It may be very much older; indeed it has been correlated, on the basis of reconnaissance mapping, with the pre-Cambrian.[19] This assignment seems quite reasonable and is the one tentatively adopted here.

HORNBLENDITE

DISTRIBUTION

A few small bodies of hornblendite are distributed apparently at random in the Cardigan gneiss. The largest mass in the quadrangle is about 1½ miles southeast of Tule well and is about 2,000 feet long and about 1,000 feet wide at its widest part. The only other body more than 100 feet in diameter and of sufficient size to be shown on plate 3, is about one-fourth mile northwest of Cardigan, in the west-central part of sec. 28, T. 12 S., R. 6 W., where an oval-shaped mass crops out on a low spur. Several much smaller bodies crop out in the neighborhood of Cardigan, and a few were seen south of Salt well, west of Tule well, and northwest of North Ajo Peak.

All of these outcrops are relatively conspicuous because of their dark-brown color, but their topographic expression is not greatly different from that of the enclosing gneiss.

STRUCTURAL RELATIONS

The hornblendite appears for the most part in the form of round pipes or bosses in the Cardigan gneiss. One body, 1½ miles west of Tule well, forms a narrow zone trending N. 10° W. at a slight angle to the foliation of

[17] Sander, Bruno, Gefügekunde der Gesteine, p. 114, Julius Springer, Wien, 1930.

[18] Moore, B. N., oral communication, 1935.

[19] Darton, N. H., and others, Geologic map of Arizona, prepared by Arizona Bur. Mines in cooperation with U. S. Geol. Survey, 1924.

the enclosing gneiss, which strikes N. 30° W. The foliation in the hornblende rock trends N. 80° E. and dips steeply north. There is thus no obvious relation between the structures of the rock and those of the enclosing gneiss. This body of hornblendite and another near Salt well are apparently the only ones that are strongly foliated; the others are either nearly massive or only mildly foliated. Some near Cardigan are cut by andesite dikes that are probably older than the Cornelia quartz monzonite, as well as by pegmatites probably derived from the Cornelia mass.

Contacts of the hornblendite against the gneiss are not, as a rule, well exposed, but there seems to be evidence of contact chilling of the hornblendite. The relations at the contact seem analogous to those of pegmatites, being locally abrupt and elsewhere more or less indistinct.

PETROGRAPHY

The hornblendite is dark green, slightly mottled with gray, and mostly massive, but in some specimens it is mildly foliated and, in a few, strongly schistose. The grain size of the hornblende ranges from 1 millimeter or even less to more than 4 centimeters. Minor minerals visible in hand specimens include feldspar, generally less than 1 millimeter in grain diameter, chlorite and biotite as much as 5 millimeters in grain diameter in the schistose specimens, muscovite plates as much as 5 millimeters across in some massive specimens, and sporadic pyrite cubes as much as 2 millimeters on a side.

In thin section the hornblendite is seen to be composed of hornblende 60 to 80 percent, plagioclase or its alteration products 10 to 20 percent, magnetite 3 to 5 percent, and generally minor amounts of quartz, sericite, chlorite, epidote, sphene, apatite, and zircon. A little garnet (species undetermined) occurs in one specimen. The hornblende is apparently all of the same variety, optically negative, with extinction angle of 21°, pleochroic, with Z blue-green, Y deep olive-green, and X light yellow-brown. The plagioclase is commonly saussuritic, but a little residual labradorite was seen in one specimen and andesine in another.

The texture is commonly interlocking, with the predominant hornblende in a matrix of plagioclase and quartz and poikilitically enclosing them. The foliated varieties show more or less parallelism of the hornblende prisms, and some of the most schistose have biotite, or chlorite derived from biotite, along the schistosity. In addition to the epidote and zoisite associated with the saussurite, there is, in some specimens, considerable epidote on joints that cut the foliation.

ORIGIN

The microstructure and contact relations of the hornblendites seem to be entirely compatible with either of two possible modes of origin. They may be normal igneous rocks emplaced at considerable depths, or perhaps they may be in part hydrothermal replacement masses representing basic analogs of the pegmatites. The coarse grain and apparent local gradational relations with the country rock perhaps suggest the second possibility but are certainly not conclusive. Exposures are not adequate to show how generally they obtain, and there is considerable evidence that hornblendites in other regions are normal magmatic rocks.[20]

AGE AND CORRELATION

The hornblendites are younger than the Cardigan gneiss in which they are enclosed. As they are slightly foliated compared to the gneiss, and as foliation, where present, is independent of that in the gneiss, they must be younger than the injection metamorphism of the gneiss. They are definitely older than the Cornelia quartz monzonite. Their relations to the Chico Shunie quartz monzonite are uncertain, and it is possible that they are of a common parentage with that rock. There is, however, no direct evidence of this, and they are here classed, very doubtfully, as pre-Cambrian.

HORNFELS IN CHICO SHUNIE MONZONITE DERIVED FROM SUPRACRUSTAL ROCKS

DISTRIBUTION

The Chico Shunie quartz monzonite, described on pp. 17-20, contains innumerable inclusions, particularly in the area south of Chico Shunie Arroyo. These inclusions range in size from dark clots a few millimeters across to blocks more than a mile long by 1,500 feet wide. Many of the larger inclusions are readily identifiable as hornfels of two varieties—one derived from the Cardigan gneiss and the other from sedimentary rock or porphyritic lava. Most of the smaller xenoliths are so much altered that their composition prior to their inclusion in the Chico Shunie magma is not apparent. The smallest are merely aggregates of dark minerals and, were it not for the wide distribution of the intermediate sizes, could not be distinguished from early facies of the Chico Shunie stock itself.

PETROGRAPHY

The inclusions that obviously are of Cardigan gneiss are described briefly on page 12. Those of sedimentary and volcanic rock, which are of more interest as bearing upon the historic geology, are described here.

The inclusion showing the best preserved sedimentary features and the only one large enough to show on plate 3 is the one trending northeastward about 1½ miles southwest of Chico Shunie Indian village. Next to this inclusion the Chico Shunie intrusive is slightly finer-grained than usual. The very border of the inclusion is locally

[20] Reynolds, D. L., The genetic significance of biotite-pyroxenite and hornblendite: Min. Pet. Mitt., Band 46, pp. 447-490, 1935.

schistose, but within a few feet of the contact the foliation vanishes and the rock is typical hornfels. Large-scale banding is common and gives the impression of bedding. One band, near the center of the northwest side of the block, is obviously altered lava with large quartz phenocrysts in a fine-grained matrix. Other bands resemble hornfelsed argillite and quartzite. Sedimentary structural features, such as bedding and cross-bedding, are readily seen on weathered surfaces but are difficult to recognize on fresh fractures. A smaller inclusion just to the east is a coarsely porphyritic andesite, with white plagioclase phenocrysts as much as half an inch long in a dense greenish base. Both varieties of hornfels strike northeastward and dip northwestward.

Under the microscope the rocks show the texture of hornfels. The minerals of the altered sedimentary rocks are quartz, andesine, microcline, chlorite, epidote, sericite, biotite, and magnetite with some tourmaline. The mineral banding, retaining the original sedimentary structure, is commonly visible under low magnification. It is chiefly brought out by a linear arrangement of the quartz, as the other minerals seem to vary in all proportions rather unsystematically. In several of the altered quartzites the arrangement of the sericite wisps suggests earlier rounded sedimentary grains of quartz, but most of the quartzites retain no recognizable relics of sedimentary origin other than the mineral banding.

There are two varieties of altered lavas, rhyolite and andesite. Both show considerable recrystallization, but the original quartz phenocrysts of the rhyolite, although recrystallized into aggregates, are recognizable in a highly sericitic groundmass that preserves the forms of feldspar. The andesite shows porphyritic texture. The plagioclase, with many unidentifiable dark inclusions ("filled feldspar"), is labradorite. It shows recrystallization into smaller crystals that retain, as aggregates, the shape of the original feldspars, but there has been some slight displacement of the crystal lattices, so that they extinguish as many separate crystals. The groundmass is hornfels-textured, with much biotite and muscovite.

AGE AND CORRELATION

This series of bedded rocks resembles, in degree of metamorphism, the hornfels exposed in some low hills about 1 mile south of the boundary of the quadrangle. The bedded series in these southerly hills includes hornfelsed dolomites, shales, and sandstones, but the intrusive rock responsible for their metamorphism is not exposed. Similar altered limestones are found in other isolated exposures on the east flank of the Growler Range for several miles. No fossils have been found in these rocks, but they are regarded by Darton[21] as probably Paleozoic. It is, of course, possible that the sedimentary rocks are pre-Cambrian, but, because Devonian and Carboniferous limestones must have existed nearby, as shown by the occurrence of large fossiliferous boulders in the Locomotive fanglomerate, and as there is no direct evidence of pre-Cambrian sedimentary rocks in the region, Darton's provisional assignment of these rocks to the Paleozoic seems somewhat preferable to placing them in the pre-Cambrian. An assignment to the Mesozoic would seem less likely than to the Paleozoic, even if the Chico Shunie intrusive (as mapped) should be in part as young as the Cornelia quartz monzonite. Although the Concentrator volcanics may contain lavas that originally resembled those associated with the altered sediments, the Cretaceous limestones of southeastern Arizona are not described as dolomitic, and, as far as known, did not extend nearly so far west as the Ajo region.

Accordingly these hornfelsed supracrustal rocks are provisionally classed as Paleozoic, even though andesite and rhyolite like that of the large inclusions in the Chico Shunie quartz monzonite are not elsewhere recognized in the Paleozoic of the region.

CHICO SHUNIE QUARTZ MONZONITE

DISTRIBUTION AND TOPOGRAPHIC EXPRESSION

The Chico Shunie quartz monzonite is widespread in the southwestern quarter of the quadrangle.[22] It crops out over at least 10 square miles and can be confidently inferred to extend over an additional area nearly as large but covered by alluvium and other rocks.

The Chico Shunie quartz monzonite makes up most of the Chico Shunie Hills and doubtless forms the basement upon which rests the alluvium of the lower ground to the west as far as the edge of the quadrangle. North of Chico Shunie Arroyo it crops out in the low hills south of the steeper mountain mass of the Cardigan gneiss and forms a similar group of foothills along the western base of the Little Ajo Mountains as far as Tule well. Three small exposures probably referable to this formation occur in the gneiss near the summit of this spur of the mountains. Smaller outcrops of this rock are present just north of Copper Canyon near Tule well and also a mile or so upstream, and there are also several small exposures west of Salt well. Inasmuch as the outcrop of the formation is limited on the east by the Chico Shunie fault, on the south by overlying sedimentary rocks, on the west by alluvium, and north of Tule well by andesite flows, the actual extent of the Chico Shunie quartz monzonite is considerably larger than its present area of exposure. There is, however, no information as to its limits.

Most of the area of the Chico Shunie quartz monzonite has gently rolling topography, but there are a few rather rugged peaks in the Chico Shunie Hills and, toward the

[21] Darton, N. H., and others, Geologic map of Arizona, prepared by Arizona Bur. Mines in cooperation with U. S. Geol. Survey, 1924. Darton, N. H., A résumé of Arizona geology: Arizona Bur. Mines Bull. 119, p. 74, 1925.

[22] Gilluly, James, Geology and ore deposits of the Ajo quadrangle, Ariz.: Arizona Bur. Mines Bull. vol. 8, No. 1, p. 23, 1937.

west, where the pediments are best developed, a good many sharply conical hills are composed of this rock. There are some rather massive ledges, but apparently the coarse granularity and brecciated character of the rock leads to its ready disintegration and a tendency to form gentle slopes in strong contrast with the topography characteristic of the Cornelia quartz monzonite.

RELATION TO OTHER FORMATIONS

The Chico Shunie quartz monzonite invades the Cardigan gneiss, with nearly complete disregard of the foliation of that rock; in fact, the only part of the contact where the foliation has been found conformable is that segment between Tule well and the hornblendite outcrop a mile to the southeast. Here, for about 1,000 feet, the gneiss foliation is parallel to the contact and to the foliation of the quartz monzonite.

Where topographic relief permits observation, the contact with the Cardigan gneiss is nearly vertical, for example, where it trends north along the west spur of the Little Ajos in the reentrant southeast of Tule well and in the three deeply incised masses near the ridge crest a half mile farther south. In the small hills 2 miles west of Tule well and also on the slopes of the promontory of gneiss 1½ miles south-southwest of Tule well, however, there is a strong suggestion that the intrusive contact now is nearly horizontal. The westward-trending contact north of Chico Shunie well is a fault dipping steeply south, and the northward-trending contact east of this well is also a fault, so that nothing can be seen of the intrusive boundaries in these directions. As nearly all the other contacts are either with unconformably overlying rocks or in exposures of little relief, no satisfactory basis exists for a generalization as to the shape or mode of emplacement of the mass. Inasmuch as the entire block of the little Ajo Mountains has been tilted about 50° to the south in later geologic time, all the present exposed attitudes must be corrected for this tilt to determine the true attitude of the contacts at the time of intrusion, and good exposures of the contact are too few to warrant such an attempt.

The Chico Shunie quartz monzonite contains many clearly recognizable inclusions, both large and small, and in many localities in the Chico Shunie Hills it is mottled with clots of dark minerals, which probably represent more completely digested fragments of foreign rocks. Most of these inclusions are recognizable as Cardigan gneiss, but some of them, especially those toward the south, are derived from a different formation. Their volume is so great in the aggregate as to suggest that stoping was an important process in the emplacement of the mass. (See pp. 16, 17.) Primary foliation related to the contacts was not observed, except very locally.

PETROGRAPHY

The Chico Shunie quartz monzonite is highly diverse in aspect, owing both to original features and to subsequent modifications. More detailed study will doubtless enable several facies of the quartz monzonite to be separately mapped and, indeed, may reveal several independent intrusions. There is a suggestion, for example, that the first hill south of Tule well may be composed of such a minor intrusion, as well as part of the hill south of Chico Shunie well. As shown by thin-section study, quartz monzonites are by far the dominant facies, but potash granites, albite granites, quartz diorites, and trondhjemites (oligoclase-rich quartz diorites) are also present. Should later work show these to be distinct intrusive masses, they should be distinguished from the type Chico Shunie quartz monzonite, but the consistent discrimination of these lithologic variants and the working out of their mutual relations were beyond the scope of the mapping permitted by the time available for the present work.

The most common variety is slightly foliated to massive, coarsely porphyritic, and light pinkish gray on fresh fracture and weathers to a light brown. Conspicuous euhedral or rounded phenocrysts of pink feldspar as much as 2 or 3 centimeters in length occur in a groundmass of quartz, biotite (more or less altered to chlorite), white feldspar, and generally a little epidote. Some specimens show flakes of muscovite as much as 1 centimeter in diameter. Generally the minerals of the groundmass range between one-half millimeter and 5 millimeters in diameter.

In thin section these porphyritic rocks are all seen to be more or less brecciated. Most are thoroughly cataclastic and, of those that are not, almost all are crystalloblastic. Were the present composition of the feldspars to be considered diagnostic, the rock would nearly all be classed as granite, for the plagioclase is dominantly albite and volumetrically equal to the more conspicuous microcline microperthite; however, the plagioclase most commonly contains considerable sericite, with or without pistacite or zoisite, and is a saussuritic aggregate whose original composition was probably that of andesine. A few of the less-brecciated specimens examined retain cores of such plagioclase (composition near An_{35}) in a saussuritic base. However, one or two rocks of very similar aspect have, in addition to microcline, true albite with no saussurite and are to be classed as granites. Biotite is of the common variety but is fresh only exceptionally. Most of it has gone over to chlorite or pistacite. Quartz, which constitutes 10 to 30 percent of the rock, is commonly dark smoky-gray and under high power shows innumerable minute hairlike inclusions, which are probably rutile. More or less sericite is present in the plagioclase of every specimen examined, but muscovite in flakes of considerable size is not plentiful. Some is strung out along shear zones, but in other specimens it forms parallel intergrowths with chlorite as an apparent pseudomorph of original biotite. As similar intergrowths occur with nearly fresh biotite, the muscovite is not necessarily all of postmagmatic origin. Accessory minerals include magnetite or ilmenite, apatite, zircon, and commonly considerable sphene. Some specimens contain a little allanite in the cores of pistacite crystals.

Less common but widespread varieties of the Chico Shunie quartz monzonite are equigranular, generally slightly if at all foliated, and range from rather dark-gray to light-colored alaskitic rocks. The mineralogy is essentially the same as that of the porphyritic variety, but there is a wider range in the content of dark minerals. Some specimens contain as much as 20 percent of dark minerals, but 10 percent is a more common tenor, and in some specimens there is still less.

Some varieties of the rock are decidedly reddish throughout and appear in hand specimens to contain large proportions of microcline, but thin sections show them not to differ appreciably from the commoner porphyritic facies in this regard. To judge from the few specimens examined, however, there are more myrmekitic and other textures indicative of replacement of microcline by albite in these rocks than in the other varieties. Despite the less conspicuous foliation of these rocks when seen in outcrop, they are fully as cataclastic as the average porphyritic specimens. Some show simple mortar structure, but others are crystalloblastic.

Rocks containing conspicuously bluish quartz are found in a few exposures, especially near Teepee Butte, near the west edge of the quadrangle. These are both gneissose and massive varieties. Thin sections reveal unusually sodic feldspar (An_5 or less), with very little microcline and not very much epidote, though considerable calcite is locally present. Some specimens carry a little biotite. Mineralogically they are albite granites and as far as direct evidence is concerned show little sign of saussuritization of originally more calcic feldspars. These rocks show crystalloblastic or, locally, even completely schistose textures and a little residual cataclastic texture as well. In none is there any sign of granitic texture. These features, together with the milky-blue color of the quartz, are analogous to those of many other albite granites, and detailed study may show that these rocks owe their composition to such replacement processes as appear to have occurred in similar rocks of eastern Oregon.[23] Local exposures were not adequate to test this suggestion.

Exceptional rocks occurring in the Chico Shunie quartz monzonite are coarse-grained pink gneisses with rounded, almost spherical porphyroblasts of pink feldspar in a quartz-feldspar base. These porphyroblasts are as much as 3 centimeters in diameter but average about 3 millimeters. Several narrow zones of this variety of rock were seen. One about 30 feet wide was followed south-southwestward for about a mile from the lower western slopes of the 2,051-foot hill south of Chico Shunie well. Another parallel zone was seen about 2 miles west-northwest of Chico Shunie well. Some of the porphyroblasts in these rocks are sheared and displaced. The microscope shows them to be microcline, set in a partly cataclastic partly crystalloblastic base of quartz, muscovite, and albite with sporadic crystals of epidote and chlorite. Over 95 percent of the rock is salic. Doubtless it is a recrystallized crushed rock or blastomylonite, developed along a steep shear zone. The recrystallization occurred concurrently with the crushing. The possible significance of these rocks is further discussed in the section on structure.

One other variety of rock, although mapped as part of the Chico Shunie quartz monzonite, is almost surely an igneous mass separate from the main body. It forms a large part of the group of hills just south of Chico Shunie well, between the two branches of Chico Shunie Arroyo.

On weathered outcrops the rock resembles some of the more contaminated varieties of the main mass, as it is notably spangled with dark clots of biotite and contains feldspar phenocrysts as much as 1 centimeter in width. Even on fresh fracture it shows some resemblances to the inclusion-filled facies, but the two thin sections examined show that it is probably distinct. It is practically a quartz diorite in composition, with andesine, biotite, hornblende (extinction angle 21°, X yellow-green, Y pale bluish-green, and Z bluish-green), quartz, and considerable magnetite or ilmenite, and other accessory minerals. A very little microcline is present, making up not more than 5 per cent of the rock. Both specimens contain a little pistacite. One specimen is slightly cataclastic and saussuritic, but not to a degree comparable to the common facies; the other is granitic. Although this dark dioritic facies may be a border variant of the main mass of the Chico Shunie quartz monzonite, its slight granulation as compared with the rest of the rocks of the mass, its subordinate content of microcline, and the presence in it of fresh hornblende and biotite with no chlorite suggest that it is a younger and probably independent intrusion. Except for being somewhat coarser grained, it strongly resembles the border facies of the Cornelia quartz monzonite and may be closely related to it.

ORIGIN AND HISTORY

The composition of the Chico Shunie mass, though variable, is, on the average, near that of a quartz monzonite, and there are numerous residual textural features that are typical of plutonic intrusives. There is no doubt that the rock is intrusive into the Cardigan gneiss; however, as has been emphasized in the preceding descriptions, little of the rock has retained its granitic texture without change. Features suggesting primary foliation have been so obscured by superposed deformation that they are not readily recognizable. The mashing and deformation that the rocks have undergone are not particularly marked in the outcrops, but practically all the thin sections show

[23] Gilluly, James, Replacement origin of the albite granite near Sparta, Oreg.: U. S. Geol. Survey Prof. Paper 175, pp. 65-81, 1933.

cataclastic textures, and in several localities the rocks are crystalloblastic or completely schistose. Similarly the saussuritization and sericitization of the plagioclase, the chloritization of the dark minerals, and the widespread development of epidote and muscovite testify to the alteration of the rock after its consolidation. For the most part this mild metamorphism has reduced the mineral assemblage almost to that characteristic of the "green schist" facies of Eskola,[24] although the residual biotite and calcic plagioclase, which are rather common, show that equilibrium had not been attained throughout.

The deformation of the Chico Shunie quartz monzonite recorded in this brecciation is comparable in degree to the paracrystalline deformation of the Cardigan gneiss, though it was imposed on a granitic rather than a crystalloblastic rock. The mineral assemblages of the two formations are likewise very similar. As the entire area occupied by these formations seems to have undergone this brecciation and mineralogical alteration, the metamorphism was probably the result of regional diastrophism, but the apparent lack of regularly oriented gneissic foliation in both formations throws some doubt on this suggestion. The few strong blastomylonite zones noted in the field trend north-northeast, but they seem exceptional and may be younger than the intimate brecciation of the mass, despite their somewhat more recrystallized state. The solutions necessary for the recrystallization may have been localized by the recurrent movement. Whether so or not, there is no pronounced gneissic banding with this trend outside of these rather distinct zones, as would be expected if they were contemporaneous with the more widespread brecciation. The crushing is perhaps a result of "stress tectonic" rather than "kinetic tectonic" conditions in the sense used by Sander,[25] that is, the deformation was between relatively fixed "jaws." The rocks were crushed over a wide area, but the movement that ensued within the crushed rock was not great. The rocks were cracked intimately, but mass flowage and rock transport, such as are common in orogenic zones and such as must take place at depth in regions of great overthrusting, did not occur. Insofar as the blastomylonite zones record displacement, the deformation extended locally into the field of kinetic tectonics, but as a whole the rocks of the Cardigan gneiss and Chico Shunie quartz monzonite record in their structure simply the application of crushing stresses rather than rock motion.

This interpretation of the structural and mineralogic features of the Chico Shunie quartz monzonite seems to require that its deformation took place prior to the intrusion of the Cornelia quartz monzonite, for the Cornelia quartz monzonite is only locally metamorphosed and has altered the Cardigan gneiss (which is elsewhere cataclastically metamorphosed like the Chico Shunie) to hornfels along the contacts. The small exposed length of the contact of Chico Shunie against Cornelia quartz monzonite does not show clear evidence of a similar alteration of the Chico Shunie mass. However, the Cornelia quartz monzonite definitely cuts the Chico Shunie mass cleanly in Copper Canyon. That the two monzonites are independent is practically certain, as dikes like some that cut the Chico Shunie body are themselves cut north of Cardigan and near Salt well by aplites derived from the Cornelia quartz monzonite.

AGE AND CORRELATION

The age of the Chico Shunie quartz monzonite is a matter of indirect inference only. Should the metamorphosed sedimentary rocks in the southwestern part of the Chico Shunie Hills be correlated with the Paleozoic (?) rocks near Bates well, as has been tentatively suggested, the intrusion would necessarily be post-Paleozoic. It is believed to be older than the Concentrator volcanics, but only on indirect evidence, as the much more intense hydrothermal metamorphism that has affected the volcanics might conceivably have obliterated a metamorphic stage similar to that shown by the Chico Shunie. The Concentrator volcanics are themselves of uncertain age and are only referred to the Cretaceous (?) on suggestive rather than positive evidence. Future work may show the metamorphosed inclusions to have been derived from pre-Cambrian rather than Paleozoic rocks and the Concentrator volcanics to be Tertiary; however, intrusive rocks are assigned to the Mesozoic in many places in southern Arizona, though without any direct evidence except at Bisbee.[26] Thus monzonitic and granitic intrusive rocks have been so referred at Patagonia,[27] Ray-Miami,[28] and Silver Bell[29] and in the Palo Verde Mountains,[30] Maricopa Mountains,[30] O'Neill Hills,[30] Tule Mountains,[30] Tinajas Altas Mountain,[30] Dome Rock Mountains,[31] Kofa Mountains,[32] Harcuvar Mountains,[33] and Buckskin Mountains.[34] This lack of direct proof is of course not surprising in view of the paucity of fossili-

[24] Eskola, Pentti, The mineral facies of rocks: Norsk geol. tidsskr., vol. 6, pp. 143, 194, 1920.

[25] Sander, Bruno, Gefügekunde der Gesteine, p. 55, Julius Springer, Wien, 1930.

[26] Ransome, F. L., Geology and ore deposits of the Bisbee quadrangle, Ariz.: U. S. Geol. Survey Prof. Paper 21, p. 84, 1904.

[27] Schrader, F. C., and Hill, J. M., Mineral deposits of the Santa Rita and Patagonia Mountains, Ariz.: U. S. Geol. Survey Bull. 582, p. 57, 1915.

[28] Ransome, F. L., The copper deposits of Ray and Miami, Ariz.: U. S. Geol. Survey Prof. Paper 115, pp. 51-56, 1919.

[29] Stewart, C. A., The geology and ore deposits of the Silver Bell mining district, Ariz.: Am. Inst. Min. Eng. Trans., vol. 43, pp. 263-264, 1913.

[30] Bryan, Kirk, The Papago country, Ariz.: U. S. Geol. Survey Water-Supply Paper 499, pp. 58-59, 1925.

[31] Jones, E. L., jr., Gold deposits near Quartzsite, Ariz.: U. S. Geol. Survey Bull. 620-C, p. 47, 1916.

[32] Jones, E. L., jr., A reconnaissance in the Kofa Mountains, Ariz.: U. S. Geol. Survey Bull. 620-H, pp. 154-155, 1916.

[33] Bancroft, Howland, Reconnaissance of the ore deposits in northern Yuma County, Ariz.: U. S. Geol. Survey Bull. 451, pp. 29-30, 1911.

[34] Ross, C. P., The lower Gila region, Ariz.: U. S. Geol. Survey Water-Supply Paper 498, p. 29, 1923.

ferous Mesozoic or Tertiary rocks in the region, but it should be emphasized to avoid the "freezing" of the tentative age assignment into a dogma. It may be pertinent in this connection to note that the Chico Shunie mass was assigned by Bryan to the pre-Cambrian on the basis of reconnaissance studies at the time when he referred the Cornelia quartz monzonite to the Mesozoic.[35] The considerations outlined here and on page 17 are surely far from conclusive but appear to render the present assignment of the Chico Shunie to the Mesozoic slightly more satisfactory.

ANDESITE DIKES IN PRE-CONCENTRATOR ROCKS

DISTRIBUTION

The Cardigan gneiss is cut by many andesite dikes. Although some are found in almost any exposure of the gneiss more than a few acres in extent, they are particularly numerous and bulky near Cardigan, Salt well, and Tule well. Owing to their small size, none are shown on plate 3, but many are mapped on plate 20, which is on a larger scale.

STRUCTURAL RELATIONS

Most of these dikes are irregular. Individual bodies only rarely exceed 2,000 feet in length and a few tens of feet in width, but locally they swell out to widths as great as 200 feet.

The dikes strike generally east and dip nearly vertically, and before the tilting of the Little Ajo Mountain block they evidently dipped about 40° to the south. They are very irregular, however, and individual dikes may trend at rather large angles to the general course. Dikes of divergent strike commonly dip steeply northward. Near the Gibson fault the entire group of dikes diverges toward the northeast from its regional trend, perhaps because of drag along the fault. In some places the dikes coalesce and again split, but no age difference among the several members could be shown at any of these localities.

At no point could any control of the dikes by the structure of the country rocks be ascertained. They appear to be controlled by fractures that were formed after the latest period of regional metamorphism had ended. Most of the dikes are massive, and such joints as are present in them are highly irregular. They present no suggestion of schistosity.

PETROGRAPHY

These dikes are composed of fine-grained greenish-gray rock, mottled with green and weathering to brown. The minerals visible in hand specimens are chlorite, in clots that average 1 millimeter in diameter but that may be as much as 5 millimeters, plagioclase, which is generally one-half to 1 millimeter long, and in some rocks epidote, which is present along seams. Some specimens are porphyritic, with chlorite phenocrysts in an aphanitic base.

The minerals seen in thin section include plagioclase, chlorite, hornblende, actinolite, biotite, orthoclase, quartz, sericite, epidote, sphene, apatite, calcite, and magnetite. Most of the feldspar is more or less saussuritic, with sericite and epidote in an albite base, but residua of andesine (zoned from An_{50} to An_{25}, averaging An_{40}) are common, and some specimens show no saussurite. Most of the mafic minerals are altered to chlorite, but a few specimens retain more or less hornblende. Some, from near the Cornelia quartz monzonite, contain long radiating tufts of actinolite, which penetrate the associated feldspar. These actinolite-bearing rocks are rich in biotite, which occurs in minute crystals and is doubtless a product of alteration near the intrusive mass of the Cornelia quartz monzonite. Orthoclase was found in only a few specimens and only in small amount. Quartz, though a few corroded crystals occur in some specimens, is not common, and is in part probably secondary. Sericite is present in almost all specimens and replaces part of the plagioclase. Calcite is probably a weathering product but may be due to hydrothermal alteration. None of the accessories are notable beyond the fact that in one specimen apatite prisms are very abundant and show marked fluidal arrangement.

The textures vary considerably. Some specimens are divergent granular, with small feldspar laths of random orientation embedded in a matrix of smaller chlorite grains that have apparently replaced augite or hornblende. Others consist of a felt of feldspar laths with interstitial dark minerals and show some tendencies toward a flow arrangement (pilotaxitic texture). Still others consist of aggregates of fine round grains forming a mosaic (granulitic texture); the rocks that contain biotite and actinolite have a fine pepper-and-salt texture in which almost any mineral grain may contain any other mineral as an inclusion, a characteristic feature of hornfels. A few specimens show slight brecciation.

CORRELATION

The magmatic relationships of these andesitic dikes are not clear. They definitely cut the Chico Shunie quartz monzonite, and some are cut by pegmatites and aplites that are apparently related to the Cornelia quartz monzonite. Some of them, as mentioned in the descriptions, are clearly converted to hornfels near the Cornelia quartz monzonite; on the other hand, they resemble certain andesite dikes that cut the Cornelia quartz monzonite east of Gibson Arroyo, and some of the dikes near the head of Gibson Arroyo that are closely similar to these cut the pegmatites. Thus at least two ages of dike intrusions and probably three, as discussed on pp. 39, 40, 41, are represented, although those of different ages can not be distinguished. For this reason, all the dikes west of the

[35] Bryan, Kirk, op. cit., pl. 9 and p. 58.

Gibson fault are mapped as pre-Cornelia, although it is certain that some are younger. The older dikes may be related to the Concentrator volcanics but are clearly not so siliceous as most of that formation. Some of the younger dikes may be post-Cornelia and pre-Locomotive, and others may be of the Ajo volcanics or Sneed andesite.

CONCENTRATOR VOLCANICS

DISTRIBUTION AND TOPOGRAPHIC EXPRESSION

The Concentrator volcanics, named from the conspicuous outcrops on Concentrator Mountain, southeast of Ajo,[36] are exposed in two relatively small areas, aggregating less than 2 square miles. One of these areas occupies most of the triangle bounded by Cornelia Arroyo and the New Cornelia pit on the west, the Little Ajo Mountain fault on the northeast, and the Locomotive fanglomerate on the southeast. It is separated at the surface from the second somewhat larger body by the southward projecting prong of Cornelia quartz monzonite. This second body also forms a crude triangle, with its northerly point on the divide just south of Camelback Mountain, its southwesterly point near Cardigan, and its southeasterly point near Arkansas Mountain. A few much smaller bodies of rock just east of the Gibson fault, in Gibson Arroyo, are also referred to this formation.

The Concentrator volcanics form the rugged divide between Gibson and Cornelia Arroyos, culminating in Pinnacle Peak, a conspicuously craggy landmark. Arkansas and Concentrator Mountain, too, are rather precipitous and rugged. The formation also makes smooth and even slopes of low relief, such as those just west of the New Cornelia open pit and those east and north of the waste dumps from the mine. This diversified topography reflects the heterogeneity of the formation.

STRATIGRAPHIC RELATIONS

The basement upon which the Concentrator volcanics were deposited is not known from direct observations. The Cornelia quartz monzonite is definitely intrusive into the volcanics, and the two formations are overlain with profound unconformity by the Locomotive fanglomerate. The volcanics are cut off by faults from the Cardigan gneiss, against which they abut, so that their mutual age relations are not directly revealed. There can, nevertheless, be no question that the volcanics are much younger than the gneiss, and, in view of the close association of small fault blocks of volcanic rocks with those of gneiss just east of the fault in Gibson Arroyo, it is probable that the volcanics were deposited upon the eroded surface of the gneiss.

The structural observations on the Concentrator volcanics were too uncertain to make a confident measure of thickness. Certainly the formation is several hundred feet thick and, if the structural readings obtained are accepted at face value, it may be as much as 3,000 feet thick.

[36] Gilluly, James, Geology and ore deposits of the Ajo quadrangle, Ariz.: Arizona Bur. Mines Bull., vol. 8, No. 1, p. 27, 1937.

PETROGRAPHY

The formation comprises flow breccias, tuffs, and flows. Although almost all the rocks are now more or less quartzose, many highly so, much of the quartz has been introduced. Much of the rock that has been changed to hornfels near the contacts of the Cornelia quartz monzonite contains no quartz, but elsewhere some of the rock has obviously been replaced by quartz, although it contains recognizable residuals of typically andesitic (pilotaxitic) textures. Not every rock that on superficial examination might be regarded as a rhyolite really contains original quartz, although much phenocrystic quartz is doubtless present in the formation. Probably nearly a third of the formation has been so silicified as to mask a probable originally andesitic composition. The other two-thirds of the exposures contain quartz, commonly in partly resorbed phenocrysts and in glassy groundmasses that have every appearance of being primary.

The rocks range in color from practically white, through buff, light gray, pinkish gray, various hues of greenish gray, to red and brown. The dominant rocks are flow breccias, with tuffs probably next in quantity, and subordinate flows. The locally intense alteration, impregnation by hematite and quartz, and the irregular fracturing of the entire formation obscure the distinction of the several facies, and only in the least-altered or most-contrasting parts of the formation can they be readily identified.

Definite flow breccias are widespread along the southerly border of the volcanics. Some sedimentary breccias with a few limestone pebbles are also included in them. Toward the east the finer fragmental tuffs seem to become more plentiful, and in the area east of the New Cornelia waste dumps most of the rocks are tuffs. Flow rocks were noted on the north slopes of Arkansas Mountain, on the north slopes of Pinnacle Peak, and near the saddle between Gibson and Cornelia Arroyos.

Although some effort was made to map the different lithologic varieties of the volcanics, their alteration prevented any satisfactory separation. If the few structural observations (see p. 51) in which confidence could be placed are representative of the far larger area in which no consistent information could be gathered, the volcanic formation strikes just north of east and dips steeply southward. The more-brecciated flows and tuffs, according to this hypothesis, are stratigraphically higher than the massive flows, and the amount of original quartz in the rocks also seems to increase upward. It is very doubtful, however, that such generalizations are valid, as the structure of most of the volcanic area could not be deciphered in the time available.

Alteration of the rocks obscures the original character. Only in a few places is there clear distinction between the flows and breccias. However, as the rocks seem to be essentially the same, both in the fragments and matrix, the microscopic descriptions that follow seem applicable both to the flow rocks and the breccias. In almost all varieties albite is the only plagioclase present, but in some, especially those near the contacts of the monzonite, the plagioclase is more calcic. The rocks containing calcic plagioclase are still recognizable as andesites, slightly to greatly altered, and are so described below. Those containing albite, either as the only feldspar or accompanied by a little orthoclase, are here classed as keratophyres and quartz keratophyres. It is likely that many, though perhaps not all of these rocks, are merely albitized andesites. There is ample precedent for referring to such rocks as keratophyres whether the feldspars are original or altered.

ANDESITE

The least-altered andesite is medium-gray to dark gray, weathering light brown, with millimeter crystals of plagioclase and a little hornblende set in a dense groundmass. Exceptionally the phenocrysts attain dimensions of as much as 1 centimeter, but 2 millimeters is the usual maximum.

In thin section even the freshest specimens show much alteration, with the development of chlorite, epidote, sericite, and cloudy alteration products of feldspar. However, remnants of andesine (zoned An_{48}–An_{28}, average about An_{40}) are present with hornblende (pleochroic in dark green and light green), a little biotite, and the accessory minerals apatite, zircon, sphene, and magnetite or ilmenite. Chlorite and epidote are widespread. Orthoclase has not been seen in fresh specimens but occurs with quartz in intimate intergrowth in the more-altered rocks. In even the fresher rocks the original texture is obscure but may be inferred to have been originally fluidal if not pilotaxitic.

Immediately at the contact with the Cornelia intrusive mass the andesite is altered to dense brittle hornfels with spangles of biotite or hornblende. (See pl. 10, *B*.) Under the microscope the hornfels appears much fresher than the nonhornfelsed rock. It consists largely of water-clear feldspar (commonly andesine but exceptionally oligoclase), very little orthoclase, and commonly considerable quartz and biotite. The texture is the granulitic one characteristic of hornfelsed lavas.

KERATOPHYRE

Most of the andesite close to though not immediately abutting against the monzonite has been rather completely altered. The original feldspar is cloudy and contains epidote grains, wisps of sericite, and perhaps other minerals in a matrix of albite (An_{2-4}, exceptionally An_{10}). The hornblende and biotite are chiefly altered to epidote and chlorite. Quartz and orthoclase occur in the groundmass and in some specimens constitute almost all of it. In part they appear to replace the feldspar phenocrysts, and their texture resembles notably that of the quartz monzonite intrusive where it has been later silicified and pegmatized. Calcite veinlets are common, and the accessory minerals usual in the andesite are present.

QUARTZ KERATOPHYRE

In most of its exposures the quartz keratophyre has undergone such intense alteration by mineralizing solutions that it is nearly, if not quite, impossible to get fresh specimens. Except where stained by impregnating hematite, limonite, or copper minerals, the rocks are light colored, gray or buff, and glassy to felsitic, with phenocrysts of feldspar rather abundantly distributed and of the quartz, biotite, or chlorite after biotite less commonly distributed.

Representative specimens show rounded quartz phenocrysts as much as 2 millimeters in diameter, but averaging less than 1 millimeter, and feldspars as much as 5 millimeters in length but averaging about 2 millimeters. Biotite flakes, rarely fresh, are almost all less than 1 millimeter in diameter, and in a few rocks pseudomorphs of chlorite nearly 1 centimeter long indicate the former presence of hornblende.

The microscope shows practically all the rocks, even those superficially appearing fresh, to have undergone notable alteration. The dominant feldspar is albite, ranging in composition from An_2 to An_{10}, commonly more albitic than An_5. It is invariably cloudy with sericitic wisps and even holds rather coarse muscovite flakes. Some specimens show epidote or zoisite in small amount, but in many the minute inclusions to which the cloudy appearance of the albite is due are too small for determination.

Orthoclase does not appear as distinct grains, except in close association with feldspathized monzonites which show the effects of replacement by orthoclase. Orthoclase, intergrown with quartz, is not uncommon in the groundmass of the less-sericitic specimens.

Quartz forms phenocrysts, invariably showing some resorption, and is widespread as a fine-grained constituent of the groundmass. It also occurs in veins and nests that have cut and replaced the rock.

Biotite crystals are rarely found fresh, except in a few specimens that show granular aggregates of this mineral characteristic of contact-metamorphosed lavas. Similarly, hornblende has remained well enough preserved for determination in only one specimen of several scores examined. Both these minerals have been replaced by chlorite, but the chlorite aggregates preserve their shapes. Epidote is present in some specimens as a replacement product of hornblende, biotite, or plagioclase. Sericite is very widespread as curved wisps and rosettes, and several specimens show rather coarse blades of muscovite.

Accessory minerals include magnetite, apatite, zircon, and sphene.

QUARTZ KERATOPHYRE TUFFS

The tuffs are for the most part light-gray to pinkish-gray mottled rocks. They contain small pellets of quartz keratophyre that average perhaps 2 centimeters in diameter but that may be as large as one's fist, in a fine-grained lithoidal or pumiceous matrix. In some the tuff is mottled greenish and purplish; elsewhere it is strongly impregnated by hematite along joints and contains sporadic blades of specularite as much as 5 centimeters long set in a bleached matrix.

In thin section the rocks show pyroclastic texture, with fragments of lava held in a matrix of similar but smaller grains. Some pumiceous specimens have relics of vitric shards, but most of the tuff has a microcrystalline stony texture. As far as determined, there is no compositional difference between matrix and fragments. The larger fragments contain angular and resorbed phenocrysts of quartz as much as 2 millimeters in diameter, very cloudy plagioclase of about the same or somewhat smaller size and with the optical properties of albite (An_{4-8}), considerable chlorite and epidote, and the usual accessory minerals, sphene, magnetite, or hematite, and zircon. The rocks are very sericitic, and the feldspars invariably contain many wisps of sericite, some in rather large crystals. Zoisite was doubtfully identified in some of the feldspar, but for the most part the minute inclusions to which its cloudiness is due are indeterminate. Orthoclase was identified in only two specimens, in each of which it forms sparse phenocrysts, or more probably, metacrysts. Calcite has locally veined and replaced the rock.

ORIGIN AND ALTERATION

This formation represents the surficial accumulation of volcanic material from an unknown source. The tuffs forming the eastern exposures are less coarse than the fragmental rocks at Arkansas Mountain and Pinnacle Peak, perhaps implying a westerly source of the material. Inasmuch as so little of the material is exposed and the boundaries against other formations are either erosional unconformities, faults, or intrusive contacts, the section is incomplete, and no confidence can be put in such variations as a clue to the source of the formation.

The original formation was probably andesitic and rhyolitic, and the intense albitization that most of the rocks have undergone, except near the monzonite contacts, was doubtless postmagmatic. The mineral suite formed by later alteration, namely, albite, chlorite, epidote, quartz, and sericite, is characteristic of hydrothermal alteration, and, as similar mineral composition is found in many of the other formations of the area, it can hardly be regarded as a product of factors wholly indigenous to these volcanics.

There have been several periods of albitization in the Ajo region. One period apparently coincided with the time of brecciation of the Cardigan gneiss and Chico Shunie quartz monzonite, but the Concentrator volcanics have not been affected by this brecciation and are hence younger. The Cornelia quartz monzonite was partly albitized at the time of the mineralization that produced the New Cornelia ore body. The albitization of the Concentrator volcanics, however, seems to have been independent of that of the Cornelia quartz monzonite, at least in part. It was quite as complete in areas remote from the ore body and from other albitic areas in the Cornelia quartz monzonite as it was near them; for example, the volcanics on the ridge east of Gibson Arroyo, half a mile from the ore body, are thoroughly albitized, though the Cornelia quartz monzonite nearby contains unaltered plagioclase of intermediate composition. Similar contrasts occur elsewhere, far from mineralized areas. This evidence is not conclusive because of the highly variable permeability of the volcanic rocks, yet it does suggest that part of the albitization of the Concentrator volcanics antedated the Cornelia quartz monzonite. Accordingly, it is suggested that the volcanics have been subject to albitization at two periods, one prior to and the other coincident with the albitization of the Cornelia quartz monzonite.

Whether or not the hornfelsed portions of the formation that are not now albitic may formerly have been albitized and owe their present more anorthitic feldspars to the contact-metamorphic effects of the Cornelia quartz monzonite revealed by the hornfels textures, cannot be fully determined. The residua of the normal zoning of the plagioclase in these hornfelses suggest that they have not been greatly affected by such remetamorphism, which commonly eliminates zoning or even reverses the normal arrangement. The feldspars, therefore, probably have their original composition. If so, the lack of albitization in this hornfels zone may be in part fortuitous, because the formation is locally unalbitized elsewhere; but in part it may be due to the elimination of porosity in the rocks during their conversion to hornfels, so that they were not readily affected by later albitizing solutions. Inasmuch as albitization seems especially strong near the mineralized area of the Cornelia quartz monzonite, some additional albitization of the volcanics at the time of this mineralization is likely, but it may have been inhibited at the direct contact by earlier metamorphism that closed the pores.

AGE AND CORRELATION

As with all the other formations of the quadrangle, direct fossil evidence to date the Concentrator volcanics is lacking. The only bases for an age assignment are the tenuous ones of lithologic similarity to rocks of known age and lengths of time required for different geologic events.

The Concentrator volcanics are almost surely younger than Paleozoic, for, although the few limestone boulders (see p. 22) found in some of the breccia members did not yield fossils, they are so similar to fossiliferous limestone boulders of Pennsylvanian age found in the nearby

Locomotive fanglomerate that it appears almost certain that they are from the same formation. The volcanics are cut by the Cornelia quartz monzonite, and both formations are unconformably overlain by the Locomotive fanglomerate. The complex history of the area subsequent to the accumulation of the Concentrator volcanics appears to require that they be not younger than early Tertiary. See pages 67-68.

The Cretaceous period was one of known volcanic activity in southwestern New Mexico[37] and in southeastern Arizona, where, in Graham, Pinal, and eastern Pima Counties volcanics are known in association with fossiliferous sediments of this age.[38] Andesites of probable Cretaceous age are also known in central Sonora.[39] The volcanics of the Tucson Mountains contain both andesite and rhyolite members, thus resembling the Concentrator volcanics. At the other places mentioned in Arizona and New Mexico, only andesites have been recorded. Although postvolcanic granitic intrusions are known from both Arizona and New Mexico, and thus add a point of similarity to the history at Ajo, a correlation of the Concentrator volcanics with these Cretaceous formations solely on the basis of lithology and somewhat similar later histories must of course be tentative. With this recognition of the uncertainties involved, the Concentrator volcanics are here assigned to the Cretaceous (?). This is in approximate agreement with Bryan's reconnaissance work,[40] for he speaks of the Mesozoic monzonite intruding these rocks, but Darton[41] assigned them to the Tertiary, without other comment.

The possibility that the Concentrator volcanics are early products of the same igneous cycle as the Cornelia quartz monzonite can neither be proved nor disproved on the evidence at hand. Their alteration appears to be more irregular and more intense than might be expected on this assumption, but no evidence known to me directly opposes it.

CORNELIA QUARTZ MONZONITE

DISTRIBUTION AND TOPOGRAPHIC EXPRESSION

The Cornelia quartz monzonite and its dioritic border facies are exposed over an area of about 6 square miles, embracing much of the Little Ajo Mountains. The most easterly exposure is at the southeast end of the New Cornelia mine, south of Ajo. The monzonite widens westward and northwestward from here to Camelback Mountain, where it is almost separated into two masses by the belt of Cardigan gneiss and Concentrator volcanics that lies just east of and parallel to the Gibson fault. Beyond the Gibson fault the monzonite again widens westward and includes practically all of the Little Ajo Mountain area. Small bodies of quartz monzonite that are referable to this formation are found in the northwestern spur of the Little Ajos, near Salt well, and in the southeast corner of the Chico Shunie Hills, 2½ miles south of Chico Shunie well.

The Cornelia quartz monzonite is relatively resistant to erosion and forms most of the highest peaks in the quadrangle. Probably because of its massive structure, it forms steep and rugged slopes. Most of the upper slopes are barren and rocky, with coarse talus accumulations in the high ravines.

CONTACT RELATIONS

The Cornelia quartz monzonite intrudes the Concentrator volcanics in the neighborhood of the New Cornelia mine. Farther west it invades the Cardigan gneiss, and a mile and a half above Tule well the border facies cuts the Chico Shunie quartz monzonite. The small body in the Chico Shunie Hills also cuts the Chico Shunie quartz monzonite. The Sneed andesite may be, and the Locomotive fanglomerate definitely is, deposited on its eroded surface.

All intrusive contacts seen are sharp and distinct, except in mineralized areas. Most stand at relatively high angles and seem indifferent to the wall-rock structures. The contact along the southern border now dips steeply southward, both in the Cardigan Peak mass and the New Cornelia pit projection. It is shown on pages 52 and 53 that the original attitude of this contact was much less steep. The western border, too, though less well exposed, seems to dip outward. On the north the mass is cut off by the Little Ajo Mountain fault, so that the former extent and contact attitude in this direction are unknown.

Diamond drilling in and near the New Cornelia mine suggests that the south end of this intrusive is in the form of a westward-dipping dike with a definite lower contact.[42] (See pls. 22-25.) How far north this relation obtains is uncertain, as no drilling was done beyond the area of direct economic interest.

As far as could be determined, there is no suggestion that the emplacement of the Cornelia quartz monzonite affected the structures of the wall rocks. Where the country rock has been contact-altered it is massive hornfels, not schist. There has been no recognizable reworking of the old gneissic structures in the Cardigan gneiss that can be referred to the intrusion of the Cornelia quartz mon-

[37] Paige, Sidney, U. S. Geol. Survey Geol. Atlas, Silver City folio, N. Mex. (No. 199), pp. 7, 12, 1916. Lasky, S. G., oral communication, 1935.

[38] Campbell, M. R., The Deer Creek coal field, Ariz.: U. S. Geol. Survey Bull. 225, pp. 245-247, 1904. Ross, C. P., Geology and ore deposits of the Aravaipa and Stanley mining districts, Graham County, Ariz.: U. S. Geol. Survey Bull. 763, pp. 25-28, 1925; Ore deposits of the Saddle Mountain and Banner mining districts, Ariz.: U. S. Geol. Survey Bull. 771, pp. 11-14, 1925. Brown, W. H., Tucson Mountains, an Arizona basin range type, Geol. Soc. America Bull., vol. 50, No. 5, pp. 713-715, 1939.

[39] King, R. E., Geological reconnaissance of central Sonora: Am. Jour. Sci., 5th ser., vol. 28, pp. 91-92, 1934.

[40] Bryan, Kirk, The Papago country, Ariz.: U. S. Geol. Survey Water-Supply Paper 499, p. 58, 1925.

[41] Darton, N. H., A résumé of Arizona geology: Arizona Bur. Mines Bull. 119, p. 287, 1925.

[42] Ingham, G. R., and Barr, A. T., Mining methods and costs at the New Cornelia Branch, Phelps Dodge Corporation, Ajo, Ariz.: U. S. Bur. Mines Inf. Circ. 6666, fig. 3, 1932.

zonite. No arching or other displacement of the Concentrator volcanics has been detected. Indeed, the attitude of this formation, as far as it has been made out, is almost identical on the opposite sides of the New Cornelia prong of the monzonite, although on neither side is the structure so well exposed as to warrant stressing this relation. (See fig. 4.)

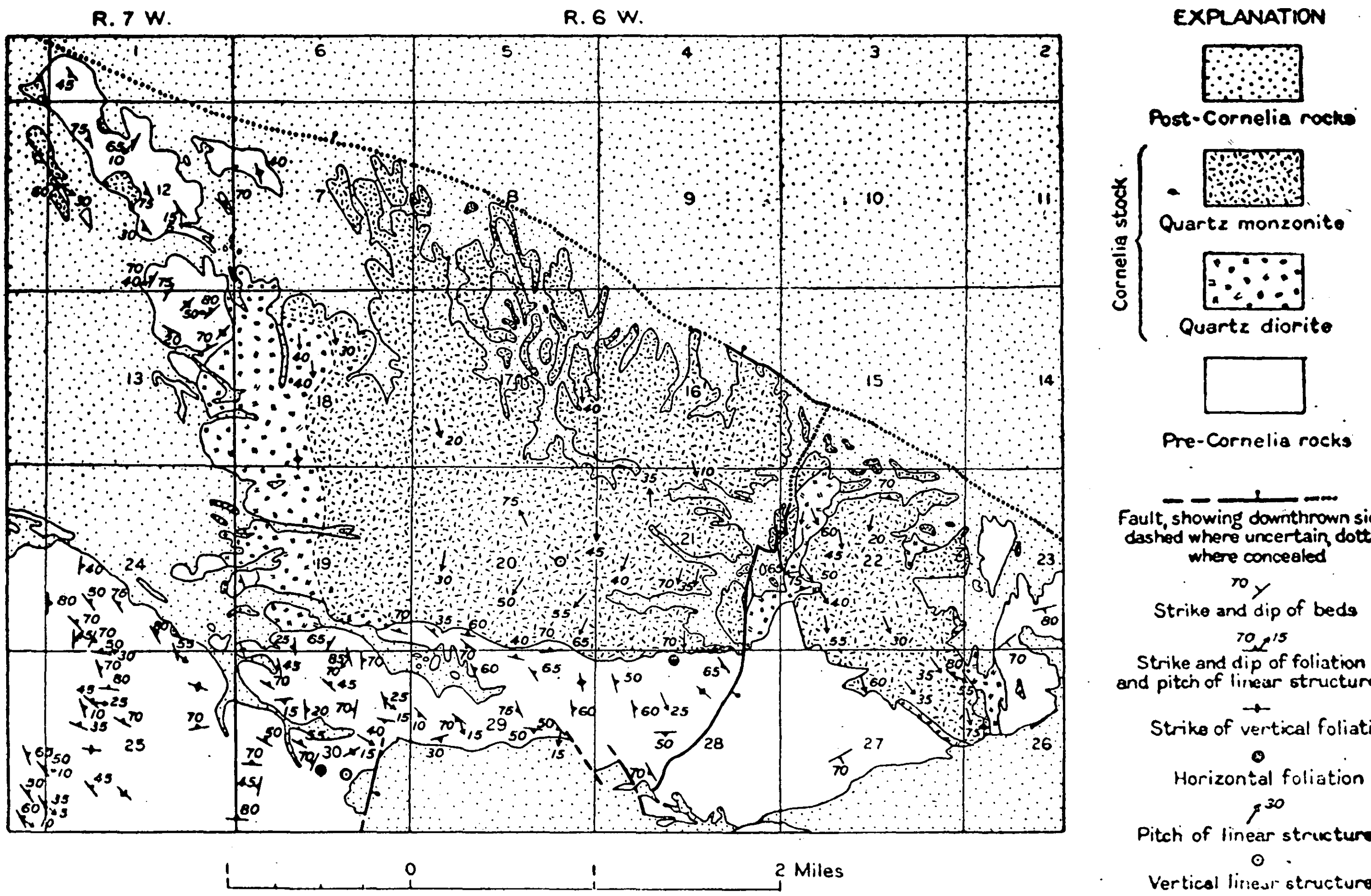


FIGURE 4.—Structural features of the Cornelia quartz monzonite and its host rocks showing general independence of the two.

FACIES

A rather large variety of rocks composes the Cornelia quartz monzonite. These rocks range from fine-grained, equigranular quartz diorite through equigranular quartz monzonite and porphyritic quartz monzonite to aplite and pegmatite. Only the quartz diorite facies, which is almost confined to the borders of the intrusive, has been separately mapped. The other varieties either grade imperceptibly into each other or, if distinct, are too small to be shown on the map. In general, however, it may be stated that the main mass of the Little Ajo Mountains is composed of the equigranular facies, with more aplitic varieties on the northern slopes; and the smaller body extending eastward and southeastward from Camelback Mountain is largely composed of the more porphyritic facies. Representatives of each of these varieties may be found in bodies of each of the others, and the age differences between them are doubtless very slight. The aplitic rocks are somewhat younger than the others, however, and cut the equigranular facies in eastward-trending dikes with indistinct walls. (See pl. 1, *D*.)

BORDER FACIES (QUARTZ DIORITE)

Occurrence.—Fine-grained dioritic rocks occur along the west border of the Cornelia quartz monzonite mass in secs. 18 and 19, T. 12 S., R. 6 W. This zone is as much as 3,000 feet wide in places and averages perhaps 2,000 feet. A narrower projection from this dioritic mass extends eastward along the south contact of the main body for nearly 2,000 feet. This quartz diorite is rather uniform in texture and is not cut by many dikes. Similar rocks crop out in a band along the contact of the gneiss in Gibson Arroyo from just south of Gibson to a point about 2,000 feet southwest of Camelback Mountain. Although elsewhere massive, just north of Camelback Mountain the body is invaded, veined, and cut to pieces by quartz monzonite stringers in great profusion and most diverse orientations. Narrower bands of quartz diorite are present along the south and east sides of the New Cornelia mine, and dikes and irregular intrusive masses extend out into the Concentrator volcanics to the east of the New Cornelia pit.

The outcrop width of these diorite masses near the mine rarely exceeds 300 feet, although most of the "peninsula" between the main pit and the approach is underlain by diorite which is here fully 1,000 feet wide. (See pls. 20 and 21.) Diamond drilling indicates that this mass is wedge shaped and is only a few hundred feet thick. (See pls. 22 and 23.) Where both rocks have undergone silicification and other alteration it is locally difficult to distinguish the diorite from the Concentrator volcanics, which form the country rocks (see pl. 10, *B*), but study of thin sections seems to indicate that it is more likely that the maps exaggerate the diorite at the expense of the country rock than the contrary.

Despite the close association of monzonite with the diorite, the contacts between the two rocks are nearly everywhere sharp and clean-cut rather than gradational and are easier to draw than the keratophyre-diorite contacts. Nevertheless the field distribution, chemical composition, and microscopic features all agree in suggesting that the quartz diorite is an early border facies of the quartz monzonite. If, as appears likely from the breccia relations on Camelback Mountain and clean-walled dikes elsewhere, its intrusion antedated that of the quartz monzonite, it was nevertheless controlled by the same magmatic conduit.

Petrography.—Where least altered by postmagmatic processes, the quartz diorite is a medium-gray rather fine-grained rock, weathering to a dark gray. The minerals recognized in hand specimens are plagioclase, in grains averaging less than 1 millimeter in length but exceptionally attaining 1.5 millimeters, hornblende, largely chloritized, in prisms as much as 1 centimeter long, and biotite, also chloritic, in small books generally 2 millimeters or less in diameter. A few sporadic books of chlorite after biotite attain 1 centimeter in diameter. Quartz is only exceptionally identifiable, and pink feldspar occurs only near aplitic veins or contacts of monzonite.

Under the microscope the rock shows euhedral to subhedral plagioclase. In some specimens the plagioclase is moderately zoned from An_{40} to An_{30} and in others strongly zoned, with central cores having the composition An_{50} and the rims An_{20}. These more sodic rims doubtless reflect postmagmatic replacement in part. In most of the rocks near the mine, however, the plagioclase is highly sericitic and indeterminate; in some the sericite is in an albitic base. Biotite of the usual variety, $\beta = 1.640 \pm .003$, is, in most specimens, partly altered to chlorite. Hornblende, pleochroic in dark and light yellow-green with extinction angle of 22°, is plentiful in the more westerly exposures but has been largely altered to chlorite near the mine. Augite is present in a few specimens from the hills near Copper Canyon. Many specimens are free from recognizable orthoclase, but some, especially those from outcrops near the quartz monzonite boundary, have the other minerals poikilitically enclosed in orthoclase. In some specimens there is a tendency for the orthoclase to coat the plagioclase. Quartz is present in all specimens examined, but only in the finer-grained groundmass between the plagioclase crystals. Accessory minerals are magnetite, apatite, generally in corroded prisms, zircon, a little rutile, and considerable sphene, euhedral in the freshest specimens but anhedral in the more altered.

The texture of the quartz diorite is granitic, varying to monzonitic, with euhedral to subhedral plagioclase, chloritized biotite, and chloritized hornblende set in a finer aggregate of quartz, chiefly in rounded granules, finely divided chlorite, and variable amounts of orthoclase. Orthoclase, where present, envelops the other minerals poikilitically and, in less amount, is intergrown graphically with quartz.

EQUIGRANULAR FACIES

Distribution.—The equigranular facies of the Cornelia quartz monzonite is preponderant. It makes up most of the large mass west of Gibson Arroyo, where it is cut by many aplitic dikes.

Petrography.—This facies of the Cornelia quartz monzonite is somewhat variable in aspect. Commonly it is a light pinkish-gray, but it ranges from white, chalky varieties on the one hand to green-gray rocks on the other. These variations are largely dependent on the content of potash feldspar but also on the extent of hydrothermal alteration.

The feldspars range in size from 2 to 6 millimeters. The rock grades into the porphyritic facies, with unequal development of sporadic feldspar individuals. Finer-grained varieties form transition members to the aplites.

Hand specimens of all these rocks show pink orthoclase, white plagioclase, quartz, biotite, hornblende, magnetite or ilmenite, and commonly some sphene. Biotite and hornblende are partly altered to chlorite. In most rocks the pink feldspar forms crystals of about the same size as those of plagioclase, but less commonly it is slightly finer-grained and forms a matrix for the plagioclase phenocrysts.

Under the microscope the plagioclase is seen to be strongly zoned, from An_{45} to An_{20} (locally almost from An_{50} to An_{10}). The potash feldspar is largely microperthitic orthoclase, but some specimens contain microcline microperthite, with oligoclase veinlets. Quartz is commonly in rounded lobate forms. Brown biotite is the dominant mafic mineral, locally developed at the expense of hornblende, elsewhere as independent crystals. The hornblende is of the common green variety, pleochroic with X yellow-green, Y brownish-green, and Z deeper brownish-green, extinction angle 22° $Z \wedge c$. A few sections show sparse grains of augite, altered in part to hornblende. Apatite, zircon, and magnetite or ilmenite are accessory, with sphene particularly conspicuous, as it attains crystal sizes of as much as 3 millimeters or even more. Commonly more or less alteration of the rocks is evident, with the production of actinolite after hornblende, chlorite, and epidote after all the dark minerals, and sericite and albite after the plagioclase. In a few specimens from along mylonite zones there is a little broadleaved muscovite.

Texture ranges from normal granitic (pls. 12, *C*, and 14, *A*) through monzonitic (pl. 12, *D*) to micrographic (pl. 13, *A*, *D*).

The proportions of the minerals vary considerably but without apparent system beyond the tendency for potash feldspar to be slightly less abundant near the contacts of the mass—a tendency not very pronounced outside the clear-cut quartz diorite border facies. Individual specimens have potash feldspar-plagioclase ratios ranging from 2:1 to 1:5, but the average is probably not far from 2:3, and the mass is thus classed as a quartz monzonite, as quartz everywhere makes up more than 10 percent of the rock.

PORPHYRITIC FACIES

Distribution.—Although locally present in the larger mass to the west, most of the notably porphyritic quartz monzonite is in the area southeast of Camelback Mountain, enclosing the Cornelia ore body. The porphyritic facies is not, however, coincident with the strongly mineralized area, and there is no apparent relation between this texture and the mineralization.

Petrography.—The fresh porphyritic quartz monzonite is light-gray to medium-gray, with a pinkish cast that on weathering changes to buff. The phenocrysts are conspicuous, those of plagioclase being as much as 15 millimeters in length, though averaging perhaps about 4 millimeters (see pls. 13, *E*, *F*, and 14, *D*); the books of biotite and the less plentiful prisms of hornblende are slightly smaller. Quartz and orthoclase are less common as phenocrysts, but crystals as much as 5 millimeters in length are found in some specimens. These crystals are in a groundmass composed of both feldspars and quartz, which has an average grain size of perhaps 0.2 millimeter, although some specimens are practically millimeter-grained. Of the feldspars, plagioclase is much more abundant as phenocrysts, and pink orthoclase is much more abundant in the groundmass. Both feldspars are seriate in texture, but practically all the biotite and most of the hornblende are confined to phenocrysts, and most of the quartz is confined to the groundmass. Sphene forms crystals as much as 1 millimeter in length (see pl. 14, *C*) and can be recognized megascopically. Gradations to the equigranular variety described above are common.

Under the microscope the rock shows a normal porphyritic texture in which hornblende, biotite, plagioclase, and accessory minerals are euhedral to subhedral, with the quartz and orthoclase molded upon them. A small amount of graphically intergrown quartz and orthoclase is found in some rocks. The plagioclase of fresh specimens is zoned rather widely, exceptionally as much as from An_{45} to An_{20}, but commonly from about An_{35} to An_{20}. The exterior zones in some specimens reach compositions as sodic as An_5. In the specimen analyzed, No. 1, table 4, the feldspar core is close to An_{28}, with repeated zones of composition An_{20} and An_{28}, and an external shell of albite-oligoclase An_{10}, probably slightly more sodic than the average.

Hornblende is generally subhedral, pleochroic with $\gamma = \beta$ dark-green, α light-yellow green, with extinction angle of 24° $\gamma \wedge c$ ($\alpha = 1.645 \pm .003$ $\beta = 1.654 \pm .003$ $\gamma = 1.664 \pm .003$, opt.—). Biotite, of the common variety ($\beta = 1.637$— 1.644), strongly pleochroic in brown, is chiefly in euhedral books, some containing inclusions of zircon and rounded apatite crystals.

Orthoclase is present in large crystals, a few of which suggest by their slight mottling that they may be cryptoperthite. A suggestion of microcline twinning in one or two specimens could not be verified. Some quartz is intergrown with the orthoclase, and it commonly holds crystals of plagioclase, with the dark minerals and accessory minerals as inclusions.

Quartz is anhedral in irregular grains, some of them interfering with the development of plagioclase (see pl. 13, *E*, *F*) but chiefly with orthoclase (see pl. 14, *C*). A few narrow stringers of quartz penetrate undeformed orthoclase crystals in a way reminiscent of perthite. (See pl. 12, *E*, *F*.) In some specimens it forms rounded phenocrysts. (See pls. 13, *F*, and 14, *C*, *D*.)

Of the accessory minerals, sphene is interesting because of the large size (as much as 1 millimeter in diameter, average 0.3) and good form of its crystals. Apatite is also common in crystals as much as 0.3 millimeter long but is notable by reason of its rounded forms. Zircon, rarely exceeding .05 millimeter in length, and a few opaque grains, probably of magnetite, are also present.

A little chlorite occurs after both hornblende and biotite, sericite wisps are found in the cores of some plagioclase crystals, and a few grains of epidote are present in all specimens examined. Presumably these minerals are of deuteric origin in the freshest rocks.

ALTERATION

Although small masses of the Cornelia quartz monzonite have elsewhere been slightly altered, with their plagioclase transformed to albite, the only considerable area of intense alteration centers in the New Cornelia ore body, south of Ajo. This alteration, of which the copper mineralization of the New Cornelia mine was a stage, was considerably more widespread than the metallization. Its principal effects were the impregnation of the rocks with potash feldspar and quartz, the transformation of the plagioclase to aggregates of albite and sericite, the alteration of the dark minerals to chlorite, and the more localized introduction of the metallic minerals, magnetite, pyrite, chalcopyrite, bornite, molybdenite, and specularite.

These alterations are considered in more detail in the section of this report dealing with metamorphism; because of their intimate connection with the magmatic processes they are here dealt with briefly.

Large volumes of the quartz monzonite have been impregnated with microcline and orthoclase, usually accompanied by considerable quartz. This impregnation by potash feldspar seems to have occurred in two stages—one late magmatic, the other postmagmatic. The earlier stage, which affected a much larger area than the later, is recorded by a peculiar microscopic texture of the monzonite groundmass.

This texture is not only well developed in the obviously pegmatized rocks but is much more widespread in the area southeast of Camelback Mountain. It consists chiefly of rounded blebs of quartz, commonly 0.3 to 0.1 millimeter in diameter, in the interstices between and poikilitically enclosed within slightly larger (0.8 to 0.3 millimeter) subhedral crystals of orthoclase. The feldspar and quartz grains of this groundmass differ from the interstitial minerals of the normal granitic texture in their common indentation or corrosion of the phenocrysts, both of plagioclase and quartz. Practically no cleanly developed crystal faces occur on the phenocrysts; all are interrupted by the rounded penetrations of the minerals of the groundmass, as seen on plates 13, *E, F,* and 14, *B, C, D.*

This texture differs markedly from the normal granitic texture that elsewhere characterizes the rock, and relics of the normal, presumably original, texture are locally present in it. It seems significant that normal granitic (hypidiomorphic granular) texture commonly occurs at Ajo only in rocks with andesine or oligoclase feldspars, whereas the albitic and sericitic varieties generally show this intergrowth in the groundmass. Neither of these associations is without exceptions; a few specimens show this texture though the plagioclase is fresh andesine.

That replacement has been a factor in the development of this texture is indicated by (1) the indentation of the phenocrysts by quartz and orthoclase, though the major form of the crystal is preserved, and (2) the growth of small orthoclase crystals throughout some of the plagioclase phenocrysts, as shown in plate 14, *B.*

However, there is only local evidence of any control of the replacement by fractures (See pl. 11, *A, B, E, F*) and the alteration is general through large volumes of the rock. Furthermore, the fact that the boundary faces of the phenocrysts are so indented as to suggest some replacement is offset by the practically identical content of potassa in both the equigranular and the porphyritic facies (see table 4), which shows that, in general, little K_2O was introduced after the rock was emplaced. The persistence of plagioclase phenocrysts practically throughout the mass south of Ajo is also opposed to an assumption of much bulk replacement. The plagioclase phenocrysts are of generally similar size and of recognizable prismatic shape everywhere and are rarely transected by orthoclase or quartz without brecciation. If the groundmass were entirely of replacement origin, this preservation of major form of the plagioclase crystals would be inexplicable.

The alternative appears to be that in a late magmatic stage, prior to complete consolidation of the groundmass, the equilibrium conditions were suddenly changed and the part that was still liquid began to attack the earlier crystals. The generally available energy was so slight that the attack was no more than begun when final consolidation stopped the process. Locally, as in and near the pegmatites in the New Cornelia mine, replacement continued after the rock was consolidated and fractured.

What the factors may have been that produced this late magmatic shift in equilibrium is uncertain. The process may have been like, but not so intense as, that described from Pioche, Nev., by Gillson,[43] who attributed the change in equilibrium to transfer of material by gases passing upward from underlying parts of the magma chamber. The matter is discussed further in connection with mineralization.

Because of the features enumerated above, this alteration is referred to a late magmatic stage. It was followed by a long series of alterations that are considered postmagmatic, because they are obviously related to fractures in the monzonite.

Postconsolidation replacement by potash feldspar has been less widespread than the mild late-magmatic replacement, though it was much more intense. In the New Cornelia body rather large masses of coarsely crystalline microcline have been formed along northward-trending zones, and near these pegmatitic masses the monzonite is minutely and intricately veined by replacement orthoclase. Narrow microscopic veinlets of orthoclase pass entirely through albitic phenocrysts in the monzonite, and blending contacts between pegmatite and host rock testify to the replacement origin of much more of the microcline, orthoclase, and accompanying quartz.

The rocks southeast of Camelback Mountain that show the "corroded" texture just described, generally, though not invariably, have albitic plagioclase. (See pl. 14, *B.*) Similar albitization of the monzonite, though without the introduction of orthoclase, and hence probably younger than the orthoclasization, has occurred at many other places in the quadrangle, notably west of Gibson Arroyo, in secs. 16 and 21, T. 12 S., R. 6 W., and also west of Cardigan Peak. The rocks so altered appear rather fresh, with glistening or only slightly dulled feldspar cleavages.

[43] Gillson, J. L., Petrography of the Pioche district, Lincoln County, Nev.: U. S. Survey Prof. Paper 158-D, pp. 78-84, 1929.

The hornblende and biotite have been altered to chlorite and less abundant pistacite, but it is only under the microscope that the alteration is strikingly apparent. Many of these rocks show quartz replacement of the plagioclase. (See pls. 12, *E*, *F*, and 13, *A*.)

These rocks show their originally more-calcic plagioclase crystals pseudomorphically replaced by albite, An_2 to An_5, cloudy with minute inclusions. Many of these inclusions are indeterminate; however, sericite is present in most specimens, a little pistacite in others. No zoisite or clinozoisite was detected with the oil-immersion lens, but they may be represented by a great number of extremely minute highly refringent included grains. If so, they are apparently quantitatively inadequate to account for all the lime originally in the plagioclase. In a few specimens plumose chlorite occurs in the cloudy albite. (See pl. 13, *F*.) Calcite is also present locally.

Following the pegmatization, and probably accompanying the albitization, the monzonite in the neighborhood of the New Cornelia ore body was veined and partly replaced by metallic minerals. Near the pegmatites magnetite is plentiful, together with the copper minerals chalcopyrite and bornite, but it fades out within a relatively short distance away from the pegmatites. The impregnation of the monzonite by copper minerals, with which smaller amounts of pyrite and molybdenite are associated, extended beyond the area of pegmatization but was not as extensive as the sericitization and albitization of the plagioclase. The details of mineralization are discussed in a subsequent section; it will merely be pointed out here that, if, as seems certain, the Gibson Arroyo fault is postmagmatic and if allowance is made for the tilting of the block of rocks making up the Little Ajo Mountains, the mass in which the New Cornelia mine occurs was the original apex of the Cornelia quartz monzonite stock. Accordingly this is another example of mineralization in the apex of a stock, a structural setting that has been recognized as common to many ore deposits since it was first emphasized by Butler.[44]

CHEMICAL COMPOSITION

Rocks representative of several of the varieties of the Cornelia quartz monzonite and its altered facies were chemically analyzed with the following results:

[44] Butler, B. S., Relation of ore deposits to different types of intrusive bodies in Utah: Econ. Geology, vol. 10, pp. 101-122, 1915.

TABLE 4.—*Analyses and norms of quartz diorites and quartz monzonites*

[Analysts: 1-6, J. G. Fairchild; 7, R. C. Wells and assistants]

ANALYSES

	1	2	3	4	5	6	7
SiO_2	60.59	62.27	65.29	66.23	65.66	66.92	65.57
Al_2O_3	17.39	17.40	15.74	15.71	15.98	15.78	15.42
Fe_2O_3	1.60	2.35	2.05	2.20	1.45	1.30	1.05
FeO	1.98	2.79	2.03	1.98	2.70	1.08	2.40
MgO	2.38	2.86	1.84	1.58	2.14	1.40	1.66
CaO	5.06	1.19	3.66	3.78	1.88	.76	.39
Na_2O	4.09	4.10	3.77	3.89	3.55	3.46	3.33
K_2O	1.63	2.76	4.11	3.22	3.70	5.26	5.01
H_2O-	.78	.50	.14	.03	.20	.71	.79
H_2O+	3.29	2.65	.62	.67	1.52	1.92	1.06
TiO_2	.61	.84	.54	.47	.60	.56	.36
P_2O_5	.36	.30	.24	.24	.31	.28	.23
MnO	.08	.05	.07	.08	.02	.05	.03
CO_2	....	....	....	....	.47	....	.41
F	....	....	....	....	....	.03	....
Cl	....	....	....	....	....	None	....
SO_3	....	....	....	....	....	.30	....
BaO	....	....	....	....	....	.11	.05
B_2O_3	....	....	....	....	....	[a]None	....
Li_2O	....	....	....	....	....	....	.05
V_2O_3	....	....	....	....	....	....	.011
Cr_2O_3	....	....	....	....	....	....	.001
$CuFeS_2$	....	....	....	....	....	....	[b]1.00
$CuFeS_4$	....	....	....	....	....	....	.70
FeS_2	....	....	....	....	....	....	.20
	99.84	100.06	100.10	100.08	100.18	99.92	99.72
Specific gravity:							
Bulk at 25°	....	....	....	....	....	....	2.653
Powder at 25°	....	....	....	....	....	....	2.669

NORMS

	1	2	3	4	5	6	7
Quartz	16.92	20.82	17.58	21.18	24.54	23.64	23.34
Orthoclase	9.45	16.68	24.46	18.90	21.68	31.14	30.02
Albite	35.58	34.58	31.96	33.01	29.87	29.34	28.30
Anorthite	22.24	3.89	13.62	15.85	4.73	1.95	....
Corundum	.71	6.22	....	....	4.49	3.67	4.39
ΣSalic	83.90	82.19	87.62	88.94	85.31	89.74	86.05
Enstatite	6.00	7.20	4.60	3.95	5.40	3.50	3.50
Forsterite	1.45	1.98	1.06	1.06	2.77	....	2.77
Wollastonite	....	....	1.51	.93	....	....	....
Magnetite	2.32	3.25	3.02	3.25	2.09	1.86	1.62
Ilmenite	1.22	1.52	1.06	.91	1.22	1.06	.76
Apatite	1.01	.67	.34	.34	.67	.67	.34
(Calcite)	....	....	....	....	(1.00)	....	[c](.68)
(Sulfides)	....	....	....	....	....	....	(1.90)
ΣFemic	12.00	14.62	11.59	10.44	12.05	7.09	8.99
Symbol	(I)II.4.3.4	(I)II.4.(I)2.4	I(II).4.2".3".	I(II).4.2(3).(3)4	I(II).4.(I)2.3"	I"4.1.3	I(II).4.1.3

[a] Tests by E. T. Erickson show that not more than 0.001 percent of B_2O_3, if any, is present.
[b] Copper present, 0.82 percent.
[c] Calcite 0.20, magnesite 0.48.

1. Biotite quartz diorite, 700 feet southwest of office of New Cornelia mine, Ajo.
2. Albitized sericitic quartz diorite, west side of approach cut, 1,200 feet south of office of New Cornelia mine, Ajo.
3. Hornblende biotite quartz monzonite (equiangular facies), 2,890-foot peak, SE ¼ sec. 20, T. 12 S., R. 6 W.
4. Hornblende biotite quartz monzonite (porphyritic facies) 600 feet south of east crest of Camelback Mountain, SW ¼ sec. 22, T. 12 S., R. 6 W.
5. Albitized sericitic quartz monzonite (porphyritic facies), southwestern side of New Cornelia mine pit, due east of Arkansas Mountain.
6. Albitized sericitic porphyritic quartz monzonite. East spur of hill west of Mexican town, east-central part of sec. 22, T. 12 S., R. 6 W., Ajo.
7. Porphyritic quartz monzonite, mineralized, albitized, and pegmatized. Center of New Cornelia mine pit.

The analyses show that the relatively unaltered quartz diorite facies (No. 1), compared with the fresh quartz monzonite (Nos. 3 and 4), is about 5 percent lower in silica, about 1½ percent higher in lime, about 2 percent lower in potassa, and 2½ percent higher in H_2O+. The higher proportions of normative orthoclase in the monzonite and of anorthite in the quartz diorite correspond to these differences. Although part of the combined water is doubtless present in biotite and hornblende, most of it probably represents muscovite and clay minerals resulting from alteration. The chemical analyses of Nos. 5, 6, and 7 correspond with usual percentages for granites, but the rocks are recognizably altered and were most likely originally very similar to Nos. 3 and 4. The Na_2O content as well as the albite content of the norm is remarkably uniform, not only in the fresh rocks but in all the rocks; in fact it decreases slightly in the rocks with albitic feldspars. This relation shows that the albitization is due more to removal of CaO from the plagioclase mix-crystals than to introduction of the Na_2O. The increase in K_2O, with no significant change in Al_2O_3, is reflected modally in the production of sericite at the expense of the anorthite constituent of the plagioclase, the lime set free by this replacement being removed from the rock. In the norm this relation is reflected strongly in the artificial corundum molecule. The chemistry of this alteration is discussed further in the section on metamorphism.

EMPLACEMENT

Owing to the fact that the Cornelia quartz monzonite is cut off along its entire northern border by the Little Ajo Mountain fault, the relations of the intrusive to the rocks bordering it in that direction are unknown. The entire block of country south of the Little Ajo Mountain fault has been tilted southward at an angle of about 50° since the intrusion of the quartz monzonite (see pp. 52, 53, and pl. 24). If, in imagination, the country is restored to the attitude prevailing before this tilting, the steep southward tilt of the southern contact of the quartz monzonite becomes a gentler dip, perhaps 30° S. Similarly, if the flattish westward-dipping thick dike in which the ore body of the New Cornelia mine is developed were restored to its original attitude, it would have a more northerly trend, and its present upper contact would dip steeply to the west. Thus the roof of the intrusive at the time of emplacement was formed of the rocks now along the southern contact, chiefly of Cardigan gneiss, but, east of the Gibson fault, also of Concentrator volcanics.

The Gibson fault seems to die out northward in the NW¼ sec. 22, T. 12 S., R. 6 W., and cannot be followed in the arroyo or east of it. It may be buried by alluvium on the east bank. The contact of monzonite against diorite on the west is definitely an intrusive contact on the line between secs. 15 and 22. This suggests that the Gibson fault is a normal fault, which cut the roof of the stock and dropped the cupola on the east against an originally deeper part of the stock on the west. The fault could not have been formed by collapse during the intrusion, however, for it has slickensided and brecciated monzonite along it, and there is no evidence of injected bodies following it where it cuts off post-Cornelia dikes. It is parallel to a regional set of faults not recognizably controlled by the Cornelia quartz monzonite. For these reasons it seems almost certain that the fault was formed after the consolidation of the quartz monzonite and was due to regional rather than local control.

The internal structure features and the relation of the mass as a whole to its country rocks have been studied in the hope of deducing some picture of the process of emplacement of the mass. The data are discussed in the following section, but do not afford a sufficient basis for any final conclusions.

The few poorly defined parallel linear elements (largely streaks of hornblende or biotite) in the quartz monzonite (See pl. 3 and fig. 4), which are probably to be interpreted as flow lines,[45] dip steeply south (nearly parallel to the contact) at the south border of the intrusive and at generally decreasing angles to the north. This arrangement would accord with the interpretation that these linear structures record a flow of the magma upward to the north just before its complete consolidation. The wall rocks to the north of the stock, however, are not exposed, and the linear structures present are certainly so weak and sporadically developed that one cannot deduce a complete picture of the final movement even on the assumption that these structures are correctly interpreted. How far such features record movements at stages prior to the advanced crystallization of the magma is an open question. If such features are to be interpreted as recording movements in a stage just prior to consolidation, the absence of such features must logically be referred to absence of movements in the magma at comparable stages of consolidation. The lack of shearing effects or other apparent deformation of the wall rocks points logically to the same conclusion—that magma was to a large extent emplaced when its effective viscosity was not very high, that is, prior to the development of a compact crystal mesh.

The quartz diorite facies is interpreted as an early differentiate of the magma that later evolved the equigranular facies of the quartz monzonite. If so, according to the crystallization-differentiation theory, crystals would be expected to be present in the quartz monzonite magma at the time of its intrusion, as its plagioclase contains cores that are nearly as calcic as the plagioclase of the quartz diorite. On the north slope of Camelback Mountain, however, the quartz monzonite cuts the previously consolidated quartz diorite into a multitude of isolated fragments without any recognizable flow streaking, either of the fragments or the matrix. Low viscosity and lack of strong localized movements seem also indicated by the absence of schlieren among the wall-rock inclusions near the contacts west of Gibson Arroyo. (See pl. 5, *F.*) As far as they go, these observations are thus more suggestive of emplacement by stoping than by forcible intrusion. The sparse distribution of quartz diorite along the south (roof) contacts of the intrusive and its presence along the east and west (lateral) contacts perhaps conforms with the idea that the principal quartz monzonite magma was farther above its crystallization temperature and less crystalline or viscous than the earlier dioritic fraction. Because of its different composition this might be true if the actual temperatures of the two fractions were identical. Upward motion of the monzonitic magma to the north during early stages may have furnished sufficient heat to the roof to prevent the formation of quartz diorite border facies or to have removed all traces of one that might have existed. That the magma did not "erode" such a border by corrasion is almost certain from the absence of shearing phenomena in either the wall rock or the monzonite.

The weakness of lineation seems clearly to indicate weakness or irregularity of movements in the magma at a period so late in the process of consolidation that crystals were available to record them. These features evidently do not permit any unequivocal decision as to the mechanism of emplacement of the magma as distinguished from its state of crystallization at that time. Were the magma forcibly injected it might have been in a wholly liquid state, so that the weak crystal alinement found would record only slight later movements. The apparent absence of crowding of the wall rock, the lack of schistosity in the hornfels borders, and the apparent nondisturbance of the Concentrator volcanics are facts not favorable to the theory of forcible injection of the mass, but they do not disprove it, as the missing rocks may have been pushed up to the north ahead of the intrusion. One would expect on this hypothesis that the intrusive would parallel or affect preexistent structures in the wall rocks more closely, but this objection is perhaps not insuperable.

On the other hand, the transection of the wall-rock structures and absence of systematic schlieren, although compatible with a theory of emplacement by stoping, are certainly not conclusive evidence of it. The absence of

[45] Cloos, Hans, Der Mechanismus tiefvulkanischer Vorgänge, Sammlung Vieweg, Braunschweig, 1921. Balk, Robert, Primary structure of granite massifs: Geol. Soc. America Bull., vol. 36, pp. 679-696, 1925; The structural behavior of igneous masses: Geol. Soc. Amer. Mem. 4, 1937.

many dikes in the roof is unfavorable to the stoping theory, even though the weak flow structures indicate that the magma was in essentially its present position before crystallization was very far advanced. If the Gibson Arroyo fault actually records roof collapse, as seems unlikely, this may indicate emplacement by stoping. The wall-rock inclusions are few and do not appear to be diagnostic of the process. The evidence at hand thus seems inadequate to warrant any conclusion as to the manner of emplacement of the stock.

Presumably because of a small body of Concentrator volcanics ("rhyolite") that capped one of the hills over the ore body that has since been mined away, Joralemon[46] interpreted the quartz monzonite mass containing the New Cornelia deposit as a laccolith. Several xenoliths of both Concentrator volcanics and border-facies diorite occur near the mine (See pls. 20, 21). The "rhyolite" body was probably such an inclusion, for the continuation of the monzonite in depth, as shown by the drill (See pls. 22, 23), is not compatible with a laccolithic origin, and, so far as the structure of the volcanics can be ascertained, the intrusive contact transects it at high angles.

The aplitic and andesite porphyry dikes in the stock (See pl. 1, *D*), which are especially numerous toward the northwest slopes of the mountains, trend generally westward and dip north. Their local variations in trend (N. 70° E. to S. 50° E.) and in dip (45°-80° N.) are so great and their deviations from the normal to the faint lineation of the monzonite are so wide that it would appear gratuitous to assume that they occupy cross joints analogous to those so commonly reported in other intrusive bodies. Most of these dikes probably dipped steeply south before the tilting of the block south of the Little Ajo Mountain fault, thus in a direction toward the source of the magma, on the assumption that the linear structures represent flow lines. However, their connection, if any, to the mechanics of emplacement of the stock remains obscure.

AGE

The Cornelia quartz monzonite is of unknown age. Inasmuch as the Concentrator volcanics are probably not older than Cretaceous, this puts the lower limit of its possible age as Cretaceous also. Comparisons with other intrusive rocks of southern Arizona suggest that it is comparable with those that have been assigned to the early Tertiary, but few of these intrusives are definitely dated. The granitic and quartz monzonitic porphyry at Morenci intrudes the Upper Cretaceous[47] and is unconformably overlain by volcanics of probable Tertiary age. Similar relations obtain in the Aravaipa and Stanley districts[48] and the Saddle Mountain and Banner districts.[49] At Bisbee the relations are controversial; Ransome[50] interprets the granite porphyry with which the ores are associated as pre-Cretaceous, whereas Tenney[51] believes that the granite porphyry intrudes the Cretaceous (Comanche) and is Tertiary. An early Tertiary age has been assumed by Ransome[52] for the granitic rocks at Miami and Ray, but the evidence is far from conclusive. The Cornelia quartz monzonite is here tentatively referred to the early Tertiary on no more compelling evidence, as such an assignment would readily accommodate the historical events of subsequent time without doing violence to preconceptions as to the rate at which geological processes operate.

FELDSPATHIC ANDESITE PORPHYRY

OCCURRENCE

Dikes of andesite porphyry are most conspicuous in the area between Ajo and the head of Gibson Arroyo, although isolated examples occur farther west, on the northern slopes of the Little Ajos north of Cardigan Peak and in the foothills near Salt well. No dikes of the porphyritic variety here described were seen west of Gibson Arroyo on the south flank of the mountains. They are thus most plentiful in the apical portion of the Cornelia stock. The dikes near Ajo form ridges as much as 300 feet wide that trend slightly north of east and project above the general level of the country rock. The most conspicuous outcrop is on the crest of Camelback Mountain. The dike that crops out here forms the ridge to the east as far as the administrative office of the Phelps Dodge Corporation, east of Ajo. Within this distance it has several offsets en échelon. Several discontinuous dikes occur to the north of this most conspicuous one. These dikes are shown on plates 20 and 21 but are not shown on plate 3.

STRUCTURAL RELATIONS

The feldspathic andesite porphyry dikes are the earliest of the many andesitic dikes that followed the intrusion of the Cornelia quartz monzonite. Their relations to the pegmatites and aplites of this mass are unknown, but the andesites are thought to be the younger, because the siliceous dikes have blending contacts with the quartz monzonite and the andesite porphyry cuts the quartz monzonite cleanly. These dikes are in turn cut by nonpor-

[46] Joralemon, I. B., The Ajo copper-mining district: Am. Inst. Min. Eng. Trans., vol. 49, p. 597, 1914.

[47] Lindgren, Waldemar, Geology and ore deposits of the Clifton-Morenci district, Ariz.: U. S. Geol. Survey Prof. Paper 43, p. 85, 1905.

[48] Ross, C. P., Geology and ore deposits of the Aravaipa and Stanley mining districts, Graham County, Ariz.: U. S. Geol. Survey Bull. 763, p. 51, 1925.

[49] Ross, C. P., Ore deposits of the Saddle Mountain and Banner mining districts, Ariz.: U. S. Geol. Survey Bull. 771, p. 21, 1925.

[50] Ransome, F. L., Ore deposits of the Southwest: 16th Internat. Geol. Cong. Guidebook 14, p. 11, 1933; U. S. Geol. Survey Prof. Paper 21, p. 84, 1904.

[51] Tenney, J. B., The Bisbee mining district: Eng. and Min. Jour., vol. 123, p. 841, 1927.

[52] Ransome, F. L., The copper deposits of Ray and Miami, Ariz.: U. S. Geol. Survey Prof. Paper 115, p. 59, 1919.

phyritic hornblende andesite dikes and by the much younger Hospital porphyry. (See p. 44.)

PETROGRAPHY

The big dike forming the crest of Camelback Mountain is greenish-gray on fresh fracture, weathering to light buff-gray. It contains phenocrysts of plagioclase as much as 1 centimeter in diameter and of chlorite (after hornblende and biotite) ranging between 1 and 5 millimeters in length. These are contained in a dense groundmass. Under the microscope the rock shows calcic andesine, chlorite, locally a little biotite or hornblende in a microcrystalline groundmass of oligoclase, a little quartz, orthoclase, considerable sphene, and the usual accessory minerals. Locally there has been considerable albitization and sericitization of the feldspar, and epidote commonly replaces the dark minerals in part.

ORIGIN

The feldspathic andesite porphyry in the area east of Gibson Arroyo forms dikes that trend slightly north of east and dip about 70° N. This attitude is at an angle of about 60° to the sparse lineation in the monzonite, a considerable deviation from the normal attitude to be expected of the so-called "cross joints" of Cloos, which are common in intrusive massifs. It is possible that the dikes fill joints transverse to the direction of extension of the mass, but the relation is not rigorous and the en échelon arrangement of the dikes suggests control of their intrusion by torsional forces that cannot be easily referred to magmatic pressures. Whether or not the dikes occupy true cross joints and thus represent part of the main intrusive process, they are almost surely late representatives of the same parental magma as the Cornelia quartz monzonite. This relationship is strongly suggested by the similarities in mineralogy to the Cornelia, especially by the notable content of euhedral sphene and the size of the biotite and hornblende crystals in the dikes.

NONPORPHYRITIC ANDESITE DIKES OLDER THAN LOCOMOTIVE FANGLOMERATE

DISTRIBUTION

Many nonporphyritic andesite dikes cut the Cornelia quartz monzonite in the area east of Gibson Arroyo. A very few similar dikes were also found in the monzonite far to the west, south of Salt well, but none were found in the intervening area. Most of these dikes now trend east or slightly north of east and dip north at intermediate angles. A few trend nearly north. The post-dike tilting of the Little Ajo Mountain block implies a steeper dip for these eastward-trending dikes at the time of their intrusion than they now possess. Dikes similar in petrography and trend occur in the Locomotive fanglomerate, so that some of the dikes here discussed may belong to a later suite. On the other hand, some of the dikes that cut the Cardigan gneiss near Cardigan and have been mapped on plate 20 as of the pre-Cornelia suite also cut pegmatites and aplites that are related to the Cornelia quartz monzonite. They may therefore belong either to the suite here discussed or to the post-Locomotive group. The unequivocal assignment of each mapped dike to one of the three groups of nonporphyritic andesites, all of which show more or less albitization, chloritization, and sericitization, would require more detailed study than could be devoted to it during this work. The structural evidence that there are at least three separate suites of these dikes appears indisputable, and in the main, the distinctions on the map are believed to be reasonably consistent, but it is clearly recognized that each of the two younger suites may be under-represented on the map. It should also be mentioned that there may be a few more of these hornblende andesite dikes in the areas of Concentrator volcanics than would appear from the maps (pls. 20, 21), but the petrographic contrast between the two groups is sufficient to give assurance that such omissions, if any, are not very numerous. There is a real dearth of these dikes near Pinnacle Peak.

Most of the dikes are narrow, nowhere more than 60 feet wide and rarely exceeding 15 feet. They commonly extend unbroken for 1,000 feet and, with slight discontinuities at the ground surface, for several thousand feet. The few northward-trending dikes are much less persistent than those with easterly trends.

PETROGRAPHY

These andesites are generally dark, greenish gray, and fine-grained, either aphanitic or mildly porphyritic, with dark-green chloritic clots that have the shapes of hornblende crystals. They break down readily on weathering, so that their exposures are generally not very good, and it is not easy to find fresh material for petrographic study.

The freshest of these rocks show, under the microscope, andesine, hornblende, a little biotite, quartz, and orthoclase, and the accessory minerals magnetite, apatite, and sphene. In many specimens, however, the feldspar is saussuritic, and in a few it has been changed to nearly water-clear albite. Epidote and chlorite replace the dark minerals, and sericite and calcite are also widespread. The textures are divergent granular to pilotaxitic. No brecciation was seen in any of the rock sections.

STRUCTURAL AND GENETIC RELATIONS

Dikes of this suite cut the feldspathic andesite porphyry dikes near Ajo, and some cut aplites related to the Cornelia quartz monzonite west of Gibson Arroyo. They are therefore clearly post-Cornelia in age. Those east of the Gibson fault are apparently cut by the fault for, although no dragged blocks were seen, the dikes stop abruptly at the fault and do not spread into it; furthermore, dikes west of the Gibson fault appear to accommodate themselves to the fault in a way suggesting drag. The dikes, therefore, are considered pre-Locomotive in age, as the Locomotive fanglomerate is not offset by the Gibson fault.

The dike exposed in the diorite just east of the saddle on the low hill (see pl. 20) 1,000 feet southeast of the common corner of secs. 15, 16, 21, and 22, T. 12 S., R. 6 W., is of interest because it is apparently cut by a narrow stringer of quartz monzonite. Thin sections show no chilling of either monzonite or andesite at the contact. As the general geologic relations strongly suggest that the diorite is simply a chilled early facies of the quartz monzonite and the andesites of this group elsewhere clearly cut the Cornelia quartz monzonite, it seems reasonable to interpret this apparent transection of the andesite by monzonite as a failure of the younger andesite dike to cut the trivial monzonite stringer at the particular level of exposure. The dikes of this suite in the New Cornelia ore body seem to be clearly postmineral, as several contain quite fresh andesine feldspar, and, though they are all chloritized, they contain no sulfides except locally a little supergene chalcocite; furthermore, they have been much less fractured than the host rock.

No other igneous rocks of like age are known in the area. The surficial Ajo volcanics are clearly much younger. It may be that these dikes represent very late offshoots from the parental magma of the Cornelia quartz monzonite, but such a suggestion is purely speculative on the evidence at hand.

LOCOMOTIVE FANGLOMERATE

DISTRIBUTION AND TOPOGRAPHIC EXPRESSION

The formation which is named, from its characteristic exposure at Locomotive Rock (see pl. 6, *E*), the Locomotive fanglomerate[53] is exposed widely in the pediments and lower slopes south and southeast of the main mass of the Little Ajo Mountains. A small outlier occurs west of the Chico Shunie fault. If the formation were ever much more widely extended in this direction on the south flank of the Little Ajos, it has since been eroded away. Scattered outcrops of the formation are numerous in the pediment north of the Little Ajo Mountain fault from a point southeast of Clarkstown to a point nearly 2 miles northwest of Gibson, and for more than 1½ miles northward from the fault. One small outcrop of fanglomerate correlated with this formation is found about a mile south of the fault, near Salt well. There can be little doubt that the rocks of these exposures were continuous with those south of the mountains prior to the displacement on the Little Ajo Mountain fault.

[53] Gilluly, James, Geology and ore deposits of the Ajo quadrangle, Ariz.: Arizona Bur. Mines Bull., vol. 8, No. 1, p. 40, 1937.

For the most part, topography carved on this formation is subdued. Much of the pediment country of the quadrangle is underlain by it. Locally, however, there has been stronger cementation, and rather prominent "beehive" hills, such as Locomotive Rock and others near Cardigan, stand out above the rest of the landscape. Although the Ajo Peaks are among the most spectacular in the quadrangle, they owe their prominence to the capping of Ajo volcanics rather than to the resistance of the Locomotive fanglomerate, which makes up their northeastern faces. The fanglomerate locally forms sheer cliffs on these peaks. (See pl. 1, *E*.)

STRATIGRAPHY

The fanglomerate rests unconformably upon the Cardigan gneiss, Concentrator volcanics, and Cornelia quartz monzonite. The unconformity represents a period of erosion sufficiently long to have exposed the plutonic Cornelia quartz monzonite at the surface and to have produced a zone of secondary enrichment in the New Cornelia ore body. The erosion surface upon which the formation rests was one of considerable relief, as several thousand feet of fanglomerate wedge out against it. (See pls. 3, 20, 21.) In several places thick beds of fanglomerate wedge out against the base within short distances.

The irregularity of the surface on which the fanglomerate was deposited is illustrated by the relations on the extreme western spur of North Ajo Peak, west of the Chico Shunie fault. The north face of this spur is composed of fanglomerate that contains a thin-bedded sandstone layer conforming to the crude bedding of the formation. These rocks are overlain conformably by andesitic breccia of the Ajo volcanics. The formation is now tilted so that it has a dip of about 40°, but it was deposited with a small original dip, as is shown by the fine-grained water-laid sandstone; nevertheless, the Cardigan gneiss underlies the spur at about the same altitude on both sides, showing that the original hill slope against which the sedimentary formations were deposited had a northward slope of the order of 40°. (See fig. 5.)

The fanglomerate is composed of materials that are extremely variable in both composition and grain size. The sorting of most of the formation is as poor as can well be imagined. Boulders of great size rest in a matrix of cobbles, pebbles, and silt, without any lamination or other sign of water sorting. (See pl. 6, *A*.) Four-foot boulders are not uncommon. The largest measured, of Chico Shunie quartz monzonite, was 7 by 6 by 3½ feet with an estimated weight of more than 10 tons. Probably most of the exposures of the formation would show boulders, angular or subrounded, as much as 2 feet in diameter, although the average diameter of fragments is probably less than 1 inch. The degree of sorting, the excellence of the bedding, and the proportion of finer materials in the formation seem to increase toward the southeast. There are, how-

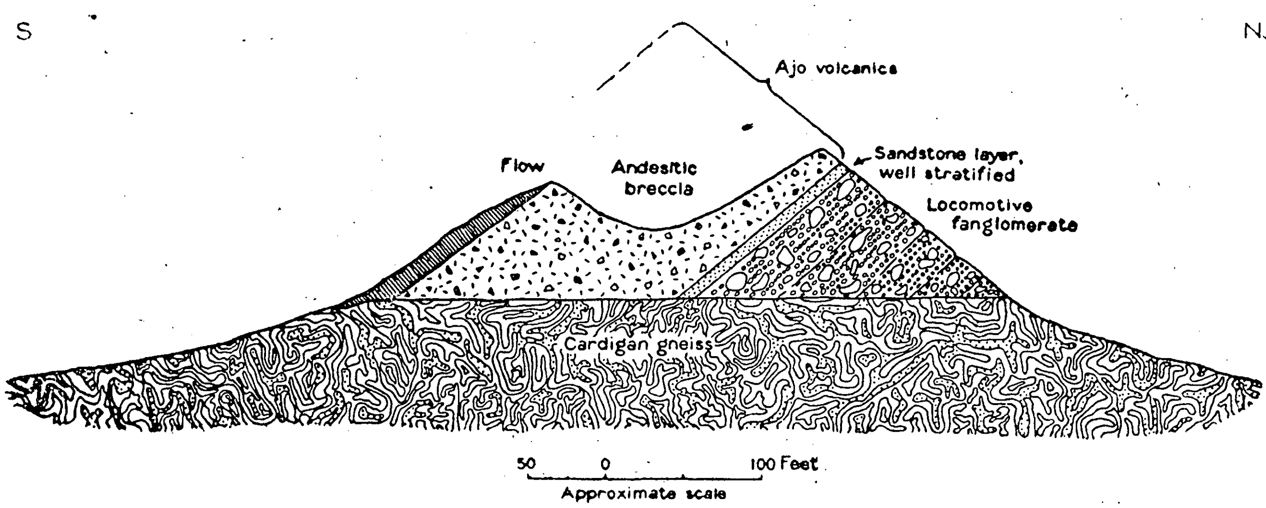


FIGURE 5.—Diagrammatic section through the west spur of North Ajo Peak, west of the Chico Shunie fault. Shows angular unconformity separating the Locomotive fanglomerate and Cardigan gneiss. The fanglomerate was deposited against a northward-sloping hill on a surface of notable relief. The attitude of the well-stratified sandstone layer indicates the subsequent tilting.

ever, local well-bedded intercalations almost throughout the formation, so that it is generally possible to observe the attitude of the bedding with some confidence.

The fragments in the fanglomerate include (1) keratophyres, quartz keratophyres and andesites derived from the Concentrator volcanics, (2) quartz monzonitic and quartz dioritic facies of the Cornelia quartz monzonite, including mineralized material with strong copper impregnations, (3) quartz monzonite of Chico Shunie aspect, (4) gneiss and schist derived from the Cardigan gneiss, (5) limestone, much of it containing Paleozoic fossils, of unknown source, (6) quartzite, also of unknown source, and (7) andesitic material derived from the partly contemporaneous Ajo volcanics. Many of the sandstones and shaly sandstones are composed of individual mineral grains rather than rock fragments, but they have not been examined in detail. They probably constitute less than 5 percent of the formation.

Generally speaking, one rock or another of those listed above is locally predominant, and especially where the fanglomerate rests on a basement of one formation detritus from that formation is generally most abundant. Even at some distance from the apparent sources, each layer (from 2 to 40 feet thick) is likely to be composed almost wholly of fragments of a single rock variety, although overlying beds may contain quite different rocks.

The Locomotive fanglomerate interfingers with and is conformably overlain by the Ajo volcanics.

About three-fourths of a mile southwest of Darby well and at an apparent stratigraphic interval of more than 8,000 feet (see p. 39) above the base, there is an intercalation of andesitic lapilli tuff with subordinate flows. This andesitic tongue is a precursor of more and thicker accumulations and is here classed as part of the Ajo volcanics. (See p. 39.) Although this tongue is about 450 feet thick at its most easterly exposure, it dies out within less than 2 miles toward the northwest. It is overlain by somewhat finer-grained, more quartzose beds, which were evidently deposited in water and rather well sorted. These well-sorted beds are only a few feet thick and are overlain by coarse fanglomerate like that lower in the section. This fanglomerate member is only about 350 feet thick in the neighborhood of Locomotive Rock and is overlain by almost 250 feet of andesitic lapilli tuff belonging to the Ajo volcanics. These andesitic beds are also lenticular and thin to a knife edge about 2 miles toward the northwest. They are overlain by more fanglomerate, which contains finer grained and more quartzose material than usual and passes upward through a few feet of better-rounded conglomerate into the normal nonsorted fanglomerate. This fanglomerate member in which is carved the well-known landmark, Locomotive Rock, for which the formation is named, is apparently about 2,500 feet thick. It contains a minor lens of Ajo volcanics a mile or so northwest of Locomotive Rock and is overlain, with some alternations of layers, by more andesitic lapilli tuff of that formation. This transition zone is best seen about 2,000 feet east of Ajo Peak. Like the lower intercalations, this tongue of the Ajo volcanics likewise lenses out toward the northwest, although extending farther in this direction than the lower tongues. It thickens to fully 500 feet toward the southeast before being buried by alluvium.

Overlying this andesitic member is about 1,000 feet of nonvolcanic sedimentary rock. Southwest of Locomotive Rock this zone is dominantly composed of thinbedded red sandy shale and ripple-marked sandstone, with some intercalations of coarse gray grit, and is very evenly stratified as a whole. To the northwest the well-stratified portion seems to be confined to the upper part of the member and to be underlain by fully 800 feet of normal crudely bedded, nonsorted fanglomerate in the lower eastern slopes of Ajo Peak.

The relations of the thin-bedded strata on the east slopes of Ajo Peak are particularly clear. The lower 5 or 10 feet is composed of red and green flaggy, ripple-marked, and mud-cracked micaceous sandstone passing upward into thinly alternating layers, from one-eighth inch to 2 inches thick, of green sandstone, grit, and micaceous shale. Some of the shale is extremely well-laminated, approaching a paper shale. Some poorly preserved fragments of fossil wood collected here proved unidentifiable. Somewhat higher stratigraphically are several beds of coarse fanglomerate as much as 10 feet thick, intercalated in the finer-grained well-bedded sediments. (See pl. 6, *B*.) The entire fine-grained member, including these interbeds, is about 175 feet thick here. At its top it passes by transition through a series of alternations with fine-grained lapilli tuff into coarse breccias of the Ajo volcanic series. There is thus evidence, in the relations of the obviously water-laid member to its adjoining strata, that part of the fanglomerate, even of the very coarse, poorly sorted facies, was laid down with a nearly horizontal surface, and similarly that the Ajo volcanics were deposited on a topography of low relief. (See p. 40.)

The contact relations on North Ajo Peak are difficult to evaluate, because the critical exposures are on inaccessible cliffs and can only be studied at a distance or from unfavorable angles of view. However, there seems to be intertonguing of fanglomerate and sandstone with the Ajo volcanics and no evidence of other than depositional irregularities such as are readily reconciled with the probable conditions of deposition of these coarse deposits. Similarly, there is evidently a tongue of Locomotive fanglomerate in the Ajo volcanics in the NE¼ sec. 9, T. 13 S., R. 6 W., and perhaps in the SE¼ sec. 15, in the same township. In summary, the Locomotive fanglomerate is believed to be conformable with and gradational to the Ajo volcanics.

The small body of fanglomerate a mile south-southwest of Salt well that is tentatively correlated with the Locomotive is unconformably overlain by the Sneed andesite. This is the one exposure in the quadrangle that gives information as to the time of tilting of the Little Ajo Mountain block.

THICKNESS

It is difficult to detect faults in the Locomotive fanglomerate because of its crude bedding and the lack of good "marker beds," other than the intercalated members of the Ajo volcanics. No faults were found that could be traced more than a few feet beyond the contact with one of the other formations. If the fanglomerate exposed from south of the east spur of Concentrator Hill to the alluvium south of Locomotive Rock is regarded as a continuous section, the formation has an apparent maximum thickness of about 12,000 feet. The remarkable regularity with which changes of strike and dip occur in this area seems to make the assumption of unseen duplicative faults unlikely. The lithologic character of the formation, however, implies a considerable relief in the nearby area, even toward the close of its period of deposition, and it is entirely possible that such faults do occur and that the true thickness of the formation may be several thousand feet less than it seems to be; but on no reasonable assumptions of such concealed faults can the formation be regarded as less than 6,000 feet in maximum thickness and it is probably much thicker.

ORIGIN

The composition of the formation, its poor sorting, the relief of the surface upon which it was deposited, and the increase in degree of sorting toward the southeast, with its finer texture and better bedding in the same direction, all agree in suggesting that the formation is a desert fan deposit, formed on the lower slopes of a desert range and in the basin at its foot. The finer-grained, well-bedded, ripple-marked, and mud-cracked members are reasonably interpreted as playa sediments, and the coarse, ill-bedded, nonsorted layers as mud flows, such as are common on the slopes of desert mountains. The local sorting and stream rounding of the detritus also accords with such an interpretation. Interbedding of supposed playa and mud-flow deposits is entirely compatible with this theory of deposition, for the margin separating playa and alluvial cone deposits characteristically changes backward and forward to some extent under desert conditions.

The principal components of the formation are readily identified as of local source—the mountain slopes that furnished the materials of the deposit were in part on the site of the present Little Ajo Mountains. Gradually these slopes were buried beneath their own detritus. The quartzite and fossiliferous limestone were either derived from beds formerly present on the Little Ajo Mountains but now eroded, or from nearby areas now buried beneath later rocks. The size of the fragments, as much as 6 feet across, give ample ground for inferring that they were derived from sources close at hand.

It is not meant to imply that the Little Ajo Mountains as they stand at present have any close relation to the mountainous topography that must have prevailed during the formation of the Locomotive fanglomerate. The evidence of materials whose sources are rather definite seems to show, as does, indeed, the occurrence of the fanglomerate north of the Little Ajo Mountain fault, that the sediments were formed against the eastern slopes of a mountain mass and that playa conditions prevailed toward the east of the area now occupied by them. The fact that the present dip of the fanglomerate between Ajo Peak and Cardigan would, if projected, carry the formation over the top of the present mountains, suggests the same thing, although it is not conclusive. The lensing out of the lower tongues of the Ajo volcanics toward the northwest and the thickening of both these volcanics and the intervening tongues of nonvolcanic material toward the southeast, in the direction of finer grain, suggest that the basin was undergoing depression with respect to the mountainous source of the sediments during the deposition.

Marked unconformities within or between the formations are lacking. This implies that the depression of the basin with respect to the mountains during deposition was relatively continuous and slow, so that any angle of tilting between two adjacent beds was slight; or, if there were no tilting of the basin block, that the basin ended abruptly against the mountain that supplied the sediment. Such a sharp boundary cannot now be recognized, and it is clear that, if it ever existed, it must have been considerably to the west of the Chico Shunie fault. The small outliers mapped as Ajo volcanics northwest of Chico Shunie well testify to a lensing out of the fanglomerate to the east of them, but the possibility that these outliers should be referred to the Sneed andesite throws doubt on their significance in this connection.

The great thickness of the coarse fanglomerate seems to require contemporaneous relative uplift of the block furnishing the detritus.

AGE AND CORRELATION

The only definite information as to the absolute age of the Locomotive fanglomerate is that it contains transported noncrystalline limestone boulders with fossils of Devonian, Mississippian (?), and Pennsylvanian age. Fossils from limestone boulders from the NW¼ NW¼ sec. 33, T. 12 S., R. 6 W., were identified by Edwin Kirk as *Atrypa reticularis* and *Cladopora* sp. According to Kirk,[54] "the *Atrypa* is identical with the variety found in the Martin limestone, and there is no doubt that the boulders were derived from the Martin." Another lot of fossiliferous boulders of limestone was collected just south of Arkansas Mountain, and examined by G. H. Girty, who reports as follows:

These boulders can be referred to the Carboniferous with more or less certainty. Several of them might be older, but this possibility is open only because they lack decisive paleontologic evidence. In fact, most of them lack evidence that is actually decisive, for though on the surface many show sections of fossil shells the rock is so altered that fractures pass through the shells instead of around them. Where a fossil is known only by a section through it, its generic position is mostly a matter of surmise, and commonly only one or two genera thus surmised are present in any one boulder. Nevertheless, it is possible to state definitely that several of the boulders are of Pennsylvanian age, and one of them can be assigned with hardly less assurance to the Mississippian. The Pennsylvanian age is testified by the presence of *Fusulina* in abundance. The Mississippian age of the single boulder thus identified rests upon the presence of an indeterminable crinoid, of a *Spirifer* of the *striatus* group (related to *S. grimesi* and *S. logani*), of a small Camarotoechia related to *C. metallica*, and of a small smooth brachiopod probably belonging to the genus *Composita*. This boulder is further distinguished by the fact that it is composed almost entirely of crinoid stems (though most of the other boulders contain crinoid stems in more or less abundance) and by the fact that the fossils readily separate from the matrix.

For the purpose of this report each boulder is considered an independent collection. Those which contain *Fusulina* and on that account are confidently regarded as of Pennsylvanian age contain the following forms: (1) *Fusulina* sp., *spirifer* sp., *Composita?* sp.; (2) *Fusulina* sp., *Productus?* sp., *Spirifer* sp.; (3) *Fusulina* sp., *Spirifer?* sp.; (4) *Fusulina* sp., *Spirifer?* sp.

The boulders less definitely referred to the Pennsylvanian contain: (5) *Spirifer* sp.; (6) crinoid stems, *Composita?* sp.; (7) crinoid stems, *Fistulipora?* sp.; (8) *Productus?* sp.; (9) *Composita?* sp.; (10) *Spirifer* sp., *Composita?* sp.; (11) crinoid stems, *Derbya?* sp. These boulders are probably Carboniferous but are indeterminate as between Pennsylvanian and Mississippian.

The Spirifers in 5 and 10 are sufficiently well shown to warrant an opinion that the age at least is younger than the Escabrosa limestone; they might, however, occur in some Mississippian horizon younger than the Escabrosa as well as in the Pennsylvanian.

No. 12 is a hard, dense limestone almost black in color, containing so far as observed only a small imperfect zaphrentoid coral (*Triplophyllum?* sp.); for this boulder I hesitate to suggest a geologic age except that it is unquestionably Paleozoic.

No. 13 has above been mentioned as of early Mississippian age (Escabrosa limestone) and its fauna there listed.

The alteration referred to by Girty is chiefly fracturing; there is no indication of internal metamorphic alteration of these boulders.

These boulders are of considerable paleogeographic significance, because they indicate rather definitely that the Martin, Escabrosa, and Naco limestones at one time extended to within a short distance of the present Little Ajo Mountains. The size of the boulders precludes their having traveled very far. The most westerly point at which the Carboniferous formations have been found in place is the Vekol Mountains, about 50 miles to the northeast, and the Devonian has not been recognized west of the Tucson Mountains.[55] The occurrence here thus extends the known range of these formations considerably westward.

With respect to the local problems, however, the fossils serve merely to fix the age of the Locomotive fanglomerate as post-Pennsylvanian. No fossils except indeterminate woody fragments have been found in the matrix material. If the long history represented in the post-fanglomerate record is taken into account, the fanglomerate can hardly be younger than middle Tertiary.

Without fossils it is practically impossible to correlate local deposits over any considerable area. The occurrence of coarse conglomerate and fanglomerate of roughly

[54] Kirk, Edwin, personal communication, July 20, 1934.

[55] Bryan, Kirk, The Papago country, Ariz.: U. S. Geol. Survey Water-Supply Paper 499, p. 56, 1925.

comparable lithologic character and structural relations at many points in southern Arizona suggests their possible correlation only on the basis that all are likely to be deposits formed in closed basins and hence to have been formed shortly after the structural disturbances that produced the basins. As such disturbances commonly affect rather large areas, the sedimentary rocks of the basins are likely to be of comparable age over similarly large areas. So far as known, however, none of these sedimentary rocks, which have been reported by Bryan[56] from near Tempe, Comobabi, north of the Table Top Mountains, Totebit Tanks, Sand Tanks, east of Wellton, and north of Blaisdell have yielded fossils, so that there is no direct clue as to the date of the basin formation, even if it be assumed that these rocks were all formed at the same time.

AJO VOLCANICS

DISTRIBUTION

The Ajo Peaks are capped by a conspicuous and thick formation of andesitic breccias, flows, and tuffs to which the name Ajo volcanics has been applied.[57] This formation forms the hills west and southwest of the Ajo Peaks and extends for about 3 miles in the low range of hills southeastward from the Ajo Peaks. At the base, both in the Ajo Peaks and to the southeast, the volcanics interfinger with the Locomotive fanglomerate, and the thinner pyroclastic layers in the fanglomerate half a mile northeast of Locomotive Rock are considered parts of this formation. There are three such layers of considerable thickness and several short lenses. All thin toward the northwest and die out in the fanglomerate. (See pls. 3 and 20.)

Similar andesites crop out in the pediment in Gibson and between the Gila Bend highway and the tailings dump north of Clarkstown. These rocks are also associated with fanglomerate and are here correlated with the andesites of the Ajo Peaks. Small patches of andesite lie on the pediment 3 or 4 miles west-northwest of Chico Shunie well. Though they may belong to the Sneed andesite, they resemble the Ajo volcanics somewhat more closely and are referred to this formation.

TOPOGRAPHIC EXPRESSION

The conspicuous Ajo Peaks are capped by lavas of the Ajo volcanics and show the resistance of these rocks to erosion. The coarse breccia members, which constitute most of the formation, are not so resistant, yet they generally form ridges. The finer-grained breccias and tuffs, however, are no more resistant than the associated fanglomerate, perhaps even less so, and weather down to slopes nearly uniform with them. The andesitic lavas of the localities on the north side of the Little Ajo Mountains are not topographically conspicuous.

[56] Bryan, Kirk, op. cit. pp. 59-63.

[57] Gilluly, James, Geology and ore deposits of the Ajo quadrangle, Ariz.: Arizona Bur. Mines Bull., vol. 8, No. 1, p. 43, 1937.

STRATIGRAPHY

The several lenticular volcanic members mentioned in the description of the Locomotive fanglomerate are considered as part of the Ajo volcanics. (See pp. 36, 37.) These interbeds are chiefly composed of lapilli tuff, with little lava.

The main member of the Ajo volcanics contains a few thin intercalations of fanglomerate at the base. At Ajo Peak the lower 500 feet is composed of angular unstratified breccia with fragments of andesite, averaging perhaps 1 foot in diameter but attaining as much as 8 feet, set in a finer matrix. Some flows are interbedded with this breccia, and it is overlain by a considerable thickness of flows and breccia. The proportion of lavas in the formation increases upward. This member, the main part of the Ajo volcanics, is about 3,500 feet thick as exposed, and, inasmuch as the top is overlain by alluvium, the true thickness is still greater.

About a mile southeast of Ajo Peak a lens of fanglomerate begins in this member, about 1,000 feet above the base, and thickens southeastward to the west edge of sec. 10, T. 13 S., R. 6 W., where it passes beneath the alluvium.

There are many small exposures of very similar porphyritic andesites with plagioclase phenocrysts in the pediment between Gibson and Clarkstown, just north of the Little Ajo Mountain fault. These rocks are closely associated with the fanglomerate, which is also sporadically exposed in this district, but outcrops are not sufficient to prove that the relations are as intimate as they are between Darby well and the Ajo Peaks. However, the andesites are provisionally referred to the Ajo volcanics. They have been distinguished on the map from the Sneed andesites, farther northwest, but may be more closely related than appears superficially. (See p. 42.) All these andesitic rocks differ among themselves only in the size of their component fragments. This lithologic similarity and their interfingering relations with the Locomotive fanglomerate show the essential unity of the group. As far as exposures show, the deposition of the Ajo volcanics outlasted that of the Locomotive fanglomerate, but the blanket of alluvium conceals the top of the volcanics, and it is entirely possible that there was deposition of conglomerate later than the breccia.

The small outliers of andesite flows referred to this formation west of Chico Shunie well rest directly on the Chico Shunie quartz monzonite. If the andesite is correlated correctly, the Locomotive fanglomerate must have wedged out in this direction, but it is possible that these outliers should be referred to the Sneed andesite instead of the Ajo volcanics.

THICKNESS

The thickness of the Ajo volcanics is uncertain, owing to the overlap of alluvium in the pediments carved on the formation. Near the Ajo Peaks about 3,500 feet is exposed, and if account be taken of the maxima of the lenticular intercalations with the Locomotive fanglomerate, the thickness may be 4,700 feet or even 5,000 feet. The exposures on the north side of the mountains are too scattered to justify even a guess as to the thickness there.

PETROGRAPHY

The Ajo volcanics include a wide variety of rocks. The members interbedded in the Locomotive fanglomerate are largely tuffaceous, with most fragments less than one-fourth inch in diameter. Higher beds are coarser. In those on the slopes of Ajo Peak, fragments are as much as 8 feet in diameter and average about 1 foot. The west pinnacle of Ajo Peak and the pinnacles of North Ajo Peak are formed of massive flows.

The component fragments of the fragmental rocks are closely similar to the flow rock. They consist of purplish-brown porphyries containing phenocrysts of plagioclase and less abundant biotite and hornblende in an aphanitic groundmass. The phenocrysts are commonly 1 or 2 millimeters across, but some are as much as 1 centimeter.

The minerals seen under the microscope include plagioclase, biotite, hornblende, augite, chlorite, epidote, magnetite, calcite, and sericite. In the tuffs the feldspar is too much weathered for determination. The breccias and flows have some fresh plagioclase, zoned from An_{45} to An_{35}, but in some of them the feldspar has been altered to albite, which contains wisps of sericite and epidote. Augite occurs in a few specimens and in some shows the smaller optic angle and lesser extinction angle that indicate a composition intermediate between augite and pigeonite. The hornblende is invariably coated by iron oxide rims, and the biotite also commonly shows this feature. It seems clearly a result of magmatic reaction. The biotite is deep red-brown with intense pleochroism. In some specimens the dark minerals are all altered to chlorite. The textures are all andesitic (pilotaxitic). The saussuritic alteration of these rocks is discussed elsewhere. (See p. 83.)

ORIGIN

The source of the Ajo volcanics is not definitely known. The interfingering of the volcanics and the Locomotive fanglomerate furnishes little clue to the source of the volcanics, for the accumulation of the fanglomerate and associated volcanics must depend largely upon fortuitous circumstances. The fanglomerate was deposited in a basin that deepened eastward, and the lower tuff beds of the Ajo volcanics doubtless were deposited by water in the lower parts of this basin, thus accounting for their lensing out westward toward the old highland. The upper members seem to have been laid down on a nearly level surface, as shown by the conformable contact with the overlying fine silts. The proportion of lavas among the volcanics seems to increase toward the Ajo Peaks, possibly indicating approach to the source of the material, but this inference is not quite certain, because there is less volcanic material of all kinds preserved above the alluvial cover toward the southeast. However, there are several dikes composed of andesite that resembles the rocks of the flows that cut the Ajo volcanics near North Ajo Peak, and these dikes may indicate nearness to the vent. No crater or neck has been recognized near the Ajo Peaks, and no definite suggestion can be made as to a source near them. It may be, of course, that some of the relatively narrow dikes in the Cardigan gneiss and Chico Shunie quartz monzonite west of the Chico Shunie fault may represent sources of these extrusive rocks, but, if so, erosion to these deeper levels has destroyed any easily recognized signs of the vents. It may be that the vent or vents lay several miles west of the quadrangle or beneath alluvial cover within it.

AGE

In absence of definite information, this formation is tentatively referred, like the Locomotive fanglomerate with which it is conformable and partly interfingering, to the middle part of the Tertiary.

NONPORPHYRITIC ANDESITE DIKES YOUNGER THAN LOCOMOTIVE FANGLOMERATE

DISTRIBUTION

In the fanglomerate area between Clarkstown and Darby well there are a few hornblende andesite dikes, strongly resembling the pre-Locomotive dikes in the Cornelia quartz monzonite but with less regular orientation. These dikes may indeed be of the same age as some of those in the gneiss near Cardigan and some of those in the Cornelia quartz monzonite at Ajo. Only their structural relations, where known, have served to distinguish the several suites of dikes. The evidence that there are at least two suites of hornblende andesite dikes older than the Locomotive fanglomerate has been indicated on pages 21 and 34. It remains to describe here the andesite dikes that cut the Locomotive fanglomerate.

These dikes fall into two groups, one trending generally north and the other generally east. In this respect they resemble the dikes described as pre-Locomotive. The dikes in the fanglomerate appear somewhat less regular, perhaps because of their less homogeneous host rock. All of these dikes are narrow. Nowhere are they more than 20 feet wide and they rarely exceed 15 feet. They commonly extend unbroken for only a few hundred feet and even linear groups are not much more than a thousand feet long. Generally northward-trending dikes are less persistent than the eastward-trending.

PETROGRAPHY

These andesites are generally dark, greenish-gray, and fine-grained or aphanitic and are almost identical petrographically with those described on p. 34 as pre-Locomotive. They break down readily on weathering, so that their exposures generally are poor and it is not easy to find fresh material for petrographic study.

The microscope shows, in the freshest of these rocks, andesine, hornblende, a little biotite, quartz, and orthoclase, and the accessory minerals, magnetite, apatite, and sphene. In many specimens, however, the feldspar is saussuritic and in a few has been entirely altered to water-clear albite. Epidote and chlorite have replaced the dark minerals, and sericite and calcite are widespread weathering products. The textures are divergent granular to pilotaxitic. No brecciation was seen in any of the rock sections.

ORIGIN, AGE, AND CORRELATION

The dikes that cut the Locomotive fanglomerate do not differ petrographically from those in the Cornelia quartz monzonite, but, because of their structural relations, they are here interpreted as belonging to a different group. These dikes in the fanglomerate were not seen in contact with any other igneous rocks. Their approximately uniform grain size and texture throughout the area of their exposure suggests, however, that they are younger than the tilting of the Locomotive fanglomerate to its present attitude. Prior to this tilting the rocks now exposed at the surface in the localities of the different dikes differed in depth of overburden by many thousand feet—a difference that would be expected to be recorded in different textural habits of the rocks of the extreme southernmost dikes as compared with those to the extreme north, if the dikes antedated the tilting. If this deduction is sound, the dikes are younger than the Ajo volcanics, although they were not seen in contact with that formation. Intersections with the Hospital porphyry dikes are concealed. Their relations suggest, but by no means prove, that these nonporphyritic andesites are the older.

The local albitization of these dikes might be thought, in absence of brecciation, to be due to hydrothermal alteration connected with ore deposition at Ajo, but the dikes in the fanglomerate are as much albitized as those in the ore body, and, as the fanglomerate is clearly considerably younger than the mineralization and contains boulders of copper-bearing monzonite isolated in it, all of the albitization is not directly referable to the same period of hydrothermal activity.

So far it has been impossible to correlate these dikes with any of the surface volcanic rocks of the region. As the Hospital porphyry dikes are very probably the intrusive equivalent of the Childs latite and as these andesite dikes are probably older than the Hospital porphyry and younger than the Ajo volcanics, they may correlate with the Sneed andesite. The matter cannot be decided on the evidence at hand.

SNEED ANDESITE

DISTRIBUTION

Hornblende andesite crops out along the lower slopes of Childs Mountain from Sneed Ranch to a point half a mile northwest of Salt well, near Sneed Ranch, in sec. 5, T. 12 S., R. 6 W., and north of Dunn's well. These rocks have been called the Sneed andesite.[58]

Weathered andesites of uncertain affinities in the pediment and low foothills north of Tule well are mapped as representing the same formation.

STRATIGRAPHIC RELATIONS

The basement upon which the andesite rests is not exposed at the type locality at Sneed Ranch. The Locomotive fanglomerate and Ajo volcanics are the only formations exposed north of the Little Ajo Mountain fault that can be older than the Sneed andesite. The possibility that the Sneed andesite is closely related to the Ajo volcanics is discussed on page 42. It is not certain that the andesite at Sneed Ranch rests on the fanglomerate, for the nearest outcrops of the two formations are separated by a wide interval (2,000 feet) of alluvium.

The andesites near Tule well rest unconformably on the Chico Shunie quartz monzonite and a mile south-southwest of Salt well on the Locomotive fanglomerate. This is the only locality north of the mountain mass where the Sneed andesite rests on rocks younger than the Cornelia quartz monzonite and the only place where the fanglomerate occurs to the south of the Little Ajo Mountain fault and north of the mountain divide. The fanglomerate is steeply tilted and strikes northwest, whereas the overlying andesite dips gently northwestward. These relations indicate that there is a marked unconformity between the fanglomerate and the Sneed andesite and that the Sneed andesite is younger than the petrographically very similar Ajo volcanics, which are conformable with the fanglomerate. As the great thickness of the fanglomerate doubtless implies contemporaneous mountain making, it may be that the unconformity is only local and that the Sneed andesite is essentially contemporaneous with the Ajo volcanics.

No rocks overlie the Sneed andesite except at the south end of Childs Mountain. In the E½ sec. 6, 2. 12 S., R. 6 W., the andesite, which strikes north-northeastward and dips gently westward, is overlain first by andesitic gravels of obscure attitude but correlated with the Daniels conglomerate (see p. 42) and then by the Batamote andesite, which dips gently eastward. The Batamote andesite can be followed southwestward to a point where it rests directly and with discordant dip on the Sneed ande-

[58] Gilluly, James, op. cit., p. 45.

site. The Sneed andesite is thus bounded by unconformities both above and below.

THICKNESS

Exposures are not adequate to furnish a very definite measure of the thickness of the formation. In the pediment north of Tule well the thickness is estimated as about 3,000 feet, but the formation is so lacking in determinable stratigraphic surfaces that this is not worthy of confidence. At the southeast corner of Childs Mountain the exposed thickness is 600 feet and on the isolated hill and surrounding pediment south of Sneed Ranch it is about 1,200 feet. At no place are both top and bottom determinable in the same section. When allowance is made for irregularities at both top and bottom a provisional estimate of 3,000 feet for the formation seems of the right order.

PETROGRAPHY

At Sneed Ranch the andesite consists chiefly of reddish porphyritic rocks containing phenocrysts of hornblende and less commonly of feldspar in a dense base. Some flows are glassy and lighter gray in color but contain similar phenocrysts. A conspicuous hill near the center of the south line of sec. 5, T 12 S., R. 6 W., is largely composed of flow-banded glassy andesite. Farther west there is more andesitic breccia in the section, although flow rocks predominate throughout.

The andesitic rocks between Salt well and Tule well are commonly more altered than those on Childs Mountain and correspondingly are dull greenish-gray even on the freshest fractures. The feldspar phenocrysts are all chalky, and the hornblende is represented chiefly by casts. These are all flow rocks, apparently.

Microscopically the fresh glassy rocks near Sneed Ranch show a perlitic groundmass containing phenocrysts of zoned andesine (An_{50} to An_{40}), common green hornblende, a little biotite, apatite, and magnetite. In places the hornblende and biotite have been changed to chlorite and the feldspars to saussuritic albite. Less glassy rock from near Dunn's well shows slightly more sodic andesine (An_{30}) and, where fresh, a few small crystals of augite, but they too are largely chloritized and saussuritized. The textures are pilotaxitic. Andesites from north of Salt well have similar textures but more anorthitic zoned feldspars (An_{55} to An_{45}). The hornblende in these rocks is much corroded.

The andesites between Tule well and Salt well are all highly altered, with albite-sericite pseudomorphs replacing the original feldspar, calcite and chlorite replacing hornblende, and secondary (?) quartz and epidote impregnating the groundmass. They are pilotaxitic, with the feldspar laths arranged in a partly fluidal alinement in a fine felted groundmass.

CORRELATION AND SOURCE

The relation of the Sneed andesite to the Ajo volcanics is puzzling. The two formations are very similar lithologically and have not been distinguished in the same area—facts that furnish good ground for the suspicion of their identity. However, the conformity of the Ajo volcanics with the Locomotive fanglomerate is clearly demonstrated, and it seems also definite that the andesite in the northwestern spur of the Little Ajos, south of Salt well, is unconformable on fanglomerate. The possibilities are (1) that the two andesites are identical, and different ages of fanglomerate are represented, (2) that the fanglomerates are identical and two andesites are represented and (3) that, as the fanglomerate is so thick that it probably demands contemporaneous faulting to account for its coarseness in almost all exposures, the tilted and eroded fanglomerate beneath the andesite near Salt well is perhaps equivalent to a lower part of the Locomotive fanglomerate, disturbed during Locomotive time and overlain unconformably by the same volcanics that overlie the southern outcrops conformably. The demonstration of the third possibility would require much more information than is available, and, as the mutual resemblances of the fanglomerates seem closer than those of the andesites, the second possibility has been adopted as a working hypothesis. This hypothesis implies that the tilting of the Little Ajo Mountain block occurred in the interval between the two volcanic episodes.

The source of the Sneed andesite is uncertain. No plugs that might represent a volcanic vent have been recognized. It may be significant that at several localities the hornblende crystals of horizontal lava beds in this formation are notably alined in a trend of N. 60° E. This alinement may indicate flow in this direction or in a S. 60° W. direction. Possibly a source near the Growler Mountains or near the Batamote Mountains is indicated, but the evidence is too slight to warrant any conclusions. There are many altered hornblendic dikes in the andesites near Tule well, but the exposures are not plentiful enough to indicate whether there was a volcanic vent in the neighborhood.

DANIELS CONGLOMERATE

DISTRIBUTION AND TOPOGRAPHIC EXPRESSION

The formation to which, from its exposures in the hills just north of Daniels Arroyo, the name of Daniels conglomerate has been applied,[59] is relatively poorly exposed. Except in fresh cut banks, as along Daniels Arroyo (pl. 6, *C*), it is broken down at the surface and covered by a veneer of unconsolidated talus. In places, it is only distinguishable from the much younger terrace gravels and fan deposits by its topographic position. However, the

[59] Gilluly, James, Geology and ore deposits of the Ajo quadrangle, Ariz.: Arizona Bur. Mines Bull. vol. 8, No. 1, p. 46, 1937.

smoothly sloping topography carved on the formation is characteristic and serves as an adequate guide to its distribution.

The principal exposure of the conglomerate is in the southwestern part of the Chico Shunie Hills, just north of Daniels Arroyo, where it forms a belt about 1½ miles wide practically from the west edge of T. 13 S., R. 6 W., to the west boundary of the quadrangle northwest of Teepee Butte. Small outcrops occur on either side of the hill in sec. 32, T. 13 S., R. 6 W., on the south edge of the quadrangle. Three small exposures of similar gravel, but whose correlation with the type Daniels conglomerate is uncertain, have been mapped as representative of the Daniels conglomerate in the southern part of Childs Mountain. These exposures are on the southeast slope, west of Sneed Ranch; on the southwest slope, half a mile northwest of Salt well; and on the lower slopes of the mountain, 2 miles northwest of Salt well.

STRATIGRAPHY

The Daniels conglomerate rests upon an irregular surface carved on Cardigan gneiss and Chico Shunie quartz monzonite in the southern part of the quadrangle and on Sneed andesite and Childs latite in the Childs Mountain localities. The relief of the surface in both areas is as much as 200 feet along the contact and shows that the conglomerate buried a rather hilly topography.

Exposures of the conglomerate are poor, and details of its bedding are difficult to make out. Along Daniels Arroyo, where there are good exposures in the cut banks, the conglomerate consists of alternating pebbly and sandy current-bedded layers. In places the cross bedding shows a southerly component of dip, probably indicating deposition by a stream that locally was flowing southward, but such observations were too few to support a generalization that the entire conglomerate was deposited in this way. The boulders contained in the conglomerate are as much as 4 feet in diameter, although most are less than 3 inches. They are dominantly of hornblende andesite, like the southerly exposures of the Sneed andesite, with some of hypersthene andesite, Cardigan gneiss, and Chico Shunie quartz monzonite. The exposures due south of Chico Shunie village, 3 miles south-southwest of Chico Shunie well, reveal interbedded andesite breccia. On the east side of the hill, in sec. 32, T. 13 S., R. 6 W., there is about 60 feet of flow-banded quartz latite interbedded in the conglomerate. The base of the conglomerate is not revealed here, but there is about 100 feet of it exposed below the lava and another 80 to 100 feet above the lava.

In the outcrops west of Sneed Ranch there is about 70 feet of poorly consolidated material referred to this formation. It contains a few boulders as much as 1 foot in diameter, but for the most part it is composed of rounded pebbles less than 1 inch in diameter. The pebbles are chiefly of andesite of several varieties, such as could have been furnished by erosion of the underlying Sneed andesite. Similar conglomerate near Salt well is also dominantly composed of andesite fragments but includes detritus from the Chico Shunie quartz monzonite and the Cornelia quartz monzonite. The small exposure 2 miles northwest of Salt well contains pebbles derived from the Cardigan gneiss.

The degree of consolidation of the conglomerate is variable. Some is nearly incoherent, and some is well-cemented with calcite, but nowhere to the extent that would bring about fracture across the pebbles.

The conglomerate along Daniels Arroyo is not overlain by other bedrock formations, but in T. 13 S., R. 6 W., and at the Childs Mountain localities it is unconformably overlain by Batamote andesite.

THICKNESS

The Daniels conglomerate at its type locality has its top eroded, and its base rests on an irregular topography, so that its original thickness is unknown. About 250 feet of the conglomerate is preserved in this locality. In the hill at the south edge of the quadrangle, in sec. 32, T. 13 S., R. 6 W., about 180 feet is exposed, and just west of Sneed Ranch about 70 feet.

ORIGIN

The Daniels conglomerate is obviously of fluviatile origin where it is well enough exposed for study. Some of the boulders that weather out on slopes are so large, however, that there may be some question of the competence of streams to carry them, and they may have been borne by mudflows. There is thus a possibility that the formation should actually be classed as a fanglomerate rather than a conglomerate, but it is clearly a subaerial deposit—presumably formed on debris fans.

The wide distribution of the source rocks that provided detritus to the conglomerate and their unknown extent on all sides beneath younger rocks prevent any confident deductions about even the major features of the topography that existed at the time of deposition of the conglomerate. Part of the material evidently was derived from nearby basement rocks.

AGE AND CORRELATION

No fossils have been found in the Daniels conglomerate. The fact that the Ajo area has been, at least intermittently, part of a basin of internal drainage since the time when the Locomotive fanglomerate was formed renders it very likely that deposits such as the Daniels conglomerate have been repeatedly formed in local areas and later removed by erosion. There is thus considerable uncertainty in correlating conglomeratic material, even within the area of the quadrangle. All the rocks mapped as parts of this formation are definitely older than the flows of Batamote andesite on the Childs and Growler Mountains. All contain fragments of andesite similar to the

Sneed andesite, which places them broadly in the same geologic time setting. The fact that deposits of this sort more than likely are being formed locally under conditions of internal drainage at almost any time is the principal cause for uncertainty in their correlation with each other. The conglomerate strongly resembles, in degree of consolidation and attitude, much of the Gila conglomerate of southeastern Arizona, of late Pliocene and Pleistocene age, and may actually be part of this or a similarly widespread formation. This does not appear probable though, because the local geologic history of post-Daniels time is more complex and seems longer than the time that has elapsed since the deposition of the Gila conglomerate. Here, great thicknesses of latite and andesite were erupted, deformed, and deeply eroded, probably in more than one erosion cycle, after Daniels time. This history seems too long to be reconciled with a late Pliocene age, as would be implied by a correlation with the Gila conglomerate. The Daniels conglomerate seems more likely to be early Pliocene or even older rather than a correlative of the Gila.

HOSPITAL PORPHYRY

DISTRIBUTION

The rocks here called the Hospital porphyry, because of their good exposures on the hill just west of the Phelps Dodge Hospital at Ajo, form a group of dikes trending north-northwestward in the region between Ajo and Black Mountain. These dikes are readily decomposed and weather into topographic depressions. They are shown on plates 20 and 21 but not on plate 3. None were noted beyond the limits of the area represented on plate 20.

The dikes are notably parallel, although considerably interrupted along the strike. Although some of the apparent interruptions may be due to lack of adequate exposures, it is clear that the dikes are not continuous, nor do their discontinuities result from later faulting. The dikes range in thickness from a few feet to 125 feet, and individual segments are from a few hundred feet to 2,500 feet long. The dikes are the youngest intrusive rocks exposed in the area, except the volcanic necks in the Childs and Batamote Mountains.

PETROGRAPHY

The Hospital porphyry is a dark-gray fine-grained rock whose only distinguishable mineral is glassy plagioclase in roundish phenocrysts that are as much as 2 centimeters in length. Under the microscope the phenocrysts are shown to have the composition An_{40} to An_{50}. Microphenocrysts of augite, a few minute flakes of biotite, and small crystals of orthoclase and plagioclase (near An_{30}) make up the groundmass. There is commonly much chlorite after augite and, in one specimen, after olivine (?). Locally the groundmass shows variolitic texture. The composition, to judge solely from microscopic features, is that of an augite andesite porphyry, approaching a latite. Its practical identity with the Childs latite, which has a high potash content (see p. 45), makes it probable that this rock is also a latite, with its orthoclase largely hidden in the groundmass.

RELATIONS

The Hospital porphyry is obviously very much younger than the Cornelia quartz monzonite, because it cuts the Locomotive fanglomerate, which rests on the eroded surface of the monzonite. Petrographically it strongly resembles the porphyritic latite of the Childs latite flows. The Hospital porphyry is thus probably related to this much younger regional volcanic activity rather than to the Cornelia quartz monzonite. There is no direct evidence as to whether or not these dikes represent the conduits that served as feeders for the extrusions.

CHILDS LATITE

DISTRIBUTION

Augite latite flows are widespread in and near the Ajo quadrangle at localities scattered from the Crater Mountains, just north of the quadrangle, to the Puerto Blanco Hills, more than 10 miles south of the quadrangle. The largest exposures in the quadrangle are along the western and northwestern slopes of Childs Mountain, and the formation has therefore been called the Childs latite.[60] A small outcrop is present in sec. 4, T. 11 S., R. 5 W., on the north slope of the spur of the Batamote Mountains in the northeast part of the quadrangle. Two low hills in secs. 14, 23, and 26, T. 13 S., R. 6 W., are also formed of this rock. In the two northern localities the Childs latite is overlain by Batamote andesite flows, with, at one point, about 50 feet of intervening conglomerate that contains subrounded pebbles of andesite, monzonite, and gneiss as much as 6 inches in diameter. The base is not exposed at this point, though in the canyon 6½ miles west of Batamote well, on the north side of Childs Mountain, the Childs latite appears to rest on a thickness of about 250 feet of Batamote andesite, suggesting that the latite is merely an intercalation in the Batamote series. This apparent anomaly may be due to faulting, and is so shown on the map, though without direct evidence; accordingly the possibility of intercalation of the latite in the andesite series has not been eliminated. In the southern locality no overlying rocks are present. There is about 700 feet of latite on the northwest slope of Childs Mountain, about 500 feet southwest of Black Mountain, and probably less than 100 feet in the Batamote Mountains.

PETROGRAPHY

The augite latite southwest of Black Mountain forms flows 30 to 80 feet thick, not clearly separable because they are scoriaceous and autobrecciated. Some flows

[60] Gilluly, James, op. cit. p. 47.

appear to be block lava, and others are scoriaceous. Fragments as much as 4 feet in diameter, included in a matrix of identical material, are recognizable. The latite of Childs and Batamote Mountains is perhaps less brecciated but is still far from massive. It is light-gray on fresh fracture (reddish in the southerly exposures) and weathers dark-brown with a notably mottled surface. It is conspicuously porphyritic, with phenocrysts of glassy plagioclase as much as 2 centimeters across, in an aphanitic base. The rocks are generally very scoriaceous or vesicular and locally are amygdaloidal. In thin section the phenocrysts are determinable as andesine-labradorite (An_{45} to An_{60}), and much smaller microphenocrysts of augite are found, set in a pilotaxitic groundmass of plagioclase (near An_{30}) and brownish glass. A little orthoclase is locally present, iddingsite is common, and the usual accessory minerals occur. The rock may be classed as an augite latite, carrying well over 70 percent of feldspar.

CHEMICAL COMPOSITION

Two representative specimens of the Childs latite were analyzed, with the results given below:

TABLE 5.—*Analyses and norms of Childs latite and of average latite and average augite andesite*

ANALYSES

	1	2	3	4
SiO_2	56.66	55.61	57.65	57.50
Al_2O_3	18.14	17.48	16.68	17.33
Fe_2O_3	5.61	5.09	2.29	3.78
FeO	1.65	2.81	4.07	3.62
MgO	1.05	1.46	3.22	2.86
CaO	5.01	6.38	[a]5.58	5.83
Na_2O	4.39	3.40	3.59	3.53
K_2O	4.00	3.65	4.39	2.36
Rb_2O	None	None	....	....
Cs_2O	None	None	....	....
H_2O-	.77	.50	} .77	1.88
H_2O+	.64	1.25		
TiO_2	1.09	1.55	1.00	.79
ZrO_2	.04	....	....	....
CO_2	Trace	....	.14	....
P_2O_5	.40	.61	.36	.30
S	.05	....	....	....
Cr_2O_3	None	....	....	....
MnO	.10	.10	.10	.22
BaO	.09	....	.16	....
	99.69	99.89	100.00	100.00

NORMS

	1		2	
Quartz		5.40		8.82
Orthoclase		23.91		21.68
Albite		37.20		28.82
Anorthite		17.51		21.68
Diopside:				
Ca sil	1.97	3.67	2.67	4.97
Mg sil	1.70		2.30	
Hypersthene:		1.00		1.40
Mg sil		4.16		1.92
Hematite		2.13		3.04
Ilmenite		2.09		4.64
Magnetite		1.01		1.34
Apatite				
		98.08		98.31
H_2O		1.41		1.75
Symbol	(I)II."5.2(3).3(4)		"II.(4)5.3.3"	

[a] Includes 0.07 percent of SrO.

1. Augite latite, SE¼ sec. 14, T. 13 S., R. 6 W. R. E. Stevens, analyst.
2. Augite latite, canyon on northeast side of northwest spur of Childs Mountain, about 5 miles west of Batamote well. J. G. Fairchild, analyst.
3. Average latite. Daly, R. A., Igneous rocks and the depths of the earth, p. 13, New York, McGraw-Hill, 1933.
4. Average augite andesite. Daly, R. A., idem, p. 16.

These analyses show higher alkalies, especially potassa, as compared with average andesite, and though perhaps not sufficiently potassic to be typical, the rock obviously approaches very near to the latites in composition. The high ratio of ferric to ferrous iron shown by the analyses accounts for the red color of the flows, which is due to hematite, and for the fact that there is no iron silicate in the "hypersthene" of the norms.

ORIGIN

All the latite mapped on plate 3 is definitely of surficial origin and represents lava flows. There is a suggestion in the crude "current bedding" of the lava southwest of Black Mountain that it was flowing westward as it consolidated, but the evidence is far from conclusive. The present attitude of the flows is, of course, no clue to their original attitude, and no definite evidence was noted as to the source or sources from which they were derived. The rocks in T. 13 S. are more highly stained with hematite, even on fresh fractures, than those of the northern localities, but this cannot be regarded as evidence of derivation from a distinct source. As mentioned in the description of the Hospital porphyry dikes, these intrusives so strongly resemble the Childs latite, both petrographically and in geologic relations, that they may well represent feeding dikes for the surface volcanics. No direct connection between the two was found however.

BATAMOTE ANDESITE

DISTRIBUTION AND TOPOGRAPHIC EXPRESSION

The most widespread of the bedrock formations of the Ajo quadrangle is a dark, basaltic-appearing andesite, which crops out over at least 30 square miles. It has been called the Batamote andesite, from its exposures in the Batamote Mountains.[61] The largest areas of outcrop are in the Batamote and Childs Mountains, where this rock is the overwhelmingly dominant formation, but it is also prominent in the low hills in the southwestern part of T. 13 S., R. 6 W., and in the hills south of Daniels Arroyo, in the southwest corner of the quadrangle. The shafts of the "watermine" at Childs Siding, after passing through about 170 feet of alluvium, penetrate this formation to their full depth of 650 feet. Deeper drilling has shown that the rocks extend to a depth of at least 1,348 feet, practically to sea level. Doubtless the andesite of this formation occurs widely beneath the alluvium of the valleys in both east and west parts of the quadrangle.

[61] Gilluly, James, op. cit. p. 48.

The topography developed on the basaltic andesite is characteristically rugged and irregular, with abrupt cliffs terminating the individual flows and benches of greater or less extent at the tops of many flows. Owing to the generally moderate dips of the formation, it appears on distant view to form smooth mesas and cuestas; on closer view, however, this smooth appearance is absent, and even the flat areas are not easy to traverse.

STRATIGRAPHY

The Batamote andesite is the youngest bedrock formation in the area. It rests unconformably upon the Childs latite in the Batamote Mountains; upon the Childs latite, Daniels conglomerate, and Sneed andesite in Childs Mountain; and upon the Daniels conglomerate and Cardigan gneiss in the southwestern part of T. 13 S., R. 6 W. Elsewhere the base of the formation is not exposed.

The most conspicuous of the masses of basaltic andesite is Black Mountain. (See pl. 6, *D.*) This consists of dark flow breccias and massive flows that range in thickness from about 20 to 60 feet, averaging about 30 feet. Many of the individual flows are massive internally and scoriaceous for several feet on top and bottom. Some is block lava, and some is scoriaceous throughout. Very few of these flows have reddened tops. There is no doubt that the series is a unit, but individual flows are discontinuous and interrupted. A few weathered soils, one of which is apparently stratified, are included in the series.

The flows of the Batamote Mountains seem to be in general less blocky and scoriaceous than those of Black Mountain. They dip away irregularly in all directions from the volcanic plug on the east edge of the quadrangle, suggesting that this may have been their source. The andesites near the base of this formation on Childs Mountain are in noticeably thinner scoriaceous flows, which average about 20 feet in thickness, and are much thicker and more fluidal toward the top of the mountain.

PETROGRAPHY

There are three principal varieties of basaltic andesite flows referred to this formation in the Ajo quadrangle. Supposed throat breccias or cinder cone breccias related to the flows also occur.

One variety of lava that crops out in the small hill about 1½ miles northwest of Tule well and also at the base of the Batamote andesite at the south end of Childs Mountain is dense and dark-gray, weathering to reddish brown. It contains rare crystals of hornblende and feldspar less than a millimeter in length as the only minerals recognizable in hand specimens. Under the microscope the rock shows a few scattered much-resorbed crystals of brown hornblende, each surrounded by an opaque reaction rim. Granules of augite occur amidst a felt of labradorite crystals. The texture is pilotaxitic. No. 1, table 6, is an analysis of this facies.

The second variety occurs near the base of the formation on Childs Mountain and near the base of Black Mountain. There are also a few flows near the top of Black Mountain. It is commonly platy, dark-gray but weathering to brown, generally more or less vesicular, and finely porphyritic, with clots of feldspar approaching 0.5 millimeter in diameter set in a dense aphanitic base. In thin section the feldspar is recognizable as andesine-labradorite in a divergent granular texture, with augite, pigeonite (?), magnetite, and considerable glass. (See analysis No. 2, table 6.)

The most widespread variety is olivine andesite, which forms the bulk of Black, Batamote, and Childs Mountains. It is medium-gray, generally massive though locally platy, and aphanitic, with red oxide or iddingsite pseudomorphs after olivine as the only recognizable minerals. Recognizable glassy olivine phenocrysts remain in a few specimens. In thin section these rocks show olivine, augite, plagioclase near An_{60}, and magnetite in a glassy base. The texture ranges from pilotaxitic to intersertal. (See analysis No. 3, table 6.)

These rocks are all dark and basaltic in appearance. Although they give some suggestion, in their streaky and slightly mottled aspect, of being more siliceous and feldspathic than the true basalts, and the microscopic studies show considerable glass and commonly pilotaxitic textures, the rocks of the nonhornblendic facies were not definitely recognized as andesites until the chemical analyses were available. In fact, it may well be that there are some flows, especially in the Batamote Mountains, that are true basalts, as it seems that intersertal textures are more common there than elsewhere. If they are present, however, they are probably not so plentiful as the more siliceous flows, such as were analyzed as representative of the dominant facies of the formation. Specimens from the flows in the southwestern corner of the quadrangle, although also referred to this formation, seem to be true basalts.

Andesitic breccias, described below, occur in three localities in such relation with the flows as to suggest that they are accumulations in volcanic necks that may have fed the lava flows. Although they are shown separately on the geologic map, plate 3, they are described in the sections on volcanic plugs below, and are considered a part of the formation here described.

CHEMICAL COMPOSITION

Three specimens, regarded as representative of the several facies of the Batamote andesite, were selected for analysis. The results appear in table 6.

TABLE 6.—*Analyses and norms of Batamote andesites and of average augite andesite and average basalt*

ANALYSES

	1	2	3	4	5
SiO_2	58.42	59.88	54.79	57.50	49.06
Al_2O_3	17.20	15.75	15.69	17.33	15.70
Fe_2O_3	4.29	3.10	3.92	3.78	5.38
FeO	1.41	3.31	4.19	3.62	6.37
MgO	3.08	2.76	5.85	2.86	6.17
CaO	7.75	5.31	7.31	5.83	8.95
Na_2O	3.48	3.62	3.30	3.53	3.11
K_2O	1.94	3.25	2.05	2.36	1.52
H_2O-	.18	.74	.63	1.88	1.62
H_2O+	1.10	.72	1.07		
TiO_2	.90	.81	1.40	.79	1.36
P_2O_5	.17	.36	.21	.30	.45
CO_2	.70	.07	Trace	....	....
S	....	.06	....	....	....
MnO	.09	.13	.09	.22	.31
ZrO	....	.04	....	....	....
BaO	....	.08	....	....	....
V_2O_5	.22	....	....	....	....
	100.93	99.99	100.50	100.00	100.00

NORMS

	1	2	3
Quartz	12.72	12.36	5.64
Orthoclase	11.12	19.46	12.23
Albite	29.34	30.39	27.77
Anorthite	25.85	17.24	21.96
ΣSalics	79.03	79.45	67.60
Diopside:			
Ca sil	4.99 } 9.29	2.67 } 5.13	5.57 } 10.50
Fe sil	......	.66	.53
Mg sil	4.30	1.80	4.40
Hypersthene:			
Fe sil	...... } 3.40	1.58 } 6.78	1.58 } 11.88
Mg sil	3.40	5.20	10.30
Magnetite	2.09	4.41	5.57
Ilmenite	1.67	1.52	2.74
Hematite	2.88	....	....
Apatite	.34	1.01	.34
ΣFemics	19.67	18.85	31.03
Symbol	II.4".3.4	II.4(5).(2)3.3(4)	II."5.3.4

1. Hornblende augite andesite, NW ¼ sec. 6, T. 12 S., R. 6 W., near the south end of Childs Mountain. J. G. Fairchild, analyst.
2. Nonporphyritic augite andesite, north central part of sec. 36, T. 12 S., R. 6 W., north spur of Black Mountain. R. E. Stevens, analyst.
3. Porphyritic olivine andesite, summit of Black Mountain, west central part of sec. 1, T. 13 S., R. 5 W. J. G. Fairchild, analyst.
4. Average augite andesite, as computed by Daly, R. A., Igneous rocks and the depths of the earth, p. 16, New York, McGraw-Hill, 1933.
5. Average basalt, as computed by Daly, R. A., idem, p. 17.

These analyses show the rocks to be considerably higher in silica and potassa and lower in lime and iron than typical basalts, despite the occurrence in No. 3 of olivine and labradorite (An_{60}) as prominent minerals. They resemble the Childs latite in composition far more than might be expected in view of the contrast in appearance of the formations.

BRECCIAS OF BATAMOTE ANDESITE AND ASSOCIATED BASALTIC DIKES

OCCURRENCE

Three localities were recognized as possible sources of the Batamote andesite flows—one on and just east of the quadrangle boundary in the Batamote Mountains, in the SE¼ sec. 14, T. 11 S., R. 5 W., and two in the northeast part of Childs Mountain, in the SE¼ sec 17, and the SW¼ sec. 7, both in T. 11 S., R. 6 W. Apparently the most voluminous eruptions came from the first of these vents; in fact the relations of the flows to the other two vents are such as to suggest that these were both overwhelmed by flows from other centers and did not furnish much of the lava now exposed. It is not likely that either the Childs Mountain flows or those of Black Mountain and the lower hills to the southwest were derived from the two Childs Mountain vents, but they may have come from the Batamote vent. Although there is no direct evidence, it seems likely that the basaltic andesite flows in the southwestern part of the quadrangle were once continuous with the volcanics of the Growler Mountains to the west and possibly were derived from a center in that direction.

BATAMOTE PLUG

From a distance the conical peak of the Batamote Mountains, which rises just east of the Ajo quadrangle, appears like a volcano. On closer examination it is seen that the cone does not preserve its constructional surface. Although the component lava flows dip away from the summit in all directions, they dip more steeply than the upper slopes and more gently than the lower slopes, thus showing their edges both downdip and updip. The relations on the north flank of the peak in secs. 2, 11, and 14 are shown in figure 6. A valley extends into the center of the old cone and exposes the intrusive plug and an irregular central core of red throat breccia, also basaltic in aspect, but probably andesitic in composition.

The dense intrusive rock exposed in the center of this eroded cone forms a blunt, wedge-shaped dike about a mile long and 1,500 feet wide at the southeast end, tapering to a point toward the northwest, perhaps in part because of faulting. This rock is moderately coarse hypersthene olivine basalt, cut by irregular but crudely vertical joints. It is composed of olivine, augite, hypersthene, iddingsite after olivine, plagioclase ranging from An_{65} to An_{50}, and considerable magnetite. Locally it is almost coarse-grained enough to be called gabbro, but the average grain rarely exceeds 0.2 millimeter. The texture is granulitic, divergent granular, and locally intersertal along selvages. The hematitic breccia was not examined microscopically.

The relations are consistent with the interpretation that the dike fills the throat of an old volcano. No detailed study was made of it, however, and the high hills lying farther to the east of the quadrangle were not examined, so no additional details are available. It is obvious that there has been much erosion since the last volcanic activity in this area, and, because of the known post-volcanic deformation in the area, there may be some slight doubt that this is a major vent, despite the topographic eminence

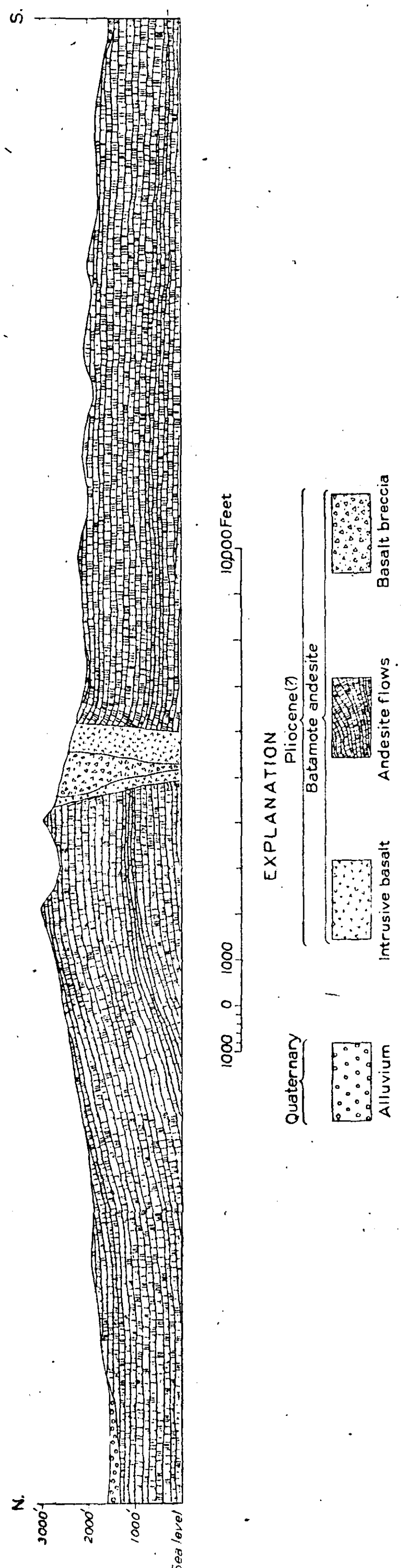


FIGURE 6.—Section through spur of Batamote Mountains at east edge of Ajo quadrangle showing erosional topography on the Black Mountain andesite flows and breccias and intrusive basalt. The section is somewhat eccentric to the plug, so that the dips of the flows appear anomalous, but, as far as seen, all have a component of dip away from the plug.

of the nearby hills. The present height may be due to some extent to deformation rather than to construction by the volcanic neck.

CHILDS MOUNTAIN PLUGS

The saddle in the ridge in the SW¼ sec. 7, T. 11 S., R. 6 W., and the opposing stream valleys that head in it are carved on a reddish basaltic breccia. Three sides of a quaquaversal dip are exposed, and the breccia is penetrated by several vertical dikes. The breccia is largely composed of rounded fragments that resemble basalt. Most of them are 3 inches or less in diameter, although a few larger and more angular fragments exceed 3 feet. Both to the south and north the breccia is overlain by massive flows, which do not participate in the dips away from the center. Hence, if this dike-filled breccia does represent an old crater, or more probably, part of a cinder cone, it was later buried by flows from other vents. Perhaps it was considerably eroded before being buried, but it seems that no long time interval would be needed for the removal of such relatively unresistant material.

The narrow canyon that drains the SE¼ sec. 17, T. 11 S., R. 6 W., has exposed another probable volcanic plug. A ring of red hematitic basaltic breccia here shows rather uniform dips of about 15° away from the center. Fully 300 feet stratigraphically is exposed. In the center of this ring is a plug of fine-grained gray massive olivine andesite, irregularly jointed and with its outcrop strewn with spheroidal blocks. This plug is exposed for about 200 feet vertically and is about 700 by 400 feet in plan. The rock of the plug is composed of olivine, augite, labradorite-andesine, and magnetite, in a glassy base. The texture is granulitic. Here, as at the breccia locality of sec. 7, the breccia is overlain at the border by massive flows that do not dip with the bedding of the breccia but lap over it unconformably. It appears, therefore, that the vent was overwhelmed by lavas from other sources. Thus there is no significant age difference between the plugs, breccias, and flows, all of which are accordingly referred to one formation.

AGE AND CORRELATION

The Batamote andesite, as is obvious from the geologic map, has been faulted, tilted, and deeply eroded. It is everywhere more or less deformed, and no complete constructional forms remain. (See p. 47.) The edges are overlain by alluvium, and, as shown at the "water mine" at Childs siding, the formation is locally buried to considerable depths by alluvium. For these reasons Bryan's conclusion[62] that these rocks are pre-Pleistocene seems entirely satisfactory; on the other hand, their wide occurrence and the fact that they are relatively less disturbed than the older volcanic rocks, which are themselves most probably of Tertiary age, render it likely that they are of late Tertiary, possibly Pliocene, age. Unfortunately no fossils were found in the sedimentary material overlying and underlying the lavas, so that nothing more definite is known as to their age. Lavas very similar in both structure and lithologic character are widespread in southern Arizona.[63]

[62] Bryan, Kirk, The Papago country, Arizona: U. S. Geol. Survey Water-Supply Paper 499, p. 64, 1925.
[63] Bryan, Kirk, idem.

ALLUVIUM

DISTRIBUTION

The most widespread formation of the Ajo quadrangle is the alluvium, which covers between one-half and two-thirds of the area. The alluvium is prominent as gravel terraces along nearly all the streams, forms debris fans along the foot of the mountains, and fills the intermontane valleys to variable depths.

STRATIGRAPHY

On the dissected pediments the alluvial veneer is commonly less than 5 feet thick, although it ranges in thickness from a knife edge to perhaps 30 feet. Away from the mountains the thickness increases, as is evident in general from the scarcity of bedrock inliers but more directly from the records of wells and prospect pits. At well No. 1, at Childs Siding, the shafts of the "water mine" penetrate about 170 feet of alluvium before reaching bedrock, and at Childs Ranch, close to the axial stream of the Valley of the Ajo, a well penetrated 820 feet of unconsolidated alluvium without reaching bedrock.

The alluvium belongs to at least two groups. The older alluvium forms terraces along streams and occurs as a veneer on the dissected pediments that nearly surround the Little Ajo Mountains. The younger alluvium is that carried by the present streams and occupies their channels and the lower parts of the surface of the intermontane valleys.

Where the older alluvium is exposed in cut banks near the mountains it is seen to be composed of coarse gravels that are fairly well rounded but not well sorted, in a matrix of sand, silt, and even clay. Caliche is common, especially near basaltic hills. The size of the material decreases rapidly downstream. At the mouths of the stream courses, where they leave the mountains, cobbles are abundant, but a mile or two from the mountains it is unusual to find cobbles as much as 6 inches in diameter, and most of the pebbles are less than an inch in size. The proportion of silt also increases downstream.

The younger alluvium contrasts rather remarkably with the terrace gravels at the same localities and is almost invariably much finer. It is, of course, obvious that the material carried by these ephemeral streams during floods must be much coarser than is evident in their channels, because the decreasing competence of the streams during waning stages must lead to deposition of finer material, thereby masking the largest-sized detritus, which is first deposited. Nevertheless, it seems certain that the grade size of the recent gravels is much smaller than that of the adjacent terrace deposits. It seems more likely that the conditions governing the formation of the older alluvium were different in some important respect from those now prevailing, a difference that seems doubtfully explicable by the somewhat steeper gradients of the terraces.

Toward the valleys this fineness of grain of the younger alluvium becomes still more marked. Most of the alluvium near the valley centers is silty, with local clay patches. Gravels are generally present only in stringers and lenses. In some places, perhaps because of wind erosion, the flattish slopes near the center of the valley are veneered with small pebbles. These lie, one pebble deep, on a silty alluvial deposit that contains sporadic pebbles of the same size as those constituting the "pavement," and are probably to be explained as residuals left when the finer matrix was blown away by the wind.

As the drainage of the region is external and there is no evidence of recent structural disturbance, it is likely that the volume of the alluvium is undergoing little net increase at present. Additions to it brought down from the mountains are about counterbalanced by removals to the Gila drainage.

AGE

The widespread development of the rock plains around the Little Ajo mountains and the lack of direct topographic expression of the larger faults (see pp. 52, 54) testify to the long time that has ensued since the last considerable structural disturbance in the area. It is practically certain that part of the alluvium buried in the valleys dates from that period of active faulting. The absence of fossils, of course, precludes a definite age assignment, but the perfection of the pediments seems to imply erosion of relatively stable blocks for a time as long as the Quaternary period. Perhaps the oldest alluvium may be Pliocene in age, but certainly much of it is Pleistocene, and some is Recent.

STRUCTURE

GENERAL FEATURES

The internal structural features of the rock formations have been briefly treated in the descriptions of the rocks. In this section, it is proposed to discuss the relations of the several formations to each other in the endeavor to decipher the larger structural features of the area, and the internal features are referred to only insofar as they throw light on the structural synthesis.

Despite the relatively good exposures in the mountainous areas, the major structural features of the Ajo quadrangle are largely matters of inference rather than direct observation. Many of the critical localities, such as those along the Little Ajo Mountain fault and the Black Mountain fault, are largely masked by the alluvium, and other decisive features may be elsewhere entirely concealed. Inasmuch as more than half of the area is alluvial, structural evidence is very incomplete. It is discussed in detail, but the interpretations based upon it are necessarily not so conclusive as would be desired. The structural features that seem most significant economically are those relating to the emplacement of the Cornelia quartz monzonite, its fracturing, and the relation of these episodes to the erosion and block tilting of the Little Ajo Mountains. (See pp. 51, 53, 106-108.)

Structural features older than the Concentrator volcanics are mostly complex and obscure because of repeated metamorphism. Little of significance to the present regional structure has been learned from them. The structural features younger than the Concentrator volcanics are dominated by faulting. These faults divide the bedded rocks into many generally homoclinal blocks, within each of which the variations in attitude are slight. The only recognizable folds are gentle and apparently unsystematic flexures of the youngest volcanic formation, the Batamote andesite. Although similar flexures may be present in areas of older rocks and may have been overlooked because of the greater prominence of structural features that have resulted from faulting, there is a distinct possibility that these flexures are the response, above a blanket of bedded rocks, to faults in the basement. Even where they occur, more of the deformation is due to faulting than to the flexures.

The principal fault in the area is the Little Ajo Mountain fault, which bounds the Little Ajo Mountains on the north. The block to the south of this fault has been tilted southward to an angle of 50°, and the throw along it must be many thousand feet. This major fault more closely approaches the general trend of the mountains in the surrounding region than do any of the others, though the smaller faults are in groups that suggest regional control.

The subordinate faults of the quadrangle tend to fall into three fairly definite systems: that trending N. 15°-30° E., which is largely confined to the southern half of the area; that trending practically north, in the northern part of the quadrangle; and that trending N. 20°-40° W., in the northwestern part of the quadrangle. Possibly faults of similar trend bound Black Mountain on the southwest.

The faults of the north-northeast system have formed at different times. Some of these faults are older than the Concentrator volcanics; one is younger than the Concentrator volcanics but older than the Little Ajo Mountain fault; and others are clearly younger than this fault. There is evidence of basement structure that may have controlled these faults of parallel trend at different times. The northward-trending faults are small and are probably all relatively young. The northwestward-trending faults are also probably all younger than the Little Ajo Mountain fault. Most of them are small, though the fault bounding Childs Mountain on the west has a considerable throw. In the following section the structural features will be described primarily in order of their age.

STRUCTURAL FEATURES OLDER THAN THE CONCENTRATOR VOLCANICS

The rocks older than the Concentrator volcanics display structural features of at least three, probably four, generations that are not recognized in the younger rocks. The oldest structural element recognized is the gneissic layering of the Cardigan gneiss. If the original rock was sedimentary, the evidence does not warrant the inference of four deformations in pre-Concentrator time, but it is more probable that the oldest gneissic structure is itself secondary and records intense deformation. This deformation must be regarded as the least definitely established of those postulated here. Later deformation has obscured any regional regularity that may have governed the structure.

This oldest foliation was later followed in part by injection layers of dioritic composition and still later refolded in most complex patterns, so that no ruling structural features can be recognized in the injection gneiss (See pl. 4, *A*, *C*.) Possibly the northwest trends that seem to predominate among the readings of foliation attitude plotted on plate 3 are significant of controlling orogenic pressure transverse to this direction. The foliation is so contorted in almost every outcrop that, despite attempts to avoid selection of a false average in recording its attitude, it is by no means sure that the general trend is correctly portrayed by these random sample observations.

Both of the deformations just discussed are older than the Chico Shunie quartz monzonite, for they are transected by it. This quartz monzonite, although somewhat gneissoid, shows chiefly widespread microbrecciation and fracturing, with only subordinate recrystallization (cataclastic texture). On the other hand, the Cardigan gneiss, though at one time probably broken up in much the same way, has been largely recrystallized, either along with or subsequent to the brecciation (crystalloblastic texture). Still later, this recrystallized rock was fractured in the same way as the quartz monzonite. The metamorphism represented by the recrystallization of the Cardigan gneiss must thus have antedated the fracturing of the Chico Shunie quartz monzonite. The few specimens of rock mapped as Chico Shunie quartz monzonite that show brecciation of an earlier crystalloblastic texture do not necessarily imply still another period of deformation. As noted on page 18 detailed mapping of the Chico Shunie quartz monzonite would probably show it to be composite, and parts of it, therefore, may be pre-Cambrian and hence old enough to have participated in the crystalloblastic metamorphism of the Cardigan gneiss.

Cataclastic deformation has affected the Chico Shunie quartz monzonite and Cardigan gneiss almost everywhere, and probably took place at the same time as the widespread hydrothermal alteration reflected in their present mineral composition. Again, no regional trends can be pointed to as resultants of the thoroughgoing crushing that the rocks have undergone, although the deformation in each of these two episodes was more intense than at any subsequent time. None of the younger rocks show comparable structural features.

Among the most interesting structural features of probable pre-Concentrator age are the steep zones of sheared rock, partly crystalloblastic and partly cataclastic, that cut through the Chico Shunie quartz monzonite along the lines that trend generally N. to N. 20°E. (See p. 19.) This trend is followed by at least two generations of post-Concentrator faults. These zones of partly recrystallized crush rock make it likely that the trend was established in pre-Concentrator time. It is perhaps a reasonable assumption that the zones are the expression in the massive Chico Shunie quartz monzonite of these post-Concentrator faults. However, as shown by the tilting of the Little Ajo block, the rocks in which these zones of partly recrystallized crushed material are found were probably at shallower levels in the earth's crust at the time of the Gibson faulting than were the rocks now cropping out along the Gibson fault. Yet these crushed rocks are partly recrystallized, whereas the fault breccias along the Gibson fault are not at all recrystallized—a contrast that is inconsistent with their being of contemporaneous origin.

STRUCTURE OF THE CONCENTRATOR VOLCANICS

The structure of the Concentrator volcanics is obscure. As the flow rocks of the formation are highly siliceous, flow lines in them are extremely contorted and can in several localities be seen to form almost completely closed curves a few feet in diameter. Flow boundaries in siliceous lavas are notoriously difficult to evaluate even in fresh exposures, and the problem is rendered far more difficult here because of the metamorphism that the rocks have undergone, both in the normal contact zone of the Cornelia quartz monzonite and in the even more intensely altered parts near the mineralized area of the New Cornelia mine. Many an outcrop that on one side appears to give indubitable flow boundaries shows, when viewed from another side, equally impressive structure at a large angle to the first. The natural result of seeing this on many outcrops is a confirmed skepticism as to the validity of observations on these flow masses as a clue to the attitude of the formation. The attitudes of even the fragmenal volcanics are commonly impossible of determination, owing to the metamorphism. Mottling due to unequal replacement and alteration locally simulates breccia structure, with the result that boundaries between different breccia members are obscured.

Attempts were made to decipher the structure by mapping larger units of similar volcanics and by studying metamorphic features in the Concentrator volcanics, but the results of this effort were practically negligible. In only four or five localities were the contacts between tuffs of different grain size so clearly determined as to furnish evidence of the local attitude of the formation. These were on the hill west of Arkansas Mountain, the south and north slopes of Concentrator Hill, the ridge east of the head of the approach incline of the New Cornelia mine, and the ground east of the northeast waste dump. At all of these localities, sedimentary surfaces in the pyroclastic rocks strike northeast and dip steeply southeast. Whether the rocks are overturned or not could not be ascertained, but it is tentatively assumed that they are not.

As these scattered outcrops yield reasonably concordant structural readings, it is inferred that the formation as a whole has this attitude, but this inference, in view of the obscurities involved, is certainly dubious. According to it the intrusion of the Cornelia quartz monzonite did not greatly disturb the attitude of the volcanics, which have closely comparable attitudes both west of Arkansas Mountain and east of the mine. With allowance for tilting along the Little Ajo Mountain fault (see pp. 52, 53), as revealed by the attitude of the unconformably overlying Locomotive fanglomerate, the Concentrator volcanics had a strike slightly east of north and a dip of about 30° to the east prior to this faulting. It cannot be determined whether this attitude prevailed prior to the Gibson faulting, next to be discussed, or whether it antedated the intrusion of the Cornelia quartz monzonite.

GIBSON FAULT

LOCATION AND RELATIONS

A fault dipping about 40° ESE. can be traced from the old prospect of Cardigan along a general N. 30°E. trend across the saddle into Gibson Arroyo, which it follows, with a few short offsets due to crossfaults, almost to the north boundary of sec. 22, T. 12 S., R. 6 W. At Cardigan, the fault passes beneath the Locomotive fanglomerate, which it apparently does not disturb. In sec. 22 it appears to pass entirely into the Cornelia quartz monzonite, as it definitely does not form the contact between the dioritic facies and the main mass of monzonite on the ridge to the north.

To the south, where the fault emerges from beneath the overlap of Locomotive fanglomerate, it has Concentrator volcanics on the east wall and Cardigan gneiss on the west. Near the south line of sec. 21 the Cornelia quartz monzonite forms the footwall, and almost directly opposite the hanging wall changes to the dioritic facies of the monzonite. This relation might at first be interpreted as evidence that the fault was formed in pre-Cornelia time, but the exposure of the slickensided fault plane, which dips 50° ESE. and cuts the quartz monzonite, and the occurrence of slivers of Cardigan gneiss and Concentrator volcanics (?) on the hanging wall for a considerable distance to the north prove the fault to be younger than the quartz monzonite. The formations of the hanging wall are considerably altered, albitized, and sericitized near the line between secs. 21 and 22, and there is probably more gneiss present than is indicated on the map, as I have found no clear criteria for distinguishing albitized quartz monzonite and albitized gneiss. Incidentally, the close association of slivers of gneiss and of Concentrator volcanics is the only evidence noted to support the presumption that the gneiss is the basement immediately underlying the volcanics. If Paleozoic rocks such as yielded the fossiliferous boulders to the fanglomerate intervene, there is no evidence of them among the dragged fragments along the fault.

The cross faults that offset the Gibson fault about a mile southwest of Gibson are northward-dipping and apparently reverse if the Gibson fault, which is there poorly exposed, dips eastward as it does farther south. However, the relations of the northern crossfault to the blocks of Concentrator volcanics and Cardigan gneiss suggest normal displacement. The apparent inconsistency can be reconciled by assuming that the north side moved diagonally down and eastward relative to the south side. The transverse faults cannot be traced far and probably die out in a short distance.

The Gibson fault can hardly be other than a normal fault bringing down the Concentrator volcanics against the Cardigan gneiss. Prior to the tilting along the Little Ajo Mountain fault the dip of the Gibson fault was much steeper than it now is. This relation has an important corollary for, if it be correct, the southeast body of the Cornelia quartz monzonite, which contains the large ore body of the New Cornelia mine, was at one time not separated from the main mass of monzonite by the screen of dioritic border facies, Cardigan gneiss, and Concentrator volcanics but was an integral part of it. This relation is further discussed on pages 104-105. A minimum measure of the displacement on the Gibson fault, 4,000 feet, is given by the widths of outcrop of Concentrator volcanics on the hanging wall, for these rocks are absent from the footwall.

AGE

The age of the Gibson fault is unknown, except that it is younger than the andesite dikes that cut the Cornelia quartz monzonite and older than the Locomotive fanglomerate. It is noteworthy that older faults marked by partly recrystallized breccias in the Chico Shunie monzonite and younger faults in the basalt and fanglomerate are parallel to it, showing a presumable control of all these faults by older structures in the basement rocks. Movement on these old structure lines was renewed at widely separate times.

FAULTS OF NORTHEAST TREND NEAR THE AJO PEAKS

There are several normal faults near the Ajo Peaks that trend northeastward and are downthrown on the northwest. They clearly antedate the faults of the north-northeast system, and one seems to be cut by a fault of northwest trend, so that they perhaps represent a period of deformation intermediate in age between the Gibson and the Little Ajo Mountain faults.

The largest of the group can be traced northeastward for about 1 mile along the southeast flank of North Ajo Peak, which it cuts off in this direction. It is clearly exposed at several points, where it is seen to dip northwestward at about 60°. It is cut off on the south by a northwestward trending fault; to the northeast it seems to die out in the fanglomerate, for it does not cut the basal contact of that formation. The throw, as indicated by displacements of the base of the Ajo volcanics, is about 2,000 feet.

Parallel to this fault and about half a mile southeast of it, a similar fault, with an apparent throw of about the same magnitude, offsets a thin lens of Ajo volcanics in the midst of the Locomotive fanglomerate. This fault is almost surely cut off on the west by the Ajo Peak fault but can hardly be the same as the one to the west, because the present relations would demand a displacement of about 3,000 feet on the Ajo Peak fault at the intersection with the northeast fault. This is three times the displacemen of the Ajo Peak fault where it is measured by the offset of the base of the main member of the Ajo volcanics. An assumption of northward-increasing displacement along it is incompatible with the fact that the Ajo Peak fault does not cut the base of the Locomotive fanglomerate only 5,000 feet beyond the intersection with the northeast fault.

A few much smaller northeastward-trending faults are recognizable to the southeast, where they cut the isolated lower member of the Ajo volcanics.

LITTLE AJO MOUNTAIN FAULT

LOCATION AND STRUCTURAL EFFECTS

The north flank of the little Ajo Mountains is bounded by a great fault, here called the Little Ajo Mountain fault. The fault is exposed in only two places along the entire 8 miles of length, and in neither place is the exposure clean enough to measure its attitude, although it is clear that it dips steeply north. One exposure is east of Dunn's well, near the center of sec. 8; the other is on the saddle about 1 mile northwest of Gibson. Elsewhere the fault is mapped on the basis of the occurrence of fanglomerate and Ajo volcanics to the north and of Cardigan gneiss, Cornelia quartz monzonite, and Concentrator volcanics to the south. In many places, for example south of Clarkstown, in the arroyo just north of the general office of the Phelps Dodge Corporation, in the pediment in Gibson, and half a mile west of Dunn's well, the location of the fault can be fixed within a very few feet, but it was not actually seen at any of these places. It is nowhere topographically expressed; the pediment of the north front of the Little Ajos is carved across it, indifferent to the contrasting formations on the two sides.

The entire mountain block to the south of the Little Ajo Mountain fault has apparently been steeply uptilted along this fault, as is shown by the attitude of the Locomotive fanglomerate and Ajo volcanics. As was mentioned on pages 37-38, despite the coarseness of the Locomotive fanglomerate, it could not have been deposited at the present angles of dip (40° to 60°); in fact, some of the finer water-laid sandstone layers must have had an initial dip of only a few degrees, so that most of the present dip is due to tilting on the fault. The bedded rocks die out a short distance west of the Chico Shunie fault, so that it is impossible to prove tilting farther west. However, the fanglomerate has an essentially uniform attitude from Darby well to the west spur of North Ajo Peak, across the strike of the Chico Shunie and Gibson faults, and across several parallel younger faults. This fact, together with the conformity of such linear structural features as occur in the Cornelia quartz monzonite west and east of the extension of the Chico Shunie fault, makes it likely that the tilting embraced the entire block of the Little Ajos west of Black Mountain.

The extent of the tilting transverse to the fault trend is uncertain. Only a few relatively minor faults parallel to the Little Ajo Mountain fault have been recognized near the Ajo Peaks. The notably gradual swings in strike and dip in the fanglomerate make it unlikely that other large faults exist but are not exposed. According to the observed facts, the Little Ajo Mountain block has been tilted up along the fault to angles of about 50° for a width of about 2 miles transverse to the fault, and the angle of tilt diminishes gradually to the south for another 2 or 3 miles. Thus the throw of the fault would be measured in thousands of feet, certainly no less than 5,000 feet and more likely as much as 10,000 feet, even with allowance for some movement along concealed minor faults. Exposures of the footwall block are too poor to give any clear idea of its structure.

The Little Ajo block is probably cut off on the east by the Black Mountain fault, although the critical area of fault intersection is concealed. The westerly extent of the structural unit is uncertain. The Childs Mountain fault, though it cuts off the Little Ajo Mountain fault (p. 56), does not appear to extend far enough south to entirely cut off the block in this direction, and it may well be that the Little Ajo block extends beyond it, even to the edge of the quadrangle, and that its borders are obliterated by later pediment cutting and by burial beneath alluvium in this direction.

On the cross sections of plates 3 and 20 the Little Ajo Mountain fault is arbitrarily projected to sea level as a straight line. There are no data to control this projection. Possibly the fault is concave to the south, so that the tilted block could have had a ball-and-socket motion with respect to the hangingwall block to the north. However, there may have been distributive faulting in the hangingwall block, which is largely buried by alluvium.

AGE

The Little Ajo Mountain fault is definitely younger than the Ajo volcanics, which it displaces. Its age with reference to the later rocks is not determinable with certainty, and the evidence is in part conflicting. The termination of the Sneed andesite against the fault near Dunn's well and westward would imply that at least part of the fault movement is post-Sneed; on the other hand, at the outcrop of Sneed andesite a mile south of Salt well the underlying Locomotive fanglomerate dips southwestward as it would if it were tilted by the Little Ajo Mountain fault prior to the Sneed eruption. If there was intra-fanglomerate faulting, the Sneed andesite and Ajo volcanics may be of the same age; however, there are more differences between the volcanics than between the several fanglomerates, and it is therefore inferred that the faulting was in large part pre-Sneed, with only a small amount of post-Sneed movement. This inference is contrary to the conclusion expressed in the preliminary paper, where it was suggested that the entire displacement was probably post-Sneed.[64] The whole question hinges upon the interpretation of the outcrops southwest of Salt well, and it cannot be said that the conclusions here expressed are necessarily more valid than the different conclusion in the earlier paper. The termination of Sneed andesite against the Childs Mountains fault south of Salt well seems to imply that the Sneed formerly extended over the northwestern spurs of the Little Ajos, from which it has been removed by post-fault erosion. The Childs Mountain fault is younger than the Little Ajo Mountain fault, so this extension does not refute a pre-Sneed age for the Little Ajo Mountain fault; but, in conjunction with the relations at Dunn's well, it renders the assignment of the whole displacement to pre-Sneed time highly unlikely. Near the mouth of Copper Canyon, the overlap of Sneed andesite on rocks that are probably part of the Little Ajo block is not conclusive evidence that the Little Ajo Mountain fault is of pre-Sneed age, because there are similar overlaps of Locomotive fanglomerate near North Ajo Peak (see fig. 5) and of Ajo volcanics west of Chico Shunie well, and these formations are clearly pre-fault in age. The Ajo volcanics conform to the fanglomerate. In contrast, the marked unconformity that separates the Sneed andesite and Locomotive fanglomerate south of Salt well records deformation and erosion in post-fanglomerate and pre-Sneed time, although no conclusive relation between this deformation and the Little Ajo Mountain fault can be made out. In summary, then, some of the movement on the Little Ajo Mountain fault seems definitely later, and the entire displacement may be later, than the eruption of the Sneed andesite, but it is believed that most of the displacement was of pre-Sneed age.

Whatever the uncertainties with regard to the Sneed andesite may be, there is indirect evidence that the Little

[64] Gilluly, James, Geology and ore deposits of the Ajo quadrangle, Ariz.: Arizona Bur. Mines Bull., vol. 8, No. 1, p. 57.

Ajo Mountain fault is older than the Daniels conglomerate, or at least than the Childs latite. The overlap of the Daniels conglomerate on the Cardigan gneiss in the southwestern part of T. 13 S., R. 6. W., implies disturbance and erosion after eruption of the Ajo volcanics. Both the Ajo volcanics and the Locomotive fanglomerate are very thick just to the north, and both are more and more fine grained toward the south, so that these formations must formerly have extended at least as far as the south edge of the quadrangle Their absence in the locality of this overlap suggests that a fault of pre-Daniels age intervenes between these hills and the Little Ajo Mountains. Such a fault, if present, is buried by alluvium; but the removal of these thick formations seems reasonably referable to erosion following a major structural disturbance, such as the uplift on the Little Ajo Mountain fault. The Daniels conglomerate may record this uplift.

This conclusion is strengthened by the evidence supplied by the dikes of Hospital porphyry. (See pl. 20.) These dikes are petrographically almost identical with the Childs latite and are most reasonably regarded as the intrusive equivalents of it. The interrupted dikes, which trend northward, were observed from a point south of Darby well to the alluvium in Ajo, a distance of more than 3 miles. Throughout this distance, the dikes are essentially identical in wall-rock relations, crystallinity, texture, and composition. The places at which the dikes are now exposed were, prior to the tilting along the Little Ajo Mountain fault, at widely different levels. If it be conservatively assumed that the Little Ajo Mountain block has been tilted 45°, the northerly exposures before the tilting were more than 2 miles deeper in the crust than the southerly exposures. If the dikes were injected in pre-fault time, one would expect some differences in wall-rock relations and in the shape of the intrusives, or at least in their crystallinity. Their present uniformity is thus regarded as supporting a pre-dike, and hence a pre-Childs latite, age of tilting.

The relations of the Batamote andesite, however, suggest further displacement on the Little Ajo Mountain fault in post-Batamote time. The thickness of the Batamote andesite on Childs Mountain implies that it must once have extended farther to the south, and although the flows may have terminated in this direction against the upthrown block of the Little Ajo Mountains or were so thin on this block as to have been entirely removed by later erosion, several features suggest that renewed faulting was a factor. Whatever the date of the faulting, very great thicknesses of rocks have since been eroded from the Little Ajo Mountain block, for it now shows subdued topography (see pl. 3, sections *A–A′*, *B–B′*), in which the fault is not directly reflected. Several thousand feet of rock must have been eroded at the north side of the block. If these thousands of feet of resistant rock have been removed and the country reduced to its present moderate relief in post-Batamote time, it is difficult to explain why the scarps on Childs Mountain have not retreated farther northward than they have, even granting the superior resistance of the andesite to erosion as compared with the rocks on the footwall side of the fault. Hence, it seems probable that although most of the movement on the fault was clearly of pre-Batamote age and the high northern edge of the tilted block was much reduced before the extrusion of the andesite, there must have been renewed faulting later. The andesite is now exposed directly in the hanging wall of the fault. This must mean post-andesite faulting, because otherwise, in view of the great erosion of the footwall block that must be postulated in pre-Batamote time, it would be expected that the andesite would rest on an eroded scarp and only by coincidence would the contact now be found to coincide with the fault itself. This post-andesite movement must have been sufficient to raise the andesite in the footwall high enough to permit its removal by erosion, perhaps a few hundred feet, and possibly much more.

The Batamote andesite on Black Mountain clearly extended farther west at one time. It may be that the butte in sec. 20, T. 13 S., R. 6 W., is an outlier of this body. The Black Mountain fault is so old that its scarp has been turned into a fault-line scarp with reverse relief, and the broad pediment carved on the Little Ajo Mountain block implies that any andesite formerly present on the main part of the block has been eroded off. That this movement on the Black Mountain fault was simultaneous with movement on the Little Ajo Mountain fault seems likely. The low dip of the Black Mountain block, 10° or less, is more likely to indicate that the Little Ajo block moved up relative to the Black Mountain block, which would imply concurrent movement on the Little Ajo Mountain fault, rather than that the Black Mountain block moved up in unison with the Little Ajo Mountain block and was later tilted down again to a nearly horizontal attitude by movement along the Black Mountain fault.

The present high stand of the Little Ajo block, despite the ready erodibility of the rocks composing its southerly part, also supports the idea of uplift on the west of the Black Mountain fault rather than downward movement on the east. The resistance to erosion of flat-lying lavas in this area is such as to throw doubt on their having been completely removed from the Little Ajo block without post-andesite tilting. Although none of these lines of thought can be regarded as conclusive, they tend to support a tentative history for the Little Ajo Mountain fault as follows:

Movement began in post-Ajo volcanic time, probably but not certainly before deposition of the Sneed andesite. Probably the Daniels conglomerate records erosion from the uplifted block—erosion that reduced it greatly, but not entirely, before the eruption of the Childs latite. Following the deposition of the Childs latite, with possibly some renewed movement at this time, the Batamote andesite was erupted, burying the surrounding country to considerable depths but the Little Ajo block much less deeply. Then faulting, probably of smaller displacement, followed on the Little Ajo Mountain fault, accompanying displacements on the Black Mountain and Childs Mountain faults. Erosion has since obscured the direct expression of this latest faulting and in places reversed the relief of the scarps.

MINOR FAULTS POSSIBLY COGNATE WITH THE LITTLE AJO MOUNTAIN FAULT

Faults with the same general trend as the Little Ajo Mountain fault are not common. Aside from the small faults that offset the northern part of the Gibson fault, there are only two exposed faults in the Little Ajo block that are probably contemporaneous with the Little Ajo Mountain fault. These are the small, gently curving, northward-dipping fault that trends generally east and brings about a repetition of the Locomotive-Concentrator contact near the common corner of secs. 27, 28, 33, and 24, T. 12 S., R. 6 W., and the fault trending northwestward from the southwest corner of sec. 32, T. 12 S., R. 6 W. This fault may continue on the east side of the Ajo Peak fault, but it has not been recognized there, probably because of similar rocks forming both walls.

Both of these faults appear to be normal, with downthrow on the north. The throw of the first is about 400 to 500 feet, that of the second roughly 1,800 feet at the northwest but apparently diminishing southeastward.

There is no direct evidence of the age of these faults, and their similarity to the Little Ajo Mountain fault is not so complete as to establish their contemporaneity with it, though it is suggestive. As noted on pages 35-38, it may be that other displacements in the same direction are present in the great thickness of Locomotive fanglomerate, but there is no direct evidence of their existence.

CHICO SHUNIE-BLACK MOUNTAIN FAULT GROUP

The most conspicuous faults cutting the Little Ajo Mountain block trend N. 15°–25° E. Four faults of this trend are definitely known, and there is a suggestion of two more buried beneath the alluvium. All are normal faults, with the east side downthrown.

The most westerly of the group is the Chico Shunie fault, which emerges from the alluvial cover about a mile south-southeast of Chico Shunie well. Here Ajo volcanics form the east wall and Chico Shunie quartz monzonite the west. The fault is poorly exposed for about a mile, but near the north boundary of sec. 6, T. 13 S., R. 6 W., drag in the volcanics is clearly visible where the fault crosses spurs north and south of the east tributary of Chico Shunie Arroyo. The trace of the fault, which, though not actually exposed, can be located to within 3 feet, indicates a rather steep east dip. The stratigraphy shows a downthrow of the east block. Drag along the fault conforms with this. Along the north branch of Chico Shunie Arroyo as far as the southwest spurs of North Ajo Peak the fault is concealed but can be closely bracketed by inliers of bedrock in the alluvium. On the divide between Chico Shunie Arroyo and Copper Canyon, the Cardigan gneiss forms the footwall of the fault. It is poorly exposed where it crosses a saddle in the west spur of North Ajo Peak. Here the hanging wall consists of Ajo volcanics, but Locomotive fanglomerate forms the footwall, with the volcanics overlying to the south. The displacement of the southward-dipping contact of fanglomerate on the gneiss basement in Copper Canyon indicates that the fault extends northward from this divide for some distance, but it cannot be followed in the Cardigan gneiss and clearly does not cut the contact of the Cornelia quartz monzonite to the north, so it must die out within a few hundred feet in this direction.

Because of the unconformity that separates the bedded rocks from the basement of Cardigan gneiss (and Chico Shunie quartz monzonite ?) no precise measurement can be made of the displacement along the fault. The base of the fanglomerate is thrown about 400 feet, but, as mentioned on page 35, there is strong evidence on the spur just to the west that the surface of unconformity is most irregular and by no means parallel to the bedding of the fanglomerate, so this is not a precise measure of the fault displacement. Farther south the throw must increase greatly, for fully 3,500 feet of Ajo volcanics are present in a homoclinal block on the hanging wall, and Locomotive fanglomerate may underlie the volcanics as well, though neither formation remains on the footwall side south of the west spur of North Ajo Peak. Thus the throw in the latitude of Chico Shunie well must be at least 3,500 feet, and it is probably still more.

The Ajo Peak fault is roughly parallel to the Chico Shunie fault and lies about a mile to the east, where it bounds Ajo Peak on the west. The outcrop of the fault was not observed, but its presence is shown by the offset of the base of the main member and of the narrow lower lens of the Ajo volcanics. The throw, as measured by the displacement of the base of the thick volcanic member, is about 1,000 feet. The thinner lower lens of volcanics was not recognized to the west of the fault, so no estimate of the throw elsewhere could be made. The fault dies out northward and does not cut the contact of the fanglomerate and Cardigan gneiss.

Slightly less than a mile farther east a parallel fault, with downthrow to the east, can be traced. It offsets the lower member of the Ajo volcanics about 300 feet and cannot be followed farther to the north. The offset of the top of the fanglomerate is only inferred, as the critical localities are masked by alluvium. The trace of the fault is probably shown by the narrow ravine cutting through the ridge of Ajo volcanics in the NE¼ sec. 5, T. 13 S., R. 6 W.

The Black Mountain fault, which bounds Black Mountain on the west, is the most conspicuous of the Chico Shunie-Black Mountain system. It is clearly exposed at only two localities, one at the west line and the other at the north line of sec. 1, T. 13 S., R. 6. W. At the first locality the hanging wall of Batamote andesite rests against fanglomerate in the footwall, the fault dipping 65° E. The second locality shows similar relations, with the fault dipping 50°. A little farther north the lava shows an abrupt east dip of 15°, probably caused by drag, and on the north line of sec. 36 a low hill exposes andesite close to fanglomerate, but the actual contact is overlain by alluvium. The hypothetical fault extension to the north is inferred from the probable age relations of the Little Ajo Mountain fault to those of this north-northeast group. The extension to the south is based on the inference that the linear topography of the hills of Childs latite, like that of the west scarp of Black Mountain, is due to the contrasting resistance of the rocks brought in contact by this fault.

The displacement on the Black Mountain fault cannot be measured, as no formation can be recognized on both walls. There was very probably considerable erosion of the Locomotive fanglomerate after the main uplift along the Little Ajo Mountain fault and before the extrusion of the Batamote andesite, so it is impossible to use the great thickness of fanglomerate transected by the fault as a measure of its displacement. Although there is inconclusive evidence of any age difference between the Little Ajo Mountain and Black Mountain faults, it is nevertheless possible that the fault is comparable in throw to the Little Ajo Mountain fault.

The hypothesis that there is a fault along the east base of Black Mountain is based on (1) the occurrence of a rather steep-faceted spur, not adequately shown on the topographic map, and the alinement of the lava hills to the north and (2) the anomalous serrate topography of the Black Mountain ridge (see p. 60). In view of the clear dominance of faulting in controlling the structure and the evidence of tectonic control of the major topographic features, the possibility that this face of the mountain is controlled by faulting does not seem far-fetched, even though the original fault scarp has been greatly modified by erosion.

The existence of a fault of parallel trend that is inferred to mark the east face of the ridge that extends from south of the quadrangle into secs. 29 and 32, T. 13 S., R. 6 W., seems more certain. The ridge is remarkably straight, and the front does not reflect the lithologic changes along it as the gneiss which extends for about a mile south of the quadrangle, the Daniels conglomerate, and the basaltic andesite all form a linear face without much irregularity. Although such scarps may be due to lateral planation during the formation of the pediment in front of it, the parallelism in trend with the Chico Shunie-Black Mountain fault set seems to warrant the inference of fault control tentatively indicated on plate 3.

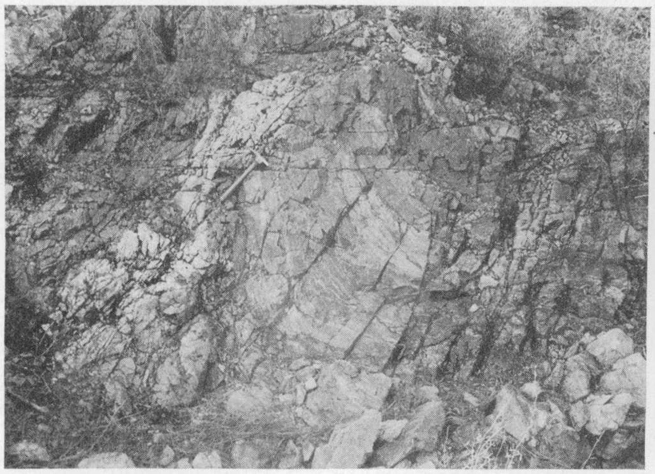
All the faults of this group are clearly younger than the Ajo volcanics, and the southeasterly group of faults is younger than the Batamote andesite. Except the fault at the south edge of the quadrangle and the hypothetical fault bounding Black Mountain on the east, none of them are directly reflected in the topography, and the Chico Shunie and Black Mountain faults are marked by scarps of reverse relief to that of the fault displacements. These features seem to indicate a pre-Quaternary age for most of the faults. They are probably, but not certainly, contemporaneous. The fault at the south edge of the quadrangle and that east of Black Mountain may be Quaternary and much younger than the others.

CHILDS MOUNTAIN FAULT

The southwest scarp of Childs Mountain marks a fault zone of large displacement. Evidence for the fault zone is both stratigraphic and physiographic. There are three exposures of steeply tilted Batamote andesite faulted down against nearly horizontal Childs latite on the northwest spur of Childs Mountain, and near the middle of the west front there is another fault with downthrow on the west, identifiable on stratigraphic grounds.

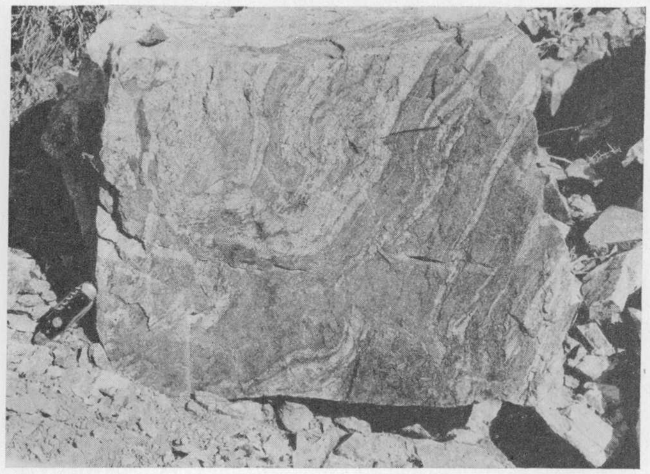
The notably straight front of the mountain on this side and its parallelism with these exposed faults offer considerable support to the hypothesis of faulting. The occurrence of a stream course fronting the scarp for nearly 2 miles toward the north end of Childs Mountain is further physiographic evidence for faulting. Were the mountain purely erosional, the stream should be more nearly axial in the valley, driven westward by the detritus from the higher ground. The crowding against the mountain front suggests some downfaulting of the valley block and burial of debris fans. The very low slope of the valley and absence of meandering of the stream make it doubtful whether lateral migration of the stream could account for its present postition. The occurrence of dense andesite (Batamote?) on the isolated hill in the valley 2½ miles northwest of Salt well may be regarded as confirmatory evidence of a normal fault between it and the main mass of Childs Mountain.

The fault separating Sneed andesite and Locomotive fanglomerate on the west from Cardigan gneiss on the east is clearly exposed in two localities about a mile south of Salt well. It cannot be traced much farther, although it may continue beneath the alluvium, as shown on plate 3. Near the southwest corner of sec. 19, the Sneed andesite overlaps on Chico Shunie quartz monzonite and Cornelia quartz monzonite, and there is no evidence that the fault persists any farther south. The connection between this fault and the Childs Mountain fault farther



A. LOCAL SYNCLINE IN CARDIGAN GNEISS.

Pegmatite dikes just to left of hammer are probably related to Cornelia quartz monzonite. The light bands to the right are quartz diorite injections into a darker diorite base. Hammer is 18 inches long. NW½ sec. 29, T. 12 S., R. 6 W.

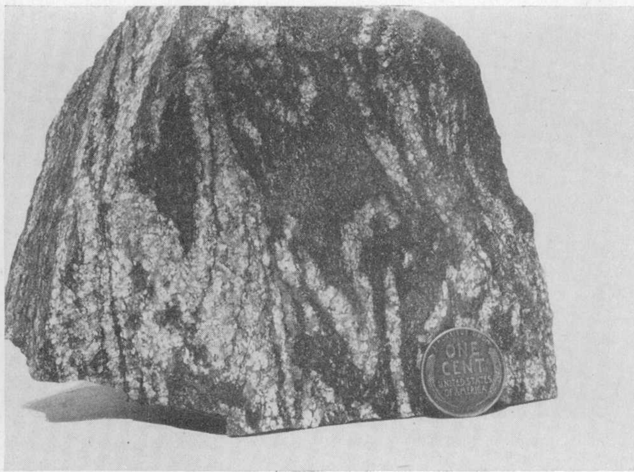


B. CONTORTED INJECTION GNEISS OF THE CARDIGAN GNEISS.

Irregular veins of light quartz diorite gneiss in darker quartz diorite gneiss. Pocket knife is 3½ inches long. Near Cardigan.

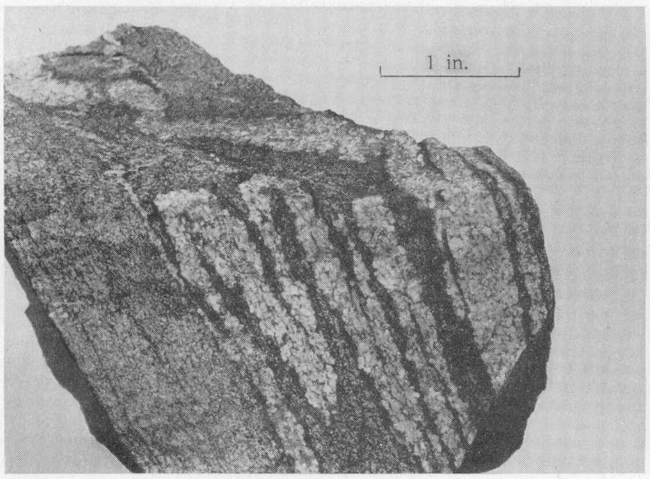
C. CONTORTED INJECTION GNEISS OF CARDIGAN GNEISS.

Shows intimate contortions. Coin is 2 centimeters in diameter. One mile northwest of Cardigan.



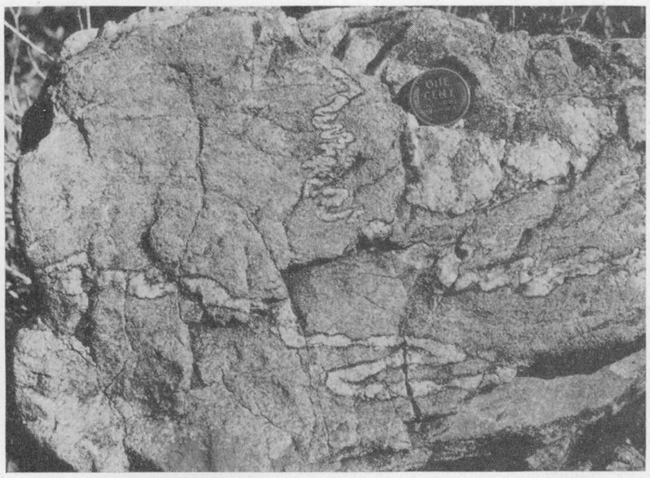
D. PTYGMATIC FOLDING IN DARK FACIES OF CARDIGAN GNEISS.

Shear surfaces with cataclastic structures (later than the folding) stand horizontally. Coin is 2 centimeters in diameter. Copper Canyon.



E. PTYGMATIC FOLDING OF LIGHT DIORITIC SEAMS IN DARK FINER-GRAINED FACIES OF CARDIGAN GNEISS.

Note that the ptygmatic veins transect the older foliation, marked by thin layers of dark and light minerals. Note scale.

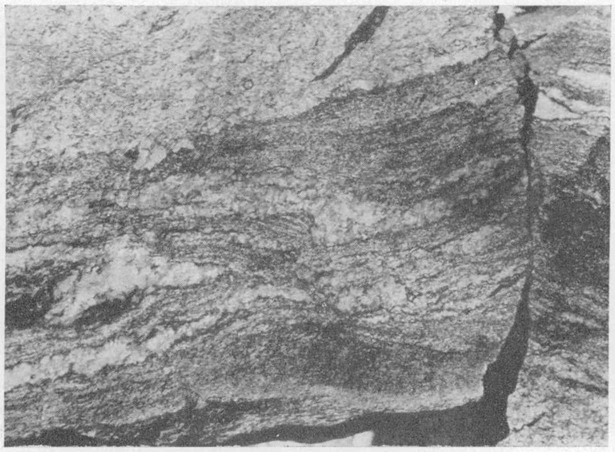


F. THIN QUARTZ-FELDSPAR SEAMS WITH NOTABLE PTYGMATIC FOLDING IN LIGHT FACIES OF CARDIGAN GNEISS.

The seams were outlined in pencil before photographing to bring out their structure. In nature they do not possess dark selvages. Coin is 2 centimeters in diameter. North of Cardigan.

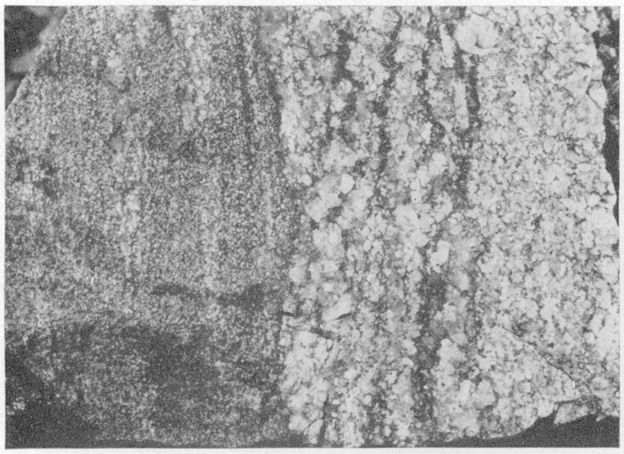
A. QUARTZ DIORITE INJECTIONS TRANSECTING BANDING OF CONTORTED GNEISS.

The bands are also of quartz diorite and closely resemble the wider dike petrographically. Dark facies of the Cardigan forms the matrix. Coin is 2 centimeters in diameter. One mile north of Cardigan.



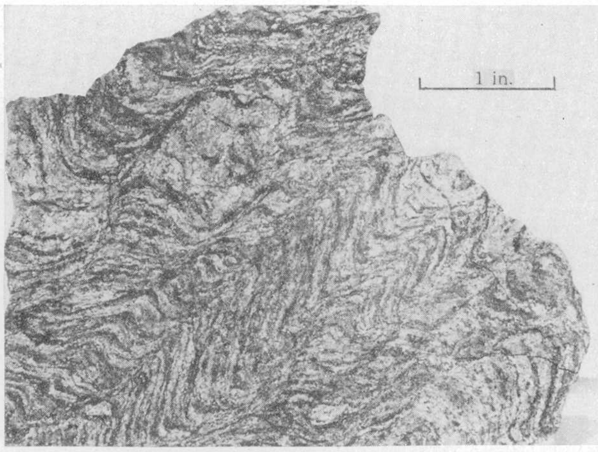
B. IRREGULARLY FOLIATED GNEISS.

Gray quartz dioritic nearly massive facies on right transects finer banding at a narrow angle. Quartz and quartz-feldspar seams in middle and lower left of specimen are probably partly of replacement origin. Some other seams appear to be true injections. Specimen is about 10 inches wide. Northwest of Cardigan.



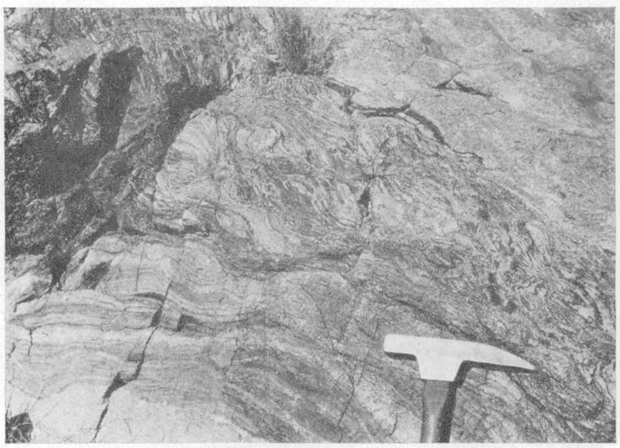
C. CONTACT BETWEEN DARK FACIES OF CARDIGAN GNEISS AND LIGHTER QUARTZ DIORITE BANDS.

Note the round feldspar in the light band at the bottom, the coarser angular feldspar in the intermediate layer, and the dark facies with discontinuous wider quartz-feldspar bands in the upper part. Some of the feldspar, especially in the middle band, is probably due to replacement rather than injection. Block is about 1 foot high.



D. REFOLIATED (POLYMETAMORPHIC) GNEISS.

Note the older gneissic banding (with some swells probably due to replacement) cut by and dragged along new shear surfaces trending from lower left to upper right. "Umfaltungsclivage." Note scale. One mile north of Chico Shunie village.

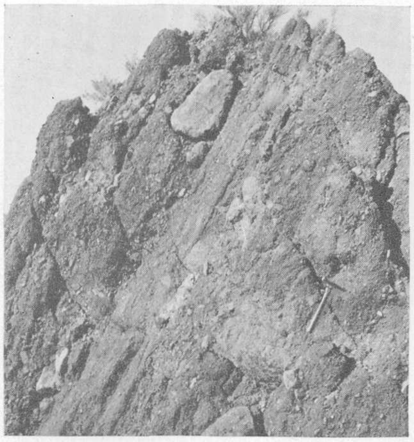


E. REFOLIATED GNEISS.

Older foliation, brought out by broader light bands (in obscure dark material above hammer) that trend upward and to the left. This is cut and displaced by the horizontal gneissic banding to the left of the hammer, which shows suggestions of displacement of upper layers to the left with respect to the lower layers and cuts them into lenses. This is crystalloblastic-cataclastic metamorphism superposed on older crystalloblastic structures. Hammer head is about 8 inches long. One mile north of Chico Shunie village.

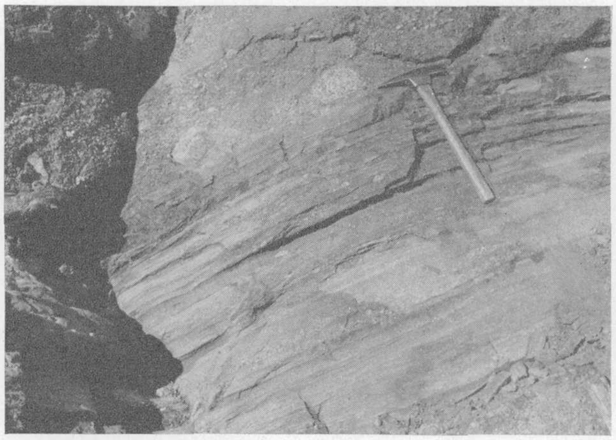
F. INCLUSIONS OF CARDIGAN GNEISS IN EQUIGRANULAR FACIES OF CORNELIA QUARTZ MONZONITE AT A POINT ABOUT 6 FEET FROM THE CONTACT AGAINST CARDIGAN GNEISS.

Contact is to left of outcrop and essentially parallel to the left side of the photograph. Note watch near center. About 1½ miles west of Gibson Arroyo, on south contact (originally roof) of the Cornelia quartz monzonite.



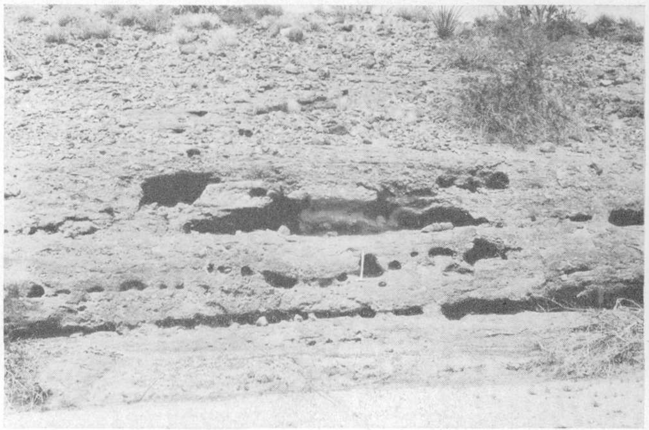
A. REPRESENTATIVE OUTCROP OF LOCOMOTIVE FANGLOMERATE ABOUT 1,000 FEET SOUTHEAST OF THE OPEN CUT OF NEW CORNELIA MINE.

Boulders are composed of monzonite and volcanics (Concentrator volcanics) in reddish matrix of similar material. Hammer is 18 inches long. Dip is about 60° S.



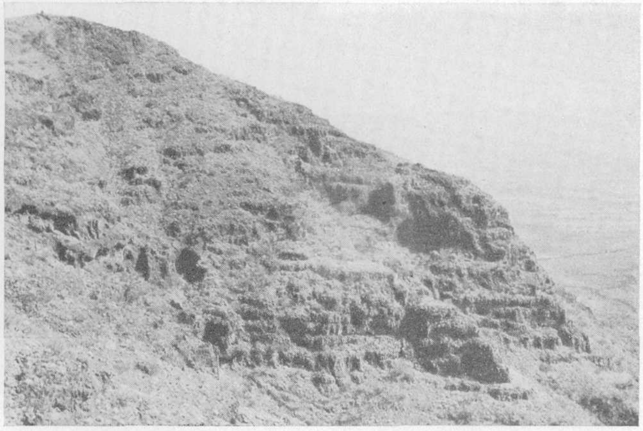
B. CONTACT OF WELL-BEDDED GREENISH SANDSTONE WITH OVERLYING FANGLOMERATE MEMBER OF THE LOCOMOTIVE FANGLOMERATE.

Note 6-inch monzonite boulder just to left of hammer point. Larger boulder of volcanic breccia is just above. Hammer is 18 inches long. The locality is near the top of the formation, on the east slope of Ajo Peak.



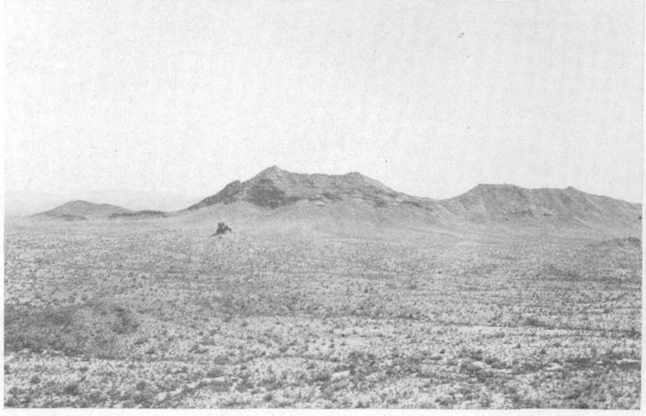
C. DANIELS CONGLOMERATE ON NORTH SIDE OF DANIELS ARROYO ABOUT 1½ MILES FROM THE EDGE OF THE QUADRANGLE.

The irregular cementation of the conglomerate is evident from its cavernous weathering. Beds dip about 2° to the left. Hammer is 18 inches long.



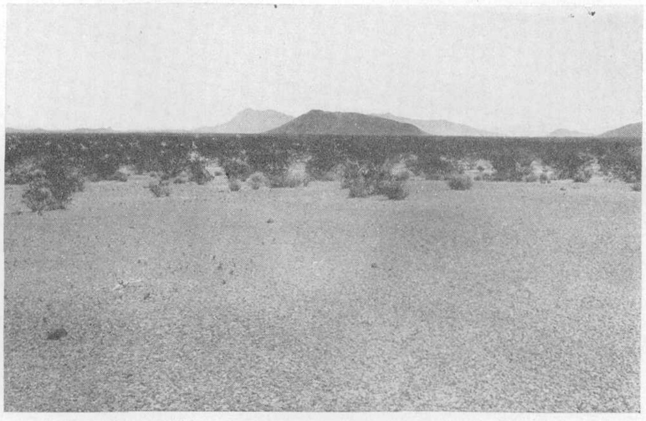
D. NORTHEAST SPUR AND CREST OF BLACK MOUNTAIN FROM THE SOUTHWEST RIDGE.

Note massive beds of lava with marked flow boundaries. Valley of the Ajo at right.



E. BLACK MOUNTAIN FROM THE WEST.

Locomotive Rock in the left center. The foreground is pediment carved on Locomotive fanglomerate that dips at 60° to 40° to the right. Black Mountain is fronted by a fault, which cuts it off from these steeply tilted rocks.



F. BLACK MOUNTAIN, BEHIND THE UNNAMED MESA IN THE MIDDLE GROUND, FROM A POINT NEAR THE NORTHWEST CORNER OF SEC. 31, T. 13 S., R. 6 W.

Desert pavement in the foreground, with creosote bushes scattered over it.

north is doubtful, because the contrast in topographic expression suggests that the more northerly fault is much younger; however, the parallel trend and similarity in direction of downthrow may be interpreted as evidence of the postulated connection. The difference in topographic expression may be due to differences in lithologic character, which are elsewhere very prominent (see p. 60), or to rejuvenation toward the north of an old through-striking fault. The more northerly portion of the fault course may be Pleistocene or even Recent. Probably some of the movement, at least in this southern part, is older and perhaps contemporaneous with the Little Ajo Mountain fault.

FAULT BOUNDING BLACK MOUNTAIN ON THE SOUTHWEST

The attitude and altitude of the Childs latite in the hills southwest of Black Mountain and of the Batamote andesite in Black Mountain imply either a fault or a sharp monocline between them. In accordance with the regional habit of the structure, I have inferred a fault. There is no evidence of its age, but, as it is roughly parallel to the Childs Mountain fault, it may be contemporaneous with it.

OTHER FAULTS IN THE NORTHERN PART OF THE QUADRANGLE

There are several northward-trending normal faults in the Childs and Batamote Mountains. Although some of these show the attitude of the rocks on the two sides to be more or less discordant, the absence of stratigraphic marker beds has not permitted unequivocal proof of their existence. They are all mapped primarily on topographic evidence—on the basis of notably discordant topography in a relatively uniform rock series. As far as could be judged from the uncertain evidence, all are normal faults downthrown to the east.

Mention has been made on page 44 of the possible existence of a second northward-trending fault in the ravine on the north flank of Childs Mountain, 6½ miles west of Batamote well. The apparent occurrence of Batamote andesite beneath Childs latite on the west side of this ravine may be due to such a fault. Existence of the northwestward-trending fault that is inferred to bound the Batamote Mountains on the southwest side, north of No. 1 well, is very doubtful. The straight edge of the mountains and the parallel tilting of the lava at the edge of the valley may indicate a monoclinal fold rather than a fault. The fault is regarded as somewhat more probable, however, because of the absence of demonstrable sharp folding in the volcanic series both here and elsewhere in the district and because of the occurrence of very fine-grained alluvium directly at the foot of the scarp for long distances, where, on the theory of a normal erosional origin of the scarp, one would expect coarse fan deposits. Furthermore, the drainage pattern of the north slope of the spur is much more complete and finer-textured than that on the south side, as though the two slopes, although cut on the same rock in comparable attitudes, are of very different ages. This difference would suggest Recent movement on the fault.

POSTULATED FAULTS NEAR DANIELS ARROYO

The hypothetical faults in the southwest corner of the quadrangle are drawn entirely on topographic evidence. That drawn on the north side of Daniels Arroyo and parallel to it is rather confidently inferred on the basis of the remarkably straight course of the stream and the fact that the stream hugs the abrupt north hills instead of flowing centrally in its valley—relations that suggest northward tilting of the block underlying the valley. There is no suggestion of more abundant waste from the hills to the southwest than from the Chico Shunie Hills. The comparatively straight front of the hills of the relatively nonresistant Daniels conglomerate also suggests a Recent fault here. The assumed fault trending northward at the extreme southwest corner of the area is mapped on the basis of the straight boundary of the lava in this direction. It is parallel to the general course of the Growler Mountains, which suggest a fault-block range,[65] and, although far from being demonstrable, its existence is regarded as very probable.

FOLDS

No systematic folding has been recognized in the Ajo quadrangle. The only folds are in the Batamote andesite and are merely gentle warps, except for local steeper structures that are generally more suggestive of drag along faults than of true folding. Gently plunging anticlinal folds are found at the south end of Childs Mountain, the northeast corner of Childs Mountain, and in the Batamote Mountains, in secs. 21 and 28. There is a suggestion of a low anticline trending west-northwest nearly parallel to the spur of the Batamote Mountains, but it passes into a northward-plunging syncline near the line between Rs. 5 and 6. The radial dips in the lava around the breccia plug at the east edge of the quadrangle are doubtless chiefly depositional, though there has been some later modification.

SUMMARY OF DEFORMATION

The lack of indigenous fossils in the sedimentary rocks of the quadrangle prevents assignment of any precise age to any of the formations and, accordingly, to the different periods of deformation.

The repeated metamorphism attested by the structure of the Cardigan gneiss favors the presumption that it has undergone several orogenic disturbances, the oldest of which may well have been pre-Cambrian. If some of the

[65] Bryan, Kirk, The Papago country, Arizona: U. S. Geol. Survey Water-Supply Paper 499, pp. 73, 77, 1925.

inclusions in the Chico Shunie quartz monzonite can be proved to be Paleozoic, the cataclastic deformation may be Mesozoic; at least it antedated the intrusion of the Cornelia quartz monzonite of inferred early Tertiary age. The Gibson fault is then doubtless of somewhat later Tertiary age; however, the long and complex subsequent history suggests that it was formed in pre-Miocene time, for the deep erosion prior to the deposition of the Locomotive fanglomerate, together with the deposition of that formation and the Ajo volcanics, must have taken a time equivalent, say to the Miocene. The early movement along the Little Ajo Mountain fault probably preceded the extrusions of Sneed andesite and almost certainly those of Childs latite and Batamote andesite. Thus it may be as old as early Pliocene, because the considerable deformation and erosion of the Batamote lava seem to require that this lava is pre-Pleistocene in age. The Black Mountain-Chico Shunie faults are then perhaps late Pliocene or post-Pliocene and the Childs Mountain fault probably a little younger, say early Pleistocene or, in part, even Recent. The minor faults, like those near Daniels Arroyo, may be Recent. All of these assignments are, of course, very arbitrary and represent merely the relative ages, with some consideration for the "reasonable" duration of geologic processes.

ORIGIN OF THE FAULTS

A consideration of the faults in the quadrangle shows that they have been active for a considerable time geologically and that it is reasonable to infer that they are the dominant factors in controlling the attitude and vertical distribution of the formations now exposed. The present topography is not directly referable to them, as several of the downthrown blocks stand topographically higher than their relatively uplifted neighbors; yet the conclusions seem irresistible that faults are reflected at least by the larger topographic features. This conclusion is believed to be true in general throughout the Basin and Range province, and the reasoning upon which it is based has been most clearly and logically presented by Ransome.[66]

The pattern of the faults in several areas, including the Ajo quadrangle, is such as to show that no considerable strike movement could have occurred along them. The known displacements are almost entirely dip-slip movements. This suggests that the faults have resulted from vertical stresses due to differential support of the relatively rigid rocks near the earth's surface by the more plastic basement upon which they must rest.

Within the Ajo quadrangle the faults have such diverse trends that it might be inferred that there was no tangential force in the earth effectively controlling their trend and vertical displacements. This impression vanishes, however, when a larger region is considered. The geologic maps of Arizona, eastern California, Nevada, western Utah, southern Idaho, and eastern Oregon show very marked regional trends of the fault block mountains. In the western part of the Papago country the dominant trends near the Colorado River are northwest, and farther eastward, near the Santa Cruz, they swing gradually to the north. Similar gradual regional swings in trend are characteristic throughout the Basin and Range province. Despite the great differences in their structure, the ranges of the province have sinuous trends such as are common in folded mountain chains. Disregard of the local surficial structure of the bedrock by the faults that control the topographic expression is characteristic also in this entire area. Taken together, these features seem clearly to show that the trends of the faults that brought about vertical displacements were controlled by tangential forces and not by the grain of the exposed geologic formations. The differential support of the crustal blocks was presumably the primary cause of the faulting, but, in general, the regional tangential forces governed the orientation of the surfaces of shear.

The ultimate control of these structural disturbances is one of the great speculative questions of geology. Gilbert[67] long ago pointed out that the ranges are generally parallel, although the faults bounding them commonly transect the older folds. He interpreted this as evidence that the ranges are due to vertical adjustments of the brittle surface rocks to folds in the lower zones, brought about by regional compression.

This theory is attractive but would seem to encounter some difficulties. It apparently implies some lateral shortening even in the surface zone during the period of block faulting. A folding in the lower zones of the crust must imply lateral shortening, for if the deeper folds were due to vertical movements they should be directly reflected in the overlying rocks as well. So far as studies of the basin ranges have gone, no evidence that they involve shortening of the surficial zone has been presented; they appear to represent actual lengthening of the surficial part of the crust transverse to their trends. If this apparent extension be real, it implies a rather sharp discontinuity within the crust, for otherwise one would expect that the upper part of the crust would be compressed in some places and stretched elsewhere. Yet the fault patterns seem everywhere closely comparable. Furthermore, in folded mountain systems there is commonly a marked asymmetry of the folds on the two sides. If such folding were going on in the lower zone of the crust beneath the basin ranges, one would expect an asymmetry of the faulting. This, too, is lacking. For these reasons, Gilbert's hypothesis does not seem to be completely satisfactory,

[66] Ransome, F. L., The copper deposits of Ray and Miami, Ariz.: U. S. Geol. Survey Prof. Paper 115, pp. 79-84, 1919.

[67] Gilbert, G. K., U. S. Geog. and Geol. Surveys W. 100th Mer. Rept., vol. 3, p. 62, 1875.

though it must be confessed that as yet no better one appears to have been presented.

Evidences of discontinuities within the crust of the order required by Gilbert's theory have not apparently been recognized. However, there are many geologic and gravimetric data to suggest a marked discontinuity at the base of the crust—a discontinuity whose recognition is implied in the very use of the term "crust." These data have given rise to several theories of orogeny, one of the most attractive being that propounded by Vening-Meinesz.

Vening-Meinesz[68] has made gravity measurements in and around the Dutch East Indies, and with his colleagues, Umbgrove and Kuenen, correlates them with the geologic structure of that region. Their results are of great interest in suggesting a possible mechanism of mountain formation, and it would be of value to test their hypothesis in the Basin and Range province.

In brief summary, Vening-Meinesz has found that a narrow belt of strong negative gravity anomalies runs through the East Indian Archipelago, coinciding remarkably with a belt of Miocene folding recognized by Umbgrove. Analysis of the gravimetric data shows that the anomalies are most likely due to the presence of thicker masses of rocks of low specific gravity along this belt than elsewhere in the region, and it is thus highly probable that a deep root of crustal material here extends downward into the specifically heavier material of the substratum. The coincidence of the belt of folding with the belt of thicker crustal rocks suggested to Vening-Meinesz that both may have been brought about by movements of the substratum, which carried the lighter crustal material passively with it. He assumed that such currents flowed from both sides toward the belt and there turned downward into the earth, in the manner of the return flow of convection currents within the body of the earth. The viscous drag of the currents carried the lighter crustal masses along, and, where the currents turned down, the lighter crustal rocks were piled together, folded, and thrust-faulted into a thick prism. This thick prism of light rocks accounts for the belt of negative anomalies.

The crustal rocks forming the root may be assumed to have the average composition of granite; the subcrustal material, whether gabbroic or ultrabasic in composition, must surely be less siliceous. As the formation of the root implies downward displacement of the granitic crustal material, it is evident, from the thermal gradient of the earth, that the root material is transferred to a hotter level and must, in time, acquire the temperature appropriate to that depth. As granitic material melts (at least in part) at temperatures considerably lower than those appropriate to gabbroic or subsilicic rocks, it is evident that the root is unstable, and after cessation of the subcrustal movements it would either melt or become partly softened and would flow laterally and eventually flatten out, owing to the difference between its density and that of the substratum. Vening-Meinesz concludes that at the same time, with the release of the root from the downward pull of the descending currents, the entire column would rise somewhat in response to isostasy, leading to the uplift of the mountain mass. After a sufficient period of quiescence a range formed in this way might be in essential balance isostatically, or like the Alps, have only faint negative anomalies along it. During the uplift differential vertical stresses resulting from inhomogeneities of the crust would occur and high-angle faulting might be expected.

The strike length of many mountain ranges amounts to a considerable fraction of an arc of the earth's circumference. If the mountain ranges were formed in the manner outlined and followed great circles of the earth, it is evident that there would be longitudinal compression in the roots, because the radius of the lower part of the root would be less than that of the higher parts. On the other hand, in sinuous ranges there would not be much longitudinal compression, and hence less energy would be required to produce them. Vening-Meinesz called attention to this fact as perhaps significant. It is true that most elongated ranges are sinuous in trend, but it is possible that the irregularities are due to inhomogeneities in the crust or to irregularities in distribution of subcrustal motion, and it does not appear that it is necessary to refer the irregularities to the effect of such potential longitudinal compression in the roots.

The strength of the negative anomalies of the Dutch East Indies, compared to the faint anomalies of the Alps, where the latest folding is also supposed to be Miocene, leads Umbgrove to conclude that there has been relatively recent renewal of the crustal deformation in Malaya. This has been expressed by graben structure in the brittle surficial rocks above the zone of compression.

It is obvious that the theory so briefly outlined requires supplements. The diversity in both structure and history of the mountain ranges of the earth is so great that many subordinate hypotheses must be adopted for their adequate explanation. Nevertheless, the objections to the older theories of orogeny appear so weighty that it seems desirable to test this new suggestion sympathetically, as it may contain the germ of an eventually satisfactory solution of this major geologic enigma.

The application of this hypothesis to the basin ranges would require considerable modification. In the first place, intense crustal shortening by folding and thrust faulting has not been demonstrated for much of the Basin and Range province, although many parts have been strongly

[68] Kuenen, P. H., Umbgrove, J. H. F., and Vening-Meinesz, F. A., Gravity, geology, and morphology of the East Indian Archipelago: Netherlands Geodetic Comm. Pub., pp. 109-194, pls. 2, 4, [1934]. (Extract from Gravity expeditions at sea, 1923-1932, vol. 2, The interpretation of the results.)

affected by it. The block faulting does not appear to be limited geographically to the thrust-faulted areas; however, the Cordilleran region has been orogenically active in one place or another for the entire Tertiary period, indeed, ever since middle Mesozoic time, and folding and faulting have persisted in California to Recent time. If this deformation has been brought about by subcrustal flow, as postulated by Vening-Meinesz for other regions, it may account both for a general thickening of the earth's crust in this area and for its differential support from place to place.

The gradual changes in trend of the basin ranges from Mexico to Oregon are like the sinuous courses of folded mountains. The local parallelism of the ranges is not rigorous, but the tendency is marked. It appears that Vening-Meinesz's theory, by referring crustal disturbance in large measure to frictional drag of a streaming in the subcrust, can account reasonably for these features. At the same time, it permits the regional trend to be established without the necessity of transmitting compression for very great distances across the strike of the ranges. Crustal segments in magmatic and nonmagmatic centers must oppose different frictional effects to the subcrustal streaming. The same is true of thicker and thinner parts of the crust formed by older orogenies. Such differences might bring about inhomogeneities in the subcrustal flow over the whole region and account for the differential support of the crust, although the general regional trend of the currents would not be affected.

Needless to say, the only value of speculations like this is in calling attention to tests of the suggested mechanism. Unfortunately there are not now at hand sufficient data, either geologic or gravimetric, to test this theory in the Basin and Range Province. Its broad features appear so attractive that the accumulation of material to this end is most desirable.

Regional movements of the sort postulated by Vening-Meinesz would not be expected to exercise complete dominance over the local inhomogeneities in the earth's crust. The response of brittle crustal rocks must in some degree be affected by the vector properties of the blocks involved, and thus one would expect local deviations from the regionally dominant trends of the faults. It appears that the variant fault trends of the Ajo quadrangle may thus record the influence of local crustal inhomogeneities in response to regional deformation.

PHYSIOGRAPHY[69]

GENERAL FEATURES

The Ajo quadrangle is a representative part of the Sonoran Desert section of the Basin and Range province.[70] The bedrock structure is dominated by faulting. The present topographic features are therefore the products of erosion and sedimentation of the desert acting upon a bedrock that is heterogeneous both horizontally and in altitude.

The surface forms of the quadrangle, like those of the Sonoran Desert section as a whole, can be classed into three groups: (1) The mountains, commonly rugged and steep-sided, with either bare rock at the surface or only a thin cover of talus; (2) the pediments, smooth carved-rock plains that generally border the mountains and are strewn with a thin but discontinuous mantle of gravel; and (3) the bajadas, smoothly rounded alluvial aprons that slope forward into the axes of the "valleys." Of these, the mountains and pediments are chiefly carved by erosion; the bajadas are chiefly depositional.

The drainage of the Ajo quadrangle is external, as is that of almost the entire Papago country, in which Ajo is centrally located. Although the climate is now arid and perhaps was formerly still more arid,[71] the drainage of the region has been integrated. This integration can only mean that a long time has elapsed since the major structural disturbances occurred, a conclusion that is supported by several other lines of evidence, both structural and physiographic. (See p. 55.)

MOUNTAINS

The mountains of the quadrangle are of two kinds, differing in their stages of erosion in such a way as to indicate control by their lithologic features and structures and presumably by their size and altitude. One, the sierra type, is represented by the main mass of the Little Ajo Mountains, the Chico Shunie Hills, and Black Mountain and the low hills south and southwest of it. All these are in a stage of mature dissection and have knifelike ridges and pointed summits. All except Black Mountain and the low hills southwest of it are composed of massive rocks or of fissile rocks whose division surfaces stand steeply. The second, the mesa type of mountain, is represented by the Childs and Batamote Mountains. The canyons in these mountains are in youthful stages, and there are broad mesas between the drainage lines, especially in the lower parts of the mountains. The sides of the mountains of the mesa type may be, on the average, a trifle steeper than those of the sierra type. The less advanced stage of dissection of the mesa type of mountain probably reflects the low-angle dips of the lavas, their permeability to water, the fact that they yield large blocks to the talus slopes, and their consequent resistance to erosion as compared to the massive or steeply tilted rocks of the sierras. As the hills and mountains of lava are generally buried in talus for a considerable height, their slopes cannot re-

[69] This section is a summary of a more complete discussion that has appeared elsewhere. See Gilluly, James, The physiography of the Ajo region, Arizona: Geol. Soc. America Bull. vol. 48, pp. 323-348, 1937.

[70] Fenneman, N. M., and others, Physical divisions of the United States: U. S. Geol. Survey map, 1930.

[71] Bryan, Kirk, Erosion and sedimentation in the Papago country, Ariz.: U. S. Geol. Survey Bull. 730, p. 65. 1922.

cede to lesser angles than those at which the talus is in repose. The fact that Black Mountain and the associated lava-capped hills are nevertheless sharp-crested sierras suggests that they have been carved from narrow blocks standing at relatively great heights above base level. This form is a further logical consequence of the faults postulated along the borders of Black Mountain and the other hills.

PEDIMENTS

DISTRIBUTION

The parts of the relatively smooth but minutely dissected slopes that can be demonstrated to be pediments or carved surfaces rather than built surfaces are limited to certain parts of the mountain bases. How much of their apparent restriction is real and how much is due to the dissection in the present subcycle of erosion having been locally too slight to expose the carved bedrock beneath the alluvial veneer, is an open question.

Exposures of planed bedrock are sufficient to demonstrate the existence of a pediment almost entirely around the Little Ajo Mountains and Chico Shunie Hills, except for parts of their southern borders. Pediments extend deeply into these mountains, and several from different directions practically coalesce near Ajo Peak. Pediments are also known west and northwest of the lava hills in the southwestern part of T. 13 S., R. 6 W., and narrowly bordering the hills of Childs latite south of Black Mountain. Elsewhere, to judge from exposed bedrock, pediments are either very narrow or absent.

With few exceptions, the maturely dissected mountains are bordered by pediments, whereas the mesalike mountains are not; in fact, except for the small areas near the south edge of the district and north of the tailings dump of the Phelps Dodge concentrator, no demonstrated pediments have been carved on Batamote andesite. This fact is especially noteworthy, as the pediment at Darby well is cut on the upthrown block along the Black Mountain fault, which cuts the Batamote lava, whereas no pediment is visible on the downthrown block fronting the andesite mountain. The virtual restriction of pediments to the mountain fronts not formed of Batamote lava may be explained by the manner in which the different kinds of rock respond to weathering, the same factor that determines a "younger" topography on the mountains of andesite flows than on those composed of other kinds of rocks, as mentioned in the description of the mountains. As there noted, the thick flows of andesite yield large blocks that are not readily moved on slopes of low gradient and that do not readily break down to finer sizes. Thus the talus slopes of the large lava blocks are stable and recede very slowly, and consequently pediments below them can be formed only very slowly. The few andesite hills bordered by pediments are all low and yield only small talus piles, so that erosion has been able to cut narrow pediments despite the resistance of the rock where it is in large masses.

SURFACES OF THE PEDIMENTS

The pediments of the Ajo quadrangle are all more or less dissected. Toward their upper ends they are trenched by dendritic streams arranged in a fine-textured pattern. The surface is thus a gently rolling one, made up in part of flat-topped interstream areas more or less strewn with gravel but in much larger part of bare rock cut into a hill-and-valley topography. The depth of these valleys averages perhaps 40 feet toward the heads of the pediments. Probably less than 10 percent of the surface next to the mountains is gravel-covered.

The depth of the channeling diminishes progressively toward the bajadas, and the average depth at the lowest bedrock exposures would be perhaps 15 feet. In the same direction the proportion of the surface that is flat-topped also increases, and the texture of the drainage pattern becomes somewhat coarser. Accordingly, there are relatively more steep arroyo walls and fewer gradual slopes transitional from the flattish interstream areas to the stream channels. As the flat-topped interstream areas are more or less strewn with gravel the proportion of the surface that is mantled by gravel also increases toward the valleys until finally there is no demarcation between pediment and the alluvium of the bajadas. It seems that the distribution of the gravel mantle, the apparently systematic variation in the side slopes of the arroyos, and the texture of the drainage pattern may furnish clues to the processes active in the formation of the pediments.

SHAPE IN PLAN

The pediments extend for greater or less distances into the mountains along all the streams of any size. They narrow headward, presumably because of less stream capacity in this direction, although the narrowing of the pediment along Darby Arroyo more or less corresponds with the wedging out of the Locomotive fanglomerate westward. Furthermore, the narrowing of pediments along both Chico Shunie Arroyo and Copper Canyon also closely coincide with upstream narrowing of the formations most favorable to pedimentation. Even on uniform bedrock, however, each segment of the pediment widens outward from the mountains, and, as the mass of the Little Ajo Mountains is roughly circular, the outer margin of the pediment as a whole is convex in plan. Any outward sloping surface conforming to the mountain base must of necessity have this shape, whatever its origin.

SHAPE IN PROFILE

The pediment is for the most part concave upward in profile, generally more steeply along the smaller stream courses and less steeply along the larger streams. The gradients range from about 70 feet to the mile along the lower segments of the larger streams to about 300 feet to the mile along the upper parts of the pediments cut along small streams. The average slope is probably less than 150 feet to the mile fronting the north and northeast segments of the mountain mass, and perhaps 100 feet to the mile on the west, south, and southeast fronts.

SHAPE IN CROSS SECTION

Whether pediments are characteristically convex in cross section (rock fans) at the mouths of streams or concave is a moot point in the study of desert topographic forms.[72] The evidence is conflicting in the Little Ajo Mountains. There seems to be a definite rock fan at the mouth of Gibson Arroyo. The critical area at the mouth of Cornelia Arroyo is obscured by the tailings dump, but there is no reason to suspect a convexity here. All the other pediment segments are perceptibly concave toward the streams rather than fan shaped.

It is perhaps noteworthy that Gibson Arroyo, of all the streams of the quadrangle, drains the largest area of resistant rock. It has a large catchment basin, almost wholly in massive tough quartz monzonite. It thus fulfills the conditions outlined by Bryan[73] as favoring fan forms of pediments, for it carries a heavy load of resistant detritus that must tend to accumulate at the canyon mouth and deflect the stream laterally from time to time.

The pediment of Darby Arroyo is one of the best developed in the area. It is carved on the Locomotive fanglomerate and Ajo volcanics, dipping steeply to the south. This pediment is within the mountain front and might not, on this account, be expected to show a fan section, even though such forms were dominant at the mountain front. However, it is clear that a moderate lateral growth of this pediment would reverse the relation. Instead of a pediment within the mountain mass, there would then be island mountains, such as Locomotive Rock, isolated within broad pediments. Certainly such additional widening would be slight compared with what has already occurred along Darby Arroyo, and, if it took place, a broadly concave pediment would still exist here crowned by sierra remnants.

This concavity is an obvious necessity in areas of coalescent drainage, such as characterizes most of the upper parts of the pediments. As long as the stream pattern is dendritic the master stream must clearly be at an axis of lower altitude than the tributaries. The lower reaches of the pediments where the streams are parallel to divergent, such as north of the mouth of Copper Canyon and the lower pediment north of Darby Arroyo, may be slightly fan shaped, but the pediment on which the most bedrock is exposed, northwest of Chico Shunie well, is concave throughout. Insofar as the pediments of the Ajo quadrangle are representative, there is clearly neither general convexity in cross section where the streams leave the mountains nor general concavity, but most of the pediments are concave.

BAJADAS

Most of the Ajo quadrangle, like the Papago country as a whole, is buried by alluvium. The broad valleys differ from the valleys of humid regions in being not primarily the work of stream erosion but of structural deformation. As the mountains show selective erosion of some rocks probably parts of the valleys are also modified by erosion, but it is clear that the dominant result of stream action in them has been deposition. Most of the low land is low because it has been relatively depressed by faults. This is shown by the entire lack of relation between the size of a drainage area and the size of the valley draining it, by the occurrence of a transverse divide in the middle of the broadest valley of the area, the Valley of the Ajo, and by the gravels buried to great depths in the bottoms of the valleys. The hard, resistant Batamote andesite, buried by 170 feet of alluvium at Childs Siding, could not have been cut down by erosion from a height equivalent to Batamote or Black Mountain and still leave the fanglomerate at Darby well standing 800 feet higher, because the planed pediment at Darby well was cut without notable modification of the base of the bold peak of Black Mountain just alongside.

The gently sloping alluvial fans that occupy the depressions cannot be sharply separated from the pediments that so commonly skirt the mountains above them, because the pediments are veneered more or less completely with gravel. At the axial depressions of the valleys the bajada fronting one mountain mass coalesces with that fronting the mountain on the opposite side, the position of the axis being determined, in the absence of tilting of the valley block, by the relative supplies of debris from the two sides.

The slopes of the bajada are moderate, ranging between 15 and 75 feet to the mile, with 50 feet to the mile being probably a fair average. The profiles of these slopes normal to the mountain front, like those of the pediments, are concave upward in consequence of the basinward diminution in size of the detritus as it is transported from the mountains. Also like the pediments, the alluvial slopes are steeper on the north than on the south side of the Little Ajos, perhaps because of the difference in the coarseness of the material supplied from the bedrock on the two flanks of the mountains.

The depth of the gravels composing the alluvial fans is uncertain but probably very irregular. As summarized

[72] Johnson, D. W., Planes of lateral corrosion: Science, new ser., vol. 73, pp. 174-177, 1931; Rock fans of arid regions: Am. Jour. Sci., 5th ser., vol. 23, pp. 389-416, 1932; Rock planes of arid regions: Geog. Rev., vol. 22, pp. 656-665, 1932. Blackwelder, Eliot, Desert plains: Jour. Geology, vol. 39, p. 137, 1931. Field, Ross, Stream-carved slopes and plains in desert mountains: Am. Jour. Sci., 5th ser., vol. 29, No. 172, pp. 313-321, 1935.

[73] Bryan, Kirk, The formation of pediments: 16th Internat. Geol. Cong. Rept. 1933, vol. 2, p. 772, 1936.

by Bryan,[74] the alluvium at No. 1 well (Childs Siding) is 173 feet deep, and at Childs well, 7 miles farther south, it is at least 820 feet deep, for the well apparently did not reach bedrock. So great a depth of alluvium at Childs well is inconsistent with the idea that bedrock there is a buried part of the pediment that borders the Little Ajo Mountain to the west. The easterly projection of the pediment along Darby Arroyo at its maximum slope would intersect Childs well at a depth of not more than 400 feet, so that even allowing for a suballuvial bench convex upward, as postulated by Lawson,[75] the reported depth of alluvium is much too great to allow the suballuvial bench to extend this far. This deduction must, however, be qualified, because the driller's log of Childs well may not have distinguished Locomotive fanglomerate from alluvium. If this is so it is possible that part of the great thickness reported as alluvium may be fanglomerate, and the pediment may intervene between them. Be this as it may, it is difficult to avoid the inference from the known faulted structure of the area, the wide extent of the alluvial deposits in the Papago country, and the almost complete integration of drainage that the alluvium is not simply a veneer over a sub-alluvial bench but, in some places at least, fills structural basins below the local base level attained by the streams.

Widespread shallow dissection of the deposits throughout the Papago country[76] and the continuous drainage lines show that the fans are not essentially below grade and that the detritus now being brought onto the bajadas by the mountain streams is approximately in balance with the material removed by the exterior drainage. The present bajada slopes, therefore, are determined by transportation rather than deposition of material.

The material composing the alluvial deposits has a considerable range in size. Near the mountains, pebbles as much as 3 inches in diameter make up much of the alluvium, and cobbles as much as a foot in diameter are common. The grade size of the material diminishes rapidly, and about a mile from the mountains pebbles as much as 4 inches in diameter are rare. Where they do occur they tend to be in nests and local patches. Silt and sand predominate 2 miles and more from the mountains. The only noted exceptions to this rule were south of Daniels Arroyo where lava boulders 2 feet or more in diameter incompletely mantle the alluvial slopes on the east flank of the Growlers for several miles from the mountains. They are much larger than those carried by the present streams that are incised in the bajada and are probably let down by erosion from an older higher gravel or conglomerate.

[74] Bryan, Kirk, The Papago country, Ariz.: U. S. Geol. Survey Water-Supply Paper 499, pp. 179-180, 1925.

[75] Lawson, A. C., The epigene profiles of the desert: California Univ. Dept. Geology Bull., vol. 9, pp. 34-38, 1915.

[76] Bryan, Kirk, op. cit., p. 107 and elsewhere.

DRAINAGE

The drainage of the Little Ajo Mountains is radial. The drainage lines all extend to the Gila River, some, such as the Rio Cornez and Copper Canyon drainages, fairly directly, others, such as Daniels Arroyo and the Cuerdo de Lena, by very circuitous routes. The course of the drainage from the Cuerdo de Lena to the Gila is very tortuous and nearly twice as long as that from the Rio Cornez. Probably none of these drainage lines are ever occupied throughout by flowing water but are maintained by local storms, and water rarely flows for more than a few hours at any one locality.

Although radial in general pattern, the streams are notable for their remarkable parallelism for distances of several miles, especially on the pediments. Even here they are dendritic on the upper slopes, but on the lower slopes the branches of the main drains extend parallel for some distance. This is especially notable west and northwest of Darby well but can be seen at many other places. In detail, the stream channels on the pediments are braided, and locally they meander. The bajadas are carved by many channels, which commonly branch and reunite, both high on the slopes and along the valley axes.

For the most part the streams are incised into both pediments and bajadas. In the bajadas the trenching is generally not more than 4 feet deep along the axial streams, and similar depths are common on the lower slopes. Practically all these trenches that are continuous from the mountains deepen upstream. Many, however, become shallow headward and die out on the bajadas within relatively short distances. At the lower ends of the demonstrable pediments the streams have commonly cut to depths of 10 feet. Locally this dissection has occurred in two stages, separated by an interval during which terraces several hundred feet wide were formed. These terraces are cut on alluvium and die out headward where they meet the pediments. Toward the upper limits of the pediments some of the larger stream trenches are as much as 40 feet deep. It must be rarely, if ever, that these deep trenches are fully occupied by water. They are valleys, not channels, and are clearly younger than the smooth gravel-coated parts of the pediment into which they are sunk. The shallower trenches of the lower alluvial slopes, however, may often be filled to overflowing, so that a braided pattern is developed.

The drainage of the west slope of the Little Ajos is notable in that from a point about 2 miles south of Salt well to a point 3 miles southwest of Chico Shunie well the alluvium and pediments are scored by shallow channels trending northwestward, whereas the major deeper trenches uniformly trend more to the west or southwest. Whether this indicates a local southwesterly tilt of the mountains, a downdropping along the south side of Daniels Arroyo of a block that probably extends northwestward beyond the map area, or some other cause, is uncertain. Downfaulting of the valley block seems more likely than tilting of the mountain block, because the straight boundary of alluvium against the wall of Daniels Arroyo would probably have been embayed if the mountain block had been tilted.

The asymmetry in the slopes on the north and south of the Little Ajo Mountains is obvious from plate 3. The streams seem to be slightly more deeply incised into the pediments on the north than they are on the south of the mountain mass, but the differences between adjacent streams in the depth of these incisions on both sides are great enough to throw doubt on the reality of a systematic difference in the depth of dissection of the two sides. If it exists, it may reflect a tilting of the mountain block, but the channel cutting does not differ greatly above and below the trace of the Little Ajo Mountain fault and thus implies that any earth movement recorded in these different slopes was not localized along this fault.

ORIGIN OF THE PEDIMENTS

The processes recognized as active in the formation of pediments include lateral corrasion by streams, rill wash, and the weathering of slopes with removal of debris by rills.[77] Doubtless other factors, such as sheet floods,[78] are also involved, but recent students of these surfaces have concerned themselves principally with the relative efficacy of the processes enumerated.[79] Paige was inclined to emphasize the work of lateral planation by streams in the production of pediments, an idea that had been developed by Gilbert[80] as long ago as 1877. This is also the view of Johnson, who declared that certain deductive reasoning, not detailed in the papers cited, required that, if pediments be primarily the work of lateral planation, they should characteristically be fan-shaped rather than trough-shaped; in fact, the absence of a fan shape would be a strong argument against origin by stream planation. Blackwelder and Field, though advocates of lateral planation by streams as the major process in pedimentation, do not find the pediments to be fan-shaped, as a general rule, but apparently regard their concavity as no argument against origin by planation. Lawson evidently considered rill wash as the dominant process in pedimentation but is not explicit in the matter. Bryan, though emphasizing the effects of unconcentrated rill wash, recognized lateral planation as especially effective at and below the mouths of the major canyons. His observation was, however, that the pediments have lower angles opposite larger streams than opposite smaller ones and that they are still steeper in the interstream areas,[81] thus being generally concave upward rather than fan-shaped. He regarded the common lack of meanders in the streams as showing that lateral planation does not dominate in forming the pediments. This is evidently Davis' view also. Rich[82] regards unconcentrated rills as the principal factor in pedimentation but reasons that pediments should be fan-shaped even on this theory, the exact antithesis, apparently, of Johnson's conclusion.

As summarized on page 62, the pediments of the Little Ajo Mountains are chiefly trough-shaped, but one is definitely fan-shaped and two may be. For the most part their upper sections with dendritic drainage are concave, and their middle sections with braided streams are probably nearly flat transverse to the stream courses.

Whatever the factors involved in the production of the pediments, it seems worth while to emphasize that here, at least, they have not been developed on the massive basaltic andesite flows of Black Mountain, Childs Mountain, and Batamote Mountain. The development of pediments is apparently conditioned by the lithologic character of the terrain, the softer and more readily disintegrated rocks forming more extensive pediments than the harder and more resistant rocks. Although the flows of Black Mountain are clearly older than the pediment of Darby Arroyo, no pediments are cut on them. Their physiographic development is generally youthful, whereas the pedimented mountains are all maturely dissected. Pediment development is probably conditioned by the same factors that control this difference in stage of the physiographic cycle in the adjacent mountains. The only apparent factor that might explain this contrast in physiographic stage is the size of the fragments yielded by weathering of the rock masses involved. Bryan, following Lawson, has pointed out the correlation between the average size of rock spalls and the average declivity of mountain slopes. It seems that this factor may also control the slope and hence the degree of perfection of the pediments. Lawson[83] has recognized that granitic rocks, which disintegrate to individual grains, furnish gentler slopes than other hard rocks in the desert. Obviously this slope angle is a measure of the relative rapidity with which physiographic evolution proceeds on the several parts of a heterogeneous terrain, and since pediments rep-

[77] Bryan, Kirk, The Papago country, Ariz.: U. S. Geol. Survey Water-Supply Paper 499, p. 96, 1925.

[78] McGee, W. J., Sheetflood erosion: Geol. Soc. America Bull., vol. 8, pp. 87-112, 1897.

[79] Paige, Sidney, Rock-cut surfaces in the desert ranges: Jour. Geology, vol. 20, pp. 442-450, 1912. Lawson, A. C., op. cit. Bryan, Kirk, op. cit. Davis, W. M., Rock floors in arid and humid climates: Jour. Geology, vol. 38, pp. 1-27, 136-158, 1930; Granitic domes of the Mohave Desert, Calif.: San Diego Soc. Nat. History Trans., vol. 7, pp. 211-258, 1933. Blackwelder, Eliot, Desert plains: Jour. Geology, vol. 39, pp. 133-140, 1931. Johnson, D. W., Planes of lateral corrosion: Science, new ser., vol. 73, pp. 174-177, 1931; Rock planes of arid regions: Geog. Rev., vol. 22, pp. 656-665, 1932; Rock fans of arid regions: Am. Jour. Sci., 5th ser., vol. 23, pp. 389-416, 1932. Field, Ross, Stream-carved slopes and plains in desert mountains: Am. Jour. Sci., 5th ser., vol. 29, No. 172, pp. 313-321, 1935. Rich, J. L., Origin and evolution of rock fans and pediments: Geol. Soc. America Bull., vol. 46, pp. 999-1024, 1935. Rich uses the term "sheet wash" in a way that appears to make it synonymous with "rill-wash" as used by Bryan.

[80] Gilbert, G. K., Report on the geology of the Henry Mountains: U. S. Geog. and Geol. Survey Rocky Mtn. Region, pp. 126-133, 1877.

[81] Bryan, Kirk, op. cit., p. 96, 1925.

[82] Rich, J. L., Origin and evolution of rock fans and pediments: Geol. Soc. America Bull., vol. 46, p. 1011, 1935.

[83] Lawson, A. C., The epigene profiles of the desert: California Univ., Pub. Geology, vol. 9, p. 45, 1915.

resent mature or later stages in the arid cycle, they are commonly better developed on granitic rocks and soft sedimentary rocks than on other varieties.

Bryan's careful descriptions of 79 mountain masses in and near the Papago country, more than 45 of which contain Tertiary volcanics (many of which must include massive lava flows), mention no pediments carved on this sort of rock. Wherever the pediments are well enough developed to be worthy of comment, they are reported to be cut on "gneiss," "granite," "Teritary sediments," or on heterogeneous volcanics.

Cross sections of the pediment transverse to Darby Arroyo reveal a consistent shallow trough shape. This, of course, is what would be expected inside the mountain mass, but, as the further development of this pediment must lead to isolation of several groups of hills from the main mountain mass and will eventually leave them as "islands" on the pediment, it seems fair to conclude that well-graded pediments can be trough-shaped for long distances and even that a trough shape is their usual form. As there is only one, or perhaps two, of the more than 20 radial streams of the Little Ajo mass that shows a fan-formed segment of the mountain pediment, it seems likely that fan forms are not characteristic of frontal pediments either. To whatever extent this fact is inconsistent with the dominance of lateral planation in pedimentation, as Johnson asserts, doubt is thereby thrown on the necessity of that process.

The local relief of the pediments increases notably headward. This increase means, of course, that the surface defined by the interstream summits—the "dissected" pediment—is still more markedly concave than the surface defined by the stream channels of today. The present streams, then, are flowing on lower gradients than those marked by the interstream surfaces, and if the pediment were molded by stream meandering one might reasonably expect the present streams to be widening their valleys by meandering. Generally, the streams on the pediments meander only locally. Commonly their channels are braided. This condition of course does not bear any necessary relation to the stream habit at the time the pediment was being formed, and the present habit may not be the one they had when the interstream surface was made. Nevertheless the rounding of the divides between secondary, tertiary, and smaller tributary streams, the fine texture of the drainage toward the heads of the pediments and the coarser texture downstream, the patchy distribution of gravel, and the common exposures of bedrock on the interfluves, all throw doubt on the necessity of postulating a former meandering habit of the streams. In the same measure, there is doubt that the pediment surface was smoothed chiefly by the lateral corrasion of the streams.

In fact, the obvious effectiveness of tributary streams and rill wash in lowering the surface at present raises tentative questions: Is it necessary to postulate a change in climatic cycle to account for the "dissection" of the pediments? If, as seems clear, the interstream areas, at least near the heads of the pediments, are today being lowered chiefly by tributary streams and rill wash, may one not suspect that the pediments were, so to speak, "born dissected?" If, as appears from the literature, no undissected pediments are definitely known, is it simply because they are concealed beneath a veneer of gravel? One may grant that it is difficult to mark a boundary at the junction of pediment and bajada and also that the streams in this boundary region meander to some extent or perhaps even widely. Nevertheless, if the present topography gives a clue to the formerly planed surfaces, gravels were by no means continuous on them prior to their dissection. The gravel in the area along Darby Arroyo is very patchy on the even interfluves themselves. (See pl. 20.) Is it necessary, then, to conclude that pediments are smoothed and traversed laterally by freely wandering streams?

If they are so traversed, one might reasonably expect the "planes of lateral corrosion" to narrow, possibly very notably, where hard rocks were encountered. One would expect, however, at least rudimentary planation of even very massive rocks. Instead we find, not exceptionally but almost universally, that blocky lavas are not even notched by the pediment surface, although adjacent granitic and clastic rocks have been lowered hundreds or thousands of feet. The relations are such as might be expected if the streams were primarily agents of transportation rather than abrasion and are indeed, such as to suggest that lateral planation, which prevails just above the bajada boundary, does little more than smooth the few remaining irregularities on a surface already far advanced toward a plain. Surely this is the suggestion from the relations along Darby Arroyo, and, though the fan-shaped pediment of Gibson Arroyo may record greater lateral planation at an earlier stage in pedimentation, higher up the slopes, the Gibson Arroyo fan is unique in the quadrangle. In other regions the relations may of course be reversed, but for this district I am much more impressed with evidence of the effectiveness of rill wash and weathering than with that of lateral planation in pedimentation.

Bryan[84] has, however, concluded, largely from studies in New Mexico and eastern Arizona, that lateral planation is relatively more effective during youth and maturity, whereas rill wash and weathering are more effective during old age. This rather startling conclusion does not seem to be borne out by the relations at Ajo, at least if one regards pedimentation in a local area as the old-age stage. If a larger area is considered, so that the existence of mature mountains at the head of the pediment is suffi-

[84] Bryan, Kirk, The Papago country, Ariz.: U. S. Geol. Survey Water-Supply Paper 499, p. 10, 1935.

cient to characterize the physiographic stage as mature, it might be accepted, but it is not positively supported by the facts known to me.

This inference as to "original" dissection of the pediments must be qualified, at least in part. The topographic contrast between interfluves and arroyo walls at the lower ends of the pediments is too great to represent equilibrium. There most probably has been, as Bryan suggested, a change in the stream regimen since these parts of the surfaces were formed. However, the topographic contrasts become less and less upstream, and the upper portions of the pediment, though still sharply divisible from the mountains, are occupied by slopes transitional from the interfluves to the tributary streams. Palo verde trees that grow in some of the stream channels high on the pediments north of the Little Ajo Mountains are as much as 3 inches or more in diameter. The annual accretions of the palo verde are visible only with a hand lens.[85] These trees must be scores if not hundreds of years old and show the "dissection" of the upper pediment to be very old in years. There is no evidence for dating the sharp dissection farther downstream, but it seems far younger. It seems possible that the upper parts of the pediment attained essentially their present form while the lower parts were still smooth surfaces.

Whatever the cause of the "dissection" of the pediments in the Ajo quadrangle, it cannot be referred to lowering of local base level. The channel of Rio Cornez has been sunk little if any below the constructional surface at the pass between Batamote and Childs Mountains, and the channels that score the bajadas are in general very shallow, although the pediments at their heads may be dissected to depths of 40 feet or more. The tributaries of the Cuerdo de Lena show similar incision into the pediments but practically die out as definite streamways before joining the shallow master channel. These features are general in the Papago country and have been interpreted by Bryan[86] as results of an increase in the available water in the streams in proportion to the available sediment and therefore not due to change in base level. The lowering of base level shown by terraces along the Gila, San Pedro, and other large streams of southern Arizona has not been felt in the Ajo region. Bryan's conclusion that the widespread dissection of pediments implies a climatic change from a somewhat drier to a somewhat wetter period seems reasonable, at least insofar as it refers to the lower parts of the pediments. As he mentions, this dissection does not necessarily imply that the present is a wet period, but simply that the last climatic change effective in altering the stream regimen was in the direction of greater humidity; however, one may doubt that all the dissection is due to this change. Much of it may have gone on along with the planation of lower parts of the pediments. The degradation of arid regions, like that of humid regions, need not lead to a completely smoothed surface even in old age. Surfaces far advanced in the erosion cycle may still proceed farther in their evolution by general slope wash, rill transportation, and resulting continual regrading of the surface.

Baker[87] has pointed out that after maturity has been reached there is a continual decrease in supply of material to the streams, so that they should normally cut down their channels without any necessity for a climatic change. It is possible that this is the true explanation of the dissection in this region, because, as has been pointed out, the pediments are confined to the fronts of sierra-type (mature) mountains.

The abrupt change in declivity of the surface at the junction of mountain slope and pediment has been stated by Field[88] to be inconsistent with the idea that rill wash is a dominant process in pedimentation. If, however, as suggested by Davis,[89] who follows Lawson and Bryan, the pediment gradient is conditioned by the minimum slopes on which the detritus can be transported and the mountain slopes by the angle of repose of blocks acted on almost solely by gravity, there seems no necessity for the two slopes to merge more than they actually do. Davis has pointed out that this contrast in angle of bedrock slopes exists in humid regions also and is there masked by soil creep, a factor that is less effective or absent in arid regions. The absence of pediment at the foot of massive lava mountains and the commonly gentler transition that they exhibit from mountain slope to bajada seem to accord with this concept. The widespread existence of basin-shaped pediments on granitic rocks that break down to individual grains is a strong argument for the efficacy of rills in molding the pediments.

The efficacy of rills and slope wash in the arid regions is much greater on the average than in humid regions, for, although the weathering in humid regions commonly yields finer-grained detritus, the vegetation cover hampers the rill work relatively much more. This fact doubtless outweighs the factors of grain size and available water, for erosion surfaces in arid regions are almost everywhere farther advanced than are erosion surfaces of comparable geologic age in humid regions.

Nothing that I have seen in the Ajo quadrangle appears inconsistent with the conclusions of Bryan that pediments are slopes of transportation peculiar to arid regions and are formed by a combination of lateral corrasion, rill wash, and weathering, with subsequent removal of detritus

[85] Shreve, F., Establishment behavior of the palo verde: Plant World, vol. 14, p. 292, 1911.

[86] Bryan, Kirk, op. cit., pp. 63-65, 1922.

[87] Baker, C. L., Notes on the later Cenozoic history of the Mohave Desert region in southeastern California: California Univ., Dept. Geol. Bull. 6, pp. 376-377, 1911.

[88] Field, Ross, Stream-carved slopes and plains in desert mountains: Am. Jour. Sci., 5th ser., vol. 29. No. 172, pp. 317, 321, 1935.

[89] Davis, W. M., Rock floors in arid and humid climates: Jour. Geology, vol. 38, p. 149, 1930.

by rills. One process may dominate in one place and another elsewhere, but all are operative.

GEOLOGIC HISTORY

The geologic history of the Ajo region is full of uncertainty. The ages of all the formations are only indirectly known, and the mutual relations of some are so open to question that any summary statement of the geologic evolution of the area must be either arbitrary or discursive. As I have tried to point out the quality of the information at hand in the preceding sections of the report, it seems preferable to refer to those sections for discussion of the uncertainties and here assume them all to be resolved in favor of the conclusions tentatively arrived at in those sections. With this assumption in mind, the reader will not, I hope, lay too much stress on the ages ascribed to the several events in the decipherable history, for, although their sequence is somewhat better established, even this aspect of the history is open to more questions than can here be adequately discussed.

The decipherable history opens in pre-Cambrian time with the intrusion of a quartz-dioritic mass into an unknown country rock, perhaps a quartzose sedimentary rock. Later, during pre-Cambrian time, this quartz diorite (the dark matrix rock of the oldest facies of the Cardigan gneiss) was sheared by mountain-making movements into thinly laminated gneiss. Perhaps during this same period of crustal disturbance, perhaps later, this laminated rock was intimately injected by many small tongues, layers, and veins of quartz diorite. The material was dominantly controlled by the preexistent foliation but also broke across it and in places formed highly-contorted cross-cutting veins in the gneiss. The rock must have been so softened that the whole formation was able to flow viscously. This produced the rock now represented by the Cardigan gneiss.

Somewhat later, though still in pre-Cambrian time, there were minor intrusions of hornblendite, chiefly in pipelike bodies. Erosion through a long period reduced the mountains, in whose depths these intrusions had occurred, to a surface of low relief or even to base level. This surface was then depressed beneath the sea in Paleozoic time. When the submergence began is unknown, but it was probably pre-Devonian, because the marine Martin limestone was deposited to within a relatively short distance of, if not within, the Ajo area. Submergence persisted, with or without interruptions, through Pennsylvanian time.

There is no known record of the early Mesozoic, and presumably the Ajo region was then a land area. Certain lava flows, now represented by inclusions of hornfels in the Chico Shunie quartz monzonite, may have been erupted at this time, but it is equally likely that they are Paleozoic. Possibly it was in early Mesozoic time that the Chico Shunie quartz monzonite invaded the older rocks. That this intrusion occurred in the depths beneath a considerable thickness of rocks is suggested by the equigranular habit and slight diminution of grain size at the borders of the intrusive mass. The invasion probably followed rather than accompanied a period of mountain making, for the general occurrence of hornfels rather than schist at its borders is a strong argument for its quiet emplacement. After the consolidation of the Chico Shunie mass, mountain-making compressive forces again acted on the region, with accompanying permeation of the rocks by hot waters. This deformation was not so extreme as to induce regionally oriented foliation in the mass but was sufficient to crush nearly all of it in greater or less degree. It was then that the Chico Shunie quartz monzonite and Cardigan gneiss were saussuritized and chloritized.

Although this crushing probably did not occur at extreme depths, there must have been considerable erosion from the area before the land was buried by outpourings of rhyolitic and andesitic breccias, tuffs, and lava flows. These rocks, which were later silicified, chloritized, and albitized and are now represented by the quartz keratophyres and keratophyres of the Concentrator volcanics, may be of Cretaceous age. Some of the eastward-trending andesitic dikes in the areas of Cardigan gneiss and Chico Shunie quartz monzonite may have been injected at this time also, but their correlation and distinction from much younger dikes of similar composition have not been satisfactorily established. The chloritization, albitization, and silicification of the Concentrator volcanics probably occurred soon after their eruption. At least this alteration largely antedated the intrusion of the Cornelia quartz monzonite, which presumably took place in early Tertiary time.

The Cornelia intrusion probably took place under a moderate cover of rocks after folding and perhaps faulting of the Concentrator volcanics. It is possible, indeed, that the Cornelia quartz monzonite and Concentrator volcanics represent the same magmatic cycle. The disregard of older structures by the intrusive, the absence of wall-rock structures concordant with its contacts, and the sporadic preservation of fine-grained (chilled) border facies indicate that the intrusion took place at a relatively shallow depth. The weakness of lineation in the rock indicates that there was little motion in the magma at late stages of its consolidation. After its consolidation, however, it was fractured along westward-trending fissures, and aplite dikes were injected in large quantities. Northward-trending fractures followed and were occupied by pegmatites in the apical part of the stock. Orthoclase was formed in large amount and as large crystals near these pegmatites, and in these areas solutions permeated freely. At later stages they chloritized and sericitized the rocks of the apical part of the stock and deposited the cupriferous and associated metallic minerals of the New Cornelia ore body.

After the mineralization of the Cornelia quartz monzonite, there was a period of dike injection. The dikes of feldspathic andesite porphyry were injected along eastward-trending fissures. Probably some of the hornblende andesites followed rather closely, for their trends are closely parallel and they show some curvature that may well be due to drag along the Gibson fault.

Probably still in early Tertiary time there came a period of faulting. The northward-trending Gibson fault was formed, slicing off the apex of the Cornelia quartz monzonite stock, the part containing the known ore bodies, from the lower-lying portion to the west. This fault threw the eastern block down with reference to the footwall block for several thousand feet. Long-continued erosion followed and removed much of the overlying rock from the ore deposit. It also planed off the wall of the Gibson fault so that the break was not topographically expressed. The copper minerals brought near to the surface by this erosion were oxidized and leached by percolating rain water. In large part they were dissolved and carried downward by the ground water to the water table, where much of the dissolved copper was precipitated on the sulfides, thereby forming a thin zone of relatively enriched ore beneath a barren or impoverished capping. Apparently this leaching and supergene enrichment was general over the entire ore body.

After this long-continued erosion, perhaps in middle Tertiary time, strong structural disturbances occurred in the region. No particular displacement can now be definitely referred to this period, but the country was buried beneath thousands of feet of coarse alluvial fan deposits. Such material as composes the Locomotive fanglomerate is now accumulating only in mountainous regions, and the deposition of so thick a mass as the Locomotive fanglomerate can only mean active mountain making during that time. After several thousand feet of the fanglomerate was deposited and most of the terrain now occupied by the eastern end of the Little Ajos was buried beneath a thick mantle of debris, volcanic eruptions began in the area. At intervals eruptions of volcanic ash and lapilli buried the country, accumulating in greater thickness toward the southeast and lensing out northwestward against higher ground. At first these eruptions (now represented by the Ajo volcanics) were mere episodes in the deposition of the fan detritus, but eventually they furnished relatively more material and thick layers of volcanic ejecta were accumulated. These later eruptions supplied coarser breccias and andesite flows as well as fine tuffs like those of the earlier episodes. As far as shown by the accessible exposure, the eruptions closed the accumulation of the fanglomerate, though it is possible that fanglomerate deposition may have outlasted them.

Probably in late Tertiary time the region was sliced by several west-northwest-trending faults, of which the most definitely marked is the Little Ajo Mountain fault. Steep tilting of the block of the Little Ajo Mountains to the southwest of this fault took place at this time and became the first step in the evolution of the present mountain mass.

The record of this deformation is obscure, and it is possible that the Sneed andesite, whose eruption is here assumed to have followed it, may be contemporaneous with the very similar Ajo volcanics. The northeastward-trending faults near Ajo Peak were formed at this time or even earlier if the northwestward-trending fault that cuts them is of the same age as the Little Ajo Mountain fault.

The present distribution of the Sneed andesite suggests that there was further movement on the Little Ajo Mountain fault after the andesite was erupted. The detritus eroded from this uplifted block was strewn widely and is now perhaps in part represented by the Daniels conglomerate. Presumably this is largely a stream deposit. A considerable period of erosion followed the tilting along the Little Ajo Mountain fault, as is shown by the uniformity in width of the dikes and in the grain size of the Hospital porphyry dikes over a long north-south distance. These features would be difficult to reconcile with an assignment of a post-Hospital age to the Little Ajo Mountain fault. The dikes of Hospital porphyry and presumably the flows of the very similar Childs latite were erupted after this long erosion interval, and the dikes may fill the channels along which the latite rose.

Probably in Pliocene time the eruptions of latite were followed, perhaps without a significant break, by those of Batamote andesite. The source of these andesites is largely unknown, although there were probably small contributions from two vents near the north end of Childs Mountain and probably much larger eruptions from the Batamote Mountains. Many hundred feet of these flows accumulated.

Pliocene time probably ended with an episode of faulting along lines of northerly trend. The Chico Shunie-Black Mountain fault system, as well as the fault along the west base of Childs Mountain was probably formed at this time. This faulting, like the earlier, disturbed the drainage system of the region. The area was cut into blocks that were partly depressed to form basins and partly upifted to form mountain masses. Detritus from the erosion of the higher blocks was washed into the basins so that thick accumulations of gravel were formed in them. At the same time the mountains were cut down and some of the fault scarps turned into fault-line scarps with relief reversed from that originally given by the fault movement. Pediments were formed at the foot of the mountains and extended headward along the belts of softer rocks. Eventually the drainage was integrated, although the roundabout wanderings of some of the present streams suggest that this integration is only a relatively late development. Minor faulting with northerly trends probably occurred during this stage of erosion. Perhaps the latest event has been a shift to a somewhat less-arid climate, which has brought about incision of the streams into the pediments.

It is notable that the latest erosion cycle has not operated under conditions favorable to the enrichment of ore deposits. The sulfides have been oxidized essentially in place, contrary to their behavior in the cycle prior to the Locomotive fanglomerate.

ROCK ALTERATION

PROCESSES

Nearly all rocks, as exposed at the earth's surface, have undergone at least some alteration after consolidation. As the processes operating to bring about these changes are generally either too sluggish to be measured or are inaccessible to observation, classification is wholly deductive. If they are inferred to occur below the zone of atmospheric influence they are called metamorphic, if within that zone they are called weathering. Both kinds of alterations have necessarily been discussed in the descriptions of the rock formations and the structural evolution of the area. It is the purpose in this section to bring together the data from the standpoints of the time of alteration and the operative processes, rather than of the rock formations affected, in order to see what can reasonably be inferred as to cause and localization of the alteration. The bearing of these factors on the origin of the ore deposits is the principal aspect of the study, but, in order to isolate the effects of this episode, the effects of alterations not related to ore deposition in the area must be evaluated also.

The processes grouped as metamorphic have been generally considered by geologists under two main heads: dynamic, or those resulting primarily from dislocations in the earth's crust, and igneous, or those brought about by the heat and fluid emanations from igneous intrusions. This is admittedly a crude division, but it serves to focus attention on the relative importance of deformation under the influence of directed stress and recrystallization and formation of new minerals under the influence of magmatic emanations. Rocks far from directly known igneous intrusives have commonly undergone some recrystallization of the minerals already present, either with or without the accompanying formation of new minerals, and hence must have been permeated by solutions, even where deformation was clearly preeminent in producing their outstanding features. Some geologists would regard all such solutions as magmatic, but probably most would admit that water originally present may have brought about the alteration of some rocks. As the contacts with igneous masses are approached these effects of alteration commonly become more evident and the igneous source of the effective solutions more certain, but the precise point where the contribution of igneous emanations exceeds the contribution of dynamic processes in giving the rocks their present stamp is entirely a subjective matter. The classification, however, is broadly useful and is adopted insofar as it seems applicable for the purpose of this section.

Weathering involves the decomposition and leaching of rocks and ores and the formation of new, characteristic minerals in them at and near the earth's surface. In the arid climate of the Ajo region its effects upon most of the rocks are not striking. In the ore body, however, weathering has profoundly modified the sulfide minerals above the water table and has almost completely transformed them into carbonates, silicates, and oxides.

METAMORPHISM OLDER THAN THE ORE DEPOSITION

METAMORPHISM OLDER THAN THE CHICO SHUNIE QUARTZ MONZONITE

Metamorphism prior to the emplacement of the Chico Shunie quartz monzonite was both igneous and dynamic. The igneous metamorphism seems to have resulted from magmatic injections under conditions of high mobility of the rocks. Essentially pure dynamic metamorphism brought about the refoliation of the Cardigan gneiss and possibly occurred still earlier, before the injection metamorphism.

EARLY DYNAMIC METAMORPHISM OF THE CARDIGAN GNEISS

The oldest planar foliation of the Cardigan gneiss, recognizable in only a few places, has been interpreted as the product of dynamic metamorphism of a quartz dioritic intrusive. The subsequent alteration that the rocks have undergone renders fruitless any attempt to evaluate the conditions under which this obscure metamorphism occurred. There is a possibility that the foliation is primary and records flow of a quartz diorite magma in the stage just prior to its consolidation, or even, though this is less likely, a sedimentary stratification that has been partly preserved despite thorough recrystallization. (See p. 14.)

INJECTION METAMORPHISM OF THE CARDIGAN GNEISS

The large-scale structural and the microscopic features of the Cardigan gneiss unite to give clear evidence of the profound modification of the rock through the most intensive igneous injection. The darker older facies, whatever its previous history, was injected by lighter gray porphyritic rocks in dikes and veinlets that range in size from rare masses 30 or 40 feet across down to the limit of microscopic vision. There is a marked tendency for these veins and dikes to lie parallel to the foliation, but many veins crosscut the foliated structure. The crosscutting veins were obviously formed after the foliation process had ceased and the gneiss had become sufficiently rigid to be fractured. As noted on page 14, the chemical composition of the veins, both those along the foliation and those across it, does not accord with an assumption that they were locally derived; they are almost surely of a source outside the rock in which they are now found.

In addition to the mechanical disruption of the preexistent gneiss by this injection, there are strong suggestions of considerable replacement of the older rock by newly introduced material. The obscure gradational boundaries of many of the veins, such as are illustrated on plates 4, *B, C, D, E, F,* 5, *A, B, C, D, E,* and the occurrence of isolated masses of quartz and feldspar in the matrix rock, strongly suggest the effectiveness of replacement during metamorphism.

The contortions of the veins, in large measure independent of the enclosing rock (see pl. 4, *B, E, F*), seem to indicate that a high internal hydrostatic pressure enabled them to seek and take advantage of the paths of least resistance through the rock. The rock, though inhomogeneous, retained its essential integrity throughout the process.

All these features combine to show that at the time of metamorphism the rocks were thoroughly permeated by magma and its more tenuous emanations and were thereby heated in the presence of solvents and rendered highly plastic. In this condition, the whole formation was doubtless almost as mobile as magma, though the retention of residual older structural details indicates a difference in viscosity between matrix and injected magma and differences in viscosity within the matrix rock itself.

The present mineral composition of the Cardigan gneiss is not consistent with its having been formed during injection metamorphism. The minerals common under conditions of such intimate magmatic penetration are plagioclase of intermediate composition, hornblende, biotite, quartz, and microcline, which are the common constituents of igneous rocks. The Cardigan gneiss locally consists of these minerals, but in general the plagioclase is albitic and crowded with sericite and epidote, and the only dark mineral commonly present is chlorite. These minerals are also found in the Chico Shunie quartz monzonite, which does not have the character of an injection gneiss, and in both formations they are attributed to a younger metamorphism to be described below. The injection metamorphism of the Cardigan gneiss is inferred entirely from the structure shown by bands of different composition rather than from its mineral composition alone.

The magmatic mass whose tenuous forerunners so intimately penetrated the Cardigan gneiss is not exposed in the Ajo quadrangle, nor is there apparently any recognizable tendency for the injection phenomena to increase or be more prominent in any given direction. Experience in more widely exposed areas of injection metamorphism suggests that a large intrusive body should be found somewhere in the vicinity, but there is no clue as to the direction in which it lies. It is clear, however, that the injection metamorphism long antedates the intrusion of the Chico Shunie quartz monzonite, for that intrusive cuts the foliation and injected veins quite indiscriminately, although the numerous blocks of hornfelsed gneiss contained in the Chico Shunie do not seem to include much injection gneiss.

DYNAMIC METAMORPHISM OF THE INJECTION GNEISS

There is clear-cut evidence of the dynamic metamorphism that is shared jointly by the Cardigan gneiss and the much younger Chico Shunie quartz monzonite (see pp. 14-15, 19), but locally there are suggestions that the injection bands of the gneiss were systematically refoliated before the Chico Shunie stock was intruded. This reworked foliation ("Umfaltungsclivage") is illustrated on plate 5, *D, E.* As is evident from these illustrations, the injection banding has been systematically cut by miniature faults, along which the banding is so curved as to suggest drag during the displacement. This structure clearly records systematic shearing of the rock masses past each other along rather closely spaced surfaces. It seems to illustrate the "gliding-board" movement described by Schmidt,[90] in which layers of rock move relatively to each other as do the cards of a deck that is pushed laterally on top while resting on a table. This type of deformation, which is being more and more widely recognized in metamorphic areas, is most clearly recorded where the new shear surfaces make notable angles with older parallel layers ("s-planes").

The deformation of this period was not sufficiently widespread to give a systematic new foliation to the entire mass of the Cardigan gneiss. Probably it chiefly involved relative movement of rather large crustal blocks rather than penetrative movement that extended down to sufficiently small rock units to be recorded in widespread refoliation. Mapping was not sufficiently detailed to work out any system that might exist among these few zones of refoliation, so that it is impossible to refer them to any particular orientation of motion. The new shear surfaces that cut the injection banding of the gneiss are coated by muscovite plates but show no associated brecciation though possibly a slightly finer average grain size. They therefore antedate the metamorphism that affects both Chico Shunie quartz monzonite and Cardigan gneiss but are later than the injection metamorphism.

METAMORPHISM ACCOMPANYING THE CHICO SHUNIE INTRUSION

The metamorphism that appears to have been genetically connected with the emplacement of the Chico Shunie quartz monzonite was almost wholly igneous. The Chico Shunie intrusive engulfed innumerable large and small blocks of the Cardigan gneiss and of a bedded series of rocks and largely altered them to hornfels. (See pp. 16-18.) A little schist is locally developed at the contact of the largest inclusions, thus showing that differential motion

[90] Schmidt, Walter, Tektonik und Verformungslehre, Gebrüder Borntraeger, Berlin, 1932.

did occur, but for the most part the metamorphism was governed by the heat and solutions of the magma. Large crystals in the included lavas were recrystallized to aggregates, and new plates of mica and chlorite and round grains of quartz and plagioclase were formed at random orientations through the rocks, destroying or obscuring the details of the preexisting textures. It is likely that this metamorphism was not accompanied by much transfer of material from magma to inclusion, for the chemical composition of both the hornsfelsed gneiss and bedded rocks conforms essentially with their nonhornfelsed analogs. Similar alteration does not seem to have been very widespread along the main contacts between large bodies of Chico Shunie quartz monzonite and Cardigan gneiss. This condition also suggests that recrystallization was primarily effected by heat rather than transfer of material, because the small inclusions completely immersed in the magma would be expected to be more thoroughly heated than the large masses of rock along the contacts, whereas transfer of material in solution would be expected to be more effectively guided by penetrability of the rock than by the size of the rock mass. In many districts metasomatic alteration has occurred along veins and zones far from the igneous contact, but no such features appear to be related to the Chico Shunie quartz monzonite.

METAMORPHISM YOUNGER THAN THE CHICO SHUNIE QUARTZ MONZONITE AND OLDER THAN THE CONCENTRATOR VOLCANICS

In the description of the Chico Shunie quartz monzonite it was pointed out that this formation, in common with the Cardigan gneiss, is characterized by widespread brecciation and cataclastic texture. Both formations, too, contain predominantly saussuritic plagioclase, accompanied by chlorite and epidote, rather than biotite, hornblende, or pyroxene, which are the original ferromagnesian minerals commonly present in unaltered monzonitic rocks. There are two strong reasons for believing that the metamorphism recorded by these features long antedated the somewhat similar metamorphism sporadically represented in and probably genetically connected with the Cornelia quartz monzonite: (1) the brecciation is much more widespread than in the Cornelia quartz monzonite and is as well developed near Cardigan, where the Cornelia stock is entirely unbrecciated and mineralogically unaltered, as it is in other localities in which the Cornelia quartz monzonite shows the same type of alteration, and (2) close to the contact zone of the Cornelia quartz monzonite, the cataclastic gneiss has been changed to andesine-hornblende hornfels, which shows no effects of brecciation, evidently because of "healing" by the crystallization of new minerals, for cataclastic textures are found only a few feet from the contact.

Although the altered parts of the Concentrator volcanics also contain much albite, chlorite, and epidote, they lack the widespread cataclastic texture of the older formations. In the partly saussuritized and chloritized facies of the Cardigan gneiss and Chico Shunie quartz monzonite there are residual masses that consist mainly of intermediate plagioclase, hornblende, or biotite but that are saussuritized and chloritized along surfaces of shear and brecciation. It is concluded, therefore, that the brecciation and alteration that gave the Cardigan gneiss and Chico Shunie quartz monzonite their present characters occurred prior to the extrusion of the Concentrator volcanics.

In both these older formations the widespread brecciation was apparently not systematically oriented, and no regular foliation was imposed on the rocks. It is likely, therefore, that regional movements did not involve marked differential motion in them; nevertheless, as the two formations were almost everywhere brecciated, the fracturing seems to have resulted from regional crustal disturbance. That solutions began to circulate while fracturing was still in progress is shown by the occurrence of local patches of recrystallized rock with marked foliation and parallel orientation of the constituent minerals and by the lack of marked contrast in grain size between the cataclastic portions and the undeformed remnants of both formations.

The new minerals formed by this process are those of the "green schist facies." Elsewhere this assemblage results from mild metamorphism under dominantly static and hydrothermal as well as dominantly dynamic conditions. The small areal exposures of the formation exhibiting this kind of metamorphism and the apparent uniformity of it throughout the area give no adequate basis for determining much about its cause or extent.

It is possible that the solutions originated at a lower level in the Chico Shunie intrusive in the way that is postulated for the more localized solutions that altered the Cornelia quartz monzonite, but the analyses of Cardigan gneiss do not show notably high water content, and it may be that the solutions were mostly local to the rocks being altered and not introduced from without. The present water content of the rocks is consistent with a higher-grade metamorphic assemblage than the present one. If the water in both formations is indeed indigenous, the metamorphism must be regarded as essentially dynamic.

The few narrow bands of coarse-grained pink gneiss with well-rounded porphyroblasts of pink feldspar that occur in the Chico Shunie quartz monzonite have been interpreted as blastomylonites, that is, partly recrystallized rock along zones of crushing. (See p. 19.) They may represent localized zones of marked displacement that accompanied the cataclastic metamorphism of the rest of the formation. The porphyroblasts grew and were further abraded during the deformation. These partly recrystallized crushed rocks may have been formed later than the "random" crushing, but, as they show some cataclastic as well as crystalloblastic texture, there is no reason for thinking so other than their marked localization. If they were formed at the same time as the "random" crushing, it would prove that the crushing was due to regional deformation; however, on this assumption more of a transition from the blastomylonites to the mass of the formation would be expected. If these zones are younger than the "random" crushing, still another period of metamorphism, clearly dynamic, must be postulated.

PRE-CORNELIA METAMORPHISM OF THE CONCENTRATOR VOLCANICS

Almost throughout their area of exposure, the Concentrator volcanics contain some sporadic andesine or oligoclase, although their dominant feldspar is albite. The more calcic feldspars are interpreted as residual, and the rocks are accordingly believed to have been albitized. In places along the contact of the Cornelia quartz monzonite the dominant feldspar of the volcanics is andesine and the texture granulitic. Away from the contact, in the neighborhood of the New Cornelia ore deposit, the feldspars are albitic and the formation is highly sericitic and cut by veins of metallic minerals. The distribution of albite is much more widespread than the zone of intense sericitization and metallization and is, in fact, practically coextensive with the formation. It seems probable, therefore, that the widespread alteration of the volcanics is another example of albitization such as is common in many other areas of keratophyres not apparently connected genetically with ore deposition, and that the conversion to hornfels and the sericitization near the New Cornelia ore body may have been superposed on a series that had previously been largely albitized.

This is a speculative matter and one upon which it is difficult to obtain any definite clues, because, except for the locally more intense sericitization near the ore body, the two possible periods of metamorphism have produced the same kinds of changes in the rocks. The plagioclase in the hornfels, however, appears to be of the same composition and has remnants of the same zoning as the rare andesine in the rest of the formation, and there is no sign of reversed zoning such as is common in metamorphic aureoles. There is thus no reason to believe that the hornfels was developed from previously albitized lavas, and, as the sericitization and albitization of the Cornelia quartz monzonite are like that in the volcanics, the areal distribution of the metamorphism furnishes the only reason for believing that it occurred in two periods, separated by the intrusion of the quartz monzonite. The permeability of a heterogeneous series of volcanic rocks like the Concentrator volcanics must be extremely variable. This variable permeability might account for the "spotty" albitization, yet, even so, the alteration seems difficult to reconcile with a source in the Cornelia quartz monzonite. The economic implications seem to warrant calling attention to the possible existence of a stage of alteration that affected the Concentrator volcanics before the intrusion of the Cornelia quartz monzonite and therefore not related to the period of ore deposition. The absence of brecciation seems to indicate that this pre-Cornelia albitization of the Concentrator volcanics was not of the same age and origin as that in the Chico Shunie quartz monzonite and Cardigan gneiss. It must have been essentially hydrothermal, but no particular magmatic source is definitely indicated for the metamorphosing solutions.

METAMORPHISM AND ORE DEPOSITION ASSOCIATED WITH THE CORNELIA QUARTZ MONZONITE

The metamorphism associated with the emplacement of the Cornelia quartz monzonite was of two kinds, (1) *"normal"* contact metamorphism, which involved the recrystallization of some of the bordering host rocks without essential change in bulk composition and (2) *additive* metamorphism, which involved the transfer of large amounts of material from the magma to the wall rocks and particularly to the earlier consolidated parts of the igneous mass itself. Both processes were dominantly controlled by the presence of circulating solutions; dynamic factors were at a minimum. To the second kind of alteration is due the New Cornelia ore body.

NORMAL CONTACT METAMORPHISM

The normal contact effects of the Cornelia intrusive are slight and inconspicuous. For intervals along the border, but not continuously, the Concentrator volcanics have been completely recrystallized, over a width of a few feet, to massive hornfels. Their mineral composition does not appear to have been changed appreciably unless the biotite has been increased at the expense of the hornblende, but the texture has been transformed from that of a lava to the granulitic one of hornfels in which each mineral holds inclusions of all the others and no sequence of crystallization is recognizable. The rock thereby became much tougher than the nonhornfelsed volcanics and, therefore, was not so readily altered by the additive metamorphism next to be described.

Similar alteration has operated in the Cardigan gneiss near the border of the Cornelia massif all the way to the west end of the intrusive, but no alteration of a comparable sort could be found in Chico Shunie quartz monzonite. It appears that this normal contact metamorphism was due primarily to the heat and only slightly to solutions emanating from the Cornelia intrusive, although tourmaline, lining joint cracks for some distance away from the Cornelia monzonite, doubtless records some transfer of material, perhaps in the gaseous phase. The topaz found in Cardigan gneiss near Cardigan Peak may also record minor gaseous transfer associated with this alteration, but so little of this mineral was found that it is impossible to refer it definitely to a source in the Cornelia quartz monzonite. It may perhaps have been derived from the Chico Shunie quartz monzonite. Andalusite accompanies the topaz but does not necessarily imply any transfer of material.

ADDITIVE METAMORPHISM, INCLUDING ORE DEPOSITION

The principal area of additive metamorphism in the Ajo quadrangle is in and near the New Cornelia ore body. In this vicinity the Cornelia quartz monzonite, and to a less extent the Concentrator volcanics, have been highly altered, with considerable changes in both texture and chemical composition. In part this is to be classed as self-metamorphism of the early-solidified portion of the Cornelia quartz monzonite by exudations from parts below that were still liquid; in part it is true exomorphism of the country rocks.

The modifications of the Cornelia quartz monzonite in the neighborhood of the ore body include not only changes that occurred after essentially complete consolidation of the local rock but also changes that seem, from textural features, to have taken place while the local rock was still in large part fluidal. These changes, which were late magmatic rather than truly metamorphic, seem so closely associated with the metamorphism as strictly defined, that is, postconsolidation changes, that they were almost surely parts of the same process and should be considered with it.

LATE MAGMATIC MODIFICATIONS OF THE CORNELIA QUARTZ MONZONITE

Late magmatic alterations of the Cornelia quartz monzonite are believed to be responsible for the local development of the peculiar "corroded" texture described on page 29 and illustrated on plates 13, *E, F,* and 14, *B, C.* This texture is found in notable volume only in the lobe, originally cupola, of the Cornelia quartz monzonite that contains the New Cornelia ore body. It records the corrosion of early-formed phenocrysts of quartz and plagioclase and the development of peculiar droplike crystals of quartz and orthoclase not only throughout the groundmass but through crystals of all the older minerals—sphene, plagioclase, biotite, and hornblende. This texture is found in rocks with fresh andesine feldspar near the ore body as well as in the ore body, where the plagioclase is entirely saussuritic or sericitic; hence, as would be expected from general experience, the texture was formed before the hydrothermal stage of alteration. This age of the modification is further suggested by the features illustrated on plate 15, *B,* where a zoned plagioclase crystal is seen to have its outer (originally more albitic) part replaced by orthoclase and quartz and its inner (originally more anorthitic) core reduced to an aggregate of sericite in an albitic base. Had the sericite-albite stage of alteration preceded the orthoclase-quartz replacement, it would be difficult to account for this localization of the orthoclase and quartz.

Had the corrosion of the crystals and groundmass occurred in postmagmatic time, one would expect to find the attack localized along breccia zones and fissures, and there should be less preservation of gross crystal forms of the plagioclase than is found. Within the ore body, where the alteration was indeed governed by the fissuring, the older crystals were destroyed wherever they were cut by cracks. The ore body is therefore a metamorphic product in the strict sense as the alteration affected a solid rock; but the local modification of the monzonite to the "corroded texture" above described is not controlled by these features, and, as it is uniformly developed through considerable volumes of rock, it is considered of late magmatic origin.

POSTMAGMATIC MODIFICATIONS IN AND NEAR THE NEW CORNELIA ORE BODY

After consolidation, the lobe of Cornelia quartz monzonite southeast of Camelback Mountain was shattered and cracked over a considerable area and was permeated by solutions of magmatic derivation. These produced a long series of mineral transformations and introduced much material to the rocks, resulting in the formation of the New Cornelia ore body. The metamorphism was controlled by the fracturing of the rock mass and its penetration by solutions.

The fracturing of the Cornelia quartz monzonite in the New Cornelia ore body has been extremely intimate. Attempts to work out a systematic arrangement of the fractures have been fruitless. The barren joints and cracks now visible in the ore body are not the same as those that governed the permeating solutions at the time of ore deposition and became cemented by vein minerals; however, examination of outcrops, hand specimens, and thin sections indicates that in the entire volume of the ore body, hardly a piece of rock a quarter of an inch on a side has remained unfractured, and in much of it the fractures are even more closely spaced. There is no regularity evident in the orientation of these fractures and little suggestion of much displacement along them; for the most part the rock is "crackled" rather than sheared.

This crackling, which obviously affects the Cornelia quartz monzonite and the bordering Concentrator volcanics over only a small area, must have had a highly localized cause. It is difficult to say whether it might be due to slight collapse in the roof of the cooling stock, caused by shrinkage on cooling, by shrinkage due to escape of magma or part of its volatiles from lower horizons in the stock, by volcanic explosions overcoming the pressure of the cover rocks, by "solution stoping," or by some other cause.

The localization of the pegmatitic rock and "high-grade" ore shoots along north-northwesterly zones (see plate 27, F, G) seems to show that at an early stage of the metamorphism channels of this trend were most open. However, as far as it is known at present, the shape of the ore body as a whole does not seem to show any such control. When, in imagination, the ore body is returned to its pre-Locomotive attitude, the subcircular outcrop area becomes a steeply tilted section and the present "keel-like" projection becomes a lateral offshoot at a low angle. The original shape has been so modified by erosion, however, that the present form of the ore body seems to offer no clue as to the cause of the brecciation that localized it. No suggestion of a pipelike form such as is commonly found in collapsed areas[91] could be detected.

Although it is conceivable that collapse might produce volumes of shattered rock in other than pipe form, the widespread occurrence of explosive eruptions and the comparative rarity of recognizable collapse structures in igneous rocks make the assumption of a volcanic explosion more attractive than that of collapse as an "explanation" of the localized shattering.

Whatever the cause of the brecciation, it did not operate simply at the beginning of the metamorphism and then stop, but, as shown by the transection of fissures by others that contain distinctly different minerals (see fig. 7, A), continued through much of the period of mineralization. There is no evidence of distinct pulses of brecciation or mineralization, and both are believed to have gone on as simultaneous and essentially continuous processes, geologically speaking. The spasmodic recurrence of volcanic eruptions in historical time might, therefore, be thought to be inconsistent with a connection of old eruptions with the brecciation and alteration of these rocks. This irregularity is striking on a human time scale but may not be on a geologic scale. The events of the geologic past are nearly all foreshortened as the geologic record is read, and spasmodic eruptivity in the human time sense might readily be interpreted as continuous from the record in the rocks.

The New Cornelia ore body is the result of this metamorphism. Solutions penetrating the brecciated ground deposited a long series of minerals, partly by replacement of monzonite (or of minerals previously deposited from similar solutions at presumably higher temperatures) and partly as fillings of open spaces along the fissures. (See fig. 7.) Figure 8 shows the apparent order of formation of the metamorphic minerals of the ore body. The evidence on which it was prepared is partly illustrated by the plates and is partly presented here and in the section on mineral distribution (p. 77).

The earliest phase of the mineralization was the introduction of considerable masses of pegmatite (pl. 27, F) along two main and several subsidiary zones. For the most part this pegmatite is clearly of replacement origin. It consists of coarsely crystalline microcline and subordinate orthoclase, quartz, a little leafy biotite, and much leafy chlorite. It blends, at its contacts, with the host monzonite and contains (pls. 7, *B*, and 17) residua of normal porphyritic monzonite interstitial to the coarse feldspar

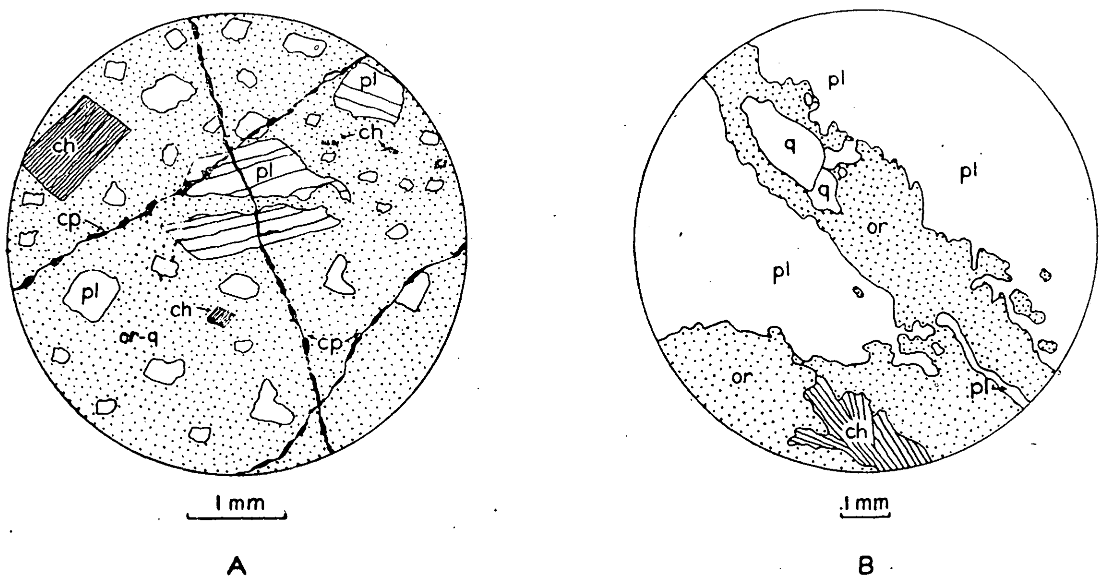


FIGURE 7.—Representative quartz monzonite ore from New Cornelia mine.

A, Camera lucida drawing of microscopic features. Shows flooding of the groundmass of the monzonite by fine-grained orthoclase and a little quartz (or-q), which also replace plagioclase (pl) along cross-cutting fractures, and distribution of chalcopyrite (cp) along veinlets later than the orthoclase. ch, Chlorite.

B, Tracing of photomicrograph. Shows a single crystal or saussuritic and sericitic plagioclase (pl), which has been veined and partly replaced by orthoclase (or). The orthoclase veinlet contains a little quartz (q) in the center. Rosette chlorite (ch) replaces the orthoclase in the lower part of the drawing.

[91] Locke, Augustus, The formation of certain ore bodies by mineralization stoping: Econ. Geology, vol. 21, No. 5, pp. 431-453, 1926.

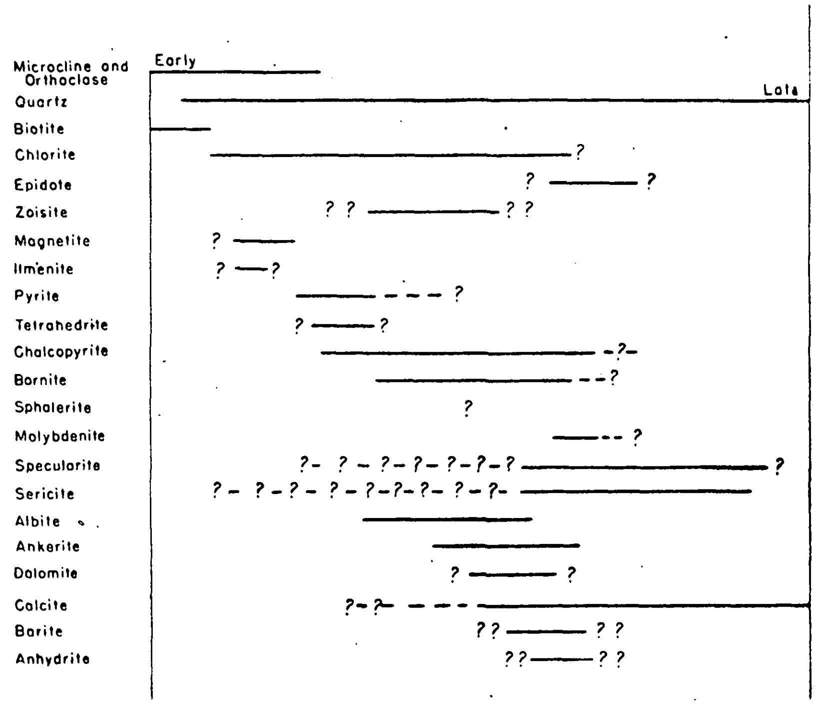


FIGURE 8.—Sequence of formation of the metamorphic minerals of the New Cornelia ore deposit, Ajo, Ariz. Based on field distribution and study of hand specimens and thin and polished sections.

and quartz; poorly defined offshoots of pegmatite extend into the monzonite along fissures.

The area of this coarse pegmatization is central to a considerably larger area (pl. 27, G) in which the normal monzonite has been penetrated along fissures (fig. 7, pl. 11, *A, B, E, F*) and its groundmass largely replaced by fine-grained pink orthoclase. (See pls. 9, *D*, 10, *D, E*, 11, *C, D*, 14, *C*.)

Along with the replacement by potash feldspar there was wholesale silicification of the rock. This silicification was most intense in the neighborhood of the zones of pegmatization (See pl. 27, B, F) but was considerably more widespread. The monzonite throughout the area of the New Cornelia pit is heavily impregnated with quartz, both along fractures and in the body of the rock. Even outside the mine area the quartz impregnation is notable.

Near the pegmatite zones the quartz is commonly very coarse and occurs in veins as much as 6 inches across, with some suggestions of comb structure (See pl. 7, *A*), as well as in replacement masses (pls. 8, *B*, 9, *E*, 10, *A*) and narrow stringers (pls. 8, *A*, 9, *B*). Locally such veins have orthoclase selvages. (See pl. 10, *D*.) Some of the replacement quartz is in small roundish grains associated with similar grains of orthoclase (pls. 11, *D*, and 15, *C*), the forms being partly due to recrystallization after brecciation (as in pls. 15, *F*, and 16, *A*) but in part without apparent close association with brecciation. (See pl. 11, *C, D*.) Over much of the area of the New Cornelia pit this quartz impregnation has been so complete that almost no trace remains of the original monzonitic texture. Toward the outskirts of the ore body the silicification fades gradually away in narrower and narrower stringers. The silicification also extends into the Concentrator volcanics for long distances.

In part of the pegmatite area coarse leaves of a dark-green micaceous mineral, some an inch or more in diameter, appear to have grown simultaneously with some of the microcline and quartz. (See pl. 9, *C*.) Most of this material is chlorite (pl. 9, *A, B*), but some is biotite. Probably the material was originally introduced as biotite and most of it has since been changed to chlorite. The material is not sharply limited to the pegmatites but follows them closely. (See pl. 27, H.)

As pointed out in the section on mineralogy (pp. 95-96), the original ferromagnesian minerals of the Cornelia quartz monzonite and Concentrator volcanics have nearly all been altered to pseudomorphous chlorite in the neighborhood of the New Cornelia ore body. A third variety of chlorite occurs as vein fillings and fine-grained replacement aggregates. This variety is definitely younger than orthoclase (pl. 11, *A, B, E, F*) and magnetite and is probably in large part contemporaneous with the copper sulfides. (See pl. 16, *D*.) Chlorite thus was formed through a considerable range of mineralizing conditions. The chlorite that fills veins or forms replacement rosettes in the rocks seems to contain slightly more iron, on the average, than the chlorite that is pseudomorphous after other dark minerals, though there is considerable variability in the composition of both varieties. (See pp. 95-96.) This contrast in composition is to be expected as the minerals formed during the ore deposition are largely more ferriferous than magnesian, testifying to a greater effective concentration of iron than of magnesium in the mineralizing solutions.

Magnetite closely followed the pegmatization and was localized near it, as is clear from plate 27, E. It is largely in veins that cut quartz and microcline but seems to be older than most of the sulfides. However, local veinlets of magnetite cutting chalcopyrite blebs may indicate that some magnetite was deposited after the chalcopyrite had begun to form. Presumably, although no direct evidence is available, the ilmenite that developed as an alteration product of the abundant sphene in the Cornelia quartz monzonite was formed at about the same time as the magnetite.

Following the deposition of most, if not all, of the magnetite, the sulfides began to form, although quartz and chlorite continued to be deposited along with them. The oldest sulfide is pyrite. This is not abundant except toward the eastern side of the New Cornelia ore body (see pl. 27, D), where it was estimated to amount to about 20 percent of the total sulfides. For the most part it is too scanty to afford enough evidence directly to place its age with respect to the other minerals, but it appears to be older than chalcopyrite in all specimens examined where the two are in contact and is, therefore, regarded as the oldest sulfide.

Chalcopyrite seems to have begun to form before bornite, but this is not certain, as there seem to be about as many examples of chalcopyrite veining bornite as the reverse. However, where pyrite, chalcopyrite, and bornite occur together, it seems that the chalcopyrite is older than the bornite in its replacing relation to the pyrite.

Tetrahedrite and sphalerite are too scanty to place in the age sequence but perhaps accompanied the early chalcopyrite.

Albitization is essentially complete in the area of the ore body, in the pegmatized area as well as around it. Sericitization tends to be less conspicuous in the pegmatized zones, perhaps because of the dominance of potash feldspar over the more susceptible plagioclase, but it is nearly everywhere present.

Sericitization and accompanying albitization of the plagioclase, with the production of a little zoisite, has been especially notable peripherally to the intensely pegmatized area and more especially toward the east, where pyrite is relatively abundant. This is believed to be definitely a lower temperature alteration than the pegmatization and probably involved much less material transfer (see pl. 15, *B*). Sericite continued to be formed very late in the mineralizing epoch, for it is found in relations strongly suggesting replacement of chlorite (see pl. 18, *B*) and elsewhere as veins in chalcopyrite.

The carbonates are difficult to place in the mineral sequence. Wherever observed, the ankerite and dolomite were formed earlier than calcite. Yet these magnesian carbonates are invariably in vugs and coating open crevices, though in places calcite forms replacement masses in the body of the rock and gives evidence of deposition at an earlier stage in the mineralization through the fact that quartz has been deposited along its rhombic cleavages. Calcite is also locally replaced by chlorite rosettes (see pl. 18, *C*), and is closely associated with chalcopyrite in a way that suggests their essential contemporaneity.

Barite and anhydrite, the two anhydrous sulfates of the deposit, are also present in such small quantities that their age relations are not readily determined within narrow limits. Anhydrite replaces chlorite, sericitized plagioclase, chalcopyrite, and quartz and is inferred to have formed at a fairly late stage in the mineralization. Barite is so closely associated with specularite and ankerite that it is believed to have been deposited contemporaneously with them.

Specularite was formed rather late in the mineralization period after most of the sulfides had been deposited, although it is possible that the hematite that follows the boundaries and octahedral partings of the magnetite was formed before the sulfides. The specularite was governed by very different controls than the previously deposited minerals. In the first place, its area of maximum concentration trends east-northeast, nearly at right angles to the trend of the pegmatites in the ore body. (Compare C, pl. 27, with D, E, F, G, and I.) This trend of the specularite mineralization is not confined to the New Cornelia mine but can be followed for a long distance eastward to the waste dumps overlooking the Valley of the Ajo and westward as far as Pinnacle Peak. Splendant crystals as much as 2 inches long are common in the Concentrator volcanics of Arkansas Mountain, and smaller ones are widespread in this belt. The larger crystals are clearly replacements of the body of the rock (chiefly Concentrator volcanics), but the smaller crystals are blades that line fissures and crevices that intimately dissect the rock.

In view of this distribution in the older rocks just beneath the Locomotive fanglomerate and parallel to the contact, it might be thought that the specularite is supergene and was formed during the period of weathering and secondary enrichment of the New Cornelia ore body that antedated the deposition of the fanglomerate. The common habit of the mineral in lining open fissures would conform with such an origin, as well as the fact that over the ore body cuprite occurs in the old oxidized zone, showing strong oxidizing influence and not much hydration at the time of this weathering. However, this hematite associated with the cuprite is not of the specular variety. Furthermore, many of the specularite crystals are slickensided and bent, and replacement bands of hematite are highly contorted along certain small faults east of the New Cornelia pit, showing deformation under considerable load. Epidote, barite, and ankerite occur with the specularite, not only in this zone of highest concentration but in veins near the northwest corner of the New Cornelia pit, on the west slope of Camelback Mountain, and at Cardigan, far from the zone of pre-Locomotive oxidation. For these reasons and because small amounts of chalcopyrite are not uncommon in the specularite it is all regarded as hypogene.

Molybdenite, because it occurs in small amounts, although widely scattered through the ore body (see pl. 27, A), is difficult to place in the mineral sequence. In several vugs it is perched on euhedral chalcopyrite and in one is itself coated by chalcopyrite; its relations to other minerals are not decisive. The mineral was probably formed late in the sulfide sequence, a suggestion that conforms to its apparently peripheral distribution with respect to the pegmatitic zones.

Alunite is present in large amounts as veinlets and stockworks in the Concentrator volcanics on the hills southwest of Concentrator Mountain, near the head of the approach to the New Cornelia mine. The area of intense impregnation with alunite occupies several acres. It seems not to be directly connected with the area of copper mineralization and perhaps represents a somewhat younger stage in the metamorphic development.

MINERAL DISTRIBUTION

In many ore deposits the minerals have been found to be systematically arranged about centers of mineralization, a relation that has given rise to the "zonal theory" of ore deposition. In a few deposits this arrangement is sufficiently definite to permit rather satisfactory prophecy as to the changes that may be expected in depth. As the recognition of such a systematic arrangement, if it exists, would be of obvious economic interest as giving clues to the extension of known ore bodies or the possible occurrence of undeveloped additional ore bodies, the mineral distribution near the New Cornelia mine was systematically studied.

For this purpose the area of the mine was subdivided into squares, 200 feet on a side. Each square was then gone over rather systematically and an attempt made to evaluate it with respect to the others. The work was entirely qualitative and based on cursory examination of random samples.

During the work, which occupied more than 2 weeks of field studies, the rather indefinite "standards" of concentration doubtless changed, though an attempt was made to discount this uncertainty by choosing squares at random for each day's work, in order that such changes of standard should not be systematically distributed areally. The first squares studied were revisited several times for the same purpose. Each square was evaluated as indicated on plate 27.

Owing to the subjective factors involved in this classification and to the fact that much of the material examined consisted of loose fragments, not precisely in place, not too much weight could be given to any individual unit square, but it is nevertheless probable that the broader distribution of the several mineralogic features is roughly as shown.

The habits of all these minerals are described in more detail on pages 86-98, together with those of minor minerals found in and near the ore body.

From the diagrams on plate 27 it is clear that pegmatite, orthoclase, leafy chlorite, and magnetite are closely grouped and were doubtless controlled by the same channels. Although introduced quartz is most abundant near the pegmatites, and hence is most likely derived from the same source, it is present in quantity over a much larger area and in part coincides with areas in which pyrite is abundant. Pyrite seems less concentrated near the pegmatite areas and reaches its greatest proportions to the east of the pegmatized area. Sericitization seems closely associated with a high proportion of pyrite. It is also abundant at the southwest edge of the pit, north of Arkansas Mountain, where quartz is abundant but pyrite is not. The higher-grade hypogene copper ore shows a tendency to follow the pegmatite areas (see pl. 25, 1800 level and 1700 level.) The molybdenite is so sparse that no generalization about its distribution appears warranted. It is clear that the specularite has no consistent relation to the ore body or the other alteration minerals.

From plate 27 it thus appears that the pegmatites are in the central part of the ore body, where microcline, orthoclase, magnetite, quartz, and copper sulfides are most concentrated. The outer zones of the ore body show locally high proportions of pyrite, with diffuse sericitization. The irregularities of mineral distribution in the outer parts of the ore body are too great to permit any deductions as to the distribution of the cupriferous ore.

In part the apparent irregularity of the mineral zoning may be due to the postmineral tilting that the entire mountain block has undergone. But, even making allowance for this tilting and imagining the present areal map as a steeply inclined section through the ore body at its original attitude, it is clear that most of the vagaries of mineralization distant from the ore shoots remain. Whatever the merits of the zonal theory in other districts, it does not appear that it can be used in this area as a specific guide to prospecting.

SOURCE AND CHARACTER OF METAMORPHOSING SOLUTIONS

The mineral zoning around the pegmatite areas of the New Cornelia mine, which is apparent on plate 27, strongly suggests, if indeed it does not prove, that whatever conditions localized the pegmatites controlled also the sericitization, chloritization, and sulfide deposition. The mineral association of the pegmatites—microcline, orthoclase, quartz, biotite, and chlorite—is that common in the late stages of magma consolidation and is almost certainly of magmatic derivation. The situation of the New Cornelia ore body in a mass of the Cornelia quartz monzonite that exhibits the peculiar "corroded" texture described on page 73 suggests that the processes responsible for the peculiar texture may, with some modification, have also brought about the ore deposition. Since the "corroded" texture is almost surely a late magmatic product, this coincidence furnishes still further support to the magmatic theory. Evidence from similar ore deposits in many parts of the world tends to confirm the deduction. If it be accepted as a working hypothesis, it may be worth while to try to deduce from it a "reasonable" picture of the processes involved in the mineralization.

As shown on pages 31-33, 51-53, and 105 and plate 24, when the Cornelia quartz monzonite was emplaced the present lobe southeast of Camelback Mountain was a ridge on the magma chamber. Judging from the scarcity of flowlines in the monzonite, it seems that the magma at the time of its intrusion was poor in crystals, a conclusion that is strengthened by the marked diminution of grain size in the dioritic border facies as compared with the main body of the monzonite. Crystallization thus occurred under essentially static conditions, and the suggestion of filter-press action as a cause of the magmatic differentiation does not seem tenable. The few narrow belts of mylonite that cut the monzonite in the New Cornelia pit and those northeast of Camelback Mountain are younger than the consolidation of the adjacent rock and can have had little effect in squeezing out any residual magma.

The composition of the magma as it was introduced is probably fairly represented by analyses Nos. 3 and 4 of table 4, except for a certain content of "fugitive" constituents that escaped on the consolidation of the rock. Of these fugitive constituents, water was by all odds the most abundant, as shown by the hydration effected in the neighborhood of the ore body. Sulfur was also present, as shown by the ore minerals. General experience and observations in regions of active volcanism show that other fugitive constituents common in volcanic exhalations include the halogens and carbon, hydrogen, boron, and nitrogen, in various compounds with each other and the metals. Presumably they were more abundant in the intruding Cornelia magma than in the crystallized rock represented by the analyses.

To evaluate roughly the content of these fugitive constituents in the original magma certain assumptions must be made. It may be assumed with confidence that the content of water given in the analyses as H_2O+ (0.62 percent) is a minimum measure of that present in the magma when injected, for some certainly escaped on consolidation. The temperature of the magma may be assumed to have been about 800° C.[92]

The depth of cover is purely a matter of surmise. From similarity of texture and composition to other quartz monzonites more favorably situated for estimate,[93] it may be put as between 3,000 and 10,000 feet, or roughly 6,000 feet. This is equivalent to a pressure of about 500 atmospheres. The solubility of water in glass formed by melting granite has been investigated by Goranson,[94] who found that at pressures equivalent to a load of about 2 kilometers (a little more than 6,000 feet) of rock and a temperature of 900° C. glass obtained from the granite of Stone Mountain would dissolve about 4 percent of water. Goranson[95] also obtained data showing that the effect of temperature on the solubility is relatively unimportant compared with the effect of pressure.

If one were to accept these experimental results as representing natural conditions, it could be deduced that under the assumed conditions the Cornelia quartz monzonite could have held only a little more than 4 percent of water when it was intruded without exerting enough internal pressure to break the roof. The fact that 6.31 percent of water has been found in a surface flow of quite fresh obsidian[96] shows, however, that equilibrium is not always reached promptly in volcanic phenomena, and the spasmodic nature of volcanic eruptions shows that this failure to maintain equilibrium is general. One is therefore not justified in asserting that 4 percent of water is the upper limit of solubility in the magma, although such a figure seems a reasonable maximum.[97] The probable water content of the Cornelia magma as it was emplaced was somewhere between 0.6 and 4 percent but probably nearer the larger than the smaller of these figures. The presence of other volatiles in the magma would doubtless affect the solubility of water and presumably would decrease it. No experimental data are known to me that would permit any quantitative estimates of such volatiles, however, nor of their effect on water solubility.

After emplacement the magma began to cool and crystallize. The early minerals that formed were relatively less hydrous than the magma, for, although biotite and hornblende carry essential water, plagioclase, quartz and potash feldspar, which would also occur as phenocrysts of early formation, are anhydrous. The separation of these minerals thus enriched the residual magma in water and other of the "hyperfusibles" as they have been called by

[92] Larsen, E. S., The temperatures of magmas: Am. Mineralogist, vol. 14, p. 94, 1929.

[93] The monzonites at Tintic, San Francisco, and Bingham, Utah, of similar composition and petrographic character, intruded into the bases of their own volcanic piles in roughly this order of thickness. Gilluly, James, Geology and ore deposits of the Stockton and Fairfield quadrangles, Utah: U. S. Geol. Survey Prof. Paper 173, p. 65, 1932.

[94] Goranson, R. W., The solubility of water in granite magmas: Am. Jour. Sci., 5th ser., vol. 22, pp. 481-502, 1931.

[95] Idem, p. 495.

[96] Fenner, C. N., Pneumatolytic processes in the formation of minerals and ores: Ore deposits of the Western States (Lindgren volume), p. 66, Am. Inst. Min. Met. Eng., 1933.

[97] Gilluly, James, The water content of magmas: Am. Jour. Sci., vol. 33, pp. 430-441, 1937.

Bowen.[98] The zoning of the plagioclase shows that the freezing of the magma did not proceed slowly enough for reactions between the previously separated crystals and the residual magma to maintain equilibrium in the system. Accordingly the concentration of the hyperfusibles in the residual magma must have continuously increased, with a consequent increase in its internal pressure.

The concentration of orthoclase and quartz in the groundmass of the porphyritic facies and their dominance among the later crystals to form in the equigranular facies of the Cornelia quartz monzonite show that although these minerals began to form early in the crystallization period their constituents were also relatively concentrated in the residual magma—a common trend in crystallizing magmas. The composition of the residual magma, therefore, approached that of a pegmatite. Goranson's work[99] shows that water is slightly less soluble in a silicate melt whose composition approaches that of a pegmatite than in the more complex melts that he investigated, so the internal pressure of the residual magma probably increased on this account also as crystallization progressed.

All rocks in nature are porous, so that a closed system is practically unthinkable. The vapor pressure of the magma was exerted on permeable walls and did not have the counter pressure of the entire rock load but only of the friction of the pores. Consequently, being hotter than its enclosing walls and with correspondingly low viscosity and loss of head by friction, a fraction of the more volatile components must have been distilled from the magma even during its emplacement. However, it is likely that the vapor pressure at this stage would be small. Only after some crystallization ensued, with corresponding enrichment of the residual magma in low-melting components, would the vapor pressure become comparable to the pressure of the superincumbent rocks, considered as a dead-weight load.

It is also highly probable that the viscosity of the residual magma was continually lessened as its water content increased. It therefore becomes possible that in the interval between the beginning of crystallization and the stage wherein a self-supporting crystal aggregate was formed there was some migration of the residual magma upward with respect to the solid phases and a corresponding enrichment of the cupola in the hyperfusible constituents. It is theoretically necessary that there should be some such migration, and it is likely that considerable migration could have occurred without leaving definite structural evidence. The analyses of table 4 are too few to make the matter clear, especially in view of the alterations superposed upon the rocks during later stages, but they do not seem to indicate any significant migration during this part of the magmatic evolution.

[98] Bowen, N. L., The broader story of magmatic differentiation, briefly told: Ore deposits of the Western States (Lindgren volume), p. 113, New York, Am. Inst. Min. Met. Eng., 1933.

[99] Goranson, R. W., op. cit., p. 496.

Although the internal pressure consequent on the concentration of hyperfusibles must have been essentially hydrostatic, it was exerted on a wedge-shaped cupola and thereby tended to split apart the walls, both of the host rocks and the earlier consolidated exterior zone of the intrusive itself. This appears to be the most likely mechanism to have brought about the peculiar shattering of the monzonite and its wall rocks in the Cornelia ore body, which was then in part of the "hood" of the monzonite stock, overlying the still-molten material at greater depth. If this is so, when the concentration of hyperfusibles exceeded a certain critical value the pressure exceeded the effective resistance and fractured the earlier chilled border and roof of the cupola. Once started, the openings doubtless were immediately occupied by the residual magma, whether by expansion as a single phase if it were above its critical temperature or by increase in volume due to vesiculation if it were below that temperature. The simple deformation of a crystal aggregate with interstitial fluid under the proper conditions can lead to the concentration of the fluid in fractures.[1] This might readily emphasize the upward concentration of the residual magma, once the explosion had shattered the border rocks and thereby deformed the crystal mesh of the underlying parts which were not yet solid. A relative concentration of hyperfusibles in the cupola thus seems probable at this stage.

Disregarding, for the moment, the effect of these hyperfusibles on the wholly consolidated border or "hood" of the intrusive, whose fracturing gave additional impetus to their upward migration, their effect on the partly crystallized material in the cupola may be considered. As the cross section of the cupola was much less than that of the underlying magma body, there would be a concentration of the hyperfusible fraction from a relatively large volume in the cupola. If, as is strongly suggested by the localization of the "corroded" texture in and near the New Cornelia ore body, this texture resulted from the influence of these low-melting components of the magma, one may infer that this increase in hyperfusibles was rather general in the upper part of the cupola. Possible causes of the attack on the early crystals were: (1) exothermic reactions in the residual magma as its concentration in hyperfusibles increased, (2) increases in temperature because of heat transferred by the migrating volatiles from deeper-lying portions of the magma chamber, (3) heat developed by expansion of the fluid owing to release of pressure such as occurs when a fluid escapes through a "porous plug,"[2] and (4) lowering of the melting point of the minerals by decrease of the pressure when the roof broke.

Possibly all of these factors contributed to the attack

[1] Mead, W. J., The geologic role of dilatancy: Jour. Geology, vol. 33, pp. 685-698, 1925.

[2] Adams, L. H., Temperature changes accompanying isentropic, isenergic, and isenkaumic expansion: Washington Acad. Sci. Jour., vol. 12, pp. 407-411, 1922.

on the early minerals. The last three do not appear to be quantitatively adequate to bring about so much solution as is indicated by the corroded texture. The transfer of heat by volatiles is limited not only by the presumably short distance of migration (and hence slight temperature difference between their source and the cupola) but also by the low specific heat of the volatiles. The mechanism of "porous plug" expansion could hardly operate before a fairly compact crystal mesh was formed and hence could probably not have produced the corrosion of the early minerals, though it might have increased the metamorphic effects in the overlying volcanic rocks. The lowering of melting point of the minerals by decrease of pressure is theoretically small. The abundant crystals in the magma at the time of their corrosion must have modified the previously hydrostatic pressure gradient in the intrusive. Nevertheless, one would expect a gradual diminution of a pressure effect away from the point of escape of the volatiles rather than the rather restricted distribution of the corrosion that is actually found. Doubtless the concentration of volatiles was greatest in the cupola, but they could not have been absent at this stage from the underlying magma. Hence, it is concluded that the distribution of the corrosion is opposed to that expected on the assumption that the solution was a simple pressure effect.

Accordingly, the possibility that exothermic reactions in the residual magma were responsible for the corrosion seems most attractive,[3] especially when the general sluggishness of volcanic activity in coming to equilibrium is considered.[4] Whatever the cause of the reversal of trend, from crystallization to re-solution of an early mineral, there seems no escape from the conclusion that it took place prior to complete consolidation of the magma, in the interior of the cupola.

When the previously consolidated hood of the cupola was broken by the internal pressure of the hyperfusibles, or rather of the polyphase system containing them, and the residual magma expanded or was forced into openings so formed, the period of pegmatization of the New Cornelia deposit began. This pegmatization seems to have been merely a continuation of the magmatic consolidation in an environment of crystallized material. Apparently the minerals are exactly the same as those in the groundmass of the nearby monzonite; they are merely concentrated in larger crystals along openings in the rock. There was no doubt a high concentration of hyperfusibles in the material as injected, but the replacement phenomena do not seem to differ qualitatively from the corrosion of the phenocrysts in the nearby monzonite, and I can see no geologic reason for assuming that the pegmatites must be products of a phase different from the residual magma that attacked those phenocrysts. In other words, it seems fruitless to speculate on whether they were deposited from a hydrothermal or pneumatolytic solution; whatever the solution should be called, there is no apparent petrographic or geologic evidence to indicate that it differed discontinuously from the quartz monzonite magma.

In Burbank's terminology,[5] the pegmatization apparently occured in a system composed of crystalline minerals plus one phase, fluid.

Doubtless, as crystallization progressed in the lower horizons of the mass, the concentration of hyperfusibles in the residual magma continued to increase, and, as the residual magma migrated upward and cooled, selective crystallization of the silicates carried the concentration still farther. Probably by the time the magnetite and chlorite began to be deposited the concentration of the hyperfusibles in the solutions permeating the consolidated hood was so great as to warrant calling their mutual solution hydrothermal, but there is nothing in the distribution, texture, or mineral composition of the sulfide, sericite, albite, and carbonate deposits that indicates a discontinuous relation with the pegmatitic liquid. The replacement relations of all these minerals are comparable, except for their obvious control by openings in the rock, with the replacement relations in the monzonite with "corroded texture." The succession of minerals is longer and the younger replace the older, but there is apparently no place, from the deposition of large microcline and biotite crystals in the pegmatite zones to the mild chloritization and saussuritization of the outskirts of the ore body, where any hiatus in the mineralization can be established.

Vugs are present in the ore body and are commonly lined with euhedral crystals of silicates, sulfides, quartz, and carbonates. Such features seem not to be diagnostic of the phase from which the crystals were deposited. The geologic evidence seems to give no support, as far as these minerals go, to a theory that would suggest that they are derived from the parental magma by discontinuous evolution.

A different story seems to be told by the specularite. As pointed out on pages 76 and 77 and as shown on plate 27, C, the specularite is distributed almost without regard to the other hypogene minerals. It lines crevices and forms replacement bodies through large volumes of the roof rocks of the Cornelia massif, without any noticeable association with the New Cornelia deposits, and thus indicates a discontinuity in mineralization. If, as seems highly probable, the other hypogene mineralization was carried forward by a continuous evolution of the residual magmatic solutions toward higher and higher concentrations of hyperfusibles, it is reasonable to suggest that the specular hematite was a product of a different phase and

[3] Fenner, C. N., The Katmai volcanic province: Jour. Geology, vol. 34, pp. 738-740, 1926.

[4] Fenner, C. N., Pneumatolytic processes in the formation of minerals and ores: Ore deposits of the western States (Lindgren volume), pp. 65-66, Am. Inst. Min. Met. Eng., 1933.

[5] Burbank, W. S., A source of heat energy in crystallization of granodiorite magma and some related problems of volcanism: Am. Geophys. Union Trans., pt. 1, p. 244, 1936.

was pneumatolytic. According to Burbank's classification[6] it was formed from a system consisting of crystalline minerals plus two phases, liquid and gas. When the concentration of hyperfusibles exceeded a certain critical value, they boiled off by fractional distillation from the residual magma as a vapor phase, carrying with them larger quantities of ferric iron (epidote is commonly associated with the specularite). Some sulfides accompanied the ferric iron, and in places in the ore body aggregates of chalcopyrite are surrounded by bornite that contains minute plates of hematite, apparently formed at this time by reaction with the older chalcopyrite. If the iron were carried as ferric chloride or some similar volatile compound, as has been commonly urged, there is no evidence in the minerals deposited to show the former presence of the chlorine.

It is possible that the volatilization of the iron was connected with the exothermic reaction involved in the formation of ferric iron from ferrous, as has been suggested by Burbank[7] for the mineralization at Ouray, Colo. Burbank has pointed out that there is commonly a higher proportion of ferric to ferrous iron in the later stages of igneous evolution than in the earlier stages. This oxidation of the iron is an exothermic process. The evaluation of the heat involved is impossible in the present state of knowledge of the thermodynamics of magmas. If the reaction were simply the oxidation of solid FeO by free oxygen, the heat evolved would be 62,620 calories per gram molecule of Fe_2O_3 produced. The oxygen involved was probably not free, however, but combined in water, which is not thought to be appreciably disassociated at magmatic temperatures. Hence, much less though still considerable heat would be evolved in the oxidation process.

The low iron content of the altered monzonite (No. 6, table 4) gives some support to the assumption of a connection between oxidation of iron and its removal in volatile emanations. But the absence of a similar change in Nos. 5 and 7 (which may be from too high in the cupola and where the rock was already solidified and low in residual fluids at this stage of mineralization) leaves the question far short of proof. The analyses in table 4 were carried out before Burbank's suggestion was made and were not on material selected to test it. As far as they go, they fail to show a consistent increase in the ratio of ferric to ferrous iron in the more silicified rocks, but so few and such ill-chosen analyses cannot be considered decisive. The widespread alteration of magnetite to hematite along grain boundaries and octahedral partings shows some hypogene oxidation of iron in the ore body.

Whatever the cause of the discontinuity in the mineralization process marked by the hematite deposition, it was transitory and was followed in the ore body by a return to the deposition of sulfides that are essentially indistinguishable from those that preceded the specularite. This may be regarded as a further suggestion that the specularite was pneumatolytic in origin, for it would be expected that hydrothermal solutions would mark the declining as well as the advancing stage of a pneumatolytic process.[8] Burbank has attributed a similar reversion to pre-hematitic mineral associations at Ouray to increased back pressure on the evolved vapors. The back pressure is increased by sealing up of openings through deposition of minerals in them. This sealing might conceivably occur more readily near the lower limit of fracturing than at higher levels.

In summary, then, it is believed that the mineralization of the New Cornelia ore body represents in large part a direct continuation of the consolidation process in the Cornelia quartz monzonite. The crystallization of the monzonitic magma led to a continual enrichment of the residual magma in the lower-melting components and in the elements that do not enter readily into solid solution in the early-formed silicates—copper, sulfur, molybdenum, antimony, barium, and the alkalies. The vapor pressure of this residual magma continually increased, with increasing concentration of the hyperfusibles, and eventually sufficed to shatter the roof of the cupola. This induced streaming of the volatiles in the residual magma toward the cupola and led to their enrichment there, relative to the rest of the magma body. Exothermic reactions in the residual magma, or some other cause, such as release of pressure by volcanic eruptions, led to attack on the earlier crystallized minerals of the part of the cupola that was not yet consolidated and produced the corrosion texture. However, there is no evidence of any discontinuity in the mineral sequence from the normal silicate crystallization of the monzonite through the pegmatization of part of the hood and silication, sulfide mineralization, sericitization, and saussuritization of the outlying part of the deposit. Apparently late in the mineralization epoch the vapor pressure of the residual magma exceeded the restraining pressure of the cover to an extent sufficient to induce vaporization of part of the hyperfusibles, and hematite was formed in the innumerable cracks in the magma hood and host rocks overlying the cupola. This was a brief episode and was succeeded by a further crystallization of sulfides with the specularite and carbonates, supposedly from cooler watery solutions.

CHEMICAL CHANGES ASSOCIATED WITH THE ORE DEPOSITION

The mineralogical changes in the rocks within and near the ore body that have just been discussed naturally involve considerable modification in chemical composition. Analyses Nos. 5 and 6 of table 4 show the modifications brought about in the quartz monzonite in the zone of mild metamorphism surrounding the ore body; No. 7 of the

[6] Burbank, W. S., op. cit.

[7] Burbank, W. S., op. cit., pp. 236-255.

[8] Merwin, H. E., Some associations of ore minerals: Am. Mineralogist, vol. 16, pp. 93-96, 1931.

same table is an analysis of representative ore (0.82 percent copper) from the mine. In order to compare the changes in components of the primary silicate minerals during metamorphism these analyses (along with Nos. 3 and 4 of the same table, representing unaltered quartz monzonite) have been recomputed to 100 percent after the elimination of water, CO_2 and sulfides. (See table 7.)

TABLE 7.—*Analyses of quartz monzonites of table 4 recomputed to 100 percent after subtraction of water, CO_2, and sulfides*

	3	4	5	6	7
SiO_2	65.74	66.64	67.00	68.77	68.61
Al_2O_3	15.85	15.80	16.31	16.22	16.14
Fe_2O_3	2.06	2.21	1.48	1.34	1.10
FeO	2.04	1.99	2.76	1.11	2.51
MgO	1.85	1.59	2.18	1.44	1.74
CaO	3.68	3.82	1.92	.78	.41
Na_2O	3.80	3.92	3.62	3.56	3.49
K_2O	4.13	3.24	3.78	5.41	5.24
TiO_2	.54	.47	.61	.58	.38
P_2O_5	.24	.24	.32	.29	.24
MnO	.07	.08	.02	.05	.03
Minor constituents	....	....	....	.45	.11
Total	100.00	100.00	100.00	100.00	100.00
Elemental Fe	3.03	3.10	3.19	1.80	3.10

From this table it can be seen that, aside from a slight increase in silica, the only considerable changes in the primarily rock-forming constituents brought about during the alteration of the quartz monzonite to a copper ore were a considerable loss in lime and a gain in potassa and probably in alumina. No. 6 shows a considerable loss in iron as compared with Nos. 3, 4, and 5, but No. 7, which contains pyrite and chalcopyrite, shows essentially the same content of elemental iron as the unaltered monzonite.

Figure 9 shows the changes brought about during the metamorphism. This graph brings out the fact that, in No. 5, which is an albitized, sericitic, and chloritic rock, there has been little change in bulk composition of the principal constituents except that lime has been removed and a little potassa added. The graph takes no account of water, which has of course been added in all the metamorphosed rocks as a constituent of chlorite and sericite. A very little silica and possibly some alumina have been added.

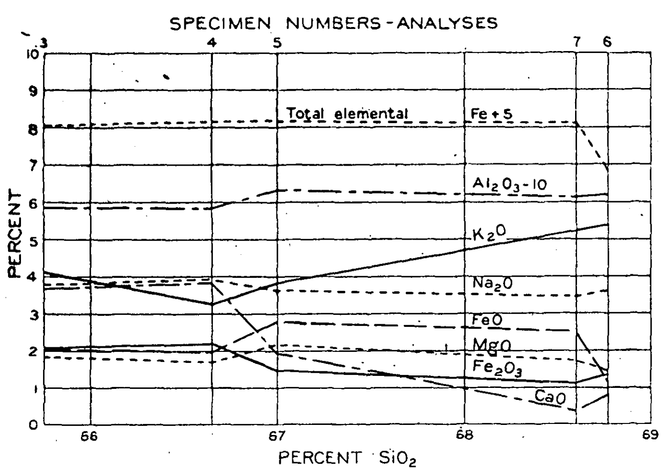


FIGURE 9.—Graph showing gains and losses of the principal rock-forming constituents of the Cornelia quartz monzonite during its metamorphism in and near the New Cornelia ore body.

Analysis No. 6, of a more intensely altered rock, shows further gains in silica and potassa, with greater loss of lime. A considerable loss in total iron is also shown. No. 7, which is representative of the copper ore, shows essentially the same changes as No. 6 except that iron is about the same as in the fresh quartz monzonite. Other ore specimens would show considerably higher silica, owing to veining and replacement of the silicates by quartz, and doubtless many of the pegmatized rocks have gained more K_2O than No. 7. Many magnetitic specimens would show considerable gains in iron, as compared with the unaltered quartz monzonite, but aside from these the specimen is probably a fair sample of the ore.

The chemical changes are those that would be expected from the petrographic study: gains in CO_2, H_2O, B, and S, of the fugitive magmatic constituents; in K_2O, Al_2O_3 (?), and SiO_2, of the silicate-forming constituents; and locally in Cu, Fe, Mo, Sb, and As, of the metals. The loss is chiefly of Ca, with the other constituents varying only by "dilution" of the original rock by the added material.

ALBITIZATION OF THE CORNELIA QUARTZ MONZONITE NOT ASSOCIATED WITH THE NEW CORNELIA ORE BODY

In addition to the area centering in the New Cornelia ore body, there are disconnected areas elsewhere in the Cornelia quartz monzonite that have undergone mild alteration, probably connected with the consolidation of the massif. In several areas near the Gibson fault and farther west, near the common boundary of secs. 16 and 21, T. 12 S., R. 6 W., the quartz monzonite has been albitized and the dark minerals altered to chlorite. Replacement by quartz is suggested in some of these rocks (see pls. 12, *E. F.*, and 13 *A, B*) and, although some of their albite is free from sericite or zoisite, other specimens contain these minerals and transitions to normal andesine feldspars. (See pls. 14, *D*, and 15, *A*.)

There has been no coarsening of the grain of the rocks in these localities and no pegmatization. There seems to have been a little fracturing and bending of the feldspar crystals. Apparently there was mild crushing of the rocks, with permeation of the crush zones by hydrothermal solutions that replaced the more calcic plagioclase with albite or saussuritic aggregates. There seems to have been no economic mineralization associated with these albitized areas.

METAMORPHISM YOUNGER THAN THE ORE DEPOSITION

POST-CORNELIA DYNAMIC METAMORPHISM

Dynamic metamorphism younger than the Cornelia quartz monzonite has been restricted to narrow zones. Microbreccias (mylonites) are found in narrow stringers and seams in the area between the town of Ajo and Camelback Mountain. These stringers trend generally westward but send off little dikelike branches into their walls and are rather irregular. They cannot be followed far.

In a narrow zone along the Gibson fault the Cornelia quartz monzonite, Concentrator volcanics, and Cardigan gneiss all show brecciation on both large and microscopic scales. There has been some sericitization, albitization, and chloritization along this crushed zone, brought about by circulating waters, perhaps heated by the friction of the fault movement or possibly by magmatic heat at depth.

There has been some crushing along the Ajo Peak and other still younger faults, but the rocks were broken on a coarse scale and their cohesion is so weak that the alteration can hardly be referred to as metamorphic.

HYDROTHERMAL METAMORPHISM

All of the post-Cornelia andesite dikes and the Ajo volcanics and Sneed andesite show local saussuritization, sericitization, and carbonation of their plagioclase, accompanied by more or less chloritization of their dark minerals. Such alteration effects have not been found in the Hospital porphyry, Childs latite, nor Batamote andesite.

Plotting the localities where such mild metamorphic effects have been recorded reveals no system in their distribution. They appear to be especially prominent in the fragmental volcanics and in the dikes that cut the Locomotive fanglomerate. In these dikes alteration may have resulted from the action of water in the sediments heated by the intrusives and actively penetrating them; in the pyroclastic rocks it may have resulted from the percolation of hot meteoric water or from the flow of lava over wet ground or shallow ponds. Such an explanation would not hold for the dikes in the Cornelia quartz monzonite, however, and it may be that they owe their alteration to hydrothermal solutions of magmatic source, though it seems possible that here, too, meteoric waters in crevices in the host rock might have been placed in active circulation by the intrusion of the dikes. The absence of like alteration in the Batamote andesite seems to eliminate the possibility that the alterations are due to weathering. In any event, it is impossible to correlate these irregular metamorphic effects with any particular intrusive body.

No economic mineral deposit has been found associated with rocks showing this mild type of alteration in the Ajo region, and there is no reason, from experience elsewhere, to expect that any will be.

WEATHERING

In the arid climate of the Ajo region weathering goes on with extreme slowness. To judge from casual examination, the dominant factors are physical, for the rocks break down for the most part into angular fragments that are apparently quite as sound as their parent ledges. The glistening crystals of feldspar that are commonly seen even in stream beds do not show much chemical decomposition. It is possible, nevertheless, that the disruption of the rocks is due to a slight hydration of the minerals, although the scarcity of soil in the region shows that the chemical weathering is generally slower than the transportation processes. The common occurrence of veneers of desert varnish on the fragments and boulders show that solution of the iron-bearing minerals is going on. The nonporphyritic andesitic dikes and the Hospital porphyry are the only rocks that seem to decompose readily on exposure. No particular attention was paid to the details of the weathering, however, and the reader is referred to the discussion of this aspect of the geology by Bryan.[9]

The chemical effects of weathering are much more conspicuous in the New Cornelia ore body. Here the primary sulfides have decomposed under the influence of percolating rain water and have been transformed to a group of secondary minerals. Two distinct epochs of weathering have been recognized in the New Cornelia ore deposit, one that antedates the Locomotive fanglomerate and one that is now going on. As the products evolved in the two epochs differ notably they will be described separately.

PRE-LOCOMOTIVE WEATHERING OF THE ORE BODY

A zone of abundant chalcocite forms a narrow belt roughly parallel to the base of the Locomotive fanglomerate across the south end of the New Cornelia mine. This zone is in places more than 150 feet wide but averages only about 40 feet. Locally it contains as much as 10 percent of copper. Though ore containing 3 or 4 percent of copper is abundant, it averages much less. It furnished most of the shipping ore of both the early and more recent periods of mining. As shown by observations at the surface, in the mine pit, and of diamond-drill cores, the top of the zone ranges in position from the base of the Locomotive fanglomerate to a level at least 450 feet below the projected base of the fanglomerate; in other words, the top of the chalcocite zone was 450 feet below the surface at some places and elsewhere was exposed at the surface prior to the deposition of the fanglome-

[9] Bryan, Kirk, The Papago country, Ariz., a geographic, geologic, and hydrologic reconnaissance, with a guide to desert watering places: U. S. Geol. Survey Water-Supply Paper 499, pp. 80-86, 1925.

rate and its later tilting to its present attitude. Where it diverges most widely from the fanglomerate, a zone containing native copper, cuprite, hematite, malachite, and chrysocolla intervenes between them. In some places a zone leached of nearly all the copper minerals overlies the zone of oxidized copper minerals. The diamond-drill cores show that these relations persist to the greatest depths yet explored at the south end of the ore body, that is, at least to 200 feet below sea level.

These relations indicate that in the time prior to the deposition of the Locomotive fanglomerate the ore body had been weathered, the surficial portion more or less leached of its copper, and the dissolved copper carried down and precipitated as chalcocite. Some copper was left in the lower part of the oxidized zone as cuprite, malachite, and native metal. Uneven erosion just before burial by the fanglomerate locally cut entirely through the leached and oxidized parts of the ore body and exposed the chalcocite layer. Elsewhere the erosion merely removed the barren leached zone, leaving the underlying rather poorly cupriferous belt of malachite, cuprite, and native copper at the surface, but, at other places leaching apparently was fully as rapid as erosion and a barren capping was formed.

The leached capping is very highly reddened by finely disseminated hematite with little or no brown (hydrous) iron oxides. It is spotted with minute blebs of cuprite and native copper that become more plentiful toward the footwall (northward from the fanglomerate). The transition from the zone of plentiful cuprite and native copper to the adjoining belt of chalcocite is abrupt.

In the zone of abundant chalcocite most of it forms narrow veinlets that in places attain widths of 2 or 3 inches. The principal variety in these veinlets is copper glance, but disseminated blebs of sooty chalcocite are also present and probably have replaced primary chalcopyrite or bornite. In places a little chalcocite is found in drill cores at intervals of several hundred feet below the zone of major concentration but nowhere in any considerable quantity. It was doubtless controlled by local paths of deep ground-water circulation during the weathering that preceded the burial by the fanglomerate.

In summary, during the erosion cycle that was closed by the deposition of the Locomotive fanglomerate, the New Cornelia ore body was weathered, the surficial portion was largely leached of its copper, and a zone of noteworthy supergene enrichment formed below the leached zone. The copper remaining in the belt of oxidation is largely in the form of the native metal or the oxide, cuprite, and very subordinately in carbonates. Fine-grained hematite is abundant in the weathered zone, but, owing to the fact that the weathered zone overlaps part of the zone of coarse specularite interpreted as hypogene, it is difficult to judge what proportion is supergene.

RECENT WEATHERING OF THE ORE BODY

Alteration effects produced in the ore body during the present erosion cycle differ strikingly from those produced in the pre-Locomotive cycle. Most of the cupriferous minerals were transformed, essentially in place, from sulfides to carbonates and silicates, with only subordinate oxides and almost negligible downward migration of the copper. This contrasts sharply with the pre-Locomotive cycle, when there was general downward enrichment, with much chalcocite, and with the residual copper in the weathered zone chiefly in the form of the native metal or cuprite. Owing to the facts that practically all the carbonate ore had been mined prior to this survey and the small amount remaining was largely covered by debris from blasting, or at least, no longer retained its original surface, no study directed toward correlation of outcrops with underlying ore could be made.

According to Joralemon,[10] the water table prior to mining marked the abrupt contact of thoroughly weathered oxidized ore above and practically unaltered and unenriched primary ore below. Throughout most of the ore body the transition from carbonate to sulfide ore took place in a zone less than 5 feet thick, so that the ore to be leached and that to be concentrated could be very satisfactorily separated even by power shovel mining.

The assay logs of 22 diamond-drill holes that penetrated this transition zone were kindly supplied by the New Cornelia engineers and were utilized in studying the abruptness of the change. The logs show, for 5-foot intervals, the average tenor in total copper and in copper soluble in dilute acid—essentially carbonate and silicate, with a little chalcocite. The ratios of soluble copper to total copper were computed from these assays, and the averages are shown in figure 11. It is seen from this graph that, despite the fact that the use of such large intervals as 5 feet must tend to obscure the sharpness of the contrast between the oxidized and unoxidized ore, the transition from 68 percent soluble to only 9 percent soluble copper occurred within a distance of 10 feet. The abruptness of the change from carbonate ore to the underlying sulfides seems to show that the water table had been stable for a relatively long time. Had there been wide fluctuations in the level of the water one would expect to find a much thicker zone of partly oxidized ore.

The proportion of chalcocite in the upper part of the sulfide zone over most of the remaining part of the ore body is far less than in the tilted zone of pre-Locomotive age. Nevertheless, the mineralogic analysis of the mill heads (fig. 10) shows a fairly consistent decrease in the proportion of chalcocite among the sulfides of the ore through the period of operations. This indicates that chalcocite was present in notable quantities throughout the upper part of the ore body (and thus largely formed

[10] Joralemon, I. B., The Ajo copper-mining district, Ariz. Am. Inst. Min. Eng. Trans., vol. 49, p. 604, 1914.

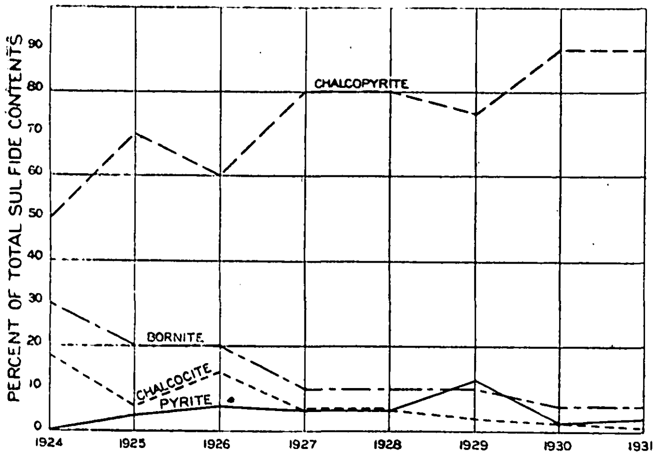


FIGURE 10.—Approximate mineralogic analysis of the flotation feed of the Phelps Dodge concentrator, Ajo. Ariz., 1924-31, inclusive. By the metallurgical staff of the concentrator.

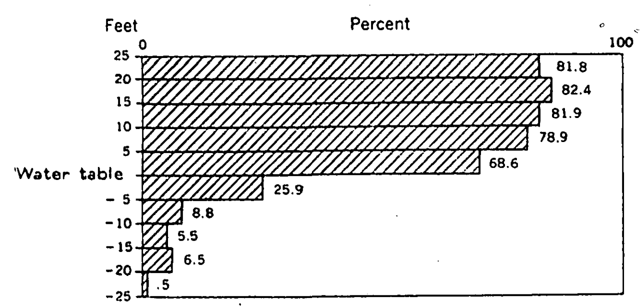


FIGURE 11.—Proportion of copper soluble in dilute acid (roughly the proportion of copper present as carbonates and silicates) to total copper. Based on analyses of 22 diamond-drill cores, using the boundary between oxidized and sulfide ore as the datum.

during the later erosion cycle) and in much smaller amounts in depth. The question thus arises as to whether this young chalcocite represents material transferred downward by meteoric waters or whether it, like the overlying carbonates, developed essentially in place.

Any impoverishment of the oxidized zone or enrichment of the top of sulfides that may have occurred is inconspicuous. However, as it is difficult to conceive that weathering could occur without some downward migration of copper in solution, it was decided to test the question statistically.

The younger weathered zone and the underlying sulfide zone, both in productive and unproductive ground, had been penetrated by 185 diamond-drill holes. The cores from these holes were assayed by the Phelps Dodge Co. at intervals of 0 to 5, 5 to 10, 10 to 15, 15 to 20 and 20 to 25 feet above the transition from oxidized to sulfide ground and at similar intervals below the transition. Although the detailed information remains confidential, it may be said that only one of the 5-foot intervals above the transition was as high in copper as the poorest of the five intervals below the transition, though the differences were measured in only a few hundredths of 1 percent. When the assays were grouped for the two 25-foot zones, the difference in mean tenor was 0.08 percent of Cu, the sulfide zone being the richer. A rough computation of the data, kindly made for me by Parker D. Trask, of the Federal Geological Survey, shows that the probable error of each of these means is about 0.027 ± 0.003 percent and that the probable error of their difference lies between 0.023 and 0.029 per cent. As the difference of the means is 0.08 percent, which is between 2.8 and 3.5 times the probable error of the difference, one is justified, on statistical grounds, in saying that the chances are at least 20 to 1 that this difference in mean tenor is significant of some supergene enrichment.[11] However, the enrichment is of academic rather than economic interest for the deposit as a whole. It has probably nearly all gone on in the rather pyritic area on the east side of the ore body.[12]

Although it is concluded that there has been some supergene enrichment of the ore body in the present cycle of erosion, it may be pointed out that quantitatively this enrichment must be wholly inadequate to account for the presence of as much as 10 percent of chalcocite among the sulfides in the enriched zone, and probably for not as much as 5 percent, taking into account the high copper tenor of chalcocite as contrasted with bornite and chalcopyrite. Hence, if the mineralogic analyses of mill heads shown in figure 10 are to be taken at their face value, much of the high chalcocite content represents copper transformed from chalcopyrite or bornite to chalcocite in place, without migration. Although this may be true, it seems more reasonable to conclude that the mineralogic analyses, which were carried out by grain counting, were in error. As chalcocite generally coats the primary sulfides as thin films before replacing the interior of the grains, its quantity is almost sure to be exaggerated when estimated by this method.

The oxidized zone over most of the ore body was stained brown with "limonite," in contrast with the red hematitic zone formed in pre-Locomotive time. Furthermore, malachite is present in much higher proportion in the younger weathered zone than in the older.

The mineral transformations that have taken place in the zone of oxidation are complex, and probably there have been reversals among them. Judging from crustification, however, it seems that azurite, where present, commonly is older than malachite, to which it appears to alter. Malachite, however, is locally altered to azurite, though more commonly it seems to be changing to copper pitch and then to chrysocolla. Beidellite and nontronite have been found as crusts on both malachite and chrysocolla, but these minerals may owe this position to mechanical transport by rainwash from higher parts of the deposit rather than to formation from solutions in place. Quartz, however, seems definitely to have been

[11] Chaddock, R. E., Principles and methods of statistics, p. 241. New York, 1925.

[12] Joralemon, I. B., op. cit., pp. 603-604.

deposited from solution as coatings on chalcocite and malachite. Jarosite locally forms crusts on hematite, and gypsum on calcite, showing the effects of sulfate-bearing solutions, but the scarcity of these minerals in oxidized ore shows that not much sulfate was present.

CAUSES OF CONTRASTED WEATHERING IN PRE-LOCOMOTIVE AND RECENT TIME

Whether the factors that determined the marked differences in the weathering of the ore body in pre-Locomotive and Recent time were mainly climatic or mineralogic cannot be determined. If one assumes that the material removed by erosion in pre-Locomotive time was essentially identical with that eroded in Recent time, it seems necessary to postulate control by climatic differences during the two epochs, but, as most of the pre-Locomotive topography and much of the ore body have been removed by erosion, it cannot be shown that the primary mineralization was so uniform as to require this postulated difference. Nor is it clear what climatic factors could be considered an explanation of the differences. The less-hydrous minerals found in the oxidized zone of the pre-Locomotive cycle, as compared to those in the Recent zone, suggest a higher temperature and perhaps even a lower rainfall than that of the Recent weathering. However, the original minerals of the pre-Locomotive cycle may have been dehydrated by prolonged exposure or by burial (and consequent higher temperatures) beneath the Locomotive fanglomerate, Ajo volcanics, and perhaps still other formations. Accordingly, it seems that no satisfactory basis exists for evaluating any climatic factors that may have operated to bring about the differences.

The apparent localization of notable leaching and supergene enrichment in the Recent cycle in the area where pyrite is relatively more abundant suggests that the proportion of pyrite may be the controlling factor. This corresponds, also, with general experience in other areas and with experimental work as it is commonly interpreted.[13] If this hypothesis is adopted, one must conclude that proportionately more pyrite was present in the rocks eroded from the ore body in pre-Locomotive time than in those eroded in Recent time. Small amounts of pyrite are apparently more widely distributed at Ajo than the cupriferous minerals. It is thus possible that the peripheral, less-cupriferous part of the original ore body, like that now exposed along the east side of the mine, was more pyritic than the part of the ore body now exposed in the main part of the mine. Such relatively pyritic parts now eroded might have supplied the acid necessary for the early enrichment, whereas, during the later erosion cycle the exposed material was in the central part of the deposit where pyrite is relatively less abundant. The lack of opportunity for adequate study of the oxidized ore or capping formed in both erosion cycles does not justify elaborate discussion of these possibilities. The oxidized ore of pre-Locomotive age is maroon in color, probably because of the dominance of hematite, whereas that of recent origin is reported to have been chiefly brown.[14] The leached capping over the pyritic ore at the east side of the ore body is reddish. This parallelism between the weathered zones overlying enriched ore of both cycles may indicate parallelism in chemical control, but there is little or no basis for preferring this suggestion over that of climatic control.

It is of interest, though the significance is obscure, that the supergene enrichment of the copper deposits of Ray and Miami, Ariz., occurred prior to the deposition of the Whitetail conglomerate and has no relation to the recent cycle or ground-water conditions.[15]

MINERALOGY

MINERALS FOUND IN THE AJO MINING DISTRICT

The minerals found in and close to the ore bodies at Ajo are listed below in the order followed in Dana's "System of Mineralogy." Notes on their occurrence are given in the section following.

Species	Composition
Gold	Au
Silver	Ag
Copper	Cu
Molybdenite	MoS_2
Chalcocite	Cu_2S
Sphalerite	ZnS
Covellite	CuS
Bornite	Cu_5FeS_4
Chalcopyrite	$CuFeS_2$
Pyrite	FeS_2
Tetrahedrite	$3Cu_2S.Sb_2S_3$
Tennantite	$3Cu_2S.As_2S_3$
Halite	NaCl
Quartz	SiO_2
Opal	SiO_2,nH_2O
Stibiconite	$H_2Sb_2O_5$
Cuprite	Cu_2O
Melaconite	CuO
Copper pitch	Mixture of Cu, Fe, and Mn oxides with water
Hematite	Fe_2O_3
Ilmenite	$FeTiO_3$
Magnetite	Fe_3O_4
Rutile	TiO_2
Brookite ?	TiO_2
Goethite	$Fe_2O_3.H_2O$
"Limonite"	approximately $2Fe_2O_3.3H_2O$
Psilomelane ?	approximately MnO_2+H_2O
Calcite	$CaCO_3$
Dolomite	$CaCO_3.MgCO_3$

[13] Emmons, W. H., The enrichment of ore deposits: U. S. Geol. Survey Bull. 625, pp. 55-56, 91-92, 106-128, 1917. Locke, Augustus, Leached outcrops as guides to copper ore, pp. 37-38, Baltimore, Md., 1926.

[14] Joralemon, I. B., op. cit., pp. 601-602, 1914.

[15] Ransome, F. L., The copper deposits of Ray and Miami, Ariz.: U. S. Geol. Survey Prof. Paper 115, pp. 147, 173, 174, 1919.

Species	Composition
Ankerite	$CaCO_3.(Mg,Fe)CO_3$
Malachite	$CuCO_3.Cu(OH)_2$
Azurite	$2CuCO_3.Cu(OH)_2$
Orthoclase	$K_2O.Al_2O_3.6SiO_2$
Microcline	$K_2O.Al_2O_3.6SiO_2$
Plagioclase	$m(Na_2O.Al_2O_3.6SiO_2)$ $n(CaO.Al_2O_3.2SiO_2)$
Actinolite	$Ca_2(Mg,Fe)_5(OH)_2(Si_4O_{11})_2$
Hornblende	Complex silicate of Ca, Mg, Fe, Al, and H_2O
Zircon	$ZrSiO_4$
Topaz	$[Al(F,OH)]_2SiO_4$
Andalusite	$Al_2O_3.SiO_2$
Clinozoisite	$Ca_2(AlOH)Al_2(SiO_4)_3$
Epidote	$mCa_2(AlOH)Al_2(SiO_4)_3$ $nCa_2(FeOH)Fe_2(SiO_4)_3$
Tourmaline	Complex borosilicate of Al, Mg, Fe, H, and F
Muscovite (sericite)	$H_2KAl_3(SiO_4)_3$
Biotite	$H_2K(Mg,Fe)_3Al(SiO_4)_3$
Chlorite	Complex silicates of Al, Mg, Fe, and H
Beidellite	$(Al,Fe)_2O_3.3SiO_2.4H_2O$
Potash-bearing clay	Hydrous Al-silicate with K_2O
Nontronite	Hydrous silicate of Fe and Al
Chrysocolla	$CuO.SiO_2.nH_2O$
Sphene (titanite)	$CaO.TiO_2.SiO_2$
Apatite	$Ca(F,Cl)Ca_4(PO_4)_3$
Pyromorphite	$(PbCl)Pb_4(PO_4)_3$
Mottramite	$2PbO.2CuO.V_2O_5.H_2O$
Planerite	$3Al_2O_3.2P_2O_5.10H_2O$
Barite	$BaSO_4$
Anhydrite	$CaSO_4$
Brochantite	$CuSO_4.3Cu(OH)_2$
Gypsum	$CaSO_4.2H_2O$
Epsomite	$MgSO_4.7H_2O$
Bieberite	$CoSO_4.7H_2O$
Alunite	$K_2Al_6(OH)_{12}(SO_4)_4$
Jarosite	$K_2Fe_6(OH)_{12}(SO_4)_4$

FEATURES OF OCCURRENCE

GOLD

Native gold is found in small amounts in the gravels of Cornelia Arroyo. It is evidently derived from the oxidized portion of the New Cornelia ore body, in which the gold content averages about 0.0067 ounce per unit of copper. The gold in the sulfide ore has not been seen, but the close parallelism in the ratios of recovered gold to total gold and of recovered copper to total copper indicates that the gold is more closely associated with the copper sulfides than with the subordinate pyrite of the ore body.

SILVER

Silver is present in the sulfide ores of the New Cornelia mine in the proportion of about 0.075 ounce to the unit of copper. No silver-bearing mineral has been recognized during the microscopic examination of the ores, and nothing is known of the mineral species in which the silver is present. The recovery ratio of the silver is slightly closer to that of the copper than is the recovery ratio of the gold; accordingly, the close association of silver with the cupriferous minerals is even more likely than that of gold. In the earlier years of sulfide concentration the silver-gold ratio was considerably higher than in later years. Perhaps this was due to the occurrence of supergene silver with the supergene chalcocite in the upper part of the sulfide ore body. Gold would not be expected to migrate downward even to the small extent that copper has, and accordingly, in the zone of supergene chalcocite it might be expected to be somewhat lower proportionately to the copper and silver than in the hypogene and oxidized ore.

COPPER

Native copper was found in small wires and irregular particles at the surface near the south side of the ore body. It is present in drill cores from more and more southerly localities at depths that increase to altitudes well below sea level. These sparse metallic blebs, associated with hematitic rock and more or less cuprite, are invariably closely beneath the erosion surface upon which the Locomotive fanglomerate was deposited. They record an old weathered zone that has been buried and later tilted to steep angles. Doubtless all the native copper was formed by oxidation of older sulfides near the bottom of the oxidized zone at the time of its formation. It has remained stable through all the later episodes of burial, tilting, and re-exposure.

MOLYBDENITE

Molybdenite is present in small gray plates that have a metallic luster and perhaps more commonly as smears on slickensided joints. It is widely distributed in the ore body (see pl. 27, A), but apparently, to judge by inspection, in amounts of less than 0.1 per cent by weight.

Where it occurs in vugs and open fissures it locally appears to rest on euhedral chalcopyrite and quartz and to be coated by quartz, but the observations were too few to establish this sequence as the usual one; in one specimen the molybdenite rests on quartz and is partly coated by chalcopyrite. In view of the relative ease of recovery, there is a possibility that the molybdenite, though present only in small amount, might be economically extracted from the New Cornelia ore as it has been at Bingham, Utah, but up to the time of this survey this had not been attempted.

CHALCOCITE

Unlike most of the other "porphyry coppers" of the Southwest, the Ajo ore body contains only relatively small amounts of chalcocite. A little occurs locally just below the oxidized zone over the whole ore body. However, the very slight difference in tenor between the sulfide and carbonate ores is evidence that there has been very little downward migration of copper, so that only a small though appreciable amount of typical sooty chalcocite was found in this setting. Figure 10, which represents the mineralogical analysis of the Phelps Dodge concentrator flotation feed, shows a fairly continuous decline in the proportion of chalcocite in the total sulfides at the mill heads—from 18 percent in 1924, when the sulfides came almost wholly from the top of the sulfide zone, to less than 2 percent in 1931, when they came from an average depth of about 50 feet below the top. This decline seems clearly to prove that chalcocitization of the sulfides has occurred in the present erosion cycle; how much downward transport of copper has accompanied this mineralogic change, however, cannot be determined, though it must be small. (See pl. 26 and pp. 84-85.)

Most of the chalcocite occurs beneath the tilted zone of weathering that underlies the Locomotive fanglomerate. When weathering was taking place in this zone, conditions were evidently more favorable to supergene enrichment than they were in the recent past, because local veinlets of copper glance (not sooty chalcocite, though definitely associated with supergene minerals and probably also supergene) as much as 3 inches thick were formed in the footwall of this weathered zone. In places, these veins are sufficiently numerous to raise the tenor of ore as high as 5 percent, and much of the early mining prior to the large-scale operations was restricted to them. Some ore was shipped from this high-grade zone as recently as 1929. A little sooty chalcocite accompanies the veins of copper glance. This represents largely the alteration of disseminated chalcopyrite and bornite in place.

SPHALERITE

Sphalerite is uncommon at Ajo. It was seen in small quantities in relations that suggest that it was formed by replacement of preexisting pyrite. In one specimen it is cut by veinlets that contain chalcopyrite and bornite. As sphalerite in many other localities was formed at a time intermediate between the formation of pyrite and that of chalcopyrite, it seems reasonable to suppose that, despite the very small amount of sphalerite present, the same relation obtains here.

COVELLITE

The blue cupric sulfide of copper, covellite, occurs as minute blebs in some of the copper glance veinlets near the south side of the ore body at Ajo. It also forms a thin sheen on chalcopyrite in many places but is not present in large amount. As an ore mineral it is negligible.

BORNITE

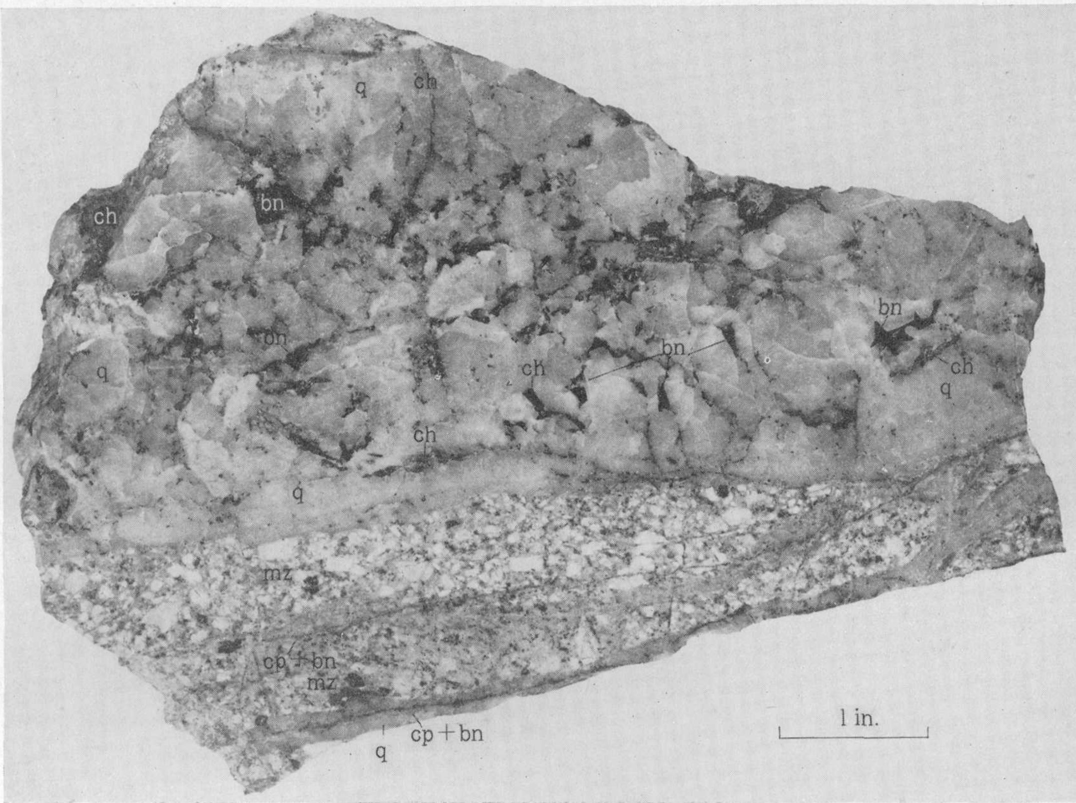
Bornite next to chalcopyrite is the most abundant copper mineral at Ajo. Like chalcopyrite, it occurs mostly as minute grains and stringers through the Cornelia quartz monzonite; in places it forms veins as much as an inch thick that branch through the rock. (See pls. 7, 8, *B*, 9, *A*, *C*.) It is chiefly of hypogene origin and in some specimens is clearly older than chalcopyrite, which veins it. Nevertheless, some of it is probably supergene and represents an early stage in the weathering of chalcopyrite, as is suggested by the diminishing proportion of bornite among the sulfides in the mill heads. (See fig. 10.) According to the analysis (by grain counting) of mill feed, the bornite content was 30 percent of the total sulfides in the first year of operation of the concentrator, when the ore came almost wholly from the very top of the sulfide zone. It has since decreased, on the same basis, to about 6 percent of the total sulfides in the mill feed. Probably some of the "bornite" of the early years was merely a superficial film tarnishing chalcopyrite, so that the actual change has probably been less than these figures would indicate, but it seems clear that bornite is less abundant as depth is gained. The deepest drill holes, however, have yielded some bornite.

Although some of the bornite is older than some of the chalcopyrite, it is equally certain that some is younger than chalcopyrite and derived from it by the breaking down of the older mineral into hematite and bornite. Several specimens show chalcopyrite grains surrounded or veined by bornite in which are embedded many plates of specularite. This is almost surely due to hypogene alteration, as is discussed on page 81. It is likely that a comparable change may be brought about by supergene solutions, and it may be that some of the bornite is of this origin, but it seems unlikely that coarse-bladed specularite is so formed.

CHALCOPYRITE

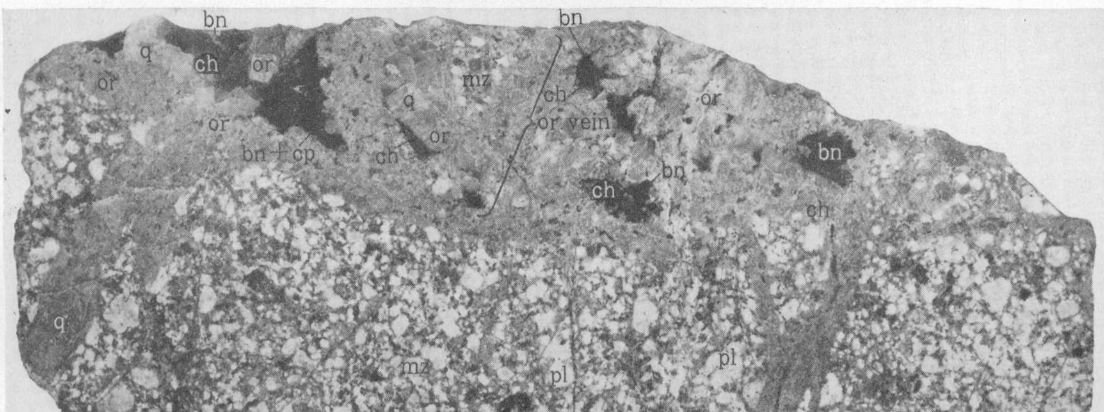
Chalcopyrite is the overwhelmingly dominant copper mineral at Ajo. In this respect the Ajo deposit is unique among the large copper mines of the Southwest. As seen in figure 10, the relative proportion of chalcopyrite among the sulfides has increased from 50 percent to 90 percent as the mine has been deepened below the weathered zone. By far the largest part of the chalcopyrite is clearly hypogene, though there may have been some slight enrichment by supergene waters.

The chalcopyrite is present as veinlets cutting orthoclase, quartz, magnetite, pyrite, hematite, bornite, sphalerite, and molybdenite. (See pls. 7, *B*, 8, 9, 10, *A*, *D*.) It is in turn locally cut by hematite veinlets, bornite, sericite, and chalcocite. In some vugs molybdenite crystals rest on euhedral chalcopyrite and are in turn coated by chalcopyrite. Chalcopyrite also occurs in what appear to be discrete, isolated grains in the monzonite, but so large a proportion is definitely veining the monzonite along clean fractures with matching walls (see pls. 14, *E*, *F*, 15, *E*, *F*, 16, *C*) that it seems chiefly to have formed as cavity filling and only subordinately by replacement. There has been, however, some replacement of silicates by chalcopyrite. (See pls. 15, *C*, *D*, and 16, *A*, *B*.) Certainly it was localized by the more open channels in the rocks.



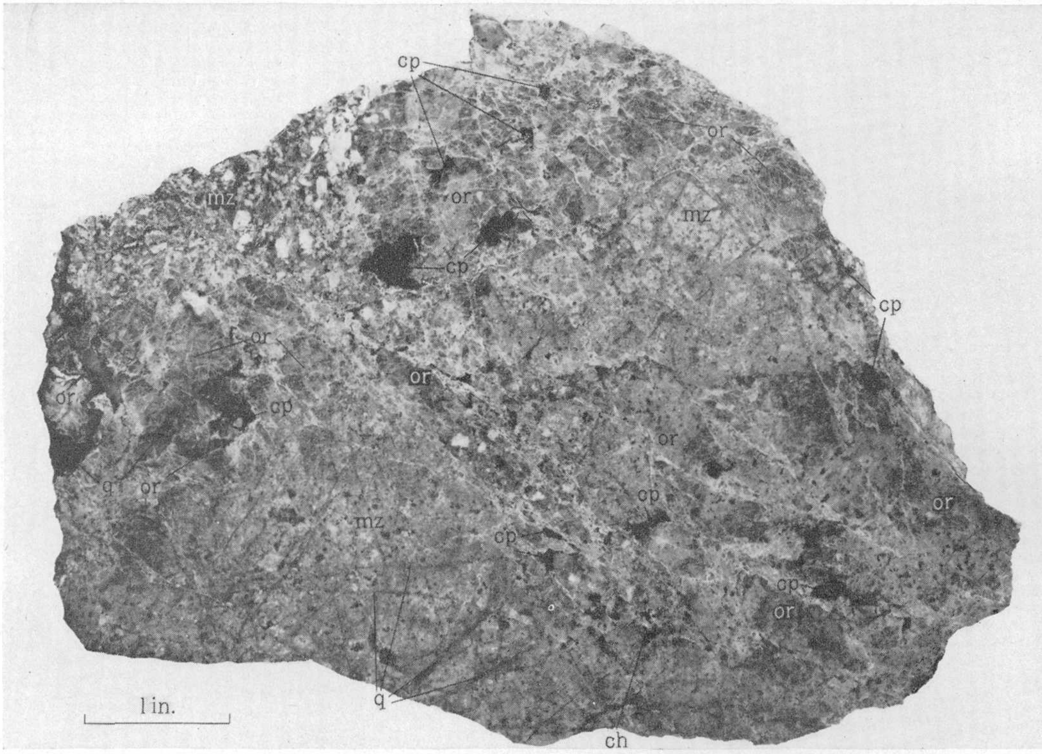
A. HAND SPECIMEN, CORNELIA QUARTZ MONZONITE.

Quartz vein shows some suggestion of comb structure. mz, Monzonite; q, quartz; ch, chlorite; bn, bornite; cp, chalcopyrite. New Cornelia mine.



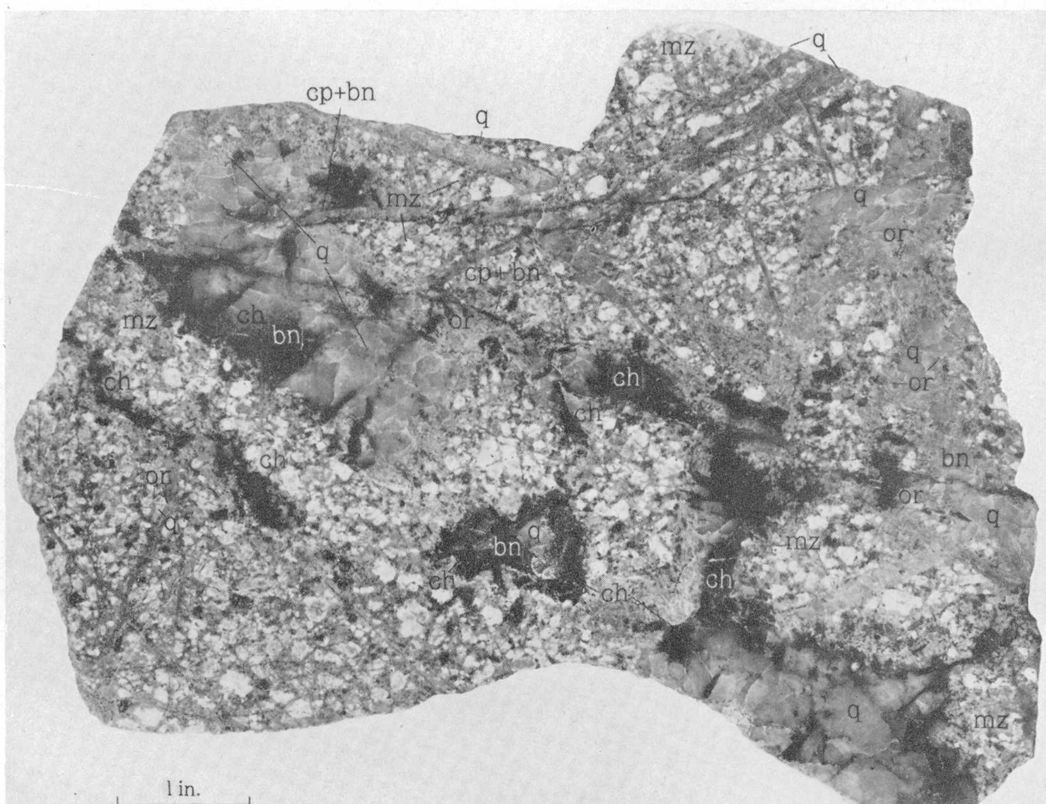
B. QUARTZ VEINS IN CORNELIA QUARTZ MONZONITE (mz), APPARENTLY CUT OFF BY REPLACEMENT VEINS (PEGMATITE) OF MICROCLINE OR ORTHOCLASE (or), QUARTZ (q), AND CHLORITE (ch), WITH SOME BORNITE (bn) AND A LITTLE CHALCOPYRITE (cp).

pl, Plagioclase. New Cornelia mine.



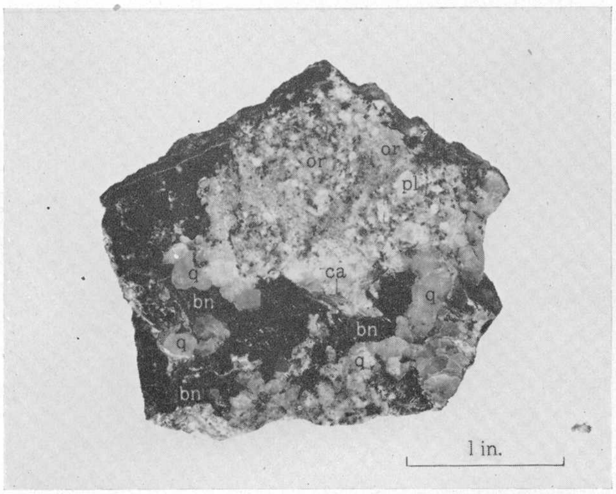
A. FRACTURED MONZONITE (mz), WITH VEINLETS OF QUARTZ (q) AND REPLACEMENT MASSES OF ORTHOCLASE AND PROBABLY SOME MICROCLINE (or).

Chlorite (ch) veins the feldspar and is accompanied by blebs of chalcopyrite (cp) and bornite. New Cornelia mine.



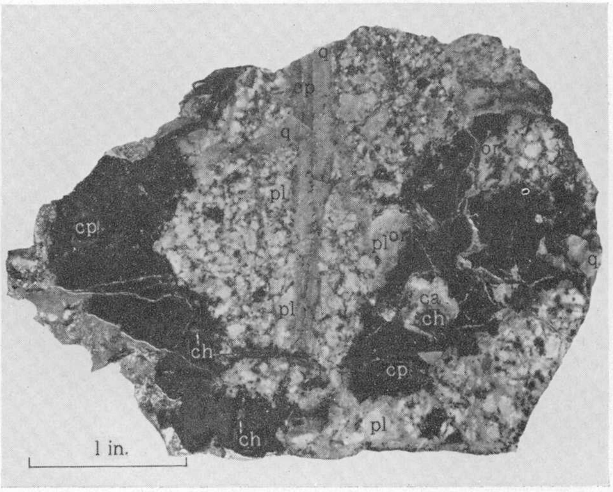
B. QUARTZ MONZONITE (mz) PARTLY REPLACED BY MICROCLINE OR ORTHOCLASE (or) AND QUARTZ (q), WITH CHLORITE (ch) IN VEINS AND ROSETTES AND A LITTLE CHALCOPYRITE (cp) AND BORNITE (bn).

The quartz is commonly central to the feldspar veins, and the sulfides show some tendency to follow cracks younger than the chlorite. New Cornelia mine.



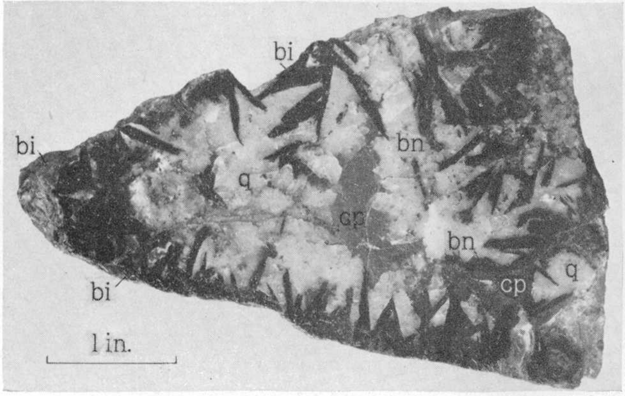
A. QUARTZ MONZONITE, WITH MUCH REPLACEMENT MICROCLINE OR ORTHOCLASE (or), VEINED BY QUARTZ (q), WITH LEAFY CHLORITE (ch), BORNITE (bn), AND CHALCOPYRITE (cp).

Calcite (ca) fills druses. pl, Plagioclase. Pegmatitic part of New Cornelia ore body.



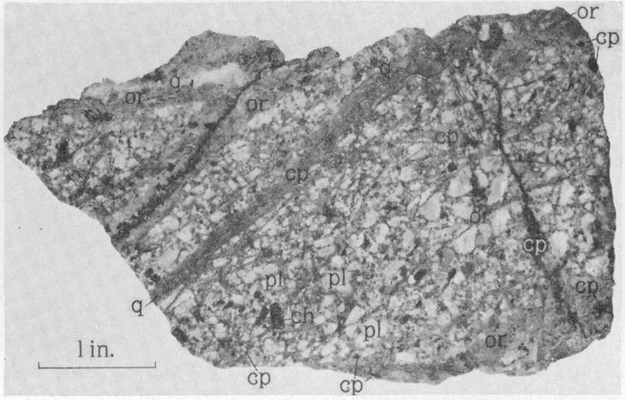
B. BRECCIATED PORPHYRITIC MONZONITE WITH RESIDUAL SERICITIZED PLAGIOCLASE (pl) IN A GROUNDMASS OF CHLORITE (ch), QUARTZ (q), AND ORTHOCLASE OR MICROCLINE (or).

Vein orthoclase, possibly including some microcline, borders the breccia fragments. These are cut by quartz veins and bordered by leafy chlorite, which has been in part replaced, along with the rest of the rock, by chalcopyrite (cp) and a little bornite. Calcite (ca) coats vugs lined by chalcopyrite and is apparently the youngest mineral of the specimen. Pegmatitic facies of the New Cornelia ore body.



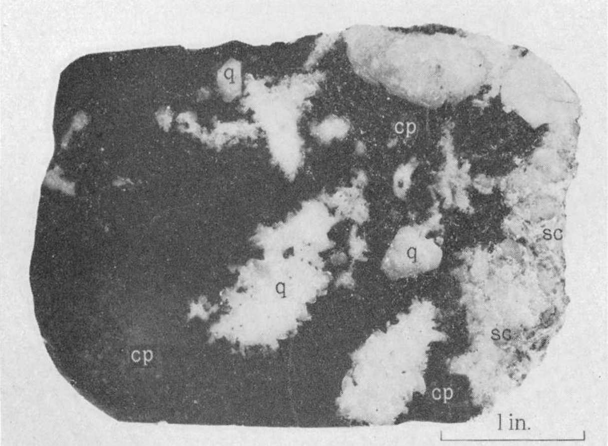
C. CAST OF A VUG IN BRECCIATED PEGMATIZED QUARTZ MONZONITE.

The vug was coated with blades of biotite (bi), the interstices between which are occupied by quartz (q) that is veined and in part replaced by chalcopyrite (cp) and bornite (bn). In small part the biotite has been chloritized. Pegmatitic facies, New Cornel'a ore body.



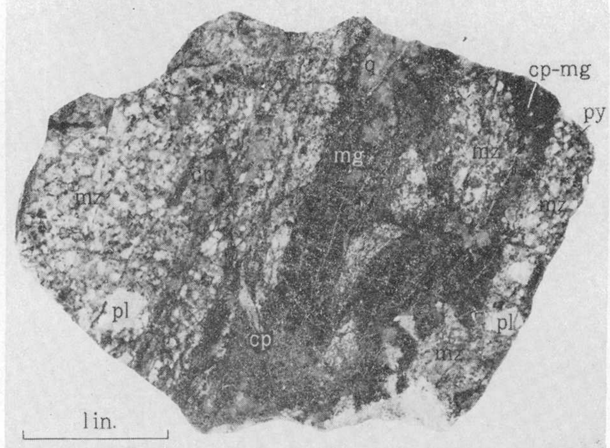
D. BRECCIATED QUARTZ MONZONITE VEINED WITH PINK ORTHOCLASE OR MICROCLINE (or), THEN CUT BY QUARTZ VEINS (q), SOME WITH COMB QUARTZ, FOLLOWED BY CHALCOPYRITE (cp), WHICH VEINS THE ROCK, COATS COMB QUARTZ, AND IN PART HAS REPLACED THE ORTHOCLASE AND CHLORITE (ch).

pl, Plagioclase. Pegmatized facies, New Cornelia mine.



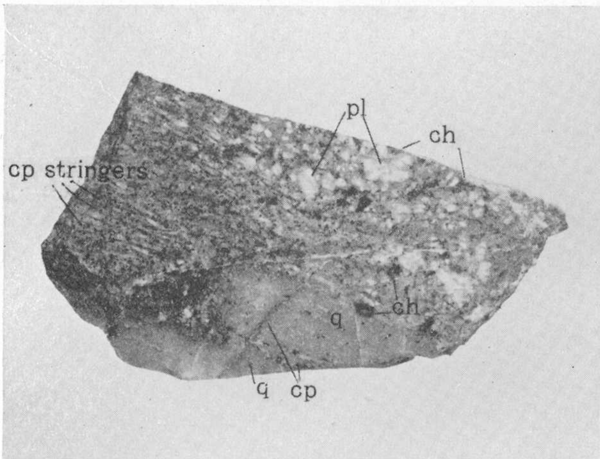
E. EXCEPTIONALLY HIGH-GRADE CHALCOPYRITE (cp) ORE.

A quartz mass (q) shows some evidence of replacement by chalcopyrite, though more of the chalcopyrite fills vugs. Shows euhedral quartz crystals and veining of the quartz by sericite (sc). New Cornelia mine.



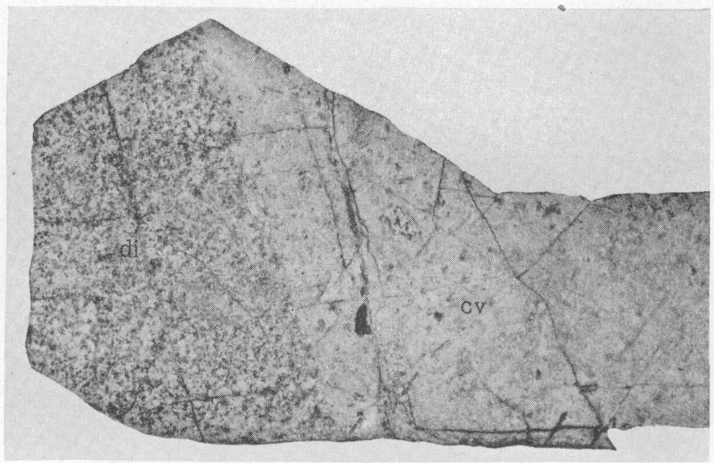
F. QUARTZ MONZONITE (mz) FROM SOUTH CENTER, NEW CORNELIA MINE, 1,725-FOOT LEVEL.

Shows replacement vein of magnetite (mg) and quartz (q) cut by veins of pyrite (py), chalcopyrite (cp), and a little bornite. pl, Plagioclase, largely sericitic.



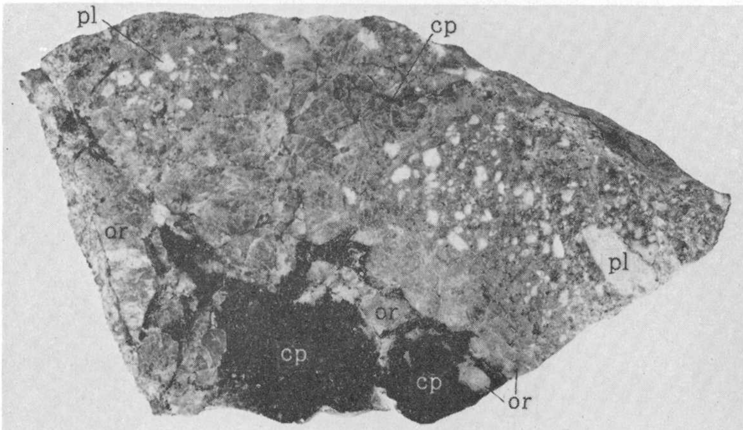
A. ORTHOCLASE-RICH QUARTZ MONZONITE IN PART REPLACED BY MASSIVE QUARTZ (q) AND THE WHOLE CUT BY STRINGERS OF CHALCOPYRITE (cp) AND BORNITE.

pl, Plagioclase; ch, chlorite. New Cornelia mine.



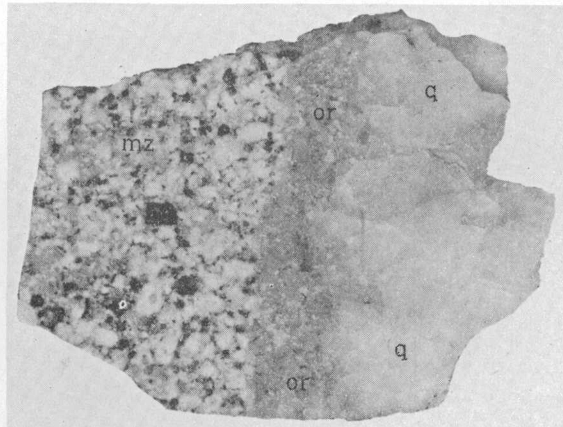
B. POLISHED HAND SPECIMEN SHOWING CONTACT BETWEEN DIORITIC BORDER FACIES OF THE CORNELIA QUARTZ MONZONITE (di) AND THE CONCENTRATOR VOLCANICS (cv).

The contact is distinct but welded. The contrast in appearance of the two rocks is less distinct in rough specimens than appears here.



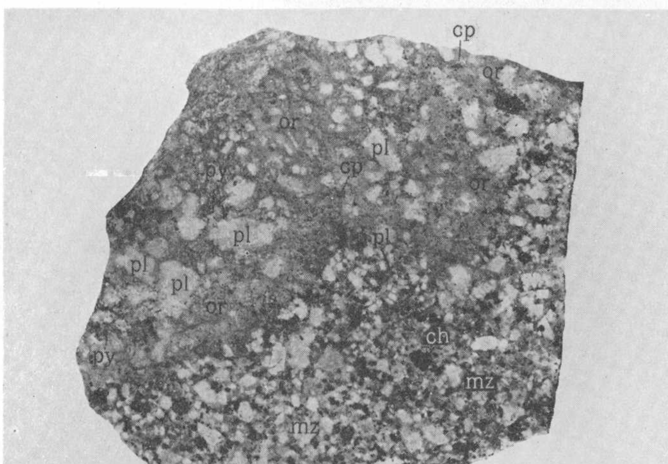
C. HIGH-GRADE PEGMATITIC ORE, NEW CORNELIA MINE.

Quartz monzonite, with sericitized plagioclase (pl) partly replaced by orthoclase with possibly some microline (or) and then veined by and partly replaced by chalcopyrite (cp).



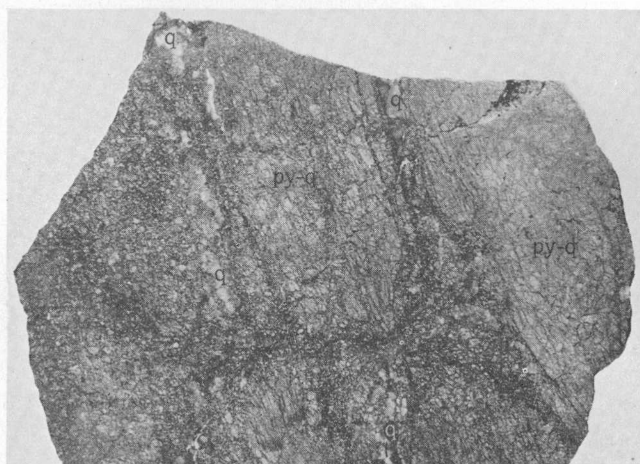
D. ONE SIDE OF A BILATERALLY SYMMETRICAL QUARTZ VEIN IN THE CORNELIA QUARTZ MONZONITE (mz).

Orthoclase (or) occurs as a selvage along the vein, in which the quartz (q) lies centrally and has comb structure (not seen in the photograph). New Cornelia mine.



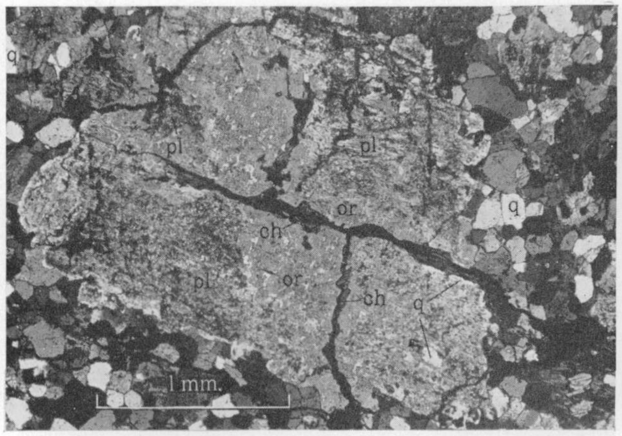
E. QUARTZ MONZONITE (mz), WITH PART OF GROUNDMASS REPLACED BY ORTHOCLASE (or).

Plagioclase (pl) is largely unreplaced, though more or less albitized. Pyrite (py) and chalcopyrite (cp) form blebs in the orthoclase groundmass. ch, chlorite. New Cornelia mine.



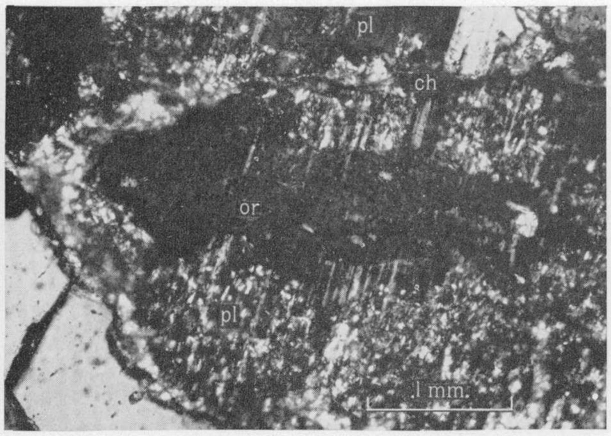
F. REPLACEMENT MASS OF PYRITE AND QUARTZ (py-q) IN CORNELIA QUARTZ MONZONITE.

The mass has been sheared and veined by hematite (hm) and quartz (q). New Cornelia ore body.



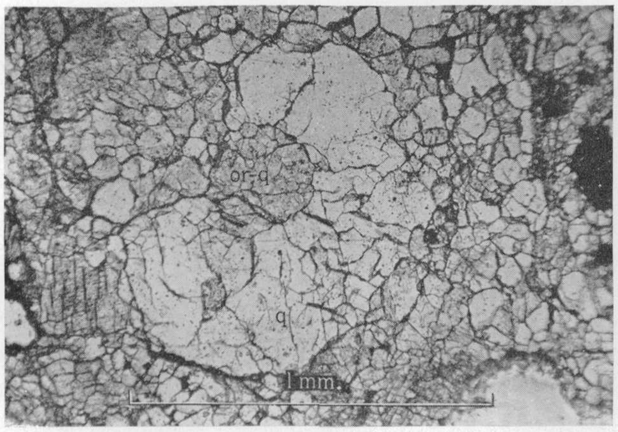
A. CORNELIA QUARTZ MONZONITE FROM A DEPTH OF 50 FEET IN A CORE DRILL HOLE AT NEW CORNELIA MINE.

Sericitic plagioclase (pl) fractured and partly replaced along the fractures by orthoclase (or). The fractures are occupied by chlorite (ch). q, Quartz. Plane-polarized light.



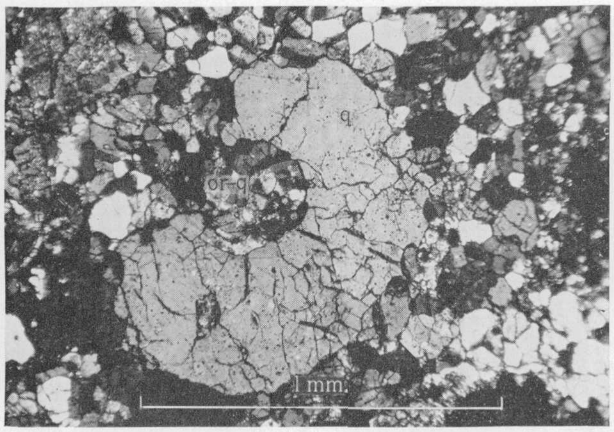
B. CORNELIA QUARTZ MONZONITE FROM A DEPTH OF 600 FEET IN A CORE DRILL HOLE AT NEW CORNELIA MINE.

Sericitic plagioclase (pl) partly replaced by orthoclase (or). Fracture filled by chlorite (ch). Crossed nicols.

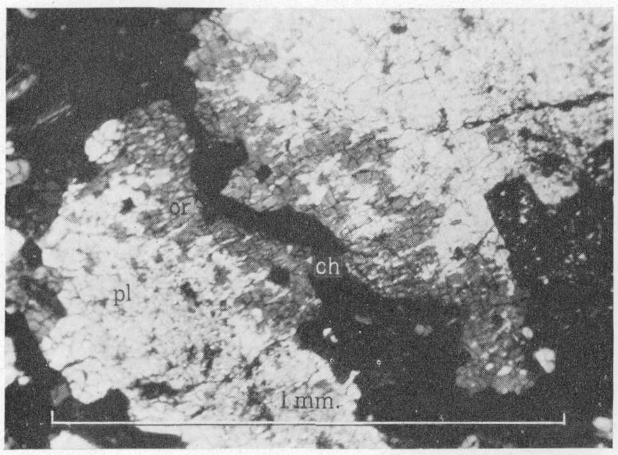


C. MONZONITE FROM DIAMOND DRILL CORE IN THE NEW CORNELIA ORE BODY.

Shows a rounded phenocryst of quartz (q) embayed and corroded by fine-grained orthoclase and quartz (or-q). A little calcite replaces part of the quartz along a crack. Plane-polarized light.

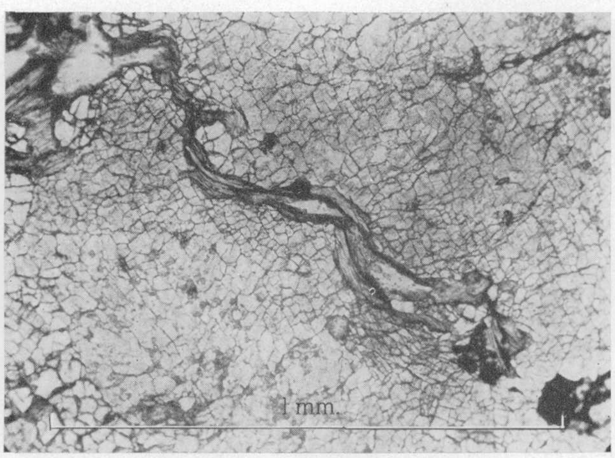


D. SAME AS *A* BUT WITH CROSSED NICOLS.



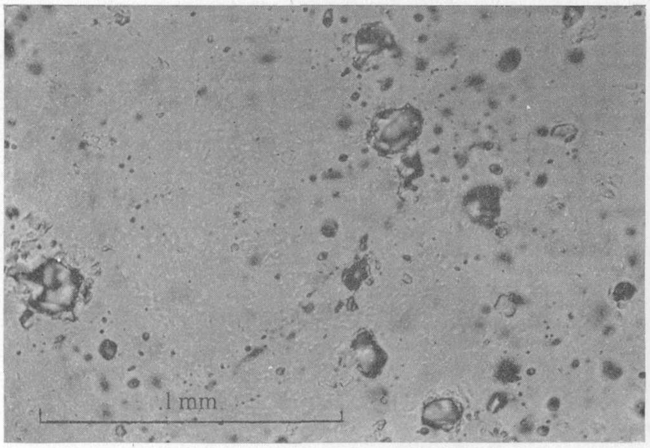
E. CORNELIA QUARTZ MONZONITE FROM THE NEW CORNELIA ORE BODY SHOWING SERICITIC PLAGIOCLASE (pl) PARTLY REPLACED, OUTWARD FROM AN IRREGULAR CRACK, BY ORTHOCLASE (or).

The crack is occupied by chlorite (ch) in curved leaves that follow the sinuosities of the break. Crossed nicols.



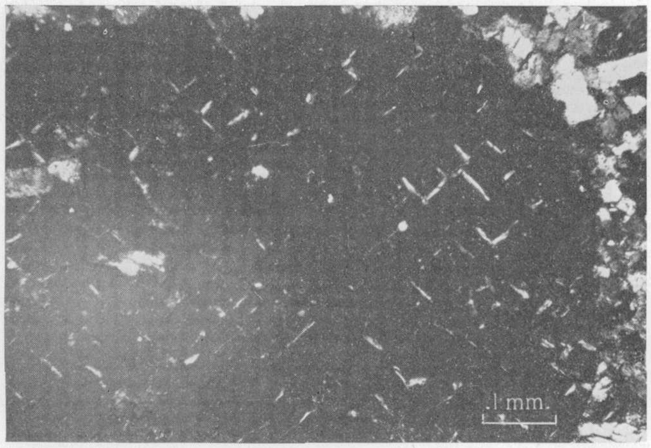
F. SAME AS *A.*

Shows curvature of the leaves of chlorite. Plane polarized light.



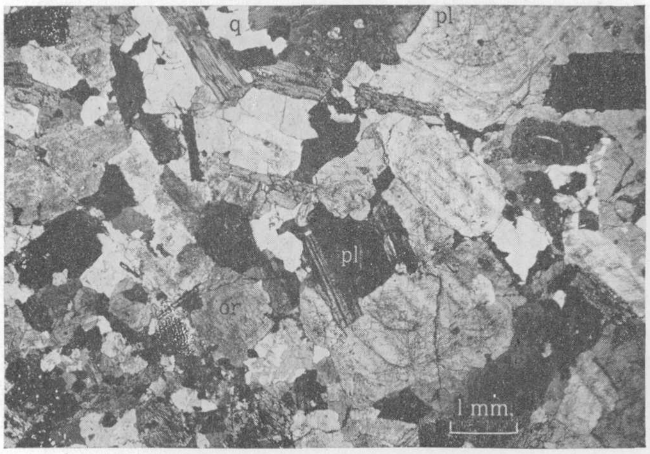
A. QUARTZ IN CORNELIA QUARTZ MONZONITE FROM A DEPTH OF 350 FEET IN A DIAMOND DRILL HOLE, NEW CORNELIA MINE.

Shows inclusions. The light irregular ones appear to be orthoclase. The smaller more or less straight-sided dark inclusions are mostly negative crystals, each filled by a liquid containing a bubble. (See lower and upper left especially.) Although not noticeable in the photograph, the negative inclusions appear commonly to be along lines that extend through several quartz crystals without regard to the boundaries or crystal orientation. Plane-polarized light.



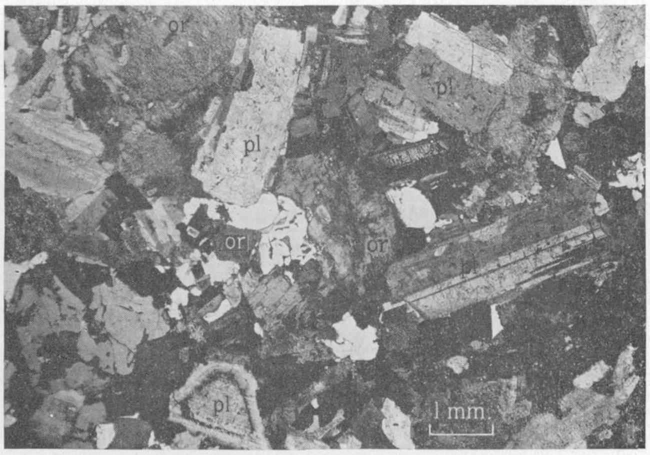
B. QUARTZ IN CORNELIA QUARTZ MONZONITE FROM A DEPTH OF 650 FEET IN A DIAMOND DRILL HOLE AT SOUTH CENTER OF NEW CORNELIA MINE.

Shows rhombic cleavage, with sericite (bright lines) developed along it. Crossed nicols.



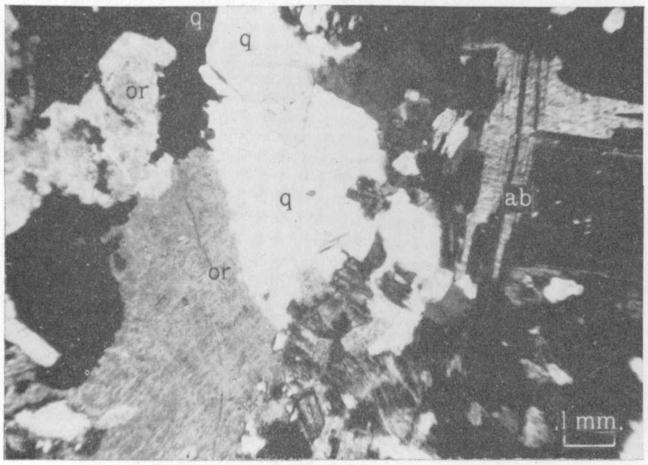
C. "NORMAL-TEXTURED" VARIETY OF CORNELIA QUARTZ MONZONITE WITH SUBHEDRAL PLAGIOCLASE (pl), THE INTERSTICES BETWEEN WHICH ARE FILLED BY QUARTZ (q) AND ORTHOCLASE (or).

A little graphically intergrown quartz and orthoclase in left center. From Camelback Mountain, 2,000 feet from the mineralized area. Crossed nicols.



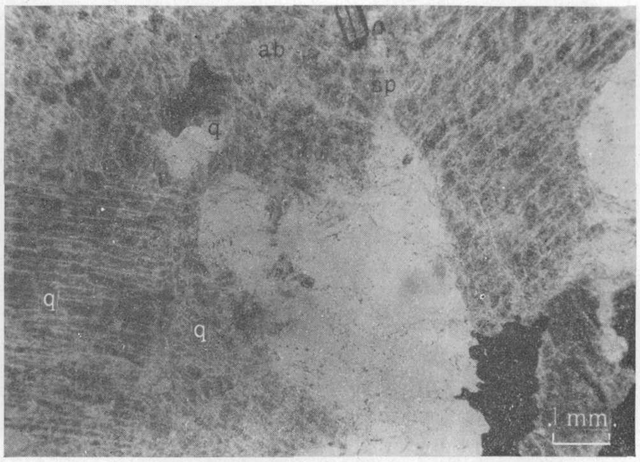
D. CORNELIA QUARTZ MONZONITE FROM CARDIGAN PEAK SHOWING NORMAL MONZONITIC TEXTURE, WITH SUBHEDRAL PLAGIOCLASE (pl) AND ANHEDRAL QUARTZ (q) ENCLOSED IN ORTHOCLASE (or).

A small amount of graphic texture occurs. Crossed nicols.



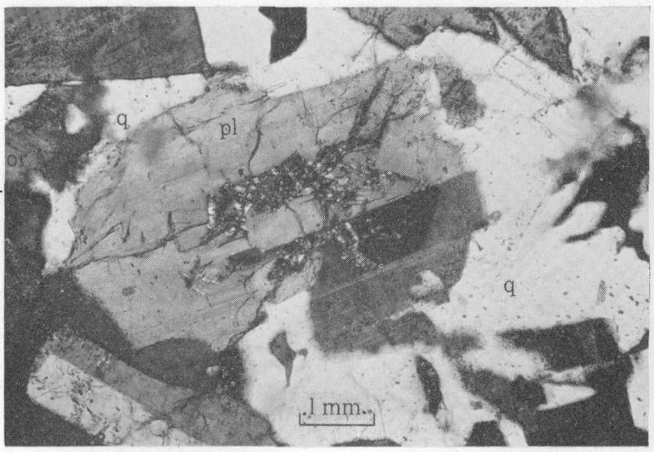
E. CORNELIA QUARTZ MONZONITE FROM CENTER OF COMMON BOUNDARY OF SECS. 16 and 21, T. 12 S., R. 6 W.

Shows replacement of albite (ab) and perhaps orthoclase (or) by quartz (q). A crystal of sphene, upper right, and one of zircon (z) are visible. Crossed nicols.



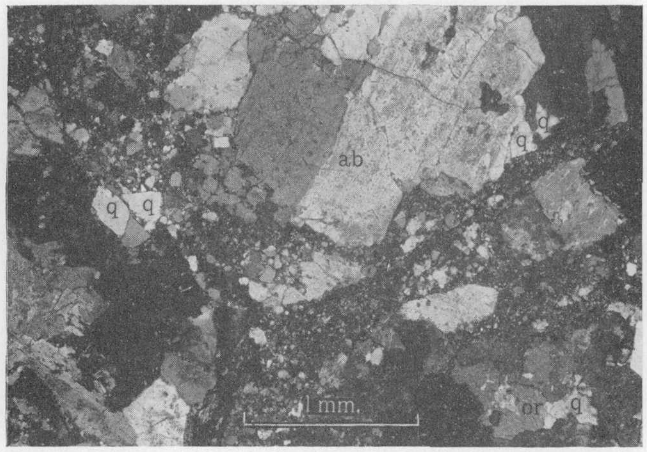
F. SAME AS *A*.

Narrow veinlets of quartz (q) in parallel arrangement in the orthoclase (lower right) recall a perthitic texture. ab, Albite; sp, sphene. Plane-polarized light.



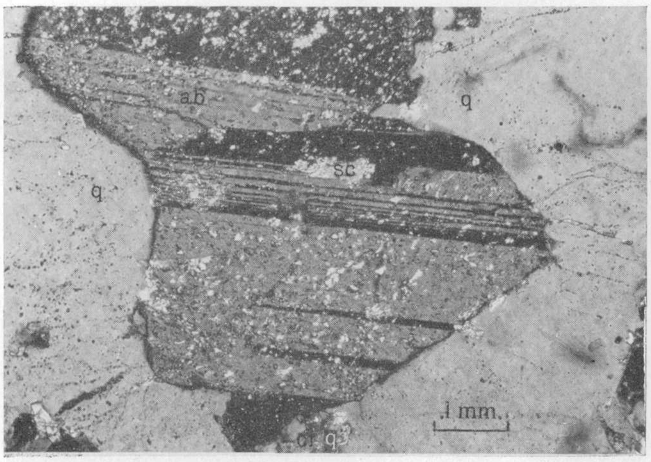
A. CORNELIA QUARTZ MONZONITE FROM NORTH CENTER OF SEC. 21, T. 12 S., R. 6 W.

Shows partial replacement of orthoclase (or) and slightly sericitic plagioclase (pl) by quartz (q) along cracks and borders. sc, Sericite. Interpreted as a late magmatic alteration. Crossed nicols.



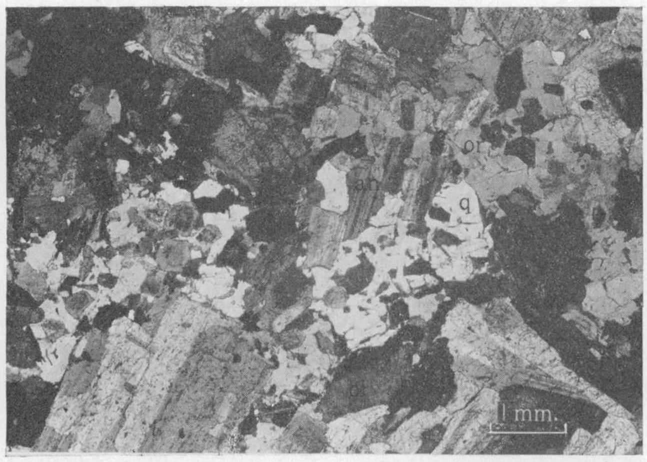
B. QUARTZ MONZONITE FROM GIBSON FAULT ZONE.

Shows breccia zone, broken albitic plagioclase, and quartz (q), which may be in part a replacement of the plagioclase and orthoclase (or). ab, Albite. Crossed nicols.



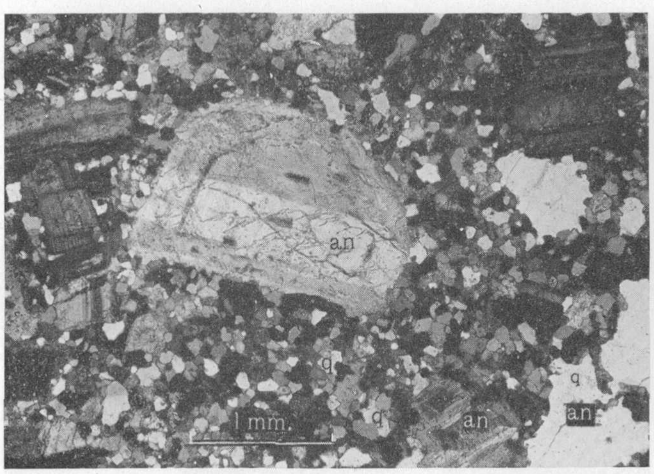
C. QUARTZ MONZONITE ORE.

Shows quartz (q) replacing albitic plagioclase that contains much sericite (sc). Quartz-orthoclase (or) in the groundmass, the whole cut by a very narrow veinlet of calcite (ca). The two separate areas of plagioclase extinguish together on both sets of twins and are probably parts of a single crystal. ab, Albite. From southwest part of 1,725 level, New Cornelia mine. Crossed nicols.



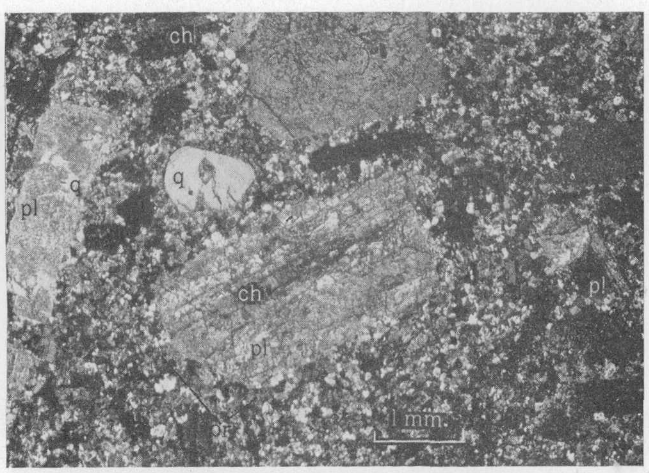
D. CORNELIA QUARTZ MONZONITE FROM NORTHEAST CORNER OF SEC. 20, T. 12 S., R. 6 W., NORTH OF CARDIGAN PEAK.

Shows approach to graphic texture, interpreted as due to late-magmatic or post-magmatic attack of quartz (q) on older andesine (an). The biotite (bi) is practically fresh. or, Orthoclase. This texture is to be contrasted with that in the mineralized parts of the monzonite. (See *E, F.*) Crossed nicols.



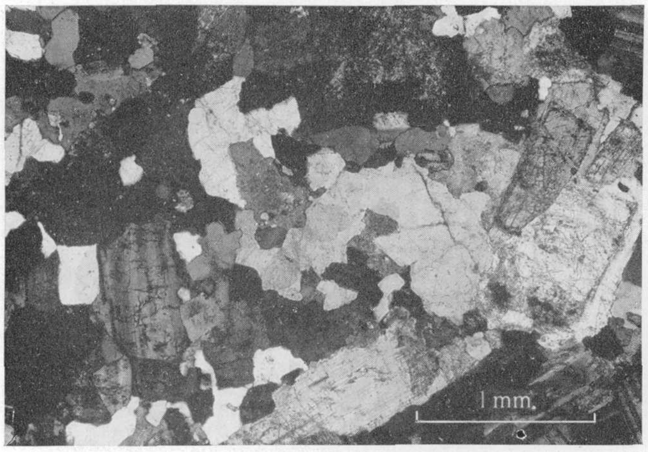
E. CORNELIA QUARTZ MONZONITE FROM A POINT 1,000 FEET NORTHWEST OF THE NEW CORNELIA MINE PIT.

Shows porphyritic texture common near the ore body, with andesine (an) only slightly sericitized and albitized in a groundmass composed of round grains of quartz (q) and orthoclase (or) irregularly indenting the borders of the plagioclase. Biotite in this rock (not seen in photo) is only slightly chloritized. Crossed nicols.



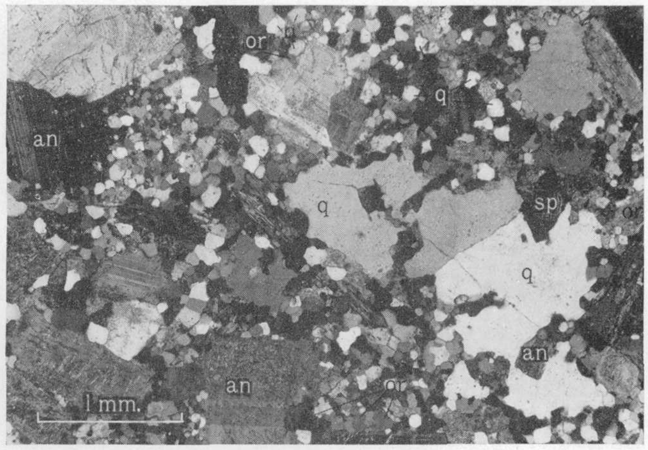
F. CORNELIA QUARTZ MONZONITE FROM A DEPTH OF 650 FEET IN A DIAMOND DRILL HOLE IN SOUTH-CENTRAL PART OF THE NEW CORNELIA PIT.

Shows porphyritic texture, with corroded quartz (q) phenocryst and irregularly bounded sericitic albitized plagioclase (pl) in a groundmass of quartz, orthoclase (or), and chlorite. ch, Rosette of chlorite in plagioclase. Crossed nicols.



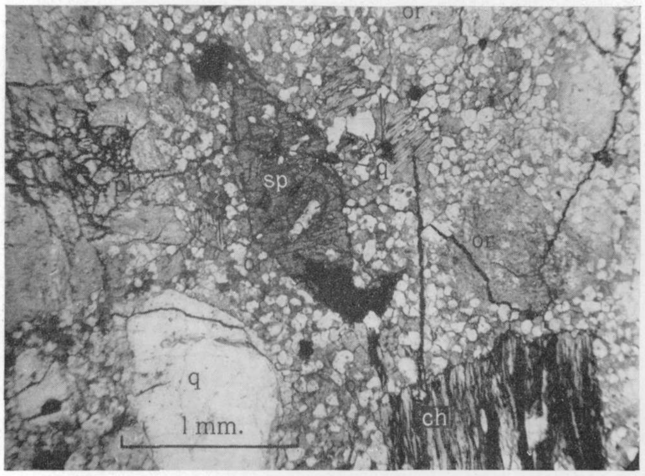
A. CORNELIA QUARTZ MONZONITE FROM 1,500 FEET NORTH-WEST OF NEW CORNELIA MINE PIT.

Shows porphyritic texture and normal granitic groundmass. Compare with groundmass texture common in the mineralized part of the monzonite, as shown in *B* (from 500 feet nearer the mine) and on plate 13, *E*. Crossed nicols.



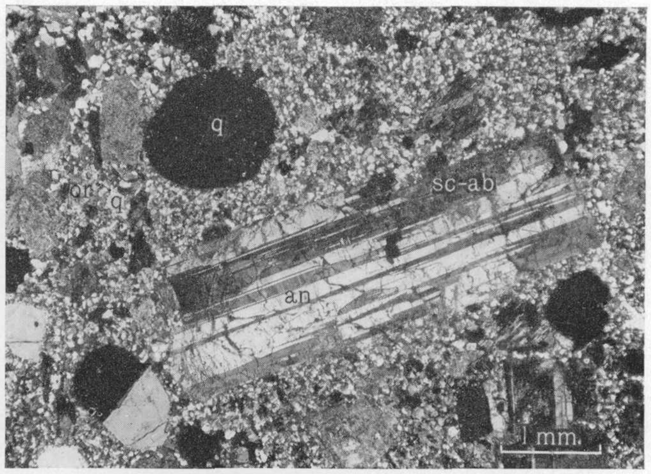
B. CORNELIA QUARTZ MONZONITE FROM 1,000 FEET NORTHWEST OF NEW CORNELIA MINE.

Same specimen as shown on plate 13, *E*. Note development of round, droplike crystals of quartz throughout the interstices between the other grains. Note corrosion of andesine (an) by quartz (q) and orthoclase (or). sp, Sphene. Crossed nicols.



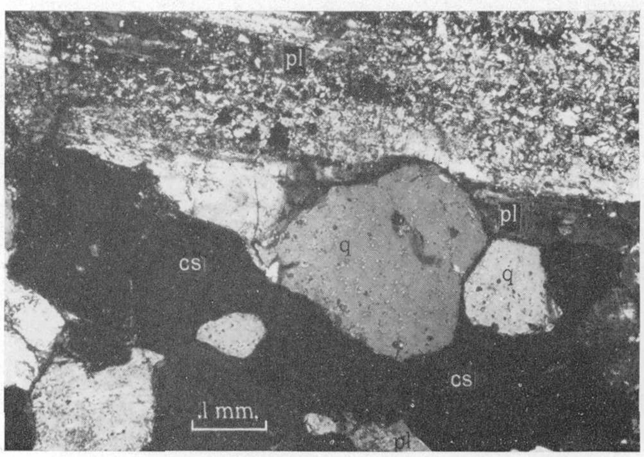
C. CORNELIA QUARTZ MONZONITE FROM DEPTH OF 600 FEET IN CORE DRILL HOLE IN SOUTH-CENTRAL PART OF NEW CORNELIA PIT.

Shows sericitic plagioclase (pl), round quartz phenocryst (q), well-formed sphene (sp), and chlorite after biotite (ch) in a groundmass of round grains of quartz and orthoclase (or). Plane-polarized light.



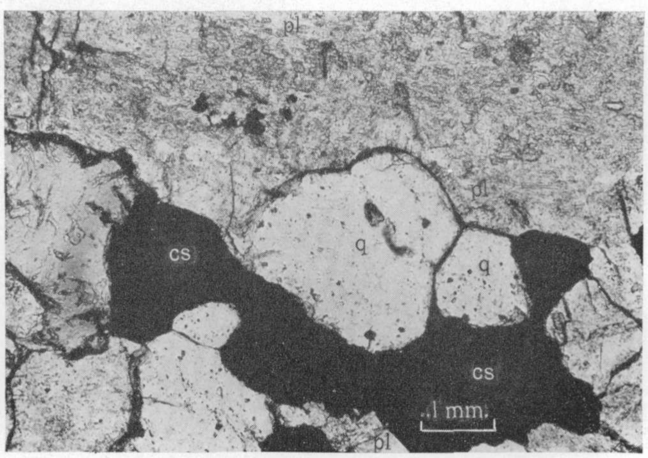
D. CORNELIA QUARTZ MONZONITE FROM 500 FEET NORTH OF THE NEW CORNELIA MINE PIT.

Shows porphyritic texture, with andesine (an) only locally sericitic and albitized (sc-ab) and round quartz phenocrysts (q) in a groundmass of orthoclase and quartz. or, Orthoclase. Crossed nicols.



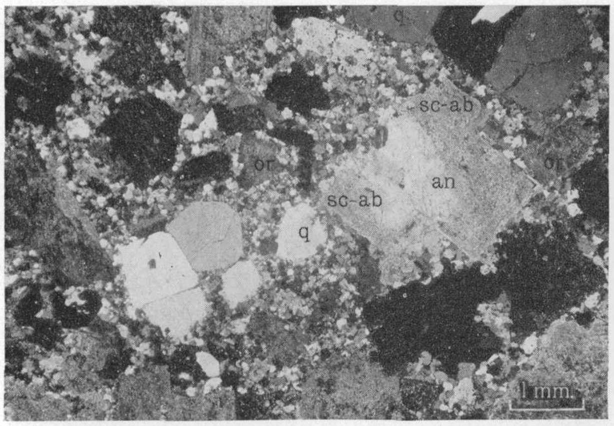
E. MINERALIZED CORNELIA QUARTZ MONZONITE FROM A DEPTH OF 350 FEET IN A CORE DRILL HOLE AT NORTHEAST CORNER OF NEW CORNELIA PIT.

Shows sericitic albitized plagioclase (pl) with its boundary embayed by quartz (q) (note rounded form of crystals) and copper sulfides (cs) interstitial to them along an irregular line. Crossed nicols.



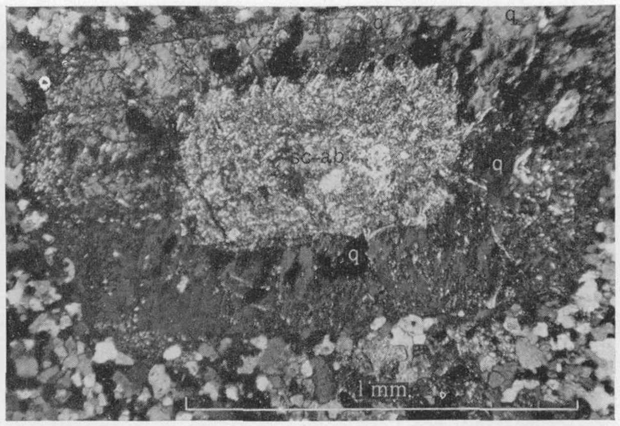
F. SAME AS *A* BUT WITH PLANE-POLARIZED LIGHT.

Shows localization of copper sulfides (cs) along a crevice and on grain boundaries. pl, Plagioclase; q, quartz.



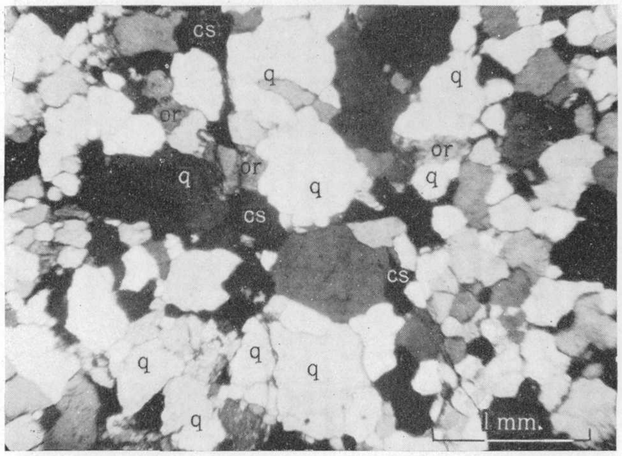
A. ALTERED QUARTZ MONZONITE FROM A POINT HALF A MILE NORTH OF THE NEW CORNELIA MINE.

Shows andesine (an) altered along the borders of crush zones to aggregates of sericite in an albitic base (sc-ab). Groundmass of orthoclase (or) and quartz (q). Crossed nicols.



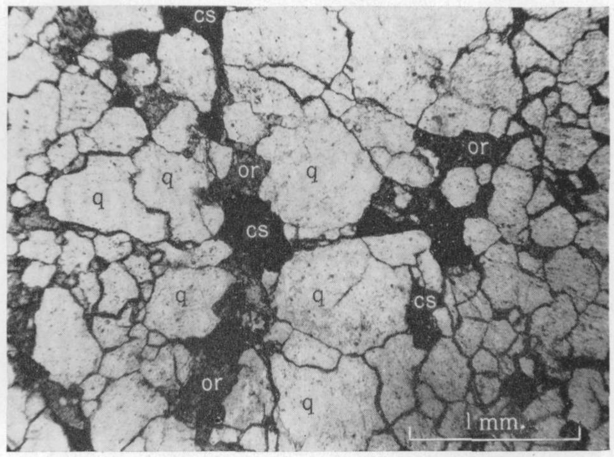
B. CORNELIA QUARTZ MONZONITE FROM SOUTHEAST SLOPE OF NEW CORNELIA MINE PIT.

Shows large crystal of plagioclase, whose central originally more calcic core has been altered to an aggregate of sericite and albite (ac-ab) and whose originally more albitic rim has been replaced by quartz (q) and orthoclase (or). Groundmass consists of round grains of quartz and orthoclase. Crossed nicols.



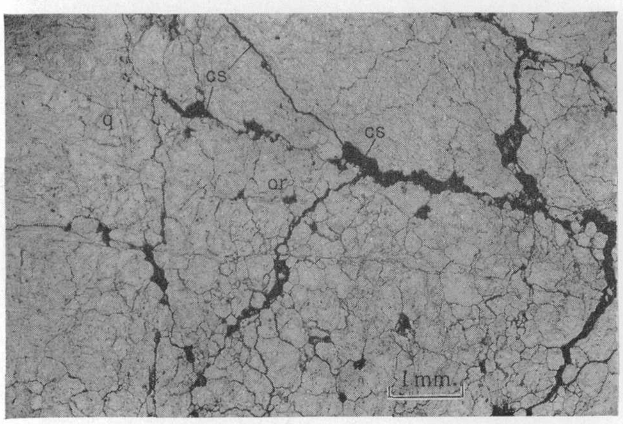
C. HIGHLY SILICIFIED QUARTZ MONZONITE FROM A DEPTH OF 350 FEET IN A CORE DRILL HOLE IN THE NORTHEAST PART OF THE NEW CORNELIA PIT.

The specimen is almost wholly quartz (q) with only a little orthoclase (or), which is interpreted as residual after the enlargement of the round droplike crystals of quartz (such as those seen on pls. 13, *E*, and 14, *B*) at the expense of all other minerals. Dead black is copper sulfide (cs). Crossed nicols.



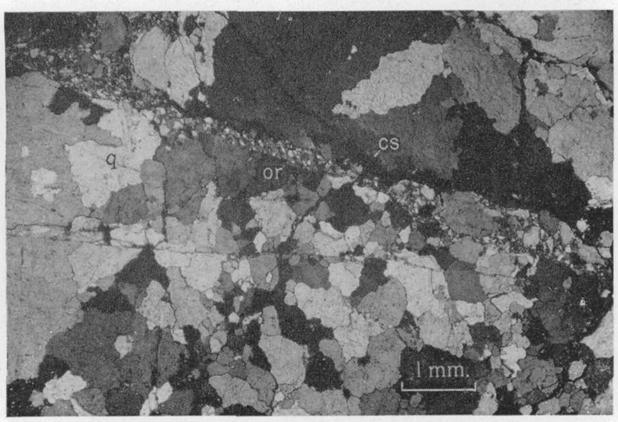
D. SAME AS *C* BUT WITH PLANE-POLARIZED LIGHT.

Black is sulfide.

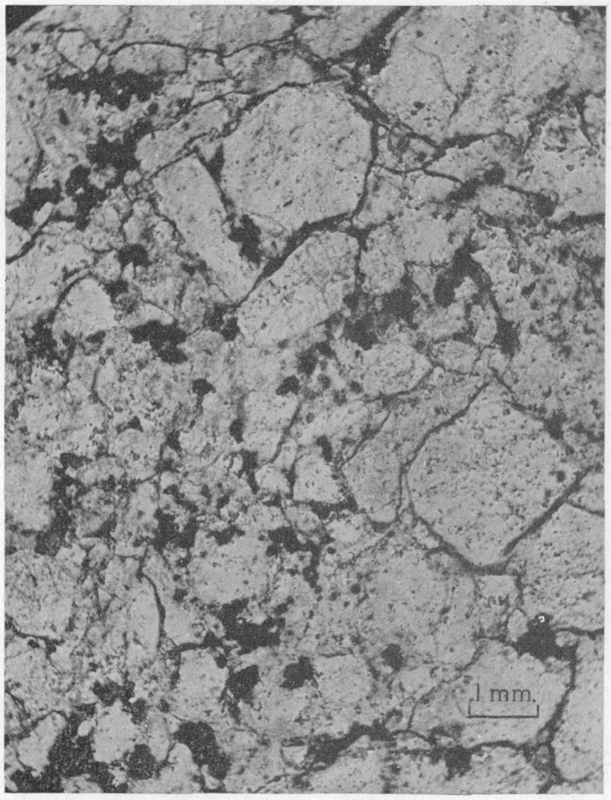


E. RECRYSTALLIZED BRECCIATED QUARTZ MONZONITE FROM THE SOUTHWEST PART OF THE NEW CORNELIA MINE, 1,750 LEVEL.

Shows quartz (q) in interlocking grains, quartz and orthoclase (or) aggregates forming the matrix, and ore minerals (cs) in narrow seams and along grain boundaries. Plane-polarized light.

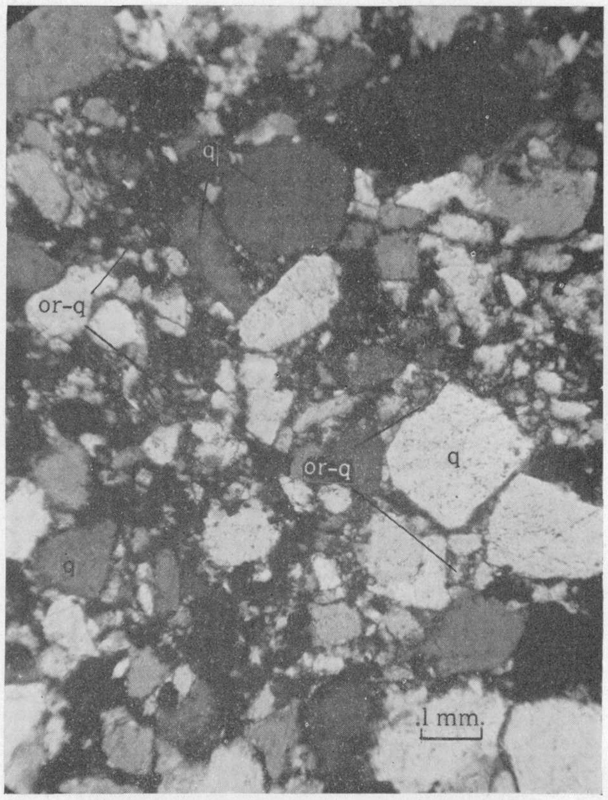


F. SAME AS *A*.



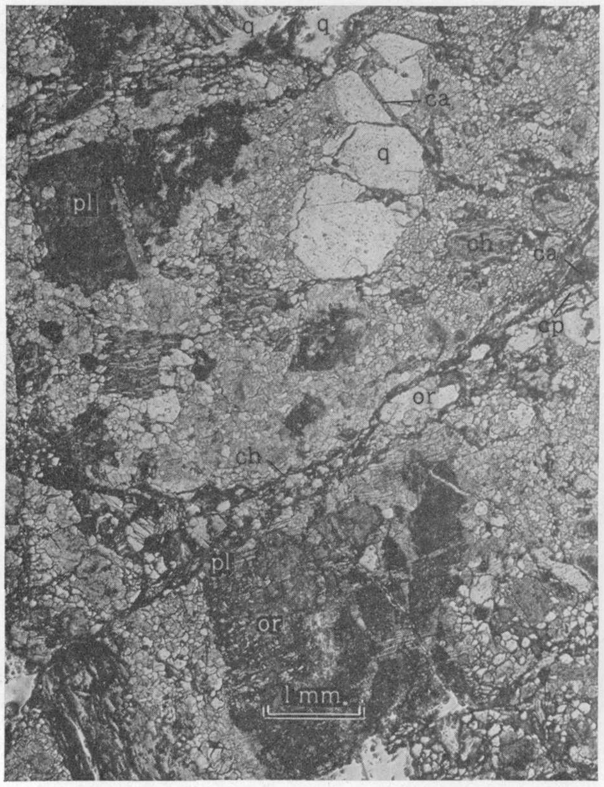
A. CORNELIA QUARTZ MONZONITE FROM DEPTH OF 500 FEET IN CORE DRILL HOLE AT EXTREME SOUTH OF THE NEW CORNELIA PIT.

Shows "crackled" quartz in a matrix of fine-grained orthoclase and quartz. All texture characteristic of igneous rock has vanished; the specimen fairly represents the silicious facies of the ore. The black minerals are chalcopyrite and bornite, which lie chiefly along grain boundaries, though there is some replacement in solid grains of quartz. Plane-polarized light.



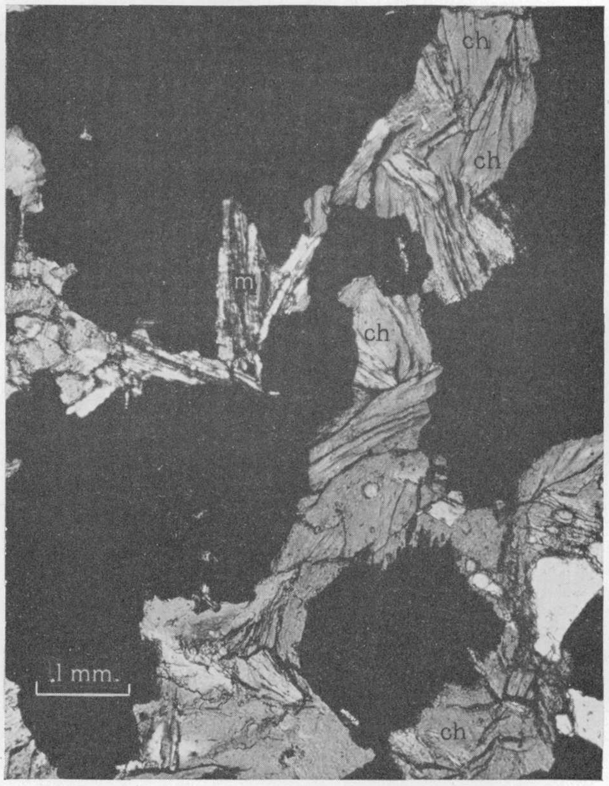
B. SAME AS *A* BUT WITH CROSSED NICOLS.

Shows breccia texture. q, Quartz; or-q, orthoclase and quartz.



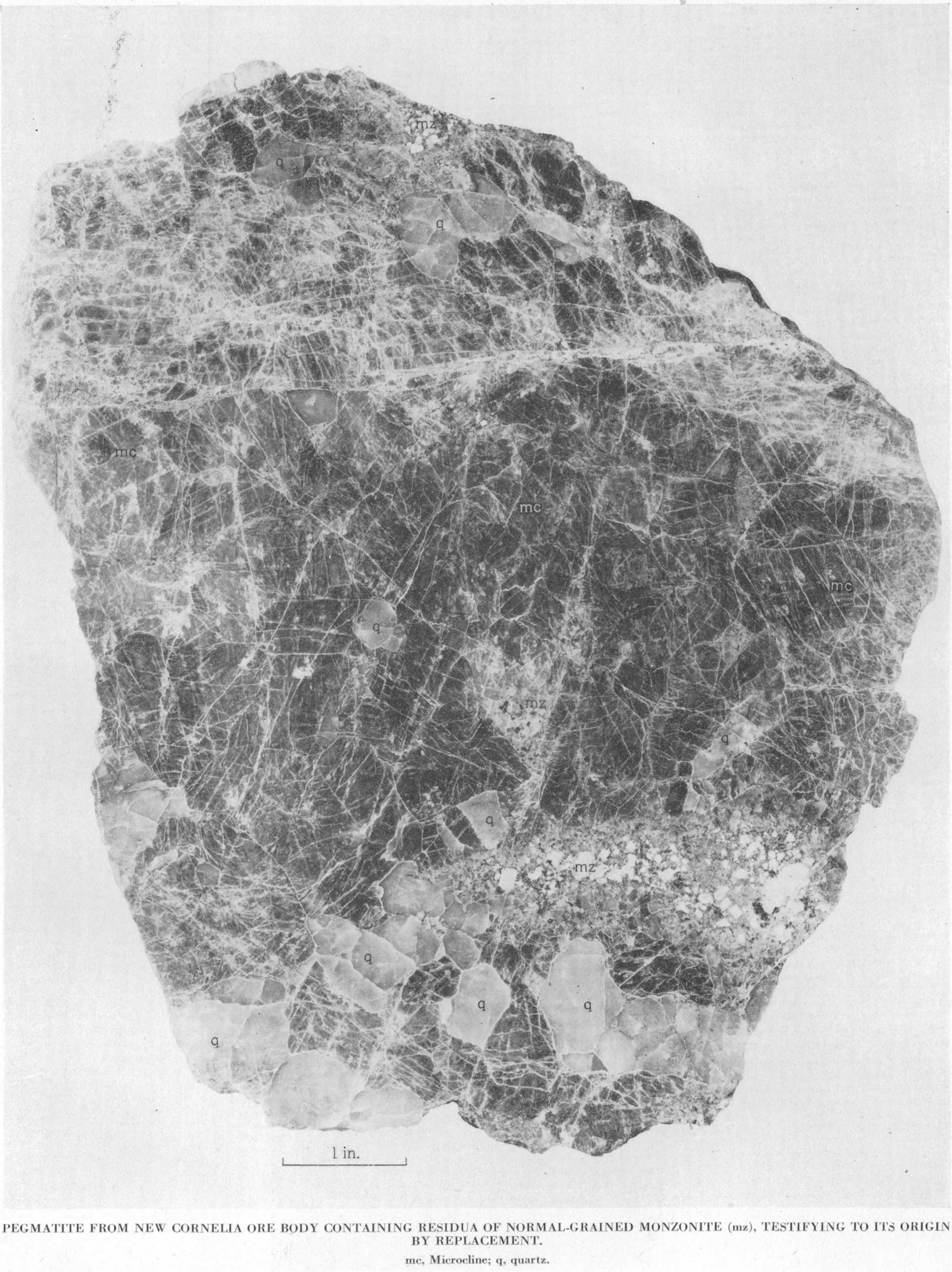
C. CORNELIA QUARTZ MONZONITE FROM DEPTH OF 600 FEET IN CORE DRILL HOLE IN SOUTHWEST PART OF THE NEW CORNELIA MINE.

Shows breccia texture, with quartz (q) deposited in cracks and seams, followed by chlorite (ch) and chalcopyrite (cp) with a little calcite (ca). or, Orthoclase; pl. plagioclase. Plane-polarized light.



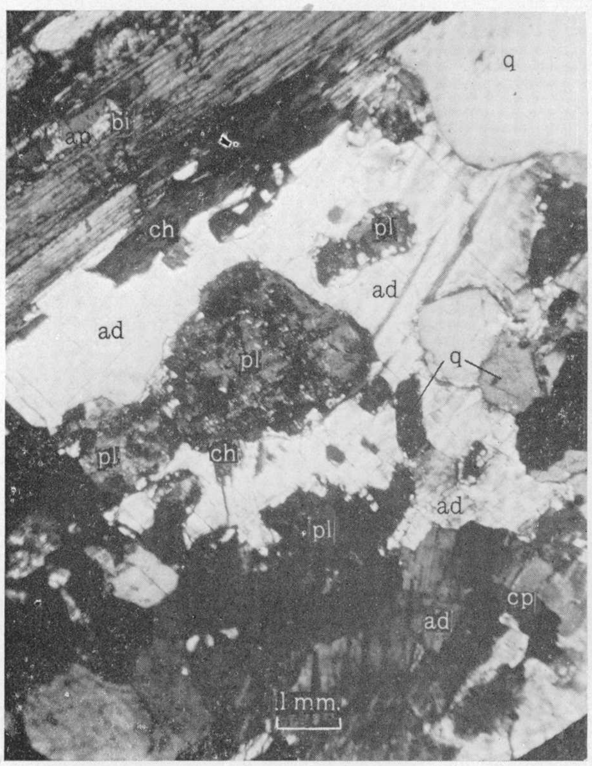
D. QUARTZ MONZONITE ORE FROM SOUTHWEST PART OF NEW CORNELIA MINE.

Shows copper sulfides (black) with chlorite (ch) and quartz. Note interfingering of chlorite plates with ore minerals and rosette arrangement of some of the chlorite. Muscovite (m) at left center with bornite molded on it. Crossed nicols.



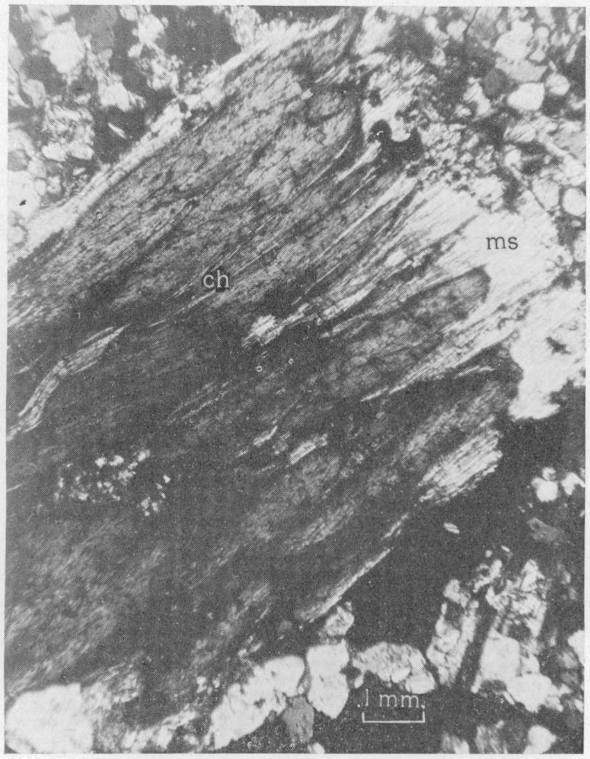
PEGMATITE FROM NEW CORNELIA ORE BODY CONTAINING RESIDUA OF NORMAL-GRAINED MONZONITE (mz), TESTIFYING TO ITS ORIGIN BY REPLACEMENT.

mc, Microcline; q, quartz.



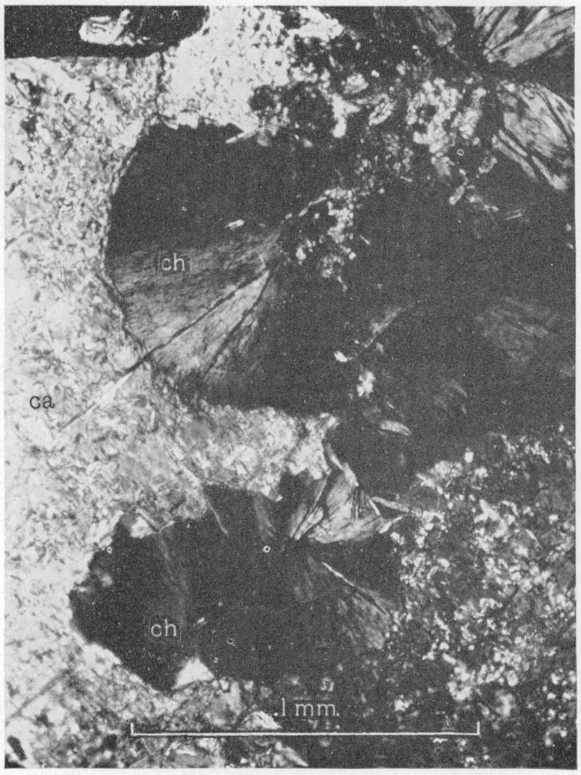
A. ALTERED MONZONITE, SOUTH-CENTRAL PART OF THE NEW CORNELIA PIT.

Anhydrite (ad) with two cleavages replacing and poikilitically enclosing sericitized plagioclase (pl) and chlorite (ch). The chlorite borders and partly replaces biotite (bi). Quartz (q) at upper right. Apatite (ap) in biotite. Chalcopyrite, cp. Crossed nicols.



B. ALTERED MONZONITE FROM A DEPTH OF 1,300 FEET IN A DIAMOND DRILL HOLE IN SOUTH-CENTRAL PART OF NEW CORNELIA PIT.

Shows muscovite (ms) rimming chlorite (ch), which is pseudomorphous after a book of biotite. The muscovite is interpreted as a replacement of the chlorite. Crossed nicols.



C. SAME AS *A.*

Shows rosettes of chlorite (ch) replacing calcite (ca). Crossed nicols.

PYRITE

Pyrite is a widespread but not an abundant mineral at Ajo. Its scarcity is noteworthy, as it is the most plentiful sulfide in such other copper districts as Jerome, Bisbee, Ray, and Miami, Ariz. It may be that the relatively slight migration of copper in supergene waters during the present erosion cycle is due to the scarcity of pyrite, whose oxidation furnishes the ferric sulfate necessary for efficient downward enrichment. On the other hand, the existence of a well-defined zone of supergene enrichment beneath the old erosion surface capped by the Locomotive fanglomerate at the south end of the ore body makes it doubtful that the dearth of pyrite is the only factor in inhibiting enrichment. This question is discussed on pages 84-86.

Pyrite occurs in veinlets and discrete grains in the silicates, quartz, and magnetite of the ore body. (See pls. 9, *F*, and 10, *F*.) It is cut by chalcopyrite, bornite, hematite, sericite, chalcocite, and "limonite." Commonly the grains appear shattered and partly replaced by these minerals, but in some places the pyrite is euhedral, in crystals as large as 1 centimeter in diameter, bounded by pyritohedral and cubic faces. For the most part, the grains are less than 0.5 millimeter in diameter, although a few veinlets in the southern part of the pit attain thicknesses of 2 or 3 centimeters.

TETRAHEDRITE AND TENNANTITE

The presence of tetrahedrite in the Ajo ores has been verified by microchemical tests by Lincoln A. Stewart. It is scarce, having been recognized in only two of several hundred specimens examined. In these specimens it occurs as nuclei of composite grains whose borders are composed of bornite and chalcopyrite. Presumably, but not certainly, the tetrahedrite is the oldest of these minerals. It contains a subordinate amount of tennantite, the arsenical analog of tetrahedrite, which doubtless accounts for the arsenic detected in the oxidized zone of the Ajo ores. No other hypogene arsenic mineral has been definitely recognized.

HALITE

A little halite, associated with epsomite and its dehydration products, was found in encrustations formed along the ditches carrying water to the sump of the New Cornelia mine. It is subordinate to the epsomite in quantity. As the Ajo district is very arid, though only about 70 miles from the Gulf of California, it seems likely that this halite is of meteoric origin and is concentrated by evaporation of rain water in the intense heat of summer. It probably has no genetic connection with the ore deposition.

QUARTZ

Quartz is one of the most abundant minerals in the Ajo district. It is present as a primary or introduced mineral in most of the Concentrator volcanics and is an essential constituent of the Cornelia quartz monzonite. Quartz also occurs in and near the ore deposit as fillings of innumerable fractures that cut the host rocks in all directions and as replacement masses. (See pls. 7-9, 10, *A*, *D*, *F*.) The approximate relative amount of this impregnation is indicated on plate 27, B.

Quartz is also present in large amounts as a microscopic component of the quartz monzonite and especially of the metallized part of it. Its relations, as shown in thin section, are discussed further in the section of this report dealing with the metamorphism. (See pp. 73-77.) It seems clear that quartz has formed or been recrystallized at many times in the history of the deposit. The primary igneous quartz has been shattered and broken and new quartz deposited in the fractures and in turn fractured, the process being repeated again and again. Rhombic cleavage is very pronounced in much of the quartz from the New Cornelia ore body. This pronounced cleavage may be a result of inversion on cooling, but it is perhaps equally explicable as a result of the intense fracturing of the rock. That it was developed during the mineralization is evident from the common development of sericite along it. (See pl. 12, *B*.) Lines of microscopic negative crystals or rounded cavities, commonly with bubbles in their contained liquid, cut across polycrystalline aggregates of such quartz and are evidence of still younger cracking and recementation. Other such cavities are not alined. (See pls. 12, *A*.) Minute crystals of supergene quartz have been seen coating malachite and chrysocolla crusts in the oxidized zone.

OPAL

A little opal was seen in association with chrysocolla and copper pitch in the oxidized zone of the ore deposit.

STIBICONITE (?)

Stibiconite was doubtfully identified by Miss J. J. Glass in gossan from near Pinnacle Peak. It is probably derived from the oxidation of tetrahedrite, although none of this assumed primary mineral was found at this locality.

CUPRITE

Cuprite, the red cuprous oxide, was found in small amount in the oxidized capping at Ajo. It also occurs with supergene hematite, malachite, chrysocolla, and native copper, in the old weathered zone of the ore body that lies beneath the Locomotive fanglomerate, and has been followed by the drill to more than 200 feet below sea level. Apparently, cuprite is somewhat more plentiful, relatively, in this "fossil" weathered zone than it is in the one developed in the present cycle, but so little of the younger zone remains that this is uncertain. Naturally, the best of the oxidized ore has been mined and leached and is not represented by the ore that remains.

MELACONITE

The black cupric oxide, melaconite, is present in relatively small amount as a pure mineral, although it has been determined as a black crust on several specimens of chalcocite from the oxidized zone. For the most part it is a component of "copper pitch," but where the metals other than copper have been removed nearly pure melaconite is present as the oxide product of weathering sulfides.

COPPER PITCH

Copper pitch, an indefinite mixture of oxides of copper, iron, and manganese with water, forms iridescent and asphaltlike crusts on some of the rocks from the weathered zone. It is of negligible economic value.

HEMATITE

The red oxide of iron, hematite, is of three varieties, of quite different distribution and origin. As the variety specularite it occurs in dark-red to black, glistening flakes and roughly equant crystals, both in the body of the rock and more especially as a lining of joints and cracks. This mineral is undoubtedly of hypogene origin and is probably closely connected in time of formation with the metallization of the Cornelia quartz monzonite. Nevertheless, its area of maximum development and coarsest crystallization by no means corresponds, either areally or in trend, with the feldspar-sulfide-quartz mineralization. As is evident from plate 27, B, D, E, and H, most of the minerals associated with the ore deposit are arranged in a belt that trends north-northwest. Plate 27, C, however, shows that the belt of plentiful specularite trends west-southwest, nearly at right angles with the other. It appears at first glance as though this belt might be the outcrop of the weathered zone that lies beneath the Locomotive fanglomerate. However, specularite is not generally a supergene mineral, and brilliantly adamantine crystals as large as some seen west of Arkansas Mountain, which were 2 inches long, are certainly quite out of keeping with what is known of hematite of supergene origin; furthermore, coarse sparkling specularite crystals are common some hundreds of yards to the north of the zone of chalcocite veins in the footwall of the pre-Locomotive zone of weathering. They occur with epidote in veins at the extreme northwest corner of the New Cornelia ore body. In this position they are well in the footwall of the zone of Tertiary supergene sulfide enrichment, a position that is also out of harmony with their intepretation as of supergene origin. Furthermore, much of the hematite shows shearing, folding, and faulting that must have occurred under considerable cover. All the specularite is therefore regarded as hypogene, and its anomalous trend is believed to be an effect of structural control during the epoch of its formation. This matter has been discussed on pages 76-77, 80, and 81.

The second variety of hematite is microscopic and occurs as bands around the edges and along cracks through the magnetite of the ore body. Nearly all the magnetite veins in the pegmatitic part of the ore body contain some of this hematite, but except locally where the whole veinlet is altered, the hematite is recognizable only under the microscope. Probably this variety of hematite is hypogene, but this suggestion has not been proved.

The third variety of the hematite is earthy and generally soft and is believed to be wholly supergene. It stains much of the rock in the weathered zone and is also prominent in the weathered zone along the footwall of the Locomotive fanglomerate. It is associated with copper carbonates, chrysocolla, copper pitch, jarosite, and cuprite, as well as with some hydrated iron oxide ("limonite," probably goethite). The earthy hematite has evidently resulted from the weathering of pyrite, chalcopyrite, and bornite, doubtless with some contributions from other ferriferous minerals. Its determination as hematite rests on its anhydrous composition, its high index of refraction, red streak, and its deep-red color even in thin plates.

ILMENITE

Ilmenite at Ajo appears to have been formed in two ways. A little of it is associated with magnetite as a primary accessory constituent of the Cornelia quartz monzonite, but much of it seems to have been formed by the alteration of sphene during the ore deposition. The titanium in the fresh rocks is represented chiefly by megascopic crystals of sphene, but in the mineralized rock there is neither euhedral sphene nor its common derivative, leucoxene, although the titanium content is roughly the same—equivalent to 1 percent of ilmenite in the norm. (See pp. 81-82.) There is, however, a considerable increase in the quantity of opaque oxides, and qualitative tests by W. T. Schaller have demonstrated a high content of titanium oxide in the heavy fractions obtained in bromoform separations of several ore specimens. It is therefore concluded that a noteworthy amount of ilmenite has been formed by the reaction of the mineralizing solutions with the pre-existent sphene of the quartz monzonite.

MAGNETITE

Magnetite, which is a common mineral at Ajo, appears to be of two generations. The magnetite of the older generation is a primary accessory constituent of the Cornelia quartz monzonite and occurs as discrete euhedral octahedra commonly a fraction of a millimeter in diameter, which constitute about 1 percent of the rock. It is partly altered to hematite along borders and octahedral partings, at least in the more intensely mineralized part of the ore body.

The second occurrence of magnetite is as veinlets associated with pegmatites in the New Cornelia copper deposit. The brecciated quartz monzonite and the pegmatite veins within the deposit are cut by veinlets of magnetite that are commonly very thin but locally are as much as 4 inches thick. (See pl. 9, *F*.) These veins branch and reunite in most complex patterns and locally are so abundant as to account for considerable masses of magnetite-rich copper ore, although they do not provide a commercial source of iron. Though the relations of magnetite to other minerals are not definite in a few places, it seems clear on the whole that the magnetite is younger than most of the orthoclase and older than most of the sulfides, even pyrite. It is clearly much older than all varieties of hematite.

The distribution of the magnetite veinlets, as shown in plate 27, E, is closely coincident with that of pegmatite and introduced feldspar but quite different from that of specularite. There is little doubt that the vein magnetite represents an early phase of a continuous process of mineralization that included the deposition of the copper ore.

RUTILE

Rutile is a microscopic constituent of the Cornelia quartz monzonite. Some, which occurs as minute needles in the web-shaped pattern known as sagenite, was formed during the chloritization of biotite. The primary rutile in contrast occurs as stumpy, euhedral to somewhat rounded prisms.

BROOKITE (?)

Brookite, a paramorph of rutile, was doubtfully identified as minute crystals less than 0.01 millimeter in diameter that replace a characteristically shaped crystal of sphene in a core fragment of quartz monzonite, which was obtained at a depth of nearly 1,800 feet from a hole south of the Phelps Dodge mine. Its high refractive index, strong dispersion, and birefringence, in connection with its obvious derivation from sphene, led to the tentative identification.

GOETHITE

The monohydrate of ferric oxide, goethite, was identified positively in only a few specimens. In these, it occurs as a constituent of a yellow-brown to deep-brown limonitic crust on the rusty outcrops of the oxidized part of the ore body. It is all in fine earthy powder, commonly too fine-grained for effective study, even with the oil immersion lens. However, it was identified in favorable specimens by its optical properties and by blowpipe tests. It undoubtedly is less abundant than hematite in the zone of weathering but is probably more plentiful than jarosite.

LIMONITE

Though discredited as a true mineral species, "limonite" is still a useful descriptive term for the unidentified, or not readily identified, minerals or mixtures of iron-bearing minerals that have a yellow-brown streak and form in the weathered zone. Most of the limonite of the Ajo district seems to consist of goethite, though it also contains some jarosite and doubtless some finely divided hematite. No special attention was given to the iron minerals formed by oxidation, as the capping of the main part of the ore body had been mined and the significance of the minerals largely destroyed.

PSILOMELANE (?)

The hydrated manganic oxide, psilomelane, was doubtfully identified as dendrites on joint and other surfaces of rocks in the weathered zone. It is commonly a constituent of the indefinite mixture classed as copper pitch and of some of the limonite, but also occurs, to judge from physical properties and bead tests, essentially unmixed with other minerals.

CALCITE

Although not conspicuous, calcite is widespread in small amounts in the Ajo ores. Some appears to represent a replacement product, but most of it clearly occupies fissures. It is probably one of the latest hypogene minerals to form, though some of it is clearly supergene. In some specimens sericite occurs on cracks through it, and in others the leaching out of the carbonate by acid reveals paper-thin quartz plates that obviously preserve the rhombic cleavage pattern of calcite. This quartz is probably hypogene, as it is found in fresh sulfide ore. In vugs containing the other carbonates, calcite is invariably younger than either dolomite or ankerite. It ordinarily has either the scalenohedral habit ("dog-tooth spar") or has the flat rhomb prominent ("nailhead spar"), but no systematic difference in the distribution of the two varieties was detected. In many districts the dog-tooth spar is of late hypogene origin and the nail-head spar of late supergene origin, but it is uncertain whether these relations obtain at Ajo.

DOLOMITE AND ANKERITE

A little dolomite ($\omega = 1.681 \pm 0.003$) was found in the Ajo ores as a lining in drusy cavities. It is obviously older than calcite, which rests on its euhedral faces, but is apparently a late mineral in the hypogene sequence, as it coats chlorite. The ferroan variety of dolomite, ankerite, is much more common than the pure magnesian mineral, though not as plentiful as calcite. Wherever seen, it occupies veins or druses coated by calcite. Commonly it has curved faces and weathers buff, but some with megascopically plane faces and clear white color was also found. Apparently it was formed rather late in the epoch of mineralization.

The composition of the ankerite is rather variable. In different specimens ω was measured as 1.705, 1.705, 1.710, 1.713, 1.750, all $\pm$ 0.003. As qualitative tests show the practical absence of Mn and the presence of Fe, Mg, and Ca, these optical properties indicate, according to the tabulation of Larsen and Berman,[16] a content of iron carbonate ranging from about 15 percent to 40 percent, the rest being $CaCO_3$ and $MgCO_3$.

MALACHITE

The most common weathering product among the cupriferous minerals at Ajo is green malachite. It was the dominant ore mineral in the leaching ores, and its ready solubility in acid was an important factor in their exploitation. As far as seen, it is chiefly present as veinlets and coatings of joints in the weathered zone, although it is also disseminated. Although the occurrence along joints suggests migration of copper during the formation of the malachite, the amount of migration has been slight, as there was no leached capping present on the carbonate ore, to judge from assay records of drill holes. (See pl. 26.) The copper tenor of the carbonate ores mined was essentially the same as that of the underlying sulfide ore in which also the copper minerals occur mostly along joints and fissures.

Malachite appears in general to be the earliest of the oxidation minerals, although there are some apparent reversals. It is commonly found coated in part by azurite, melaconite, or chrysocolla but apparently is transformed only slowly to these minerals, as it is the principal copper mineral in the weathered zone of the ore body.

AZURITE

The blue basic copper carbonate, azurite, is not common at Ajo. It does occur in small amounts, however, both as thin films coating malachite and as veinlets, some of which are as much as a centimeter thick. It is apparently formed from malachite, perhaps simultaneously with copper pitch and melaconite which seem generally to accompany it. It is negligible as an ore mineral.

ORTHOCLASE

The most conspicuous and one of the most abundant gangue minerals at Ajo is orthoclase. It occurs both as phenocrysts in the Cornelia quartz monzonite and as minute crystals in the groundmass of the monzonite. Possibly some of the coarse crystals in the pegmatites that cut the monzonite and record the earliest phase of mineralization are also of orthoclase, although most are of microcline.

The orthoclase phenocrysts are not as plentiful in the Cornelia quartz monzonite as are those of plagioclase, but they are common and are rather uniformly distributed through the rock. There is no reason to doubt their primary igneous origin as products of crystallization from the magma.

The fine-grained orthoclase that, with quartz, composes most of the groundmass of the Cornelia quartz monzonite, apparently includes material of two different origins, though they have only been distinguished in a gross way by their distribution and not by their specific characters. One is apparently the normal product of magma consolidation, like the phenocrystic orthoclase. Locally, however, and especially in the vicinity of the coarse-grained pegmatites, the rocks are notably reddened along joints and fissures and upon closer inspection are seen to owe their color to an intense feldspathization of the groundmass. That this feldspar is of replacement origin is evident from its remarkable localization, both in the monzonite body as a whole (see pl. 27, G) and along joints. (See pls. 8, *A*, and 10, *C*, *D*.) There is also clear microscopic evidence of this replacement of the groundmass by orthoclase. (See pl. 11.) Although such orthoclase has selectively replaced the minerals of the groundmass, it has also locally embayed and attacked the phenocrysts of quartz and plagioclase. (See pl. 11, *A*, *B*, *E*, *F*.) The determination of all of this feldspar as orthoclase may be open to some doubt, although none of it shows microcline twinning and some definitely has parallel extinction in sections cut parallel to (001). No exhaustive study was made, and it may be that some of it is untwinned microcline, as is most of the coarsely crystalline pegmatitic feldspar with which it is closely associated.

MICROCLINE

The triclinic potash feldspar, microcline, forms coarse crystals in pegmatitic masses in the south-central part of the New Cornelia ore body. It is also present in narrow veinlets in the normal Cornelia quartz monzonite, both near the pegmatitic areas and elsewhere.

Although it is difficult to prove, it seems probable that much, if not all, of the pegmatitic material is of replacement origin, as apparent residua of normal-grained monzonite occur within the masses and their boundaries against the normal rock are transitional. (See pls. 7, *B*, 8, *A*, 17.) Crystals of microcline in the pegmatitic zone are commonly anhedral, but cleavage faces several inches across are rather common. In places, vugs more or less filled with other minerals contain microcline crystals 3 or 4 inches across, with well-developed domes and clinopinacoids. As mentioned above, most of this pegmatitic feldspar is untwinned microcline, though there seems definitely to be a small amount of orthoclase associated with it.

In the normal quartz monzonite, microcline (recognizable by cross-hatch twinning) is found as sparsely distributed individual grains, and also in narrow veins. It may be that there is much more microcline present that does not have the cross-hatch twinning, but no systematic study was made of this possibility. Readily recognizable microcline of these habits is quantitatively negligible.

From the relations of different veins in the ore body, it appears that the coarse microcline of the pegmatites and

[16] Larsen, E. S., and Berman, Harry, The microscopic determination of the nonopaque minerals: U. S. Geol. Survey Bull. 848, p. 229, 1934.

the vein microcline and orthoclase are both older than any of the ore minerals or magnetite. Introduced quartz is largely younger but partly contemporaneous, and chlorite is almost wholly younger. Potash feldspar may thus be regarded as the earliest mineral connected with the ore deposition.

PLAGIOCLASE

Plagioclase of a wide range of composition occurs in the Ajo district; andesine and oligoclase of magmatic origin, and albite that is a hydrothermal derivative of them. The primary plagioclase of both the Concentrator volcanics and Cornelia quartz monzonite was largely andesine, although some zoned crystals show oligoclase rims. During, or perhaps before copper deposition, however, large amounts of these feldspars were highly altered by hydrothermal solutions to aggregates of sericite and epidote set in a matrix of albite. This formation of sericite and epidote at the expense of the anorthite component of plagioclase is, of course, a phenomenon known from many localities over the world. At Ajo it can be found in all stages of development. Plates 12, *C, D,* 13, *D,* and 14, *B,* illustrate the fresh andesine of the Cornelia quartz monzonite. The incipient alteration of the glassy andesine to sericite-epidote aggregates in an albite ground is shown on plates 13, *E,* 14, *D,* and 15, *A,* which also show the dependence of this alteration on local channels of access for the metamorphosing solutions. Completely altered andesine, with an albite base, is illustrated on plates 13, *C, F,* 14, E, F, and 15, *B.* Similarly altered plagioclase has been found in the Concentrator volcanics.

The chemical analyses of the fresh and altered Cornelia quartz monzonite (see tables 4 and 6) show that the alteration of the plagioclase is due to removal of lime, rather than addition of soda, although some potassa is added, in the sericitization that is coincident with the albitization. Alteration of this kind is difficult to date with respect to the other kinds, but it appears that the alteration of the plagioclase in monzonite remnants enclosed by pegmatite took place after the formation of secondary microcline. This conclusion is based not only on the general experience in other deposits and on the theoretical considerations that sericite, a hydrous mineral, should form at lower temperatures than orthoclase, but on such relations as are illustrated on plate 15, *B.* There a euhedral crystal of zoned plagioclase has been highly altered to quartz and orthoclase along its exterior zones, which were originally more sodic, and to sericite and albite in the interior, which was originally more calcic. These relations seem to indicate that the attack of quartz and orthoclase was successful only against the outer zones of plagioclase, and that the inner calcic cores, which escaped or resisted this attack, were susceptible to later attack by sericite and albite.

An alternative interpretation of these relations might be offered: It might be considered that the alteration of the calcic cores of the plagioclase to epidote and sericite may have been caused by residual solutions in the monzonite which extracted lime (and presumably carried it away) at the same time that these solutions displaced some of the soda from the central cores to form albitic rims on the plagioclase. Indeed, the indentation of some of the albite rims by the rounded grains of quartz and orthoclase might indicate that the rims grew distinctly later than the original crystal and hold the groundmass material as inclusions enveloped during this secondary enlargment. Opposed to this suggestion are two facts: (1) the "attack" on the border zones of the plagioclase by orthoclase and quartz is recorded in sporadic areas far from the ore deposit where there has been no accompanying sericitization and the plagioclase is all andesine (see pp. 29, 30) and (2) the quantity of sericite and epidote in the cores of most of the plagioclase crystals is volumetrically considerably less than the quantity of albite in many of the clear rims, and it does not appear adequate to account for all the lime lost from the rocks (see table 4, p. 30).

Andesine was thus one of the earliest minerals to crystallize and long antedated the ore deposition, whereas albite was contemporaneous with sericite and was formed during a late stage of mineralization.

ACTINOLITE

The fibrous green amphibole, actinolite, was identified by Miss Glass as a coating on joint cracks in the Cornelia quartz monzonite just west of the Gibson Arroyo. The mineral has the indices $\alpha = 1.620$, $\beta = 1.632$, and $\gamma = 1.643$, all $\pm$ 0.002, and X is colorless, Y yellow-green, and Z green. It presumably has no relation to the ore deposit, though the nearby quartz monzonite has been somewhat albitized.

HORNBLENDE

Hornblende is a primary mineral of the Cornelia quartz monzonite and the Concentrator volcanics. In the fresh Cornelia quartz monzonite it is pleochroic in green and has the indices $\alpha = 1.645$, $\beta = 1.654$, $\gamma = 1.664$, all $\pm$ 0.003; the extinction angle is 24° $\gamma \wedge c$. In most of the Concentrator volcanics the hornblende has been altered to chlorite, but its former presence is shown by its characteristic form. In the mineralized parts of the Cornelia quartz monzonite it has also been completely altered to chlorite.

ZIRCON

Zircon occurs as small stout prisms (see pl. 12, *E, F*) in the Cornelia quartz monzonite. It is a primary accessory and seems to have been quite unaffected during mineralization.

TOPAZ

Cardigan gneiss, near the contact with Cornelia quartz

Topaz is a rare mineral at Ajo. It has been found in the monzonite west of the Gibson Arroyo fault. It occurs as microscopic crystals in a crystalloblastic rock and according to Miss Glass has the following properties: $\alpha = 1.619$, $\beta = 1.620$, $\gamma = 1.627$, optically +, 2V = 60°, dispersion r>v. Topaz is commonly regarded as a pneumatolytic mineral, but this occurrence was not sufficiently studied to determine whether it is related in origin to the Cornelia quartz monzonite or to some older intrusion.

ANDALUSITE

The same specimen of Cardigan gneiss that yielded the topaz was found by Miss Glass to contain andalusite. It occurs as minute pale pink prismatic crystals, with the properties α (rose pink) = 1.640, β (colorless) = 1.645, γ (colorless) = 1.648, with birefringence 0.008, parallel extinction, large 2V, prismatic cleavage. Perhaps it records contamination of the Cardigan gneiss by included sedimentary material. It is negligible in quantity.

CLINOZOISITE (?)

Minute colorless crystals of high index, low birefringence, and both positive and negative optical elongation occur in some of the sericitic albitized plagioclase of the Cardigan gneiss, Concentrator volcanics, and Cornelia quartz monzonite. These properties are not enough for certain identification but suggest that the mineral is zoisite or clinozoisite. It is invariably subordinate to sericite, as is shown by chemical analyses (with loss of lime running parallel to the development of albite in the matrix feldspar) more clearly than can be determined optically.

EPIDOTE

Epidote, commonly of the iron-rich variety, pistacite, occurs in small amounts as an alteration product of the dark minerals and plagioclase of the Cornelia quartz monzonite and Concentrator volcanics, along with the much more abundant chlorite. It is also intimately associated with specular hematite and chalcopyrite and quartz in small veins that are widespread in the area between Cardigan and Concentrator Hill. Some of these veins are found on the west slope of Camelback Mountain, and very few of them occur in the Cornelia quartz monzonite near the New Cornelia ore body. Epidote is not an abundant mineral in either association, and its age relations are not well defined. It coats specularite, however, in some vugs.

TOURMALINE

The complex borosilicate, tourmaline, is widely distributed in the Little Ajo Mountains but is not closely associated with the ore body of the New Cornelia mine. It is found in brilliant, black prisms coating joint planes in the Cardigan gneiss, the Chico Shunie quartz monzonite, the Concentrator volcanics, and, locally, the Cornelia quartz monzonite. There are also tourmaline-bearing quartz veins in the Cardigan gneiss.

Specimens of tourmaline from each of these types of occurrence were examined optically by Miss Glass to see whether consistent differences would be found that might give a clue as to which of the intrusives was the source of a given variety of tourmaline. Miss Glass' results follow:

Country rock	Source	ε	ω	Pleochroism	
				ε	ω
1. Cornelia quartz monzonite	Cornelia quartz monzonite	1.657	1.687	Red brown	Green black
2. Cornelia quartz monzonite	Cornelia quartz monzonite	1.665	1.685	Red brown	Black
3. Concentrator volcanics	Cornelia quartz monzonite	1.635	1.660	Gray rose	Blue black
4. Cardigan gneiss	Cornelia quartz monzonite	1.647	1.678	Gray rose	Blackish olive
5. Hornblendite	Chico Shunie quartz monzonite (?)	1.625	1.645	Rose gray	Green blue
6. Chico Shunie quartz monzonite	Cornelia quartz monzonite (?) or Chico Shunie quartz monzonite (?)	1.630	1.653	Pale rose	Gray black
7. Cardigan gneiss	Chico Shunie quartz monzonite (?)	1.630	1.658	Rose	Dark green
8. Chico Shunie quartz monzonite	Chico Shunie quartz monzonite (?)	1.635	1.660	Rose	Olive green
9. Chico Shunie quartz monzonite	Chico Shunie quartz monzonite (?)	1.629	1.653	Pale rose	Indigo blue
10. Cardigan gneiss	(?)	1.630	1.655	Rose	Dark green

Nos. 2 and 4 of the above list were collected from the same vein, on each side of the contact of Cornelia quartz monzonite and Cardigan gneiss. Aside from the fact that all tourmalines that are rather definitely derived from the Cornelia quartz monzonite have ω greater than 1.66, no general rule seems to emerge from this study. The wall rocks of the different specimens seem to have been important factors in bringing about variations of composition. It is very doubtful, then, whether the optical properties of a given tourmaline can be used in this area as a safe criterion of the magmatic source from which it was derived.

MUSCOVITE

There are two varieties of muscovite in the Ajo area. In the Cardigan gneiss and associated pegmatites it occurs as "books" of the broadleaved, rather coarsely crystalline variety. In and near the ore bodies and in other places where hydrothermal solutions have been active, however, it is found as fine scaly sericite. Of the two varieties the sericite is by far the more abundant.

Sericite occurs as an alteration product of plagioclase. In some rocks there are sparse flakes of sericite distributed through the plagioclase, which is otherwise unaltered andesine. A complete series of transitions can be found, from rocks that have undergone this mild sericitization to others in which the plagioclase contains a mat of fine scales of sericite that is so dense as to obscure the groundmass, which is nevertheless determinable in favorable specimens as albite. Examples of sericitized plagioclase are illustrated on plates 13, *C, F,* 14, *E, F,* and 15, *B.* Although most of the completely albitized feldspars contain very dense mats of sericite, a few show only slight sericitization. That the alteration to sericite was localized by fractures permitting access of solutions can be seen from plates 14, *D,* and 15, *A.* It appears to have taken place at the same time as the albitization of the plagioclase in which it occurred, and thus the sericite seems to have formed wholly at the expense of the anorthite component of the plagioclase. Some sericite also formed at the expense of quartz, penetrating its edges in feathery aggregates or following its rhombic cleavages. (See pl. 12, *B.*) Sericite rosettes also replaced chalcopyrite in some specimens.

The sericitized rock connected with the New Cornelia ore body is largely peripheral to the richer part of the deposit. This is probably due to the fact that sericitization was one of the later phases of the mineralization whose earlier, more intense phases, such as orthoclasization and intense silicification, had previously rendered the host rock less subject to sericitization. No evidence of sericitization younger than the alteration of plagioclase to clay minerals, such as that noted by Ransome[17] at Ray and Miami, was observed at Ajo.

BIOTITE

Biotite was a primary constituent of the Cardigan gneiss, Concentrator volcanics, and Cornelia quartz monzonite. There is also a little broad-leaved biotite associated with the pegmatized part of the Cornelia quartz monzonite in the New Cornelia ore body. Most of the original biotite in the mineralized area has been altered to chlorite, with a little epidote, and most of the broad-leaved micaceous minerals in the pegmatite are also now chlorite, but part of this broad-leaved chlorite may be original.

In several specimens of biotite from the Cornelia quartz monzonite that were examined optically β ranges from about 1.635 to 1.647, each ± 0.003, and the birefringence is near 0.035. No data were obtained on other biotites of the quadrangle.

[17] Ransome, F. L., The copper deposits of Ray and Miami, Ariz., U. S. Geol. Survey Prof. Paper 115, pp. 137-138, 1919.

CHLORITE

Chlorite is the commonest ferromagnesian mineral in the Ajo district, being the dominant dark component, not only of the mineralized monzonite, but of all the pre-Cornelia formations. It occurs as pseudomorphs after biotite, or less commonly, hornblende; as aggregates of broad leaves in the pegmatitic parts of the ore body; and as a vein-filling and nonspeudomorphous replacement mineral.

Chlorite pseudomorphous after biotite of the Cornelia quartz monzonite is illustrated on plates 10, *A,* 14, *C,* and 16, *C.* It commonly has a little calcite, magnetite, or rutile associated with it. In several specimens examined optically β ranges from 1.612 to 1.617, both ± 0.003, birefringence is low, and the mineral optically negative. These properties agree with those of diabantite in Winchell's classification[18] of the chlorites. A chlorite pseudomorph after biotite in the Concentrator volcanics has β somewhat lower, 1.605, but would still fall in the diabantite group. Chlorite pseudomorphous after hornblende in the Cornelia quartz monzonite according to Miss Glass has $\alpha = 1.607$, $\beta = 1.610$, $\gamma = 1.612$, and $B = 0.005$, and is optically negative, whereas chlorite pseudomorphous after hornblende in the Concentrator volcanics, according to my determinations, has $\beta = 1.603$ and low birefringence and is also optically negative. These two chlorites are also diabantite and closely related in composition to those in the Cornelia quartz monzonite.

The broad, leafy "rosette" chlorite that is associated with pegmatitic masses in the New Cornelia ore body is illustrated on plates 7, *A,* 8, *B,* and 9, *A, B, C.* Somewhat smaller crystals of the same sort are shown on plates 16, *D.* Criteria to distinguish original from secondary chlorite of this variety seem lacking. Sagenite webs, which are usually regarded as evidence of secondary origin, are common but not as regular as they are in many chlorites. Optical tests on material of this variety gave the following results: $\beta = 1.615$ to 1.625, birefringence low, optically negative. The leafy chlorite thus contains a little more iron than the pseudomorphous chlorite and may be classed in part as aphrosiderite, according to Winchell's tabulation. Though the difference is not great, it is noteworthy that this variety of chlorite is confined to the pegmatitic part of the mineralized area, where, as shown by the introduced magnetite, iron-rich solutions were circulating during the ore deposition. Elsewhere in the area there seems, judging from the analyses of table 6, to have been little introduction of iron. The age of the leafy chlorite, with respect to the other minerals of the ore deposit, is not precisely known. It is younger than orthoclase, upon whose euhedral crystals it is locally molded, and it lines vugs that are filled by quartz, bornite, and chalcopyrite

[18] Winchell, A. N., Elements of optical mineralogy, pt. II, pp. 375-376, John Wiley & Sons, New York, N. Y., 1927.

(pl. 9, *C*), but elsewhere it seems to replace the copper sulfides. Apparently it was formed contemporaneously with the sulfides.

The vein chlorite, which is also confined to the mineralized area, fills fractures in the rock and to some extent appears to replace the walls of the fractures, almost indifferently to their composition. Chlorite veins of this sort are illustrated on plates 7 and 11, *A, B, E, F*.

The vein chlorites tested have a range of 1.605 to 1.647 for the index β, both ±0.003, with low birefringence and negative character. Although the extreme member of this range is the iron-rich daphnite, the average of the vein chlorites probably contains little more iron than the pseudomorphous variety, diabantite. The vein chlorite is clearly younger than the orthoclase and much of the quartz of the ore deposit. (See pls. 7, *B*, 8, *A*, 11, *A, B, E F*.) In part, at least, it is younger than magnetite, and, from its localization with the copper sulfides, is apparently contemporaneous with them, as is the leafy chlorite.

These apparent age relations, together with the optical data, suggest that there is on the average slightly more iron in the chlorites that were wholly introduced at the time of mineralization than in the chlorites that formed in place as a result of alteration of preexistent ferromagnesian minerals. This difference, however, is not consistent, for some vein chlorites, according to optical data, contain less iron than some of the pseudomorphous chlorites. The only generalization that seems warranted, therefore, is that chlorite with a high iron content indicates that the ore deposit is nearby, but the converse of this rule is not applicable.

BEIDELLITE

The clay mineral, beidellite, a member of an isomorphous series with nontronite, is common at Ajo. It occurs as mats of crystals that preserve the gross form of plagioclase phenocrysts in the outlying parts of the mineralized area. Whether, in this position, it is a mineral formed during an early stage of mineralization and later replaced by sericite as the more intense mineralization expanded, in analogy with Ransome's interpretation[19] of the relation of "kaolin" at Ray and Miami, or whether it is the result of the action of nearly spent mineralizing solutions could not be determined. Specimens of this habit have a refractive index β near 1.545, which indicates a rather low iron content.[20]

In beidellite taken from fault gouge at several places in the ore body β ranges from 1.537 ±0.003 to 1.575 ±0.003 and indicates a generally higher iron content.

Beidellite at Ajo also occurs in the zone of oxidation, where it coats malachite, and was therefore formed during a late stage of weathering. Doubtless the ingredients, if not the mineral as such, were derived by wash from higher parts of the deposit. In some of this beidellite, $\beta = 1.575 \pm0.003$ and indicates a rather high iron content. Beidellite with $\beta = 1.56 \pm0.01$ (also probably supergene) was found coating specularite on the south flank of Concentrator Hill.

POTASH CLAY

A mineral whose optical properties correspond with those of potash clay ($\alpha = 1.54+$, $\beta = \gamma = 1.565$) was found in weathered and copper-stained quartz keratophyre from the north slope of Arkansas Mountain. The mineral does not appear to be widespread, and nothing was learned of its probable genesis.

NONTRONITE

A brownish crust on malachite in the weathered quartz keratophyre on the north slope of Arkansas Mountain has optical properties that correspond to those of nontronite, the iron-rich extreme of the beidellite-nontronite series. A yellowish crust from just east of the approach to the New Cornelia pit also was identified by W. T. Schaller as nontronite. It is not abundant at Ajo nor of economic importance.

CHRYSOCOLLA

The hydrous copper silicate, chrysocolla, though subordinate to malachite, is nevertheless very widespread in the oxidized zone of the New Cornelia ore body. It also occurs in small but conspicuous amounts in many other places in the quadrangle, and its vivid color has led to considerable prospecting of areas in the Locomotive fanglomerate, even south of Locomotive Rock. Here the copper mineral merely impregnates boulders of the fanglomerate that were derived from the New Cornelia outcrop to the north. Such boulders are widespread in the Locomotive fanglomerate south and east of the New Cornelia pit but seem to be lacking in more westerly areas.

The minerals classed as chrysocolla clearly include several, possibly a dozen, species[21] whose precise compositions and properties are not well-defined. Two varieties are the most common at Ajo, though several others also occur, according to Mr. Schaller, who examined many specimens. Both varieties, whose crystals are coarse enough for determination, are fibrous. One has $\alpha = 1.54$, $\gamma = 1.605$, the other has $\alpha = 1.585$, $\gamma = 1.633$. Whether these different properties are due to chemical or structural factors is unknown. Other cryptocrystalline specimens have mean indices of 1.45, 1.53, and 1.57. Most of the Ajo chrysocolla is greenish, but some is nearly white.

[19] Ransome, F. L., op. cit. Inasmuch as the clay minerals have become better known since the date of Ransome's report, it is possible that the material called "kaolin" by him would now be classed as a member of the beidellite-nontronite series.

[20] Larsen, E. S., and Berman, Harry, The microscopic determination of the nonopaque minerals: U. S. Geol. Survey Bull. 848, pp. 156-167, 1934.

[21] Schaller, W. T., personal communication.

As in many other weathered zones, the mineral alterations at Ajo have been more or less rhythmic, with repetitions and alternations of encrusting minerals. However, there seems to be a general tendency for chrysocolla to form at the expense of malachite and to encrust it. For the most part the chrysocolla was soluble, along with the carbonates, in the leaching process, and it offered no serious problem to the exploitation of the oxidized part of the New Cornelia ore body.

SPHENE

Sphene (titanite) is a primary constituent of all the igneous rocks of the mining district. It is conspicuous, in euhedral crystals, in the Cornelia quartz monozonite, where it is commonly 1 millimeter in length and locally exceeds 3 millimeters. In the mineralized part of the Cornelia massif the sphene is altered, and the titania apparently has been combined with ferrous oxide to form ilmenite (see p. 90) or has crystallized in the form of brookite (?).

APATITE

Apatite has been found at Ajo only as an accessory mineral of the igneous rocks. Several specimens from the Cornelia quartz monzonite examined by Miss Glass have $\epsilon = 1.628$ to 1.629, $\omega = 1.632$ to 1.636, uniaxial negative. The crystals are commonly euhedral and stumpy in the fresh monzonite but are somewhat corroded and rounded in the mineralized portion.

PYROMORPHITE (?)

An unidentified mineral found in a prospect at Cardigan was examined by Miss Glass, who states that it responds partly, though not conclusively, to tests for pyromorphite.

MOTTRAMITE

Mottramite (cuprodescloizite) occurs in trifling amounts as a yellowish-green crust on weathered outcrops of keratophyre and Hospital porphyry along the east side of the approach to the New Cornelia pit. Mr. Schaller detected lead, copper, and vanadium. This is the only definitely determined mineral found at Ajo that contains lead, and the primary mineral from which it was derived is not known.

PLANERITE (?)

The rare hydrous aluminum phosphate planerite (coeruleolactite) was doubtfully identified by Miss Glass as a weathering crust from Camelback Mountain and several other localities in the quadrangle.

BARITE

Barite is not common at Ajo but has been found in narrow, irregular veins associated with specularite, ankerite, and quartz cutting the Concentrator volcanics of Arkansas Mountain and the Cornelia quartz monzonite to the north. It was also found in the Concentrator volcanics between the approach incline to the New Cornelia pit and the waste dump to the east. In some vugs it rests on euhedral quartz crystals, but its relation to specularite and ankerite is obscure. Their close spacial association, however, seems to indicate roughly contemporaneous formation.

ANHYDRITE

Anhydrite is not a common mineral at Ajo, but it occurs in relations that indicate its hypogene origin during the epoch of mineralization. It occurs entirely in minute crystals that are only recognizable under the microscope. Specimens containing it are found in several parts of the New Cornelia ore body, the most coarsely crystalline anhydrite being from a drill core obtained at an altitude of 800 feet (depth 950 feet below the surface) from diamond drill hole 161, about 1,800 feet southwest of the common north corner of secs. 26 and 27, T.12 S., R. 6 W. This anhydrite has the following optical properties: $\alpha = 1.570$, $\beta = 1.575$, $\gamma = 1.610$, all ± 0.003, 2V small, optically positive, extinction parallel to two good cleavages. These properties suffice to identify the mineral as anhydrite, a determination confirmed by chemical tests for sulfate.

In this specimen and others from elsewhere in the pit the mineral forms veins that cut orthoclase, sericitized plagioclase, biotite, and chlorite and as rosettes of plates that encroach upon and penetrate copper sulfides and quartz. (See pl. 18, *A*.) It thus formed late in the history of the ore deposition and is so far below any signs of surface alteration that its hypogene origin seems clear.

Hypogene anhydrite associated with copper deposits is known in greater proportionate amounts in several districts in the West, notably at San Francisco, Utah,[22] and Bully Hill, Shasta County, Calif.[23] Butler has pointed out the difficulties in the way of attributing it to deposition from cooling solutions, for laboratory data indicate its increasing solubility in pure water as temperatures fall. Nevertheless, hypogene sulfates have produced alunite in the Ajo district, although not in the identical areas in which anhydrite has been recognized. It thus seems reasonable to suggest that the mineral was formed practically in place by reaction between rising sulfate water and lime in the wall rocks. The lime content of the quartz monzonite adjacent to the ore body is low, but so is the total amount of anhydrite present.

BROCHANTITE

A few crusts of the green basic copper sulfate, brochantite, have been found in the weathered zone of the New Cornelia ore body.

[22] Butler, B. S., The geology and ore deposits of the San Francisco and adjacent districts, Utah: U. S. Geol. Survey Prof. Paper 80, pp. 120-125, 1913.

[23] Graton, L. C., The occurrence of copper in Shasta County, Calif.: U. S. Geol. Survey Bull. 430, pp. 99-103, 1910.

GYPSUM

Small amounts of gypsum occur in the weathered zone of the New Cornelia ore body in association with jarosite. The mineral commonly encrusts pyritic specimens and is doubtless forming today by attack of meteoric sulfate waters on the small amount of calcite present in the rock. A negligible fraction may represent hydration of anhydrite.

EPSOMITE

The hydrous magnesium sulfate epsomite was identified by W. T. Schaller in some material from the oxidized part of the ore body just north of Arkansas Mountain. Only a small amount of this material was found, and, as the specimen may have come from a drainage channel, it may be only a desiccation crust from rainwater that stood in pools.

BIEBERITE

A pink efflorescence found on the side of a ditch draining the approach to the New Cornelia pit was identified by Mr. Schaller as cobalt sulfate. No hint is available as to the source mineral whose leaching furnished the cobalt.

ALUNITE

The basic potassium aluminum sulfate, alunite, occurs in considerable amount in veins that cut the Concentrator volcanics east of the head of the approach incline to the New Cornelia pit. Over an area of several acres the volcanics are broken by innumerable fractures occupied by veins of dense, porcelanous alunite. In part the walls are impregnated with hematite and the intervening lava is much altered to clay minerals.

The alunite veins range in thickness from a knife edge to 3 inches. They are pale greenish-yellow and extremely fine-grained, with no individual crystals visible, even with the high power of the microscope. The veins, nevertheless, give a suggestion of cross-fiber structure, which does not appear to be due to pseudomorphism after any older minerals. Tests of the material by Miss Glass gave: mean index 1.583 and chemical tests for acid, water, sulfate, and K_2O. The mineral yields much water in the closed tube.

The mode of occurrence does not suggest that the alunite was formed during either period of weathering, and it is thought to have been formed by reaction between the rocks and permeating solfataric solutions. So far as known, there is no direct connection between the presence of alunite and that of copper minerals. However, in many other mining districts alunite accompanied gold deposition, and it may be that search for a gold ore body near this intensely alunitized area would yield favorable results.

JAROSITE

The yellow-brown ferric potash sulfate, jarosite, occurs in the weathered zone of the New Cornelia ore body, where it commonly encrusts earthy hematite on many of the weathered outcrops. It is largely confined to the areas of notably pyritic ore, as would be expected from its composition, and is accordingly not very abundant in the district.

MINING HISTORY

The copper deposits at Ajo were known and worked in a small way by Spaniards and Mexicans at least as early as 1750,[24] although the commonly expressed statement that the deposits were worked at the time of Father Kino (1705) finds no support in his journals.[25] Owing to the low tenor of precious metals, it is certain that production prior to the American occupation was negligibly small.

Ajo is believed to be, after Santa Rita, N. Mex., the first copper district in the Southwest to be worked by Americans.[26] According to Blake,[27] early emigrants to California by the Gila route frequently brought in masses of rich ore, chiefly native copper and cuprite or malachite, assaying as much as 90 percent of copper. For a long time it was erroneously believed that the ore was highly auriferous. One of the chief localities for this "specimen ore" was in the Sierra del Ajo, 135 miles west of Tubac and 130 miles from the mouth of the Gila, where the red oxide and green carbonates had long been used by the Indians for painting their bodies.

According to a participant in the early working of the district,[28]

> The Ajo mine was located in November 1854 by a party of Americans from California. The organization was known as the Arizona Copper Mining and Trading Co. Maj. Robert Allen, U. S. A., deputy quartermaster-general of the Department of the Pacific, was the president of the corporation, and J. Downer Wilson, of San Francisco, was secretary and treasurer.
>
> At that date the present boundary line between Sonora, Mexico, and the territory of the United States had not been determined, and its position was not ascertained until the following year, 1855.
>
> As soon as the region began to be occupied by citizens of the United States and work commenced on the Ajo mines, these mines were claimed by several wealthy residents of Sonora as being within Mexican territory. In the month of March, 1855, a Mexican company of cavalry was sent from the district of Altar and from Ures, the capital of Sonora at that time, to dispossess the Americans, to capture them, and take them to Ures as prisoners. But the miners refused to go and defended their position. With only 9 men against 110 dragoons and vaqueros, the mine was successfully held and the Mexicans were dispersed. For 6 months after this nothing was done beyond mere prospecting, but in the fall of the year 1855 the boundary line had been run, and it was found that

[24] Parsons, A. B., The porphyry coppers, p. 285, Am. Inst. Min. Met. Eng., New York, 1933.

[25] Bryan, Kirk, The Papago country, Ariz.: U. S. Geol. Survey Water-Supply Paper 499, p. 13, 1925.

[26] Joralemon, I. B., The Ajo copper-mining district: Am. Inst. Min. Eng. Trans. vol. 49, p. 593, 1914.

[27] Blake, W. P., Silver and copper mining in Arizona: Mining Mag., 2d ser., vol. 1, p. 10, 1859.

[28] Brady, P. R., Sr., quoted by Blake, W. P., Report of the Governor of Arizona to the Secretary of the Interior for the year 1899, pp. 48-49.

the Ajo mining camp was at least 40 miles inside of the boundary on the United States side. Edward E. Dunbar, one of the pioneer residents of San Francisco, was then made the superintendent of the property, and work was resumed in a formal manner. The mining locations, of which there were 17 made in that year, all had some work done on them. In the meantime 10 tons of selected ore had been taken from shaft No. 1. This ore consisted of red oxide of copper. It was shipped to Swansea and was sold for a little less than $400 per ton. There were several hundred tons of sulphurets of copper extracted from the different workings. The principal portions were in a limestone formation,[29] but the richest ores were all found near where the first work was done and were in porphyry.

The company attempted to transport the ore to San Francisco and thence around Cape Horn to Europe, but the costs were so great that their plan of transportation had to be abandoned. For the first year, on every pound of ore transported from the mine by way of Yuma to San Francisco the freight alone amounted to 9 cents. A reverberatory furnace was built at a cost of over $30,000, and not as much as 100 pounds of copper was ever produced in it. Finally, after several years of great expenditure, the company ceased operations. The property was left in charge of a keeper whose claim for services amounted to $5,000, and the property was sold at sheriff's sale.

Intermittent attempts to exploit the deposits followed, but the lack of water and the difficulties of transportation prevented any success. Among the prospectors who persisted in these attempts were Thomas Childs and Reuben Daniels, who by the late nineties had acquired many claims on the site of the present New Cornelia property. A. J. Shotwell, of St. Louis, a mining promoter of that time, took an option on the claims of Childs and others covering much of the district, for $200,000. He organized the St. Louis Copper Co. to finance a 10-stamp mill and enlisted the support of John R. Boddie in distributing the necessary stock. The St. Louis Co. produced and shipped concentrates to the value of $36,000, but at a cost of $45,000. It ended in bankruptcy, and the Rescue Copper Co. was formed by Shotwell to salvage the assets.[30] In 1900 the Rescue Copper Co. disposed of part of its holdings to the Cornelia Copper Co., organized by Boddie, Capt. Huie, W. W. Brown, and C. E. Neely. The purchase price of 4 claims was $19,500 in cash, plus a stock interest. The name, "Cornelia," was in honor of Mrs. Boddie. The Cornelia Co. authorized the issue of 100,000 shares of stock at $10 par value. At about the same time Shotwell sold other claims to the Shotwell Tri-Mountain Copper Co., retaining control of six million of the authorized ten million shares as the purchase price.

The three companies, Cornelia, Rescue, and Tri-Mountain, were unable to operate successfully by stamp milling and table concentration, and being in the hands of inexperienced miners, fell victim to several visionary schemes of recovering the copper in the ores. Among these, the Rendall process, operated by the Rendall Ore Reduction Co., and the McGahan "vacuum smelter," built by Fred L. McGahan, were perhaps among the most bizarre ever to have been floated in American mining. By 1907 these schemes had ended in failure, and the camp was again dormant.

In 1909 J. Parke Channing secured an option, on behalf of the General Development Co. (the "Lewisohn interests"), on a majority of the stock of the reorganized New Cornelia Copper Co. At about the same time, Seeley W. Mudd and associates took an option on the Rendall Ore Reduction Co., and a group of English capitalists an option from Tom Childs on some outlying claims. These three groups began development work at about the same time—the English syndicate by a shaft, the Mudd-Wiseman group by churn drilling, and the General Development Co. by core drilling—but all three avoided the three hills (see pl. 19) that capped the ore body. They were disappointed in the results achieved, and the options were allowed to lapse.

In 1911 the Calumet and Arizona Copper Co., under the direction of Col. (later Gen.) John C. Greenway, general manager, undertook an examination of the Ajo district. Ira B. Joralemon, geologist for the company, reported the existence of a large tonnage of carbonate ore containing 1 to 2 percent of copper underlain by much more hard sulfide ore with disseminated chalcopyrite and bornite. At the time, there was no known process for recovery of the copper from the carbonate ore, and the sulfide ore was much more refractory than any that was being utilized elsewhere. Nevertheless, the Calumet and Arizona Copper Co. took an option on 70 percent of the New Cornelia stock at about $1.60 a share, with the provision that the stock should be issued as the money was spent for development and equipment. The company was reorganized under the same name. At the same time the Calumet and Arizona Copper Co. took an option on a controlling interest in the Rendall property.

Drilling to test the ground began in the fall of 1911. Early results were so discouraging that the option on the Rendall property, which called for an early payment of $50,000, was relinquished. Further drilling, however, soon established the worth of the New Cornelia ground, but in the meantime James Phillips, James P. Gaskill, Utley Wedge, and others had organized the Ajo Consolidated Copper Co. and bought the Rendall claims for $200,000 cash. When, 6 years later, the New Cornelia purchased the Ajo Consolidated claims, the consideration was nearly $4,000,000. The United States Smelting, Refining & Mining Co. took an option on the Childs group, which lay in part to the east of the New Cornelia group and in part between the New Cornelia and Ajo Consolidated blocks of claims. This company soon abandoned its option, and the ground has since been taken over by the New Cornelia Copper Co.

Experiments directed toward the development of a leaching process for the carbonate ores were undertaken by the New Cornelia Copper Co. in 1912. This work was

[29] This is undoubtedly erroneous, as the only limestone in the district occurs as pebbles in the postmineral fanglomerate.

[30] This portion of the history is largely taken from Joralemon, I. B., Romantic copper, pp. 168-197, Appleton-Century, New York, 1935.

essential for turning the carbonate capping of the sulfide ore body into an asset instead of a liability. It was done under the direction of Dr. L. D. Ricketts by a large staff, of whom J. A. Potter, H. A. Tobelman, Stuart Croasdale, and F. L. Antisell were principals.

Railroad surveys were made to Gila Bend and Tucson in 1913 and explorations begun for the large water supply necessary for the proposed leaching plant. Four wells were drilled in the valleys north of Ajo. Of these, No. 1 well, at Childs Siding, was the most promising. It was drilled to a depth of 1,348 feet, through alluvium, lava, and intercalated gravel, and tapped a good supply of water at a depth of 645 to 664 feet. A shaft was sunk, pumps were installed, and the supply was found adequate. Pipe lines were laid to the mine, 6 miles away, where a 500,000-gallon tank on Reservoir Hill completed the primary supply system for the operation.

The old town of Ajo lay on or close to the ore deposit. The New Cornelia Co. therefore located and built a new town about a mile to the north, with artistically laid out streets and attractive, substantial concrete houses. It is a model town, with plaza, stores, hotels, hospital, paved streets, water supply, sewage system, and bank. As is usual, however, opposition arose to a company town, and a town site, Clarkstown, was laid out by Sam Clark on a group of mining claims just east of the proposed site of the leaching plant. At the same time, M. E. Gibson laid out a similar town site northwest of town. Both of these places are supplied with water by private wells. During 1916 and 1917 the population of Clarkstown, between 800 and 1,200, was larger than that of Ajo. During normal times, however, the population of the district is dominantly in the town of Ajo.

By 1915 the experiments on leaching were advanced to the point where success could be anticipated. In January a 40-ton experimental leaching plant was completed and operated throughout the year, treating 12,222 tons of ore. In August work was begun on the railroad from Gila Bend, called the Tucson, Cornelia, and Gila Bend R.R. The railroad was completed, and regular service began February 20, 1916. A little high-grade siliceous ore was shipped to Douglas all through 1916. Early in 1916 construction of a 5,000-ton leaching plant was begun, and, although delayed by a strike in October that shut down all construction work, by April 1917 the operation was ready to start in a large way.

From the start the New Cornelia operation was a success.[31] The leaching plant worked perfectly, the ore yielded exactly the estimated grade, and the cost was within the estimate for the very first month. Crushing began in April, the leaching tanks were put in operation on May 1, and the first shipment of electrolytic copper was made on June 18, 1917. In 1917 the New Cornelia output was 19,482,191 pounds of copper. Its total reserves were then estimated at 52,262,602 tons of ore, averaging 1.579 percent of copper, of which about 400,000 tons contained 4 percent or better and was regarded as shipping ore.[32]

[31] Joralemon, I. B., Romantic copper, p. 196, Appleton-Century, New York, 1935.

In preparation for the eventual exhaustion of the carbonate ore, funds for a test mill for treatment of the underlying sulfide ore were appropriated in 1918, and the mill was in operation in September 1919.

Early in 1919 the post-war depression led to curtailment of production. This curtailment was intensified in 1921 and continued through June 1922. In October 1922 work was begun on a 5,000-ton sulfide concentrator, and a second shaft was sunk at the "water mine" at Childs Siding. The first ore was delivered and crushed at the sulfide concentrator on December 26, 1923, and the concentrator was put in operation on January 8, 1924. Both leaching and sulfide ore was treated from then until 1930, when the leaching plant was shut down.

At the end of 1924, published reserves were:

	Tonnage	Average (percent)
Carbonate ore, Cu + 0.8 percent	4,071,099	1.27
Sulfide ore, Cu 0.8 to 3 percent	54,200,947	1.32
Sulfide ore, Cu + 3 percent	2,410,544	3.66

During 1928 and 1929 three 2,000-ton units were added to the sulfide concentrator, and modifications were made in the five older units to bring their capacity up to the same figure. The nominal capacity of the concentrator is thus 16,000 tons, but with relatively slight changes it may be increased to 20,000 tons. The rated capacity had never been reached up to 1934, for the curtailment that began in late 1929 continued. The entire operation was discontinued in April 1932 and was not resumed until July 1934.

In 1929 the New Cornelia Copper Co. was consolidated with the Calumet and Arizona Copper Co., with which its affiliations had always been close, and the new company was merged with the Phelps Dodge Corporation in 1931. The Ajo mine now operates as the New Cornelia Branch of the Phelps Dodge Corporation.

The history of the New Cornelia mine is, in essentials, the history of the Ajo district. No other mines have made more than trivial production, nor are any others known to have developed any appreciable bodies of ore.

PRODUCTION

The production of copper from the Ajo district prior to the reorganization of the New Cornelia Copper Co. in 1911 was negligibly small, though precise figures are not to be had. Apparently more than 1,000 tons of ore were

[32] Mineral Resources U. S., 1917, p. 536.

shipped to Swansea, Wales, in the 1850's,[33] and some small outputs were recorded in 1897, 1898, and 1899.[34] A small output of shipping ore was made in 1912-15,[35] and steady shipments of direct-smelting ore began in 1916, when the railroad was completed. However, the total output of the district prior to the opening of the leaching plant of the New Cornelia Copper Co. in 1917 was probably less than 1,700,000 pounds of copper.

The following table summarizes the output of the district up to 1935. Since the New Cornelia property has been controlled by the Phelps Dodge Corporation no production data have been published. However, it is known that its output has been the largest of any mine in Arizona for many of the years from 1935 on.

[33] Blake, W. P., Silver and copper mining in Arizona; Mining Mag., 2d ser., vol. 1, p. 10, 1859.

[34] Blake, W. P., Report of the Governor of Arizona to the Secretary of the Interior for the year 1898 (p. 61), 1899 (p. 48). Joralemon, I. B., op. cit., p. 170, gives the output under Shotwell's management (about 1899) as valued at $36,000.

[35] Mineral Resources U. S., annual volumes 1912-1915.

TABLE 8.—*Metal production, Ajo district, Arizona*

[Based on annual volumes of Mineral Resources of the United States 1909-23, published by the Geological Survey; 1924-31, published by the Bureau of Mines; and on Minerals Yearbook, 1932-34, published by the Bureau of Mines. Estimates for certain years from Arizona Metal Production, by M. J. Elsing and R. E. S. Heineman: Arizona Bur. Mines Bull. 140, p. 73, 1936.]

Year	Producers		Tons	Gold (ounces)	Silver (ounces)	Copper (pounds)	Total value (dollars)
	Lode	Placer					
Prior to 1909	..	..	....	....	....	[1]200,000	[1]50,000
1909	4	..	810	111.3	894	142,516	22,393
1910	5	..	926	25.0	421	97,999	13,190
1911	2	..	....	....	....	[2]100,000	[2]12,500
1912	1	..	....	....	....	[2]100,000	[2]16,500
1913	..	..	....	....	....	....	....
1914	..	..	....	....	....	....	....
1915	5	..	94	....	....	[2]20,000	[2]3,611
1916	..	..	[2]40,000	....	....	[2]1,000,000	[2]246,000
1917	11	..	[3]801,026	41.2	6,754	[3]20,201,645	5,521,466
1918	1	..	[4]1,856,417	....	....	[4]49,950,139	12,360,220
1919	1	..	1,604,653	....	....	[5]39,509,461	7,348,760
1920	1	..	1,743,439	....	....	[6]40,104,493	7,379,227
1921	1	..	931,051	....	....	[7]20,198,382	2,605,591
1922	1	..	1,339,757	....	....	[8]26,612,803	3,592,728
1923	1	..	1,805,322	....	....	[9]38,367,718	5,640,055
1924	1	..	2,984,862	11,010.8	174,359	[10]63,884,293	8,711,556
1925	1	..	3,346,770	14,355.9	209,860	[11]69,262,286	10,277,626
1926	1	..	3,405,174	18,114.0	234,139	[12]82,312,463	12,044,264
1927	1	..	3,371,261	18,349.7	200,924	72,932,670	9,897,892
1928	1	..	3,646,029	16,378.8	171,943	[13]77,995,281	11,825,915
1929	1	..	2,456,304	14,739.0	155,739	[14]71,000,000	12,768,387
1930	1	..	1,916,932	11,444.0	121,300	[15]50,474,000	6,844,341
1931	1	..	[2]1,635,000	[2]14,030.0	[2]150,000	[2,16]41,200,000	4,082,005
1932	1	1	[2]350,000	[2]3,387.0	[2]25,000	[2,16]10,000,000	[2]637,000
1933	..	1	....	11.5	....	....	294
1934	1	..	1,477,000	[17]8,040.0	[17]91,700	[17]31,900,000	[17]2,890,000
Totals	....	....	[18]34,700,000	[18]2,525,000.0	[18]1,530,000	[18]807,000,000	[18]124,700,000

1. Estimated.
2. Estimate by Elsing and Heineman.
3. 70,800 tons direct-smelting ore; remainder leached in New Cornelia Copper Co's plant.
4. 84,161 tons direct-smelting ore; remainder leached in New Cornelia Copper Co's plant.
5. 3,500,298 pounds from direct-smelting ore; remainder leached.
6. 249,353 pounds from direct-smelting ore; 409,569 pounds from experimental concentration; remainder leached.
7. A little direct-smelting ore; remainder leached.
8. 63,461 pounds from direct-smelting ore; remainder leached.
9. All leaching ore.
10. 39,407,932 pounds from concentrating ore; remainder from leaching ore.
11. 51,977,126 pounds from concentrating ore; remainder from leaching ore.
12. 64,070,190 pounds from concentrating ore; remainder from leaching ore.
13. 35,849 pounds from shipping ore; 21,975,186 pounds from leaching ore; remainder from concentrating ore.
14. Approximate total—36,762 pounds from shipping ore, 22,081,570 pounds from leaching ore; remainder from concentrating ore.
15. About 8,000,000 pounds from leaching ore; remainder from concentrating ore.
16. All concentrating ore.
17. Estimate for 1934 based on published tonnage milled, tenor assumed as in 1927.
18. Totals rounded off are probably correct to the nearest unit given.

The New Cornelia output to the close of 1931 has been analyzed by classes of ore by Parsons.[36] Though his figures differ slightly from those of table 8, the graph in figure 12, taken from his work, summarizes the trend of the output.

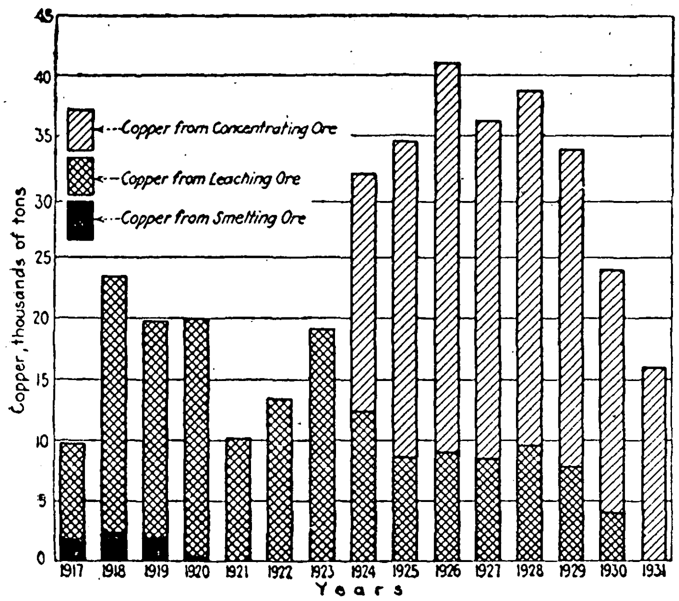


FIGURE 12.—Copper production from New Cornelia mine, by classes of ore. After Parsons, A. B., The porphyry coppers, p. 297, fig. 22. Reproduced by permission of American Institute of Mining & Metallurgical Engineers.

To the end of 1931 there had been mined about 16,340,000 tons of carbonate ore averaging 1.36 percent of copper, 15,645,000 tons of sulfide ore averaging 1.41 percent of copper, and about 150,000 tons of direct-smelting ore averaging about 3.5 percent of copper. The small content of gold and silver in the carbonate ore was not recovered in the leaching process. In the concentrating ore the average tenor of gold has been about 0.0067 ounce per unit of copper and that of silver about 0.0075 ounce. The recoveries of the precious metals parallel those of copper very closely. Concentrator returns show that for several years the ratio of recovery of silver is identical with that of copper, and in only one year has the ratio been as low as 0.82 of that of copper. The recovery ratio of gold has generally been between 0.85 and 0.95 of that of copper, but in 1931 was equal to it.

Dividends paid by the New Cornelia Copper Co. up to February 1929, when the property was taken over by the Calumet and Arizona Copper Co., amounted to $18,630,000. Since then profits from the mines have not been published separately but have been merged with those of other properties controlled by this company and the Phelps Dodge Corporation.

ORE DEPOSITS

The only mine that has thus far been productive in the Little Ajo area is the New Cornelia mine, south of Ajo. Some shallow prospecting has been done near Cardigan, south of Locomotive Rock, in Gibson Arroyo, and near Salt well, but so far no encouraging results have been obtained.

NEW CORNELIA MINE

LOCATION AND TOPOGRAPHY

The New Cornelia mine exploits by open-cut methods a large low-grade ore deposit about half a mile south of the town of Ajo. (See pl. 2, *B*.) The mine pit is roughly oval, about 3,000 feet long and nearly 2,000 feet wide, with its major axis trending northwestward. It lies just southwest of the common corner of secs. 22, 23, 26, and 27, T. 12 S., R. 6 W, and forms part of a large basin. Before mining began the site of the mine was occupied by three hills (see pl. 19), but these have been mined away and a pit occupies their place.

The mine pit lies in the south-central part of a basin about 1 mile wide by 1½ miles long drained by Cornelia Arroyo. Most of the low part of the basin is cut on Cornelia quartz monzonite and its dioritic border facies; the borders on the east and southwest are of rugged hills of Concentrator volcanics. At the southeast corner of the basin, the much less-resistant Locomotive fanglomerate rests directly on the Cornelia quartz monzonite, and the valley of Cornelia Arroyo breaks the ring of hills. West of Cornelia Arroyo the resistant Concentrator volcanics intervene between the quartz monzonite and the fanglomerate, forming the prominent landmark of Arkansas Mountain and the chain of hills extending westward along the south side of the basin. The craggy divide between Gibson and Cornelia Arroyos, carved from Concentrator volcanics, bounds the basin on the west. At the northwest corner of the mine basin stands Camelback Mountain, its summit formed of the wide dike of feldspathic andesite porphyry that extends eastward, with short interruptions, to the hill in Mexican Town. This dike forms a sharp spur on Camelback Mountain and a ridge to the east that bounds the basin on the north. Cornelia Arroyo leaves the basin through a narrow gap at its northeast corner, east of Mexican Town.

In general the topography on the intrusive rocks is smooth and the hills are rounded, except that the slopes of Camelback Mountain are steep and cliffy, owing to the wide spacing of the joints that cut the Cornelia quartz monzonite. On the other hand, the Concentrator volcanics form several rugged hills with jutting rocks and rough slopes.

The total relief in the basin is only about 800 feet. The northeastern part is a smoothly cut pediment, which widens to the north and gives an excellent town site convenient to the mine. The topography is almost wholly favorable to open-cut mining, as a short cut through the eastern ridge has given access, within a short distance, to practi-

[36] Parsons, A. B., The porphyry coppers, p. 297, fig. 22, Am. Inst. Min. Met. Eng., New York, 1933.

cally unlimited dumping space for waste, and little barren overburden has had to be removed. As work proceeds to deeper levels, however, it will be necessary to remove as waste some of the hills to the south.

DRAINAGE AND WATER PROBLEMS

The drainage of the basin in which the mine is situated is entirely through Cornelia Arroyo. During all but a very few days in the year this stream is dry, but on the rare occasions of heavy "cloudbursts" it becomes a rushing torrent. As the mine is an open pit at the low point of the basin, it is exposed to flooding. A series of check dams has been built south of the mine, impounding the water from Cornelia Arroyo and its tributaries. Tunnels and diversion canals through the interstream divides permit these reservoirs to overflow into the drainage east of the hills. Similar dams block the streams from the west, and ditches divert the flow to a northern tributary of Cornelia Arroyo that enters the main stream near the northern gap in the basin wall.

Prior to mining, the water table was a surface of subdued relief compared with the original topography. In the mineralized area, the water table was rather definitely marked by the contact between primary sulfide ore below and carbonate ore above.[37] The transition zone between thoroughly oxidized ore and wholly unaltered sulfide ore was nearly everywhere very thin (see pp. 84-85) and, accordingly, a contour map of the top of the sulfide ore is a serviceable record of the premining water table. Such a map, based on diamond drill records and hence somewhat generalized, is shown on plate 19, together with the original topography of the areas near the mine.

From this plate it can be seen that in the area of the Cornelia quartz monzonite the water table was much smoother than the original topography but conformed to it fairly well. Beneath hills 1, 2, and 3, all of which have since been removed in mining, the water table lay at depths of approximately 130, 165, and 185 feet, respectively, whereas the depth beneath the valleys was 20 to 50 feet. In this area the surface of the water table was remarkable smooth. However, though the information is generally less complete, it is clear that the water table in the Concentrator volcanics and Locomotive fanglomerate was very irregular and varied more than 100 feet in altitude within less than 200 feet. This difference seems to indicate that certain open fracture zones were very much more readily drained than other nearby areas. In the Locomotive fanglomerate it appears that the subsurface drainage may have been quite different from the surface drainage, to judge from the scanty data.

When mining reached and passed below the old water table, the mine pit naturally became a sump into which the ground water of a considerable surrounding area drained. The climate of the region, however, is so dry that the quantity of water so draining is not large, and of it a considerable proportion is removed by evaporation. When the mine was shut down, from April 1932 to July 1934, with the lowest level at about 1,700 feet, water stood to a depth of about 10 feet in the pit, and a pond of about 5 or 6 acres was formed. Evaporation from this surface nearly compensated for the normal inflow of ground water, even though the surface of the pond was about 100 feet below the general former water level.

Until 1934 intermittent operation of an air-operated pump with a capacity of 75 gallons a minute sufficed to pump the water from the pit to the external drainage system, and no difficulty was experienced in draining the mine.[38] As greater depth is attained in the mine it may be expected that more water will be encountered but it does not appear that water will prove a serious factor in mine costs. It is possible, however, that considerable water will be released when the mine penetrates the water table in the Locomotive fanglomerate, for the fanglomerate is clearly much more permeable than the Cornelia quartz monzonite. Probably the water table in the fanglomerate will not be encountered above an altitude of 1,600 feet, and perhaps not above one of 1,500 feet.

GEOLOGY

The geology of the Ajo mining district is shown on plates 20 and 21. The several rock formations and their general relations have been described on pages 8-59. It remains here to discuss the geologic features that appear to be most closely related to the known mineral deposits.

The oldest formation near the mineralized area is the Cardigan gneiss, which crops out near Cardigan and in isolated slivers along the Gibson fault. It is cut by many andesitic dikes (see pp. 21, 34, 40), some older but others younger than the Cornelia quartz monzonite. So far as known there are no commercial mineral deposits in the Cardigan gneiss; it is chiefly of interest in this connection because of the clue it gives to the structure of the other rocks.

East of the Gibson fault the oldest exposed rocks are the Concentrator volcanics. Their composition and attitude have been discussed on pages 22-24 and 51. As shown on plates 20 and 21, the Concentrator volcanics occur in two main areas, separated by the intrusive Cornelia quartz monzonite and its quartz diorite border facies. The southern exposed tip of this intrusive mass and the bordering volcanics, the host rocks of the intrusive, contain the great ore body of the New Cornelia mine. The Locomotive fanglomerate rests upon the eroded surface of the ore body.

[37] Joralemon, I. B., The Ajo copper-mining district, Ariz.: Am. Inst. Min. Eng. Trans., vol. 49, p. 601, 1914.

[38] Ingham, G. R., and Barr, A. T., Mining methods and cost at the New Cornelia Branch, Phelps Dodge Corporation, Ajo, Ariz.: U. S. Bur. Mines Inf. Circ. 6666, p. 15, 1932.

As is seen from plate 20, the wedge-shaped outcrop of Cornelia quartz monzonite widens northwestward from the fanglomerate overlap to Camelback Mountain. Along the western slope and crest of the ridge between Gibson Arroyo and Cornelia Arroyo a septum of Concentrator volcanics and dioritic border-facies separates the porphyritic Cornelia quartz monzonite of the mine area from the larger mass of nonporphyritic quartz monzonite of Cardigan Peak. In the area north of Camelback Mountain, however, the quartz monzonite forms the hanging wall of the Gibson fault, so that this strip of diorite and volcanics does not mark the extreme westward limit of monzonite in the hanging wall. As seen from plate 3, the diorite is so commonly restricted to the immediate borders of the quartz monzonite in the whole area of the Little Ajo Mountains that here, as elsewhere, it is believed to record the approximate position of the original border. The monzonite to the west may be simply a dike like those east of the mine pit, but, as mentioned on page 321, it seems more likely that this monzonite is the flaring lower part of the main stock and the easterly mass is a cupola. (See pl. 24.)

The distribution of the dioritic border facies of the Cornelia quartz monzonite is shown on plates 20 and 21. It may nevertheless be worth while to point out its absence from the western contact between Camelback Mountain and the southwest side of the mine pit; the wide area of diorite east of the mine pit; and the occurrence of several blocks of diorite isolated in the quartz monzonite north of the mine.

As shown by diamond drilling at the south end of the quartz monzonite wedge, the diorite bodies on the east and southwest of the quartz monzonite do not continue indefinitely in depth. (See pls. 22 and 23.) On both sides they narrow downward, and on the west the diorite definitely wedges out within a relatively shallow depth. On the east it narrows decidedly, wedges out on the immediate contact, and then seems to pass into the Concentrator volcanics on the east side of the main monzonite body. (See pl. 23, northeast and southwest cross sections, and pl. 25.)

The diamond drilling in and near the New Cornelia mine has shown that the southwestern boundary of the Cornelia quartz monzonite dips off to the southwest at an angle of about 50° (See pls. 22, 23, and 25.) The eastern contact dips off in the same direction at apparently somewhat gentler angles. Thus the southwestern boundary marks the outcrop of the hanging wall and the eastern boundary the footwall of a tilted body of quartz monzonite that narrows somewhat in depth. Drilling to the nearly 2,000 feet beneath the fanglomerate in this direction. The present southern limit of the intrusive is thus merely an accident of erosion prior to the deposition of south shows the extension of this monzonite mass for the fanglomerate. The quartz monzonite mass is dikelike, with its extension north-northwest 2,000 feet beneath the fanglomerate in this direction.

There is some uncertainty, owing to the wide spacing of the deeper holes, but it appears that below the 900-foot altitude a ridge in the footwall projects southward into the quartz monzonite mass, and when followed down to the 800-foot altitude, forms a saddle that nearly or quite divides the monzonite body into two parts. These two divisions of the monzonite are not closely defined because the deep drill holes are few, but the monzonite bodies appear to pitch to the southwest at the 500-foot level. At these levels a blunt, dikelike body of quartz monzonite, which apparently does not crop out, occurs in the footwall of the main mass and, still lower, seems to approach the eastern branch of the outcropping mass by the wedging down of the intervening septum of Concentrator volcanics. There are not enough deep holes to determine whether the two masses coalesce. From these results of drilling one might infer that the southern end of the quartz monzonite in the mine has a shape like a molar tooth with several deep roots. Of course, nothing is known of the attitude of the monzonitic mass farther to the north, for diamond drilling has not been done north of Hospital Hill, and, as mentioned on page 32, the lineation of the monzonite is too faint to warrant much confidence in it as a guide to the location of wall rocks. However, it seems reasonable to assume that the east wall also dips westward beneath the mass to the north, as it is known to do in the latitude of the mine. If this is conceded, the simple picture of a rootlike continuation of the monzonite in depth, such as might be deducted from the diamond drill results, requires important modification, which can best be considered in detail after discussion of the Locomotive fanglomerate.

That the Locomotive fanglomerate is postmineral has been explained on pages 36 and 83. In brief, the direct evidence of its age is furnished by (1) the presence of isolated boulders of mineralized quartz monzonite in the fanglomerate without the slightest sign of mineralization of the matrix or of feeding channels for the mineralizing solutions; and (2) the occurrence of a regular and practically continuous blanket of oxidized ore and one of secondarily enriched ore that lie parallel to and only a few feet below the base of the fanglomerate and have been followed by the diamond drill to depths of 200 feet below sea level. These features prove that the fanglomerate lies on an erosion surface that exposed a previously existent ore body. Indirect evidence for the same conclusion is that the ore is clearly related to the quartz monzonite in origin, and inasmuch as the fanglomerate is unaltered at its overlapping contact with the quartz monzonite, it is post-monzonite. As the monzonite was doubtless emplaced at considerable depth, its original cover must have been removed prior to the deposition of the fanglomerate.

The fanglomerate, as can be seen from the dips recorded on plates 3, 20 and 21, strikes about east in the vicinity of the mine pit and dips steeply south at about 50° to 60°. As has been mentioned in the description of the formation on pages 35-38, the fanglomerate was deposited upon a rough surface that rose higher toward the west; that is, the fanglomerate was deposited against the eastern (and southeastern?) flanks of an old mountain mass. Doubtless it had an original dip, as do modern alluvial fan and mudflow deposits, but such an original dip could have been only a very few degrees, and most of the present dip must be attributed to deformation. It seems entirely reasonable, therefore, to conclude from the uniformity of the present steep dip that the whole block of the Little Ajo Mountains, and certainly the eastern end of them, has been tilted at least 50° southward on an eastward-trending axis. This tilting affects the whole block south of the Little Ajo fault for several miles. The measure of the tilting is confirmed in a general way by the corresponding attitude of the zone of weathering and supergene enrichment along the south edge of the New Cornelia ore body.

With this strong postmineral tilting of the Little Ajo block in mind, it becomes clear that the geologic maps of plates 20 and 21 represent projections of the geology on a plane that, at the time of mineralization, was not horizontal but inclined northward at about 50° to 60°; in short, the areal map of the rocks in their present attitude really depicts a steep cross section of the rocks with respect to the premineral horizon.

The apparent horizontal northward offset of the gneiss on the hanging wall of the Gibson fault thus represents an offset in a plane that at the time of movement on this fault was much nearer to the vertical than to the horizontal. It is quite compatible with this fault being a dip-slip normal fault. Under this interpretation the displacement was at least as great as the width of the outcrop of Concentrator volcanics now found along the hanging wall of the fault, for none of these volcanics are now to be seen in the footwall block. Accordingly, 4,000 feet is a reasonable minimum measure of the throw.

From this line of reasoning, it follows that the wedge-shaped mass of porphyritic Cornelia quartz monzonite that appears on plate 3 as a lateral offshoot from the larger Cardigan Peak body was originally a branch that extended chiefly upward rather than laterally from this mass; in short, the igneous body in which the known ore deposit occurs was formerly a cupola on the Cardigan Peak stock. Its present location alongside of that mass is due to the movement along the Gibson fault, followed by erosion and tilting along the Little Ajo Mountain fault. These relations are shown schematically on plate 24, in which an attempt is made to portray the stages of structural evolution of the mass in which the ore body occurs. The principal element of uncertainty in this reconstruction of the pre-fault relationships is the amount and direction of displacement along the Gibson fault. However, the true structure prior to this faulting probably was not very different from that shown on plate 24, No. 1.

Was this the relation at the time of mineralization? It appears very probable that it was. A glance at the geologic map, plate 20, shows a swarm of dikes that trend generally east-by-north. The dikes are of two varieties, the coarsely porphyritic andesite porphyry represented on and east of Camelback Mountain and the finer-grained hornblende andesite dikes. East of the Gibson fault all these dikes lie north of sections 27 and 28, except for one that cuts the ore body near the middle of the New Cornelia pit. None of them penetrate the Gibson fault, although it is true that many seem to die out east of this fault and without clear relationship to it.

West of the Gibson fault there are many hornblende andesite dikes that probably include some representatives of these post-Cornelia dikes as well as pre-Cornelia dikes, but they all lie in the Cardigan gneiss much to the south of the projected strikes of the hanging-wall dikes. None are found west of Gibson Arroyo in the Cornelia quartz monzonite. As has been pointed out, the northeasterly curve in the dikes of the footwall of the Gibson fault may be due to drag, but whether or not this is so the areal distribution of the dikes gives a strong presumption that the fault is younger than the nonporphyritic dikes.

The dikes, however, are almost surely postmineral, for the mineralization was closely connected with the pegmatite stage of igneous consolidation (see pp. 75, 76, 78), and the pegmatite blended with the wall rocks, whereas the dikes cut them sharply. Although the dikes are locally chloritized, the one that cuts the center of the ore body of the New Cornelia mine has fresh andesine feldspar, whereas the bordering monzonite is thoroughly sericitized. Furthermore, the dikes trend at a high angle to the pegmatites. From all these relations it is probable that the Gibson fault is not only younger than the emplacement of the Cornelia quartz monzonite, as is clear from the occurrence of slickensided monzonite in the walls, but also younger than its mineralization.

Accordingly, there is good reason to believe that the mineralization of the New Cornelia ore body took place before the Gibson fault was formed, and hence in the cupola of the Cornelia quartz monzonite stock. This is therefore another example of mineralization associated with an apically truncated stock, such as was pointed out by Butler[39] to be common in Utah. The conclusion of Emmons,[40] based on simply a small-scale areal map, that

[39] Butler, B. S., Relation of ore deposits to different types of intrusive bodies in Utah: Econ. Geology, vol. 10, pp. 101-102, 1915.

[40] Emmons, W. H., Relations of the disseminated copper ores in porphyry to igneous intrusives: Am. Inst. Min. Met. Eng. Trans., vol. 75, pp. 797-809, 1927.

the New Cornelia deposit lies on a ridge on the cupola of the stock requires some modification, for the wedge-shaped outcrop of monzonite near the mine did not project from the side of the intrusive body but from high on its upper part. Furthermore, drilling has shown the quartz monzonite to continue at depth far to the south of its surface limits, and it has clearly been cut off by erosion in this direction. The off-shoot in which the deposit occurs may perhaps better be classed as a thick dike or even a cupola rather than as a ridge on the side of a stock. The picture is, however, in its fundamental features much like that of Emmons. This fact has considerable bearing on the probable future of the district, for if the ore deposit is associated with the former crest of the stock there is less likelihood of finding other deposits to the west of the Gibson fault or to the north of the known ore bodies than there otherwise might be.

ORE BODIES

GENERAL FEATURES

The New Cornelia deposit consists of cupriferous minerals scattered through large masses of rock. As in most other disseminated deposits, the copper tenor is low. The workability of the ore depends on the economies possible in the treatment of large quantities of material rather than upon the existence of a high concentration of metal in a small volume of rock.

Also, like other disseminated deposits, the boundaries of the ore bodies are generally indefinite. There are no readily recognizable features that distinguish ore from barren rocks, as the transition from ore to waste or country rock is gradational, and the outlining of the ore is entirely dependent on assays. These features are illustrated by the representative assay graphs shown on plate 26. It is, strictly speaking, impossible to say for any long term in advance what the lower limit of copper tenor may be that will still permit such disseminated ore to be mined at a profit. As the fluctuations in economic conditions and technologic changes are controlling factors, it is impossible to delimit the ore bodies in any rigorous way far in advance of mining. For these reasons the descriptions of the New Cornelia ore body that follow must be regarded as broad rather than specific characterizations; a shift of a few percent in costs or in the sales price of copper may greatly change the quantity of ore reserves.

For these reasons and to avoid disclosure of confidential information, the descriptions are based largely on the distribution of rock containing 0.5 percent or more of copper. Probably much of this low-grade material is below what is now considered ore, as the mill heads at the New Cornelia concentrator have consistently contained more than 1.25 percent of copper, but the distribution of the higher-grade material is merely more restricted and does not differ qualitatively from that outlined below.

The New Cornelia deposit originally contained two classes of ore, the carbonate ore that occurred above the ground-water table and the sulfide ores below. The carbonate ore, which has since been mined out, was obviously developed by oxidation of the sulfide ore essentially in place. Both copper carbonates and the sulfides from which they were derived are disseminated along minute cracks through the Cornelia quartz monzonite and its host rocks in amounts sufficient to make large tonnages of rock containing more than 1 percent of copper. The ore body as outlined in 1934 may be visualized as roughly funnel-shaped in the upper part, tapering to a crescentic root that pitches steeply southward and narrows somewhat downward.

The form of the ore body is shown at vertical intervals of 100 feet on plate 25 and on the cross sections of plates 22 and 23. The horizontal sections are drawn at elevations referred to the datum of the New Cornelia engineers. This datum is 13.826 feet lower than the Geological Survey datum.

SIZE AND SHAPE

On the original surface the principal outcrop of copper carbonate ore, on the basis of 0.8 percent of Cu as the commercial limit, covered about 86 acres and formed an irregular tapering area about 3,500 feet long and 2,000 feet wide in its widest part. This outcrop occupied essentially the same area as the present pit, and both outcrop and pit trended generally north-northwest. It was widest near the northwest end and tapered to a narrow neck at the southeast, where it finally turned northeastward. (See pl. 25.) An irregular series of small outcrops of similar carbonate ore extended along the approximate course of the present approach to the main pit—a fortunate circumstance that enabled profitable exploitation of considerable rock whose removal from the approach would have been necessary in any event.

In depth, as shown on plates 22, 23 and 25, the ore body abruptly widens, attaining a width of about 2,700 feet at an altitude of about 1,700 feet. It then tapers gradually to an altitude of about 900 feet, where it is sickle-shaped and roughly 4,200 feet long on the arc, 3,000 feet on the chord, and 800 feet broad in its widest part. The southwestern and southeastern boundaries are rather uniform in both trend and inclination; the principal variations in shape, so far as shown by drilling, seem governed by the irregularities in the northern and northeastern boundaries.

A block of waste, or slightly mineralized rock, that trends northwestward and averages nearly 300 feet in width divides the ore body almost completely at the 1,700-foot level. This block is somewhat wider at the 1,600-foot level and completely divides the ore body at the 1,500 foot level. Below this level it tapers in both length and width until it is only about 400 by 200 feet at the 1,300-foot level and 200 feet in diameter at the 1,200-foot level. It persists, however, nearly to the 1,000-foot level. Below the 1,000-foot level the ore body is less well known, but on the basis of the drilling as late as 1934 it appears to be curved somewhat like a boomerang and to shorten notably, so that it is merely a pipelike mass at the 200-foot level.

At the present state of exploration there are no obvious controls for the shape of the mineralized body. Neither the apparent flare near the surface nor the large block of waste that lies centrally in the ore body appears to be related to discernible geologic controls closely enough to enable any prophecies to be made as to other irregularities in form. It seems certain that such features are controlled by structure, but the controls are too obscure to help in exploitation of the deposit.

RESERVES

The level maps and the sections prepared from them show the approximate outlines of the ore body or rather of the ground whose copper tenor exceeds 0.5 percent. Much of this is, of course, of too low grade to be mined under present or reasonably anticipated economic conditions, so that these data do not suffice to outline the ore reserves of the deposit.

The Phelps Dodge Corporation has published no estimates of ore reserves at the Ajo mine. The reserves are, however, probably considerably larger than the figures published by the Calumet & Arizona Mining Co. in May 1929,[41] which amounted to 113,262,000 tons of ore containing 1.25 percent of copper, or 1,420,000 tons of metallic copper. Parsons,[42] on his own responsibility, estimated the reserves as of January 1, 1932, at 200,000,000 tons of 1.1 percent ore containing 2,200,000 tons of metallic copper. According to Mr. Michael Curley,[43] general manager of the New Cornelia branch until 1938, the ore in the ground in 1934 was sufficient to assure a life of 30 or 40 years at a rate of production exceeding 50,000,000 pounds a year. This is a minimum figure, about half that given by Parsons, and, as no maximum is stated, it is likely that Parsons' estimate is not far from the truth.

RELATION OF THE ORE BODIES TO ROCK FORMATIONS

From the maps and sections it is clear that the ore is chiefly in the porphyritic facies of the Cornelia quartz monzonite. However, to judge from the diamond drill data, the restriction to this formation is not so rigorous at depth as might be thought from the surface exposures. At the surface there is an abrupt falling off of metal tenor at the contact with the dioritic border facies and Concentrator volcanics, but much of the diorite to the east of the mine pit is mineralized at and below the 1,700-foot level. Similarly, the Concentrator volcanics, though on the average less mineralized than the porphyritic quartz monzonite, nevertheless contain considerable ore bodies, and at depth the eastern wing of the sickle-shaped ore body is largely in this formation. Furthermore, according to the interpretation of copper distribution (made by the New Cornelia engineers) and of the geology (made by me), the ore bodies at depth do not seem to undergo abrupt changes in tenor or trend at geologic boundaries. Too much emphasis should not be placed on this apparent independence of the ore body from its host rocks, as it is based almost entirely on drill-hole data; nevertheless it suggests that the emplacement of the commercially valuable minerals was governed primarily by the penetrability of the rocks to mineralizing solutions rather than by their chemical composition. This suggestion, if correct, has an important bearing on the prospective discoveries of other ore bodies in the district. The relations of the disseminated ores at Ray and Miami, Ariz.,[44] which also appear to depend very little upon the composition of their host rocks, strengthen the conclusion from the drill data here.

RELATION OF THE ORE BODIES TO THE PRESENT SURFACE AND TO THE PRE-FANGLOMERATE SURFACE

As has been stated, the ore bodies of the New Cornelia mine cropped out over a large area. Nearly all the outcropping ore was carbonate, but a little chalcocite cropped out along the south edge of the ore body. From the records, the tenor of the carbonate ore was essentially identical with that of the underlying sulfides, and there was practically no tendency toward the formation of a zone of supergene enrichment such as contains the commercial ore of most of the disseminated copper deposits. (See pp. 84-85.)

This failure of the copper to migrate during the cycle of erosion that was interrupted by the beginning of mining is in notable contrast with conditions that existed prior to the deposition of the Locomotive fanglomerate and the tilting of the Little Ajo block on the Little Ajo Mountain fault. The narrow zone of chalcocite ore that borders the main ore body on the south has been shown by the drill to be the outcropping edge of an essentially continuous layer that lies a short distance below the base of the Locomotive fanglomerate. This zone of chalcocite enrichment, which locally is 30 or 40 feet thick, normal to its greatest dimension, lies from 10 to 200 feet below the base of the fanglomerate. In this interval, the rocks are highly reddened and contain nests of malachite, cuprite, native copper, and hematite, but there is also generally a barren zone or a zone low in copper between the chalcocite and the unconformity on which the fanglomerate rests. These relations persist to depths of at least 200 feet below sea level and give clear evidence that, during the erosion cycle prior to the deposition of the Locomotive fanglomerate, leaching in the zone of weath-

[41] Parsons, A. B., The porphyry coppers, p. 8, Am. Inst. Min. Met. Eng., New York, 1933.

[42] Parsons, A. B., op. cit., p. 9.

[43] Curley, Michael, personal communication, 1932, published by permission.

[44] Ransome, F. L., The ore deposits of Ray and Miami, Ariz.: U. S. Geol. Survey Prof. Paper, 115, pp. 148-151, pl. 50, 1919.

ering, transportation of the dissolved copper, and redeposition as supergene chalcocite was going on. It may be repeated that Ransome[45] concluded that most of the enrichment of the Ray and Miami copper deposits, upon which their commercial value depends, occurred prior to the deposition of the Whitetail conglomerate (late (?) Tertiary) and had no relation to the recent erosion cycle or ground-water conditions.

RELATION OF THE ORE BODIES TO MINOR STRUCTURAL FEATURES

The structural features recognized in and near the ore body include joints, faults, slickensides, foliation, lineation, and dikes. In the field the distinction between faults and joints was made on the basis of the presence or absence of either definite slickensides or gouge, or both. As large areas outside the mine are concealed by alluvium and the benches in the mine are thickly strewn with broken rock, exposures are not as favorable to the study of structural details as might be supposed on first sight of the jutting crags and rocks in the walls of the mine pit and the surrounding hills. Most of the good exposures are in the banks separating the shovel benches, and even these banks are mantled for long distances by broken rock awaiting removal by the shovels.

The area was systematically gone over, and at each of several hundred points all joints and faults that could be reasonably regarded as tectonic and not due to blasting were measured. It seemed desirable to investigate these minor structural features in the hope that they might be found to bear some systematic relation to the ore body and thus perhaps give clues to other deposits or to extensions of the known ore bodies.

The attitudes of these minor structural features were analyzed by means of stereographic projections, which readily permit their reference to the premineral horizon as well as to the present horizon. Statistical studies of the orientation of these features were also made by means of the Lambert equiareal projection, but the conclusion was reached that such structural features as joints, faults, and slickensides show no systematic relation to the ore body. They probably are chiefly of the same postmineral age as the andesite prophyry dikes of Camelback Mountain and are of no use as guides to further exploration.

ECONOMIC POSSIBILITIES OF THE AREA

From the foregoing discussion of the general and local geology the following conclusions appear to be warranted:

The only known ore body in the area, the New Cornelia, is in a ridge, originally a cupola, of the Cornelia quartz monzonite.

The entire block of the eastern part of the Little Ajo Mountains, including the Cornelia quartz monzonite, its host rocks, and the overlying Locomotive fanglomerate, has been tilted southward in postmineral time. Therefore the southern border of the Cornelia stock, except where it is overlapped by the fanglomerate, now marks the roof at the time of emplacement of the mass.

The ore body has been localized by complex minor fracturing or crackling in the Cornelia quartz monzonite and its associated wall rocks. It is independent of the chemical composition of these rocks and their relation to present or former erosion surfaces. The fracturing seems to have been more intense in the monzonite than in the host rocks, probably because of a local concentration of explosive volatiles in the magma chamber.

The healing of fractures by the minerals deposited during the period of ore deposition has been so complete that the joints and faults now visible in the mine have no discernible relation to the shape of the ore body as now known. Study of the joints and faults therefore offers no help in search for extensions of the New Cornelia deposit or for other independent bodies that may exist.

Now that most of the chalcocite-bearing sulfide ore immediately below the weathered zone has been mined, no mineralogic changes of economic importance appear likely to be met with as the mine is deepened, unless it be a diminution of the proportion of bornite to chalcopyrite.

There is an area of intense alunitization just east of the approach to the New Cornelia pit. As this type of mineralization has in many other places proved to be associated with gold, it might be worth while to investigate this area. Owing to the postmineral tilting of the Little Ajo block, the northern part of the alunitized area would appear to be most worthy of testing for a possible continuation of the mass in depth, should it prove to be gold-bearing.

The small but rather persistent tenor of molybdenite in the ore invites consideration of its recovery as a by-product during the concentration of the copper minerals, but it would be difficult to get any quantitative impression of the abundance of the mineral without a mill test.

Specularite seems to be largely independent of the copper minerals in distribution, though it was probably concentrated in the roof overlying the monzonite and presumably in greater amount in the rocks that overlay the mineralized areas. Owing to the postmineral tilting of the Little Ajos, it would appear that the northerly part of the specularite belt is most worthy of investigation, on the slim chance that it may overlie areas of disseminated copper ore.

There is little possibility of discovering other ore deposits in the roof-rocks along the south flank of the Cornelia quartz monzonite west of the Gibson Arroyo fault, for the roof there seems to be smooth and to lack any cupolas that might have guided and concentrated ore-forming solutions. The entire northern border of the Little Ajos seems also to be poor prospecting ground for

[45] Ransome, F. L., op. cit., pp. 147, 173-174.

the following reasons: (1) The monzonite exposed there south of the fault was originally at a deep level in the intrusive stock, where sufficient concentration of mineralizing solutions to form ore bodies would not be expected; and (2) pre-mineral rocks in the areas north of the fault are so deeply buried beneath volcanics, fanglomerate, and alluvium that prospecting in these areas would be very expensive and entirely a matter of chance. Similarly, the prospects of finding ore bodies at any considerable distance south of the northern border of the fanglomerate on the south side of the mountains seem very poor. There is no clue in this entire area to suggest that the bedrock beneath the fanglomerate approaches the surface; certainly it does not crop out. Over most of the fanglomerate area, then, there is nothing whatever to guide prospecting. The numerous prospecting efforts in this wide area seem doomed to disappointment, as the malachite stains that encouraged the attempts are all associated with boulders transported from the Cornelia or some other buried ore deposit. There has been some slight migration of the copper in places, but there is no evidence whatever of post-fanglomerate primary mineralization, and the likelihood of commercial concentration of copper derived from these transported boulders is vanishingly small.

The areas offering most promise for the discovery of additional ore bodies seem to be the following:

1. The area extending from Cardigan camp to Arkansas Mountain, in which the Concentrator volcanics show intense impregnation by specularite. The probability is that the specularite is of magmatic derivation. Though it is not closely associated with the copper minerals, it gives evidence of an underlying source of mineralizing solutions. It is possible that the solutions deposited copper at depth. The most promising places to sink test drills would appear to lie along the northern side of this specularite area, where rocks originally at greatest depths can best be reached.

2. The area between the eastern waste dump of the New Cornelia mine and the approach to the pit. There disseminated specularite is abundant, dikes of monzonite suggest an underlying cupola on the monzonite stock, and the volcanics in the approach seem to be well-mineralized.

3. The area just north of the New Cornelia pit. The holes already drilled in this area are nearly all shallow and stopped in low-grade material. There is a distinct possibility that this waste may be simply a horse like that encountered farther south at greater depths within the recognized ore body.

4. The area east of the compressor house of the New Cornelia mine. There the presence of disseminated alunite suggests that gold ore may lie at greater depth.

None of these possibilities appear so bright as to justify a large-scale campaign of exploration, but they appear to be the most promising when the time for further prospecting comes at Ajo.

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