XVI INTERNATIONAL GEOLOGICAL CONGRESS
GUIDEBOOK 14 - - - - EXCURSION C-1

ORE DEPOSITS OF THE SOUTHWEST

International Geological Congress
XVI session
United States, 1933

Guidebook 14: Excursion C-1

ORE DEPOSITS OF THE SOUTHWEST

Prepared under the direction of

F. L. RANSOME
CALIFORNIA INSTITUTE OF TECHNOLOGY

UNITED STATES
GOVERNMENT PRINTING OFFICE
WASHINGTON : 1932

For sale by the Superintendent of Documents, Washington, D. C. - - Price 20 cents

This guidebook contains contributions by the following authors:

F. L. Ransome, California Institute of Technology.
Sidney Paige, United States Geological Survey.
J. B. Tenney, Arizona Bureau of Mines.

THIS GUIDEBOOK is published under the auspices of the United States Geological Survey, but it is not a part of the Geological Survey's regular series of publications, and the opinions expressed in it and the use of nomenclature do not necessarily conform to Geological Survey usage.

CONTENTS

ILLUSTRATIONS

INSERT

ORE DEPOSITS OF THE SOUTHWEST

Prepared under the direction of F. L. Ransome

GENERAL GEOLOGY AND SUMMARY OF ORE DEPOSITS

By F. L. Ransome

INTRODUCTION

The region comprising western New Mexico and southeastern Arizona is one within which several geomorphic divisions merge without definite boundaries. The Rocky Mountain province, as shown in Plate 1, ends near Santa Fe and is succeeded, to the south, by that division of the Basin and Range province which has been designated the Mexican Highland. This division continues southward into Mexico, where it is known as the Mesa Central. In Arizona it comprises what has, in some publications (25, 27),[1] been termed the mountain region of that State, bordering on the southwest the division of the Colorado Plateaus, locally known as the Arizona Plateau. Concerning the unity of this great Mexican Highland division there is room for diversity of opinion. Certainly the Mesa Central of Mexico, although not sharply marked off from the mountainous region of southwestern New Mexico and southeastern Arizona, is lacking, on the whole, in the rather closely spaced, linear, parallel mountain ranges that are so notable a feature of the Mexican Highland within these States, particularly in Arizona. Moreover, Lindgren, Graton, and Gordon (19, p. 26) do not recognize the extension of the Basin and Range province into central New Mexico but consider that the Colorado Plateau province extends eastward across that part of the State to coalesce with the Great Plains province.

In the extreme southern part of Arizona and New Mexico, the generally narrow mountain ranges trend nearly north. Toward the north, however, they diverge, as if split apart by the blunt wedge of the Colorado Plateau province, and although the ranges in New Mexico continue to maintain a general northerly trend, those in Arizona swing off to the northwest, in rough parallelism with the southwest margin of the plateau.

---

[1] Numbers in parentheses refer to bibliography, pp. 22–23.

The southwestern part of Arizona falls within the Sonoran Desert division of the Basin and Range province. The distinction between this division and the Mexican Highland is, in general, vague. In their structural features the two divisions are similar, but the Sonoran Desert is characterized by the great preponderance of broad desert plains over mountain ranges, which are relatively short and far apart, by generally lower altitude, and by corresponding differences in climate and vegetation.

As the Santa Rita and Bisbee mining districts, which are to be visited in the course of excursion C–1, lie within the Mexican Highland division, the following pages will be devoted mainly to a brief account of that part of this particular division which contains these districts.

Probably the most impressive feature of the landscape, to one who sees it for the first time, is the sharp contrast between steep and rugged mountains and wide expanses of desert plain. It is true that the plains merge imperceptibly with smooth, evenly graded alluvial slopes, which may attain considerable altitude where they meet the mountain fronts, but the presence of these great ramps of detritus scarcely detracts from the general striking contrast between mountain and lowland. Such topography is, of course, characteristic of most mountainous desert regions, in which the greater part of the débris washed from the mountains is deposited in the adjacent valleys, these gaining in extent and becoming more plainlike as the minor eminences are worn down and buried. In southwestern New Mexico the plains far exceed the mountains in areal extent, but in southeastern and central Arizona the plains, in part, are long and relatively narrow intermontane strips which, more appropriately than the New Mexican plains, may be called valleys.

The region to be traversed by the excursion is diversified in relief. The plains of New Mexico range in general from 4,500 to 5,000 feet (1,370 to 1,520 meters) in altitude, and the valleys in Arizona, between Bisbee and Globe, from 1,600 to 5,000 feet (490 to 1,520 meters). The longer mountain ranges commonly attain altitudes of about 8,000 feet (2,400 meters), and a few peaks rise to more than 10,000 feet (3,000 meters). Except on some of the loftier mountains, the climate is arid to semiarid and the summer temperature is high. A considerable part of the rainfall may take place in July and August.

The vegetation is prevailingly of desert type and on the whole fairly abundant. There are few of the plains to which the creosote bush (*Covillea glutinosa*) does not give a perennial tinge of green, and in parts of Arizona, particularly near Tucson, the number and variety of arboreal forms, such as the palo verde (*Parkinsonia aculeata*, *P. microphylla*, and *P. torreyana*), ironwood (*Olneya tesota*), mesquite (*Prosopis velutina*), ocotillo (*Fouquiera splendens*), sahuaro (*Carnegiea gigantea*), and cholla (*Opuntia fulgida*), impart an interest and charm to the landscape that is exceptional in desert regions. In the more mountainous parts of the area ashes, walnuts, sycamores (*Platanus wrightii*), hackberries, oaks, and junipers occupy a transition zone between the plains and the pine forests of some of the larger and higher mountain ranges. For brief periods, after rains, the desert bursts into bloom and displays a transient massing of color and delicacy of verdure such as few humid regions can rival.

The approach to the Santa Rita district from the east may be made by one of the three general railway routes. The Atchison, Topeka & Santa Fe Railway enters the region through Glorieta Pass, which marks practically the south end of the Southern Rocky Mountain geomorphic division.[2] From Glorieta Pass the railway continues westward to the Rio Grande Valley and follows this valley generally southward for about 200 miles (325 kilometers), passing through Bernalillo, Albuquerque, Isleta (whence the main line diverges westward to Flagstaff, Needles, and California), and Socorro. From Bernalillo, for some distance past Albuquerque, excellent views may be obtained of the west front of the Sandia Mountains, which together with the Manzano and Los Pinos Mountains, to the south, make up one of the typical north-south ranges of New Mexico.

At San Marcial, near the head of the Elephant Butte Reservoir, about 27 miles (43 kilometers) south of Socorro, the railway leaves the Rio Grande Valley, passing into the Jornada del Muerto, to the east of the Fra Cristobal Range, and having in view on the east the long western front of the San Andres Mountains. West of Rincon it again crosses the Rio Grande and proceeds generally southwestward, over broad desert plains, to Deming. From Deming a branch line runs northwestward to Tyrone, Silver City, Santa Rita, and Hanover.

A second line of approach is by the Chicago, Rock Island & Pacific Railroad to Tucumcari and thence over the Golden State Route of the Southern Pacific Railroad to El Paso. This route skirts the east side of the great Tularosa Valley, passing through Tularosa and Alamogordo, at the western base of the Sacramento Mountains. This group of mountains, within the Sacramento section of the Mexican Highland, presents an imposing front to the west but slopes off gradually on the east to a rather indefinite junction with the Great Plains province.

---

[2] For a fuller description of the geologic features to be seen along this route than can be included in the present outline the reader is referred to the Santa Fe guidebook (7).

Crossing the Tularosa Valley obliquely, this route rounds the south end of the Franklin Mountains at El Paso and continues, across broad desert plains, in a northwesterly direction to Deming.

The third general route is by the Sunset Route of the Southern Pacific Railroad from New Orleans through Texas to El Paso, by way of Houston, San Antonio, Spoffard, Del Rio, Sanderson, Alpine, and Marfa. From El Paso to Deming the route is the same as that outlined in the preceding paragraph.

STRUCTURAL FEATURES

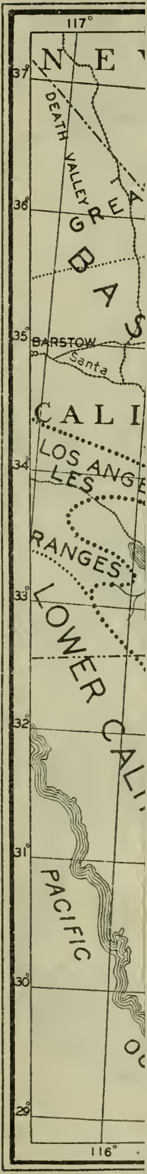
It is impossible in so brief an article as the present to do more than outline in very general fashion the broader and obvious structural features of the region.

That intense folding, accompanied by faulting and igneous intrusion, took place in pre-Cambrian time is certain. The structural features of this early era, however, were truncated by the prolonged erosion which is recorded in the great unconformity between the crystalline pre-Cambrian rocks and the oldest Cambrian sedimentary rocks. The deformational processes which, in conjunction with erosion, have given the land its present configuration are almost entirely of post-Paleozoic age.

Although the mountain ranges, to which extensive exposures of pre-Quaternary rocks are as a rule confined, exhibit some folds, particularly where limestones are present, the folds are generally of open character and are subordinate to faults in structural importance. That the mountains are relatively uplifted masses and the plains relatively depressed masses appears to be generally true. The uplifted masses, however, are not necessarily simple fault blocks, nor is the boundary between mountain and plain invariably determined by a single great fault. As shown by detailed mapping of the Dripping Spring Range (27), in the Ray-Globe region, the mountain mass may be an intricate mosaic of small fault blocks.

The great arid basin in southern New Mexico known as Tularosa Valley is bounded on the west by the San Andres Range and on the east by the Sacramento Mountains. As the Paleozoic strata in these ranges dip generally away from Tularosa Valley, the depression is, at first glance, suggestive of the erosion of a great anticline. The small areas of Paleozoic rocks exposed in the valley, however, indicate a general synclinal structure, and it is probable that the basin, instead of being an exception to the general type of structure prevalent in the region, is actually illustrative of the great part played by faulting in blocking out the major topographic units.

ORE DEPOSIT



MAP SH

PLATE 1

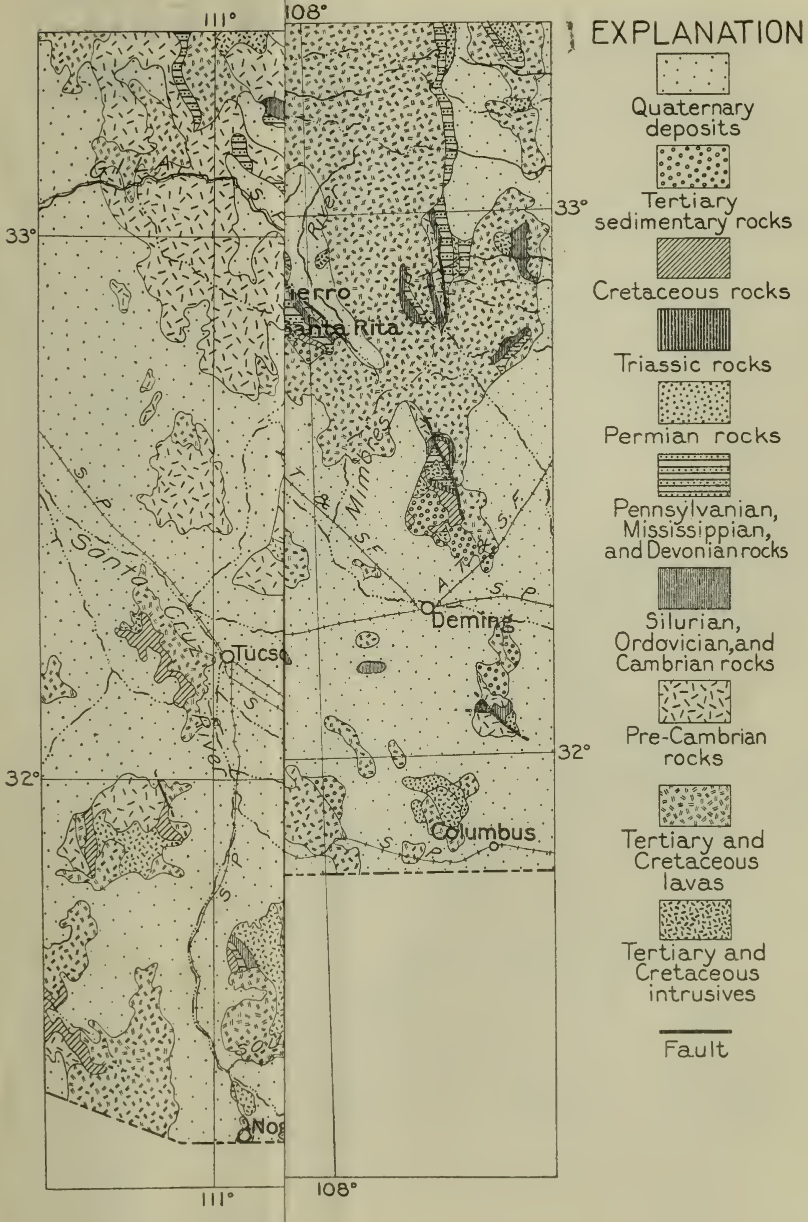
MAP SHOWING GENERAL RELATION OF MINING DISTRICTS OF THE S.W. UNITED STATES TO MAIN PHYSICAL DIVISIONS

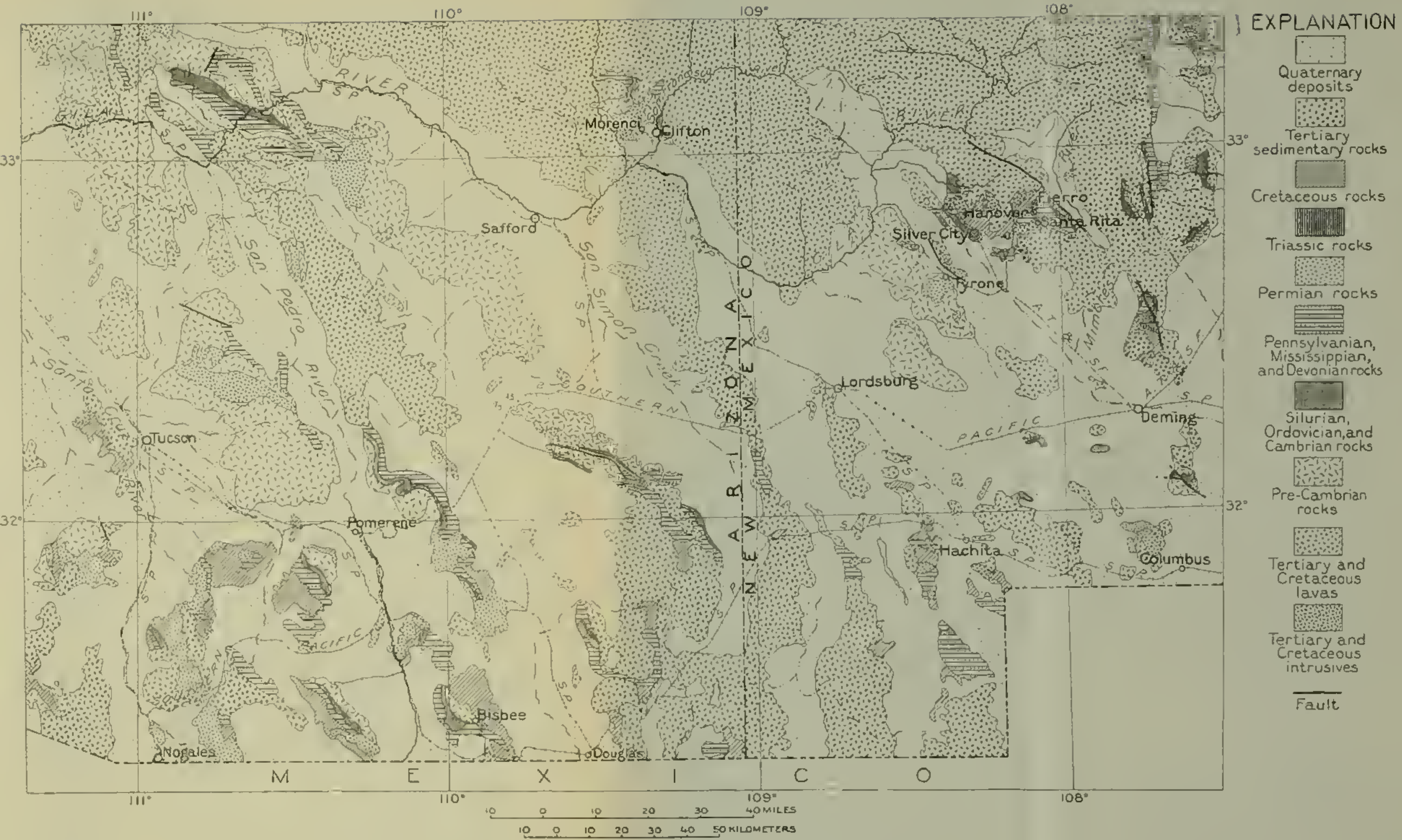
25 0 25 50 75 100
MILES

PHYSICAL DIVISIONS SLIGHTLY MODIFIED FROM N. M. FENNEMAN
PRINCIPAL METAL-MINING DISTRICTS INDICATED THUS: ⚒

25 0 25 50 75 100
KILOMETERS

PLATE 2

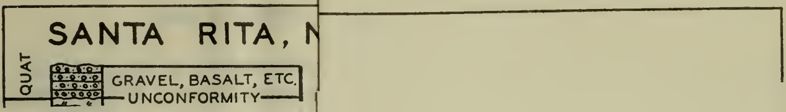

111°
108°
33°
32°
111°
108°
Gila
ierro
anta Rita
Mimbres
Santa Cruz River
Tucso
Deming
Columbus
Nog
S. P.
A. T. & S. F.
EXPLANATION
Quaternary deposits
Tertiary sedimentary rocks
Cretaceous rocks
Triassic rocks
Permian rocks
Pennsylvanian, Mississippian, and Devonian rocks
Silurian, Ordovician, and Cambrian rocks
Pre-Cambrian rocks
Tertiary and Cretaceous lavas
Tertiary and Cretaceous intrusives
Fault

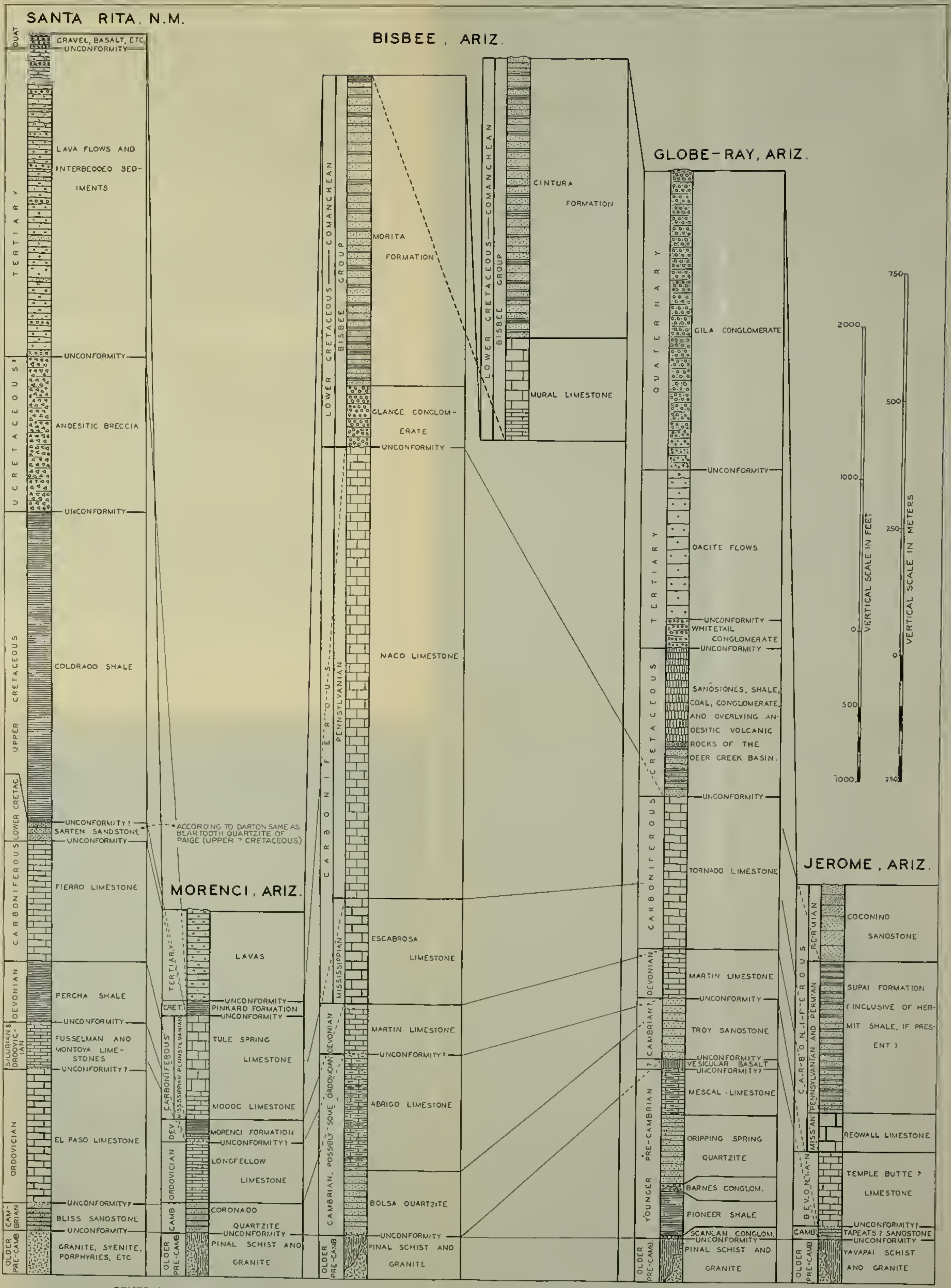


GEOLOGIC MAP OF SOUTHWESTERN NEW MEXICO AND SOUTHEASTERN ARIZONA

Generalized from State geologic maps of New Mexico and Arizona, by N. H. Darton.

SANTA RITA, N





GENERALIZED COLUMNAR SECTIONS OF THE SANTA RITA, CLIFTON-MORENCI, BISBEE, GLOBE-RAY, AND JEROME DISTRICTS

By F. L. Ransome.

Incidentally, a noteworthy feature of Tularosa Valley is the occurrence of a vast deposit of dazzlingly white gypsum sand which covers an area of some 300 square miles (777 square kilometers) west of Tularosa and Alamogordo and which may be seen from the railway near those towns (6, p. 216).

Not only has faulting, in this general region, been the chief factor in broadly outlining the general distinction between mountains and plains, but the same structural process, although its results are in places obscured by lava flows and erosion, has determined the general line that separates the nearly horizontal Paleozoic and younger strata of the Plateau province from the much tilted and disturbed masses of the same strata that occur in the mountain ranges of southwestern New Mexico and southeastern Arizona.

The deep-seated causes which determined the striking difference in structure between the Colorado Plateau province and the Basin and Range province are still inscrutable. Although the Basin and Range province in Arizona is in general suggestive of a region that has collapsed or settled through failure of underlying support, nevertheless in central Arizona the stratified rocks in the mountain ranges are, in many localities, standing at higher altitudes than the same formations within the relatively undisturbed plateau.

THE ROCKS

The fundamental terrane of New Mexico and Arizona (see pls. 2 and 3) is composed of crystalline rocks which are now generally regarded as Archean. They include granites of considerable variety; quartz diorites; gneisses of various kinds; and schists, in large part representing metamorphosed sedimentary rocks but in part derived from intrusive and extrusive igneous rocks of considerable range in character. Here belong the Pinal schists of the Globe, Bisbee, and Morenci districts, the Yavapai schist of Jerome and the Bradshaw Mountains, and the Vishnu schist of the Grand Canyon of the Colorado.

Resting with profound unconformity on the planated surface of these ancient crystalline rocks are the Upper Cambrian Bliss sandstone of Texas and southern New Mexico and, of probably the same age, the Coronado quartzite of Morenci, the Bolsa quartzite of Bisbee, and the Tapeats sandstone of the Grand Canyon. In central and northern Arizona there intervene between the oldest crystalline schists and the known or probable Cambrian rocks various groups of unfossiliferous rocks, chiefly sedimentary but including some of volcanic origin. These rocks form the Apache group of central Arizona, exclusive of its upper-most formation as originally defined, the Troy quartzite, which the work of Darton has shown is probably Upper and Middle Cambrian and separated by an unconformity from the underlying formations. The group as thus restricted comprises the Mescal limestone, Dripping Spring quartzite, Barnes conglomerate, Pioneer shale, and Scanlan conglomerate. It has become increasingly probable during recent years that this restricted Apache group is generally equivalent to the Unkar group, the lower of the two divisions into which Walcott divided the supposedly Algonkian rocks of the Grand Canyon.

Both the Apache group and the Unkar group are characteristically associated with intrusive diabase, largely in the form of sills, and the principal asbestos deposits of Arizona are found at the contacts of this diabase with calcareous members of the groups, particularly the Mescal limestone.

The upper of Walcott's divisions, or Chuar group, lies unconformably below the Upper Cambrian Tapeats sandstone but has yielded obscure fossils suggestive of early Cambrian age. Finally, in the Mazatzal Range of central Arizona (29, pp. 157–159; 36) there are conglomerates, quartzites, and shales which are unconformably above the pre-Cambrian schistose rocks and unconformably below the Apache group. Considerable work therefore remains to be done before the relationships and correlation of the younger pre-Cambrian rocks of Arizona can be fully understood.

Above the Cambrian sandstones and quartzites of southern New Mexico and Arizona the Paleozoic is represented by a thick series of beds which nowhere show conspicuous unconformity and are predominantly limestones. The lowest of these in New Mexico is the Ordovician El Paso limestone, which extends into this State from Texas and in the Silver City region has a thickness of about 800 feet (244 meters). It thins to the north and west, however, and is absent in the northern part of the State, its most northerly exposure being in the southern part of the Sierra Oscura. To the west, in Arizona, its equivalent is probably the Longfellow limestone, 200 to 400 feet (61 to 122 meters) thick, of the Clifton-Morenci section. West of Clifton the presence of Ordovician rocks in Arizona has been established by Darton in the Dos Cabezas Mountains of southeastern Arizona and recognized as probable also in the Vekol Mountains, about halfway between Phoenix and the Mexican border. The possibility that the Abrigo limestone, which has yielded Upper Cambrian fossils from its lower part and has a wide distribution in southeastern Arizona, may be Ordovician in its upper part was pointed out by Ransome (29, pp. 164–165) and has been more recently suggested by Darton (5, pp. 52–53).

The Montoya limestone, of Upper Ordovician (Richmond) age, also extends into New Mexico from western Texas and, as regards distribution and disappearance northward and westward, resembles the El Paso limestone.

The Fusselman limestone, the Silurian member of the El Paso section, is also present in southern New Mexico, but the greatest recorded thickness, about 250 feet (76 meters) is only one-fourth of that north of El Paso, and no Silurian strata have been found in Arizona. In that region the Silurian was mainly a period of erosion, which is recorded in the absence of sediments and, in places, by unconformity, although with no marked discordance in dip above and below the stratigraphic hiatus (disconformity).

The Devonian in New Mexico is represented by the Percha shale, which attains a thickness of about 500 feet (152 meters) in the Silver City region and is abundantly fossiliferous. It thins northward and is absent in the central and northern parts of the State. To the west the Morenci formation of the Clifton region, Arizona, illustrates a transition from shale to limestone, and farther west in Arizona the Devonian beds are essentially calcareous. Represented by the Martin limestone in southern and central Arizona and by the Temple Butte limestone of the Grand Canyon section, the Devonian has wide distribution in Arizona but, like most of the other Paleozoic formations, is apparently absent from the southwestern part of the State. At Bisbee, the type locality, the Martin limestone is 340 feet (104 meters) thick. The greater part of the copper ore of the Bisbee district occurs in the Martin limestone and in the lower 200 feet (61 meters) of the overlying Escabrosa (Mississippian) limestone. There is probably an unconformity at the base of the Devonian in Arizona and possibly also at its top. In most localities, however, these unconformities, if present, are obscure.

Rocks of the Carboniferous system are very well represented in southern New Mexico and southeastern Arizona and attain great thickness. In New Mexico the lower Carboniferous or Mississippian is represented by the Lake Valley, Kelly, and other limestones, attaining a thickness in the south of 500 feet (152 meters) but thinning in general to the north. In the Magdalena district, west of Socorro, the Mississippian (Kelly) limestone rests on the pre-Cambrian crystalline rocks. The Mississippian limestones of New Mexico have been important as sources of silver-lead ores near Lake Valley, of silver-lead zinc ores in the Magdalena district, and of silver ores at Chloride Flat, Georgetown, and Lone Mountain. In Arizona the Mississippian is represented by the Modoc limestone, 180 feet (55 meters) thick, at Morenci; the Escabrosa limestone, 700 feet (213 meters) thick, at Bisbee; the Tornado limestone (lower part only) in the

Ray region; the Redwall limestone of the Grand Canyon section; and unnamed limestones at many localities in central Arizona.

The Pennsylvanian in New Mexico, chiefly the Magdalena group, consisting mainly of limestone but with some sandstone and shale, attains great thickness, especially in the southern Rocky Mountains northeast of Santa Fe, where, according to Darton (6, p. 19), it is in places nearly 2,500 feet (762 meters) thick. Here it overlaps on the pre-Cambrian rocks. In Arizona the Naco limestone at Bisbee, at least 1,500 feet (457 meters) and probably as much as 3,000 feet (914 meters) thick, described originally as Pennsylvanian, is in part Permian. Moreover, as recent work has shown, some Comanche limestone is probably present in the type Naco area. Pennsylvanian limestones are found in the Santa Rita region[3] and have considerable development in central Arizona, but farther north, in the plateau and Grand Canyon region, the calcareous Pennsylvanian strata are succeeded by more arenaceous beds which have not everywhere been definitely separated from the Permian portion of the Supai formation, consisting chiefly of red sandstones and shales.

The Permian in New Mexico is represented by the Manzano group, comprising the Abo sandstone below and the Chupadera formation above. The Gym limestone of southwestern New Mexico and the Castile gypsum of southeastern New Mexico may be equivalent to the Chupadera in whole or in part. The Permian beds of New Mexico are both thick and extensive. The maximum total thickness is probably in excess of 4,000 feet (1,219 meters). In the eastern part of the State, in the Pecos Valley, the Permian contains much salt, gypsum, and anhydrite (6, pp. 249–254). The great caverns near Carlsbad are in Permian limestone. In southeastern Arizona beds of Permian age are definitely recognized only in the upper part of the Naco, but in southeastern New Mexico they have been noted near Santa Rita by Spencer. They constitute, however, an important part of the stratigraphic sequence of the Arizona Plateau, where the Supai formation, the Hermit shale, the Coconino sandstone, and the Kaibab limestone are all regarded as of Permian age.

Stratified rocks of Triassic and Jurassic age, although of widespread occurrence and present in great volume in northern New Mexico, are either absent or of such scanty and doubtful occurrence in southwestern New Mexico and southeastern Arizona that they need not be further considered in this outline.

In northern New Mexico the somewhat doubtful Cretaceous Morrison formation apparently does not extend south of latitude

---

[3] Spencer, A. C., unpublished manuscript.

33°. In southern New Mexico the chief representatives of later Mesozoic time are sandstones and limestones of Lower Cretaceous (Comanche) age, which rest with marked unconformity on the older rocks. In New Mexico the principal Comanche formation is what Darton has named the Sarten sandstone, which he regards as identical with Paige's Beartooth quartzite (nonfossiliferous), in the Santa Rita region. The age of the Beartooth quartzite, however, is still uncertain and should be regarded as possibly Upper Cretaceous, and thus the Beartooth is perhaps the base of the Upper Cretaceous in this region.

In the Bisbee region, southeastern Arizona, the Comanche attains great thickness and has been divided by Ransome (22, pp. 56–73) into four formations, as follows:

	Feet	Meters
Top (erosion surface).		
Cintura formation, chiefly shale and sandstone	1,800+	549+
Mural limestone	650	198
Morita formation, chiefly sandstone and shale	1,800	549
Glance conglomerate	0–500	0–152
Unconformity.		

Fossils, collected mainly from the lower part of the Mural limestone, were determined as belonging to the upper or Trinity division of the Comanche, perhaps also in part to the middle or Fredericksburg division. At many other localities in southern Arizona, as at Tombstone and in the Huachuca, Patagonia, Oro Blanco, Baboquivari, Sierrita, Tucson, Santa Rita, Empire, Whetstone, and Dragoon Mountains, occur masses of sediments that rest unconformably upon Paleozoic or older rocks and are probably of Comanche age. They have not, however, been correlated definitely with the Comanche formations of the Bisbee section.

Estimates of the total thickness of Comanche sediments in southern Arizona range from 10,000 to 18,000 feet (3,050 to 5,490 meters).

Stratified rocks of Upper Cretaceous age, although abundantly present in northern New Mexico and northeastern Arizona, where they contain valuable beds of coal, have relatively slight areal representation in the southern parts of these States.

A considerable outlying area of these Upper Cretaceous coal-bearing rocks (Mesaverde group) occurs in the Sierra Blanca region, north of Alamogordo. Farther west, a smaller area contains the Carthage coal field, about 16 miles (26 kilometers) southeast of Socorro. About 70 miles (113 kilometers) farther south, near the south end of the Elephant Butte Reservoir, between the Fra Cristobal Range and the Sierra Caballos, is a considerable area of lignitiferous beds, whose position within the Upper Cretaceous is not yet definitely determined (14; 15, p. 33).

In the Silver City region Paige (21) has mapped some 2,000 feet (610 meters) of Colorado shale, underlain by the Beartooth quartzite, of Upper (?) Cretaceous age; and in the Clifton-Morenci district Lindgren (17) has mapped, as the Pinkard formation, 200 feet (61 meters) or more of shale and sandstone assignable to the same Upper Cretaceous group. The only other known occurrences of Upper Cretaceous rocks in southern Arizona are those of the Deer Creek region, some 65 miles (105 kilometers) west of Morenci, where sandstones, conglomerates, and coal are associated with andesitic volcanic rocks (31).

Everywhere in Arizona there is a marked unconformity at the base of the Upper Cretaceous.

During Tertiary time the area corresponding to what is now southern New Mexico and southern Arizona was apparently land, partly occupied at times by lakes. Marine Tertiary deposits are lacking in this area. The most extensive and noteworthy lacustrine deposit of this period is the Santa Fe formation (Santa Fe marl), which occupies large areas in the upper Rio Grande Valley and has yielded many vertebrate fossils of late Tertiary age. In southeastern Arizona (32, pp. 54–56) lacustrine deposits of probable Tertiary age occur in the Patagonia, Santa Rita, and Empire Mountains. In the San Pedro Valley, between Benson and Tombstone, Arizona, are lacustrine deposits carrying vertebrate fossils of Pliocene age (10).

Although there were some eruptions of lava in late Cretaceous time (21, 31), it was in the Tertiary that volcanism and intrusion attained the height of their activity. In most parts of the region it is not possible to assign the supposedly Tertiary igneous rocks to any particular division of Tertiary time, and in some localities there may even be considerable doubt whether certain lavas are Cretaceous or Tertiary. Similar uncertainty exists as regards the age of some of the intrusive masses. Most of those in New Mexico have been regarded by Lindgren, Graton, and Gordon (19, pp. 35–42) as of early Tertiary age, but uncertainty attaches to the age assignment of some of the intrusive masses in Arizona and also in New Mexico—for example, at Tyrone, Hanover, and Santa Rita.

These intrusive rocks, which are of exceptional interest in that they are genetically related to the commercially most important ore deposits of New Mexico and Arizona, are distributed over a broad irregular belt which, from the middle of the northern boundary of New Mexico, runs south to the vicinity of El Paso, Texas, and thence west into Arizona. In Arizona the intrusive bodies are scattered over an area extending at least as far west as Ajo, or to longitude 113°, and northward into the central part of the State. Within this same area are many intrusive masses of granite, quartz monzonite, granite porphyry, and related rocks, which on the geologic map of Arizona are classed as Cretaceous. This attempted distinction between Tertiary and Cretaceous intrusives, however, apparently rests on evidence of rather doubtful and tenuous character.

In New Mexico these intrusive bodies have the forms of stocks, laccoliths, sheets, and dikes, and most of them are quartz monzonite, granodiorite, monzonite, or the corresponding porphyries. Some, however, are of granitic composition, and a few are dioritic.

Among the many mining districts in New Mexico in which the ores stand in genetic relationship to the intrusion of these monzonitic masses may be mentioned Magdalena (zinc, lead, gold, and silver), Santa Rita (copper), Hanover (iron and zinc), Pinos Altos (silver, gold, and lead), and Tyrone (copper).

In Arizona the intrusive masses are generally of stocklike form and have been regarded by Ettlinger (8) as cupolas of a batholith. It is, in general, more difficult to assign definite dates to these intrusions than in New Mexico. At Morenci the granitic and quartz monzonitic porphyry cuts the Pinkard formation, of Upper Cretaceous (Benton) age, and is unconformably overlain by supposedly Tertiary volcanic rocks. The intrusive rock is thus probably of late Cretaceous or early Tertiary age. At Bisbee the granite porphyry cuts Pennsylvanian (Naco) limestone but, according to Ransome (22, p. 84), is older than the early Cretaceous (Comanche). Consequently, therefore, the granite porphyry and presumably also the principal copper deposits of Bisbee are post-Carboniferous but pre-Cretaceous in age. During recent years, however, some geologists have expressed the opinion (35, p. 841) that the granite porphyry is intrusive into the Comanche beds and that the principal mineralization at Bisbee is of Tertiary age.

The relation of the granite porphyry to the Comanche beds at Bisbee is admittedly obscure, and the observable facts are such as may reasonably give rise to differences in interpretation. Those who have suggested a Tertiary age for the Bisbee ore deposits appear, however, to have based their opinion mainly upon the argument that inasmuch as some copper deposits of the Southwest are probably of Tertiary age, all of them should be of the same age. As a matter of fact, definite proof of Tertiary age is probably not obtainable for any of the great copper deposits of Arizona, except possibly at Morenci. Those of Jerome are certainly pre-Cambrian.

In part younger than the monzonitic intrusions but in part possibly contemporaneous or older are the great accumulations of lava, with some interbedded sediments, which occupy large areas in New Mexico and Arizona. The most extensive and probably the thickest mass of these lavas is that which covers the southern part of the Colorado Plateau and stretches from the Rio Grande Valley in New Mexico westward into central Arizona. This great lava field lies generally north of the region to be visited during the excursion, but its southern fringe is touched at Santa Rita and Hanover. Farther west, in eastern Arizona, the older rocks, in which the ore bodies of Morenci lie, are almost surrounded by the Tertiary lavas. The Mogollon district in New Mexico is entirely within them. Ferguson's study of this district (9) has shown a maximum thickness of over 8,000 feet (2,440 meters), made up of about 80 per cent of lavas and pyroclastic rocks and about 20 per cent of fluviatile sediments. The lavas include rhyolites, latites, and andesites. Smaller areas of lavas referable to the same general period of eruption are scattered over southern New Mexico and southern and western Arizona. In northwestern Arizona they contain the veins of the Oatman gold district.

Quaternary time in southern Arizona and southern New Mexico was marked by the accumulation of extensive fluviatile and bolson deposits over areas that correspond roughly but not exactly to the lowlands of the present day. One of the most noteworthy of these deposits is what in Arizona has been called the Gila conglomerate. In part, this formation has been tilted and extensively eroded, particularly in the Globe-Ray region, where the conglomerate has an estimated maximum thickness of about 8,000 feet (2,440 meters). It is possible, however, that future investigation may divide some of the material now classed as Gila conglomerate into deposits of different ages, perhaps some of it falling within the Tertiary. In Quaternary time also were poured out extensive flows of lava, chiefly basalt, some of which are conspicuous features in the present-day landscape of New Mexico.

OUTLINE OF GEOLOGIC HISTORY

From the beginning of Paleozoic time to the end of the Cretaceous the stratigraphy of southern Arizona and New Mexico records the gradual submergence of a greatly worn down land mass consisting partly of crystalline metamorphic and igneous rocks but partly also of ancient unfossiliferous sediments. This land, as it sank beneath the sea, had impressed upon it, even at that remote period, the record of a long history of sedimentation, volcanic activity, igneous intrusions, mountain building, peneplanation, and repeated oscillatory movements, above and below sea level.

The stratified rocks of the Paleozoic and early Mesozoic eras indicate the advance of the sea from the southeast over a land mass lying generally to the north. The submergence was neither uniform nor continuous and was interrupted at times by upward movement and erosion of previously deposited sediments. Apparently the whole of the northern land area, corresponding to the Rocky Mountains, was submerged in Carboniferous time and again in early Upper Cretaceous (Dakota) time, with some emergences between these periods. There are some reasons for believing that throughout much of Paleozoic and Mesozoic time a land barrier persisted to the west in what is now the lower Colorado region, but the paleogeographic history of this region is still largely conjectural.

The beginning of the Tertiary period was marked by general uplift of the region to altitudes ranging from 3,000 to 10,000 feet (915 to 3,050 meters) above sea level and by the widespread intrusion of generally monzonitic igneous rocks. Most of the great copper deposits of the region are connected genetically with these intrusions, although those at Bisbee may be older, and the pre-Cambrian deposits of Jerome are obviously so.

ORE DEPOSITS

The ore deposits of New Mexico and Arizona are of many kinds, and no classification of them can be wholly inclusive or entirely accurate. Some districts contain deposits of more than one type, but these may be so intimately associated that separation is impossible. Many deposits, moreover, are intermediate in character between those typical of different classes.

The pre-Cambrian deposits, carrying chiefly copper and gold, occur as veins, replacement deposits in zones of shearing, and disseminated deposits in schist—mainly amphibolitic schist. These ancient deposits are not of great economic importance in New Mexico but have been highly productive in central Arizona, particularly near Jerome, where the great ore body of the United Verde mine is largely the result of a replacement of schistose rhyolitic porphyries. The total production of this ore body has never been divulged but it has probably yielded approximately 1,860,000,000 pounds (843,680,000 kilograms) of copper, with considerable gold and silver. The neighboring United Verde Extension mine has probably yielded about 550,000,000 pounds (24,948,000 kilograms) of copper. The principal copper mineral of the pre-Cambrian deposits is chalcopyrite, which, with pyrite, in the United Verde Extension ore body has been largely altered to chalcocite.

Contact-metamorphic deposits, carrying mainly copper but also, in some localities, considerable quantities of iron and zinc, are widely distributed in New Mexico and Arizona. They are almost invariably associated, in obvious genetic relationship, with the intrusive bodies of granitic and monzonitic or granodioritic porphyries or with the granular plutonic equivalents of these porphyries. Most of these ore bodies are of late Cretaceous or Tertiary age, but in many localities the time of the intrusion of the mineralizing magma is not definitely determinable. In several districts the contact-metamorphic ore bodies are intimately associated with ore bodies of the disseminated type, carrying chiefly copper. The country rock of the contact-metamorphic deposits is commonly limestone, particularly the limestones of Devonian and Mississippian age.

To the group of contact-metamorphic deposits belong, in New Mexico, the zinc-lead-silver deposits of Magdalena, the zinc and iron deposits of Hanover and Fierro, and the copper deposits of San Pedro. In Arizona the copper deposits of Morenci, Bisbee, Twin Buttes, Silverbell, Christmas, and Troy belong in the same group, although, as previously noted, the Bisbee deposits may be of pre-Tertiary age. The silver-lead deposits of Tombstone, though not typical contact-metamorphic deposits, are so closely connected with contact-metamorphic action that they also may possibly be included in the group.

In the more productive deposits of this class, as at Morenci and Bisbee, supergene enrichment, with the development of chalcocite, has been highly effective. In others, as at San Pedro, Twin Buttes, and Silverbell, the ore mined has been largely hypogene chalcopyrite.

Another highly productive group of deposits is that of the disseminated copper ores. These are genetically connected with the same group of intrusive rocks as the contact-metamorphic deposits, and in some districts, as at Morenci and Bisbee, deposits of the two types are intimately associated. To this group belong the copper deposits of Santa Rita and Tyrone, New Mexico, and of Miami, Ray, and Ajo, Arizona. Here, also, belong some of the ore bodies of Morenci and Bisbee.

The disseminated ore bodies are generally within the periphery of the intrusive masses or within the adjacent invaded rocks, or both, or are in or adjacent to what are apparently projections or cupolas of the igneous body. They consist essentially of pyrite and chalcopyrite disseminated through the fractured porphyry or adjacent rock, this material constituting the protore, or the material which is too low in grade to be profitable. In the typical disseminated ore body the protore has been enriched by descending (supergene) solutions, to a depth of some hundreds of feet, and, through the deposition of chalcocite, has been converted to ore carrying from 1 to 5 per cent of copper. The deposit at Ajo is exceptional in that the hypogene sulphides are chiefly chalcopyrite and bornite, there has been comparatively little supergene sulphide enrichment, and the ore body, below an extensive oxidized zone, is of hypogene origin. At Miami some material originally classed as protore and carrying as little as 0.6 per cent of copper is now being mined as ore.

At Santa Rita and Ajo the disseminated ore is mainly in quartz monzonite or granodiorite; at Tyrone it is partly in quartz monzonite porphyry and partly in the surrounding pre-Cambrian granite; at Morenci it is chiefly in granite porphyry and quartz monzonite porphyry; at Bisbee the country rock is granite porphyry; and at Ray and Miami the ores are partly in granite porphyry and quartz monzonite porphyry, partly in pre-Cambrian schist.

At Santa Rita, Bisbee, and Ajo the ore is excavated by steam shovels in open pits. At Tyrone, Morenci, Miami, and Ray various methods of underground stoping are used.

Veins, probably of Tertiary age, connected more or less closely with monzonitic and granitic intrusive masses, are widely distributed through southern New Mexico and southern Arizona. Here probably belong the gold-silver-copper veins of Lordsburg, New Mexico; the gold-silver veins of Pinos Altos, New Mexico; and possibly the copper vein of the Magma mine, in the Superior district, Arizona. Many other veins in Arizona, some of which have been highly productive of gold, silver, copper, and lead, should perhaps be included in this group, but there is little information upon which to base an assignment of age.

Replacement deposits in limestone, not obviously associated with contact metamorphism, have produced much lead and silver in New Mexico, largely from oxidized ores. These deposits are now largely exhausted. The most productive group of these deposits was on the eastern versant of the Mimbres Mountains, north of Deming, in the vicinity of Lake Valley, Hillsboro, Kingston, Chloride Flat, and Georgetown. Probably about 20,000,000 ounces (622,000 kilograms) of silver was obtained from these deposits in the seventies and eighties of the nineteenth century. The limestone in which the ore occured is the Lake Valley limestone, of early Carboniferous (Mississippian) age.

Another group of deposits consists of gold-silver veins in volcanic rocks of middle to late Tertiary age. The chief deposits of this type in New Mexico are those of the Mogollon district, north of Silver City. In Arizona the outstanding district for deposits of this type is Oatman, in the northwestern part of the State. In the veins of this group native gold is associated with quartz (chalcedonic in part), calcite, and adularia. The ore bodies have a vertical range of less than 1,500 feet (457 meters), and the mines are not long-lived.

NOTES ON DISTRICTS NOT INCLUDED IN THE ITINERARY

In compiling the following notes the purpose has been to outline with the utmost brevity the salient features of some of the more important districts that can easily be reached from points passed through on the excursion. Anyone who decides to visit one or more of these districts will find the notes inadequate and is advised to consult the appropriate publications listed in the bibliography. The region contains a large number of mining districts, many of which have features of particular interest. It is not practicable, however, to refer, even briefly, to more than a few of the more active or economically important ones.

Morenci.—The Morenci district is in southeastern Arizona and is most conveniently reached by automobile over good roads from the south, west, or north. The district formerly yielded large quantities of copper from contact-metamorphic deposits, worked by several companies, but present-day production is obtained from low-grade disseminated deposits, all now owned by the Phelps Dodge Corporation. It was in this district that such low-grade ore was first successfully concentrated in the United States.

Upon a basement of pre-Cambrian granite and schist rest unconformably Paleozoic beds, with a total thickness of about 1,000 feet (305 meters). These are unconformably overlain by Cretaceous beds. After invasion by granitic and monzonitic porphyries, in early Tertiary time, the region was covered by later Tertiary lavas, which have in part been removed by erosion.

The ore bodies fall into three main classes—(1) irregular or roughly tabular bodies in limestone or shale, near porphyry; (2) lodes or veins; (3) irregular deposits of low-grade (2 per cent) disseminated ore in porphyry. The last are the bodies now extensively worked. All the ore bodies have undergone supergene enrichment, with the formation of chalcocite from a protore containing mainly pyrite, chalcopyrite, and sphalerite. Oxidation and enrichment probably began in Tertiary time, before the eruptions of lava, which, for a time, covered the deposits.

Tombstone.—The Tombstone district, which in the early eighties was probably the most famous silver district in Arizona, has at present only a small output and would not here be accorded individual notice were it not so easily accessible by automobile from Bisbee, from which it is about 20 miles (32 kilometers) north-northwest.

The general stratigraphic sequence at Tombstone is similar to that at Bisbee, but the sedimentary rocks have been invaded by a mass of quartz monzonite or granodiorite of post-Comanche age. The western part of the district is occupied by a large body of porphyry that is similar to the quartz monzonite in composition and may have come from the same magma reservoir. The porphyry is intrusive into the Paleozoic and Mesozoic sediments but has not been observed in contact with the quartz monzonite.

The ore bodies, probably connected genetically with the quartz monzonite, occur partly as veins, as mineralized porphyry dikes, and as extensive replacement bodies in sharply folded Mesozoic (Comanche?) and Carboniferous limestones. These bodies occur particularly on anticlines, especially in the vicinity of dikes or fissures.

The Tombstone ores are essentially pyrite, sphalerite, and galena ores, which in the bodies mined have undergone oxidation and enrichment. Exploitation of such deeper, low-grade ores as may be present has been prevented by an excessive quantity of water below a depth of about 700 feet (213 meters).

Ajo.—At Ajo, in western Arizona, 43 miles (69 kilometers) by branch railway south of Gila Bend, on the main line of the Southern Pacific Railroad, a superficially small mass of quartz monzonite is intrusive into pre-Cambrian granite and into rhyolitic and andesitic flows of presumably Tertiary age. Exploration by drilling gives some basis for the conclusion that the monzonite is a lopolith rather than, as at first supposed, a stock. The ore body, of the disseminated type, is almost entirely in the monzonite. The disseminated sulphides are chiefly chalcopyrite and bornite, with very little pyrite. The ore is an irregularly lenticular mass roughly 4,000 feet (1,219 meters) long, 2,000 feet (614 meters) wide, and over 950 feet (290 meters) in known maximum thickness. Its longer axis trends northwest and coincides in direction with the principal fissures through which the mineralizing solutions are believed to have risen and spread out in the fractured quartz monzonite under a former capping of rhyolite.

The deposit, although long known, was not worked on a large scale until 1915, when the New Cornelia Copper Co. undertook to treat the oxidized ores by steam-shovel excavation and leaching. Consequent probably upon the scarcity of pyrite in the ore, there was very little supergene enrichment, the oxidized ore having about the same content of copper as the hypogene sulphides below. The oxidized ores have now been practically exhausted, leaching has been abandoned, and since 1924 the sulphide ore has been treated by concentration. The present capacity of the concentrator is 16,000 tons daily.

From the beginning of large-scale operations, in 1917, to the end of 1930, there were mined and treated 16,340,000 tons of leaching (carbonate) ore, averaging 1.36 per cent of copper, and 15,645,000 tons of sulphide ore, averaging 1.41 per cent of copper. About 150,000 tons of sulphide ore, averaging 3.5 per cent of copper, were shipped to the smelter at Douglas.

The Ajo mine is owned by the Phelps Dodge Corporation, which, in 1931 absorbed the Calumet & Arizona Mining Co. and its subsidiaries, including the New Cornelia Copper Co.

Globe-Miami.—The Globe-Miami district is in east-central Arizona and is easily accessible by railway from the south and by good automobile roads from various directions, particularly from the south and west.

The district produced considerable silver in the eighties and then became one of the four leading copper districts of Arizona, the production coming chiefly from veins and associated replacement deposits, particularly those of the Old Dominion mine, at Globe. Since 1911, however, the output from the older mines has declined, and the greater part of the production has come from the disseminated copper ores worked near Miami, about 8 miles (13 kilometers) west of Globe, by the Miami and Inspiration copper companies.

The generalized geologic column of the Globe-Miami region is given in Plate 3.

The disseminated ore bodies are situated at the northern margin of a large intrusive body of granite, with porphyry facies, known as the Schultze granite. The age of this intrusion is not definitely determinable but is probably Tertiary. The ores occur largely in pre-Cambrian Pinal schist, near the contact with the granite, but also in part in dikes and sills of granite porphyry that are offshoots from the main granite mass.

The rocks of the region have been intensely faulted, and the most vigorous deformation is of later date than the mineralization. Both thrust and normal faults have complicated the structure of the ore bodies, particularly those of the Inspiration mine.

The protore consists essentially of disseminated pyrite and chalcopyrite. This has undergone supergene enrichment, with change to chalcocite. This enrichment probably was effected, for the most part, before the eruption of extensive Tertiary flows of dacite and before the accumulation of the probably early Quaternary Gila conglomerate. The ore bodies were once covered by these formations, which were later partly removed by erosion.

The original known ore reserves of the Miami district amounted to about 150,000,000 tons of 2 per cent, enriched chalcocite ore, in part oxidized. Of late years unenriched chalcopyritic material, containing less than 1 per cent of copper and formerly regarded as protore, has been mined and concentrated. Reserves of such material were estimated in 1930 as over 108,000,000 tons. The total output from the Miami mines has been over 2,000,000,000 pounds (907,180,000 kilograms) of copper. The ores are mined by underground caving methods. The sulphide ores are treated by flotation and the oxidized ores by leaching. Concentrates are smelted near Miami.

The early silver production from mines near Globe amounted to about 3,040,000 ounces (94,555 kilograms). From the Copper veins the output to the end of 1928 has been about 882,000,000 pounds (400,068,580 kilograms) of copper, with considerable gold and silver. The disseminated deposits to the end of the same period have yielded approximately 2,000,000,000 pounds (907,180,000 kilograms) of copper. The gross value of the entire metal output of the district to the end of 1928 exceeds $500,000,000.

Ray.—The Ray district, about 20 miles (32 kilometers) south-southwest of Globe, is most conveniently reached by automobile roads from Phoenix, Tucson, or Globe. Active production by the Ray Consolidated Copper Co. began in 1911 from bodies estimated to contain about 115,000,000 tons of ore, mostly ranging from 1 to 2 per cent of copper but including about 500,000 tons averaging between 5 and 6 per cent.

The ore bodies at Ray are similar in general character and origin to those at Miami but are genetically related to intrusive masses of quartz monzonite porphyry that are, superficially at least, much less extensive than the Schultze granite at Miami. The ore is mainly in the Pinal schist, but to a minor extent is found also in the porphyry. Geologic conditions are similar to those at Miami, although the ore bodies have been less affected by faulting. The neighboring Dripping Spring Range, east and southeast of Ray, is cut by faults in extraordinary abundance.

The ores are mined by underground caving methods and are concentrated by flotation at Hayden, where the smelter is also situated. The total production to the end of 1928 was about 1,002,700,000 pounds (454,814,700 kilograms) of copper.

Superior.—The Superior or Pioneer district is in central Arizona about 80 miles (129 kilometers) east of Phoenix and 11 miles (18 kilometers) northwest of Ray.

The geology is generally similar to that at Ray and Miami.

The only large and productive mine in the district is the Magma, which since 1910 has yielded large quantities of copper ore, much of it of high grade. In recent years the annual output has been about 27,000,000 pounds (12,246,950 kilograms) of copper, with considerable gold and silver.

The Magma deposit is an east-west vein in a fault fissure that follows in part a previously intruded dike of quartz monzonite porphyry. The rocks traversed by the dike and fissure are a thick sill of diabase, overlying Troy quartzite, and Devonian and Carboniferous limestones. To a large extent, the ores have been deposited by replacement of quartz monzonite porphyry, diabase, and quartzite. Bornite is the principal hypogene ore mineral, associated with chalcopyrite, hypogene chalcocite, and tennantite. Pyrite, sphalerite, and galena are locally abundant. Oxidation and enrichment have been extensive, supergene chalcocite and covellite extending, in quantity, to a depth of about 900 feet (274 meters) and exceptionally to 2,000 feet (610 meters). The mine has attained a depth of at least 2,250 feet (686 meters).

The Magma ore is smelted at Superior, in part after previous concentration.

Jerome.—The Jerome district is in north-central Arizona, about 23 miles (37 kilometers) northeast of Prescott, from which it is easily reached over a good road.

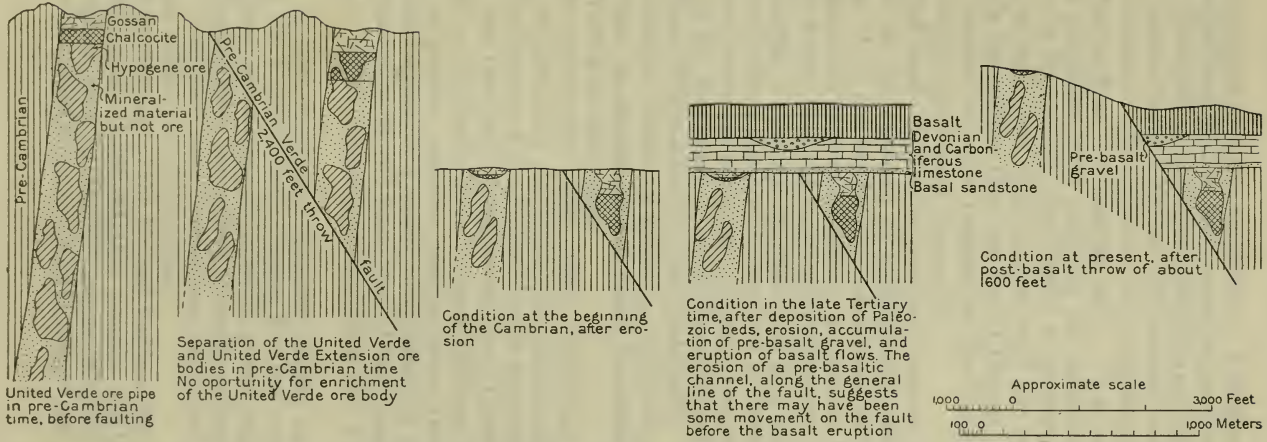
The basal rocks of the district are crystalline schists, in large part metamorphosed rhyolites and rhyolitic porphyries, with some less siliceous volcanic rocks. These are intruded by a stock of rather basic diorite. The rhyolite rocks are in part intrusive, but geologists are not agreed as to the intrusive or extrusive character of certain masses of these rocks.

All these rocks, after prolonged erosion, were unconformably overlain by reddish sandstone, probably equivalent to the Upper Cambrian Tapeats sandstone of the Grand Canyon section, and this in turn was succeeded by Devonian and Carboniferous limestones, without apparent unconformity, followed by the Supai formation. After uplift and erosion, these formations were covered by basaltic flows of Tertiary age, of which remnants remain, especially on the top of the Black Hills, on the eastern slope of which the mines are situated, overlooking the Verde Valley, with a superb view of the serried escarpment of the Arizona Plateau.

The district is traversed by several faults, of which one, the Verde fault, has been active at different periods and has a total throw of at least 4,000 feet (1,219 meters).

The district contains two ore bodies of outstanding size and productivity—namely, that of the United Verde mine and that of the United Verde Extension mine. The ore bodies of the United Verde mine, chiefly chalcopyrite, occur as lenticular masses, in which the copper is present, distributed through a great pipelike body of quartz, pyrite, sphalerite, and very sub-

PLATE 4



United Verde ore pipe in pre-Cambrian time, before faulting

Separation of the United Verde and United Verde Extension ore bodies in pre-Cambrian time No oportunity for enrichment of the United Verde ore body

Condition at the beginning of the Cambrian, after erosion

Condition in the late Tertiary time, after deposition of Paleozoic beds, erosion, accumulation of pre-basalt gravel, and eruption of basalt flows. The erosion of a pre-basaltic channel, along the general line of the fault, suggests that there may have been some movement on the fault before the basalt eruption

Condition at present, after post-basalt throw of about 1600 feet

PROBABLE STAGES IN THE FAULTING OF THE UNITED VERDE AND UNITED VERDE EXTENSION ORE BODIES

ordinate quantities of other sulphides. This mass is generally from 500 to 800 feet (152 to 244 meters) in horizontal diameter, plunges at about 68° in a northwesterly direction, and has been mined to a depth of over 3,000 feet (914 meters) with no essential change in character. The pipe lies in an embayment in the diorite, with that rock as the hanging wall. To a large extent, the quartz and sulphides have replaced the schistose and altered rhyolitic rocks into which the diorite is intrusive. Supergene enrichment of this pre-Cambrian ore body has been limited to the relatively short time that the top of the ore body has been exposed to erosion since the removal of the Cambrian and later formations which previously covered it.

The United Verde Extension ore body lies east of the United Verde mine, on the opposite or hanging-wall side of the great Verde fault. It is not exposed at the surface, being covered by about 850 feet (259 meters) of nearly horizontal Paleozoic beds and Tertiary basalt, and the story of its discovery is of absorbing interest although it can not be related in this brief note. The Extension ore body is similar in form and geologic relationships to the United Verde ore body but differs in two very significant respects. In the first place, it is definitely cut off, at a depth of about 2,000 feet (610 meters), by the Verde fault. In the second place it underwent extensive oxidation and enrichment in pre-Cambrian time, in consequence of which the main ore body was largely converted to chalcocite.

The facts mentioned, with others which can not here be presented, indicate that the United Verde Extension ore body was formerly the top of the United Verde ore body; that it was sheared off and relatively downthrown by a throw of 2,400 feet (732 meters) on the Verde fault, in pre-Cambrian time; and that it reached its present relative position by a further throw of 1,600 feet (488 meters) in Tertiary or Quaternary time, as shown by the displacement of the basal bed of the Cambrian and, of course, of the higher formations, including the Tertiary basalt. (See pl. 4.)

The ores of both mines are obtained chiefly by underground mining, but the United Verde Copper Co. has converted its old upper workings into a large pit in which power shovels are used. The ores, hauled from the mines through railway tunnels, are smelted at Clarkdale and Clemenceau, situated in the Verde Valley, a few miles east of the mines.

The total production of the United Verde mine since 1884 has been approximately 1,860,000,000 pounds (843,680,000 kilograms) of copper, over 20,000,000 ounces (622,070 kilograms) of silver, and over 400,000 ounces (12,414 kilograms) of gold. The copper output of the United Verde Extension mine, from the beginning of operations in 1914 to the present, is roundly 550,000,000 pounds (249,475,600 kilograms), with proportional silver and gold.

BIBLIOGRAPHY

The publications listed below are only a few, and these not necessarily the most important, of those relating to the geology of mining districts in Arizona and New Mexico. Many earlier works which are not directly cited in the present outline and to which references are given in the later publications listed have been omitted for the sake of brevity.

1. Bastin, E. S., Primary native-silver ores near Wickenburg, Arizona, and their bearing on the genesis of the silver ores of Cobalt, Ontario: U. S. Geol. Survey Bull. 735, pp. 131–155, 1923.
2. Bastin, E. S., Origin of certain rich silver ores near Chloride and Kingman, Arizona: U. S. Geol. Survey Bull. 750, pp. 17–39, 1925.
3. Bonillas, Y. S., Tenney, J. B., and Feuchère, Léon, Geology of the Warren mining district: Am. Inst. Min. Eng. Trans., vol. 55, pp. 284–355, 1917.
4. Bryan, Kirk, The Papago country, Arizona: U. S. Geol. Survey Water-Supply Paper 499, 1925.
5. Darton, N. H., A résumé of Arizona geology: Arizona Bur. Mines Bull. 119, 1925.
6. Darton, N. H., "Red Beds" and associated formations in New Mexico, with an outline of the geology of the State: U. S. Geol. Survey Bull. 794, 1928.
7. Darton, N. H., and others, Guidebook of the western United States, Part C, The Santa Fe Route: U. S. Geol. Survey Bull. 613, 1915.
8. Ettlinger, I. A., Ore deposits support hypothesis of a central Arizona batholith: Am. Inst. Min. Met. Eng. Tech. Pub. 63, 1928.
9. Ferguson, H. G., Geology and ore deposits of the Mogollon mining district, New Mexico: U. S. Geol. Survey Bull. 787, 1927.
10. Gidley, J. W., Preliminary report on the fossil vertebrates of the San Pedro Valley, Arizona, with descriptions of new species of *Rodentia* and *Lagomorpha*: U. S. Geol. Survey Prof. Paper 131, pp. 119–131, 1923.
11. Jones, E. L., jr., and Ransome, F. L., Deposits of manganese ore in Arizona: U. S. Geol. Survey Bull. 710, pp. 93–184, 1920.
12. Joralemon, I. B., The Ajo copper-mining district: Am. Inst. Min. Eng. Trans., vol. 49, pp. 503–609, 1915.
13. Lausen, C., Geology and ore deposits of the Oatman and Katherine districts, Arizona: Arizona Bur. Mines Bull. 131, 1931.
14. Lee, W. T., The Engle coal field, New Mexico: U. S. Geol. Survey Bull. 285, p. 240, 1906.
15. Lee, W. T., and Knowlton, F. H., Geology and paleontology of the Raton Mesa and other regions in Colorado and New Mexico: U. S. Geol. Survey Prof. Paper 101, 1917.
16. Lindgren, Waldemar, The copper deposits of the Clifton-Morenci district, Arizona: U. S. Geol. Survey Prof. Paper 43, 1905.
17. Lindgren, Waldemar, U. S. Geol. Survey Geol. Atlas, Clifton folio (No. 129), 1905.
18. Lindgren, Waldemar, Ore deposits of the Jerome and Bradshaw Mountains quadrangles, Arizona: U. S. Geol. Survey Bull. 782, 1926.
19. Lindgren, Waldemar, Graton, L. C., and Gordon, C. H., The ore deposits of New Mexico: U. S. Geol. Survey Prof. Paper 68, 1910.

20. Paige, Sidney, Copper deposits of the Tyrone district, New Mexico: U. S. Geol Survey Prof. Paper 122, 1922.
21. Paige, Sidney, U. S. Geol. Atlas, Silver City folio (No. 199), 1916.
22. Ransome, F. L., The geology and ore deposits of the Bisbee quadrangle, Arizona: U. S. Geol. Survey Prof. Paper 21, 1904.
23. Ransome, F. L., U. S. Geol. Survey Geol. Atlas, Bisbee folio (No. 112), 1904; reprinted, with supplement, 1914.
24. Ransome, F. L., Quicksilver deposits of the Mazatzal Range, Arizona: U. S. Geol. Survey Bull. 620, pp. 111–128, 1916.
25. Ransome, F. L., The copper deposits of Ray and Miami, Arizona: U. S. Geol. Survey Prof. Paper 115, 1919.
26. Ransome, F. L., Ore deposits of the Sierrita Mountains, Pima County, Arizona: U. S. Geol. Survey Bull. 725, pp. 407–428, 1922.
27. Ransome, F. L., U. S. Geol. Survey Geol. Atlas, Ray folio (No. 217), 1923.
28. Ransome, F. L., Geology of the Oatman gold district, Arizona: U. S. Geol. Survey Bull. 743, 1923.
29. Ransome, F. L., Some Paleozoic sections in Arizona and their correlation: U. S. Geol. Survey Prof. Paper 98, pp. 133–155, 1916.
30. Reber, L. E., jr., The mineralization at Clifton-Morenci: Econ. Geology, vol. 11, pp. 528–573, 1916.
31. Ross, C. P., Geology and ore deposits of the Aravaipa and Stanley mining districts, Graham County, Arizona: U. S. Geol. Survey Bull. 763, 1925.
32. Schrader, F. C., Mineral deposits of the Santa Rita and Patagonia Mountains, Arizona: U. S. Geol. Survey Bull. 582, 1915.
33. Short, M. N., and Ettlinger, I. A., Ore deposition and enrichment at the Magma mine, Superior, Arizona: Am. Inst. Min. Met. Eng. Trans., vol. 74, pp. 174–222, 1927.
34. Stewart, C. A., Geology and ore deposits of the Silverbell mining district: Am. Inst. Min. Eng. Trans., vol. 43, pp. 240–290, 1913.
35. Tenney, J. B., The Bisbee mining district: Eng. and Min. Jour., vol. 123, p. 841, 1927.
36. Wilson, E. D., Proterozoic Mazatzal quartzite of central Arizona: Pan-Am. Geologist, vol. 38, pp. 299–312, 1922.
37. Wilson, E. D., Geology and ore deposits of the Courtland-Gleeson region, Arizona: Arizona Bur. Mines Bull. 123, 1927.

THE REGION AROUND SANTA RITA AND HANOVER, NEW MEXICO

By Sidney Paige

GEOLOGY

The copper deposits of Santa Rita and the iron and zinc ores of Hanover-Fierro are situated in southwestern New Mexico. The mines lie within the Silver City quadrangle (41).[4] (See pls. 5, 6.)

Mining has been carried on for many years throughout this region. At Silver City, at Lone Mountain, to the southeast, and at Georgetown, farther east, silver was mined during the period 1873 to 1893 from replacement deposits in limestone beneath Devonian shales; at Pinos Altos gold was produced from

---

[4] Numbers in parentheses refer to bibliography, p. 40.

fissure fillings that traverse granodiorite intrusive stocks; at Tyrone, to the southwest, in the Burro Mountains, substantial deposits of disseminated copper ores have been developed in granodiorite; at Silver City manganese has been mined; at Santa Rita copper has been mined since early times; and between Hanover and Fierro there occur large deposits of contact-metamorphic magnetite and sphalerite.

The traveler will approach Santa Rita from the south over a semiarid plain covered by a great sheet of Quaternary gravel and sand. It spreads far to the west, and an arm of it, near by to the northwest, surmounts the Continental Divide in Mangas Valley (see pl. 6) to descend again toward the north and join the desert valley of the Gila River. These arid plains of aggradation, though in part the latest sedimentary accumulations in the region, nevertheless merge with deposits of earliest Quaternary time. A study of their borders throws light on recent structural events. In places the gravel sheet laps upon the mountain side, joined there through alluvial fans with the steep streamways of the mountains from which the fans were derived. In other places sharp faults abruptly bring gravel against the hard rocks; elsewhere along the mountain fronts the gravel deposits are sharply tilted; in still other places they have been eroded back from the mountain front against which they lay, disclosing remarkable planated hard-rock surfaces formed during their deposition and indicating prolonged stages of gradually rising base-level brought about by such accumulations within closed basins (40, 42). The subsequent incision of these planated surfaces by canyons indicates the lapse of time since the gravel was removed.

In the Silver City region this degradation of the gravel deposits has long been in progress. They have been and are to-day being stripped from the mountain fronts. This change from aggradation to degradation along mountain borders may have been due partly to climatic factors, but more probably, in large measure, it resulted from a shift in stream gradient incident to recent faulting and a consequent uplift of mountain relative to plain. Within the last century, in this area, there has occurred marked trenching of the open valleys within the gravel. (See pl. 7, *A*.) This trenching is proceeding vigorously to-day. In the recent past similar accelerations of erosion have occurred and they are marked by terraces at higher levels. (See pl. 7, *B*.)

The accumulation of such immense deposits of intermontane débris has not proceeded without interruption. Within the Silver City quadrangle and at many other places throughout an extensive region sheets of basalt are interbedded with the gravel deposits, and dikes break through them. (See pl. 8, *B*.) These late volcanic events mark the waning of an igneous cycle that began in Upper Cretaceous time and culminated in the enormous andesitic and rhyolite floods of the Tertiary that spread far and wide, masking the underlying Paleozoic and pre-Cambrian rocks. It is a noteworthy fact that but for postlava faulting—a movement initiated during the Tertiary and continuing down to recent times—Paleozoic rocks would not to-day be visible at the surface. (See pl. 6.)

The monotony of the desert landscape is dispelled as Santa Rita is approached. East of the railroad rise the picturesque mountains of Tertiary lava, cliff-rimmed and brilliantly colored. (See pl. 8, *A*.) Rudely bedded gravel, sand, and tuff lie at the base of the pile, and similar materials are interbedded higher up between the andesitic and rhyolitic flows. The highest peaks of the surmounting andesite reach altitudes of 7,000 feet (2,134 meters). The mountain mass is intricately carved by erosion, sometimes in highly fantastic forms. (See pl. 9, *A*.) The principal andesitic flow slopes southward about 100 feet to the mile (19 meters to the kilometer), and the disposition of the interbedded rhyolites suggests a source to the north.

Interbedding of gravel, sand, and tuff marks pauses in the eruptions, erosion, and explosive activity at the main vents.

North of Santa Rita, beyond an area of exposed Paleozoic and Mesozoic rocks, the same lavas are developed on a grander scale. Here Black Peak rises to an altitude of 9,028 feet (2,752 meters) near the edge of a great lava field that extends far north through New Mexico and Arizona.

Volcanism did not cease with the extravasation of these impressive flows. Intrusive stocks of identical composition (rhyolites), large and small, break through the piled up flows. Bear Mountain, 7 miles (11 kilometers) north of Silver City, is one of a group of rhyolite stocks that cut squarely through the basal gravel and tuff and the overlying rhyolite. Near Santa Rita similar but smaller stocks break through the Cretaceous rocks. The amazing circularity of two of these stocks raises fascinating problems of intrusion mechanics; some stocks are filled with fragments of all the invaded beds below, and the geologist may only speculate on the forces that so precisely directed the upward progress of the stock. Near the borders of one stock parallel flow structure is perfectly developed, and the mass appears to have advanced much as a punch might penetrate metal.

From any commanding hill north of Santa Rita the observer overlooks, far to the east and west and from lava scarp on the south to lava scarp on the north, an erosion surface of moderate relief, above which stand a few conspicuous hills and below which streams have cut a pattern of open valleys. From the top of the scarp at Georgetown, on the east, to a point several miles beyond Fort Bayard, on the west, this surface falls about 1,000 feet (305 meters) and joins the plain of erosion that continues west to Silver City and reaches north to the lava ranges.

That portion of this plain that lies west of Fort Bayard corresponds very nearly but nowhere exactly with the ancient surface of erosion that immediately antedated the outpouring of the Tertiary lava floods with their intercalated sand, gravel, and tuff; but it must be kept in mind that since the removal of these lavas this ancient erosion surface has been etched by Quaternary erosion. As the visitor views it to-day he must imagine the low-lying portion of the plain—that west of Fort Bayard—as once covered with a Quaternary gravel sheet that lapped upon the mountain front, and beneath the gravel a more or less planated surface that modified the ancient pre-lava surface. Then he must picture the gravel stripped back from the lava front to its present position and the plain beneath etched by recent streamways. (See pl. 9, *B*.) But quite different is the history of that portion of the surface of erosion within the Santa Rita quadrangle that lies east of Fort Bayard and extends to Georgetown. Here there is a horstlike block bounded on the east by a postlava fault on which movement has continued to very recent times; on the north by the Barringer fault, on which there has been postlava movement; and on the south by a number of postlava faults that combine to depress the adjoining block on the south. (See pl. 5.)

The horst is tilted to the southeast, as shown by the progressively diminishing throw toward the southwest on the northern (Barringer) fault and by the strong displacement along the Quaternary fault at Georgetown, to the east. It is believed that this fault relationship explains the absence of any remnant of the lava series on this erosion surface. The lava was all stripped off here long before its base was exposed in the blocks to the north and south; and in addition there was removed a considerable thickness of underlying sedimentary rocks.

At the end of this erosion cycle at least a thin veneer of Quaternary gravel covered all but the highest peaks of this erosion surface and stretched between the gravel at Georgetown, on the east, and that at Fort Bayard. The removal of the gravel was accelerated by Quaternary faulting. The topographic relief observed to-day may be regarded as a measure of the lapse of time since the gravel was removed. In Hanover Creek this relief amounts to 700 or 800 feet (213 to 244 meters).

This erosion surface reveals Paleozoic, Mesozoic, and Tertiary sediments, broken and folded and metamorphosed by successive igneous invasions of late Cretaceous(?) age and subsequently faulted during postlava time. Thus at first glance the structural pattern displayed on the geologic map (pl. 5) seems complex; but as a matter of fact the elements involved are few, the forces that operated are clearly indicated by their effects, and an orderly sequence of events can be recognized.

The Upper Cambrian Bliss sandstone everywhere rests on a complex of ancient schists and invading igneous masses. As in so many other parts of the world, here also, a base-leveled surface appears to have been prepared to receive the sediments of Cambrian age. Although within the Paleozoic accumulations there are several horizons where systemic boundaries are indicated by fossils, no discordance of bedding has been observed, nor do the formations vary in thickness from place to place. If warping occurred between the major sedimentary eras it was here of the gentlest type.

In striking contrast, however, the base of the Mesozoic succession (the Beartooth quartzite) rests with marked unconformity on the Paleozoic strata—in fact, it transgresses the Paleozoic and along the west side of the Silver City quadrangle rests on the pre-Cambrian granites and schists. The structure of the Paleozoic rocks prior to this erosion interval is so masked by lavas and bolson deposits that little more can be affirmed than that a marked tilting of the Paleozoic land mass is indicated, a tilting of sufficient magnitude to account for the erosion of about 3,000 feet (914 meters) of Paleozoic beds within a distance of 20 miles (32 kilometers) and of 300 feet (91 meters) even within the small area of the Santa Rita quadrangle.

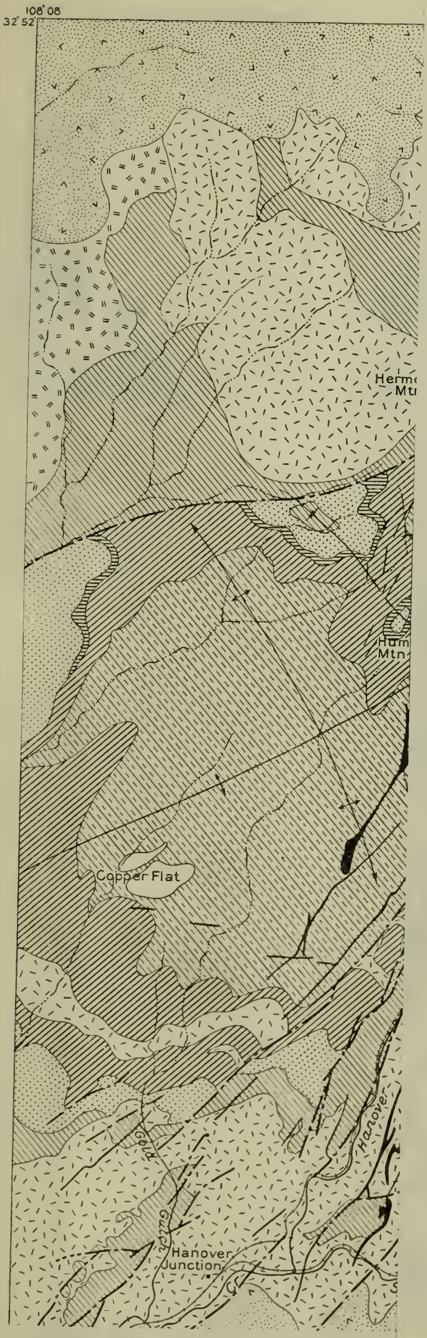
Early in Colorado time (Upper Cretaceous) over a wide area the Mesozoic seas were violently disturbed by volcanic eruptions. Near Santa Rita perhaps 1,000 feet (305 meters), perhaps somewhat more, of Colorado shale had been deposited when flows of andesitic lava and explosion breccias interrupted orderly sedimentation. Only a few miles east of Santa Rita such breccias appear interbedded in Colorado shale and cut by countless andesitic dikes, and the complex so formed covers many square miles to the west. The shales adjoining this complex on the west are likewise cut by numberless dikes, but in the Santa Rita quadrangle such dikes are rare. A small area of this igneous complex, however, is found in the extreme northwest corner of the quadrangle.

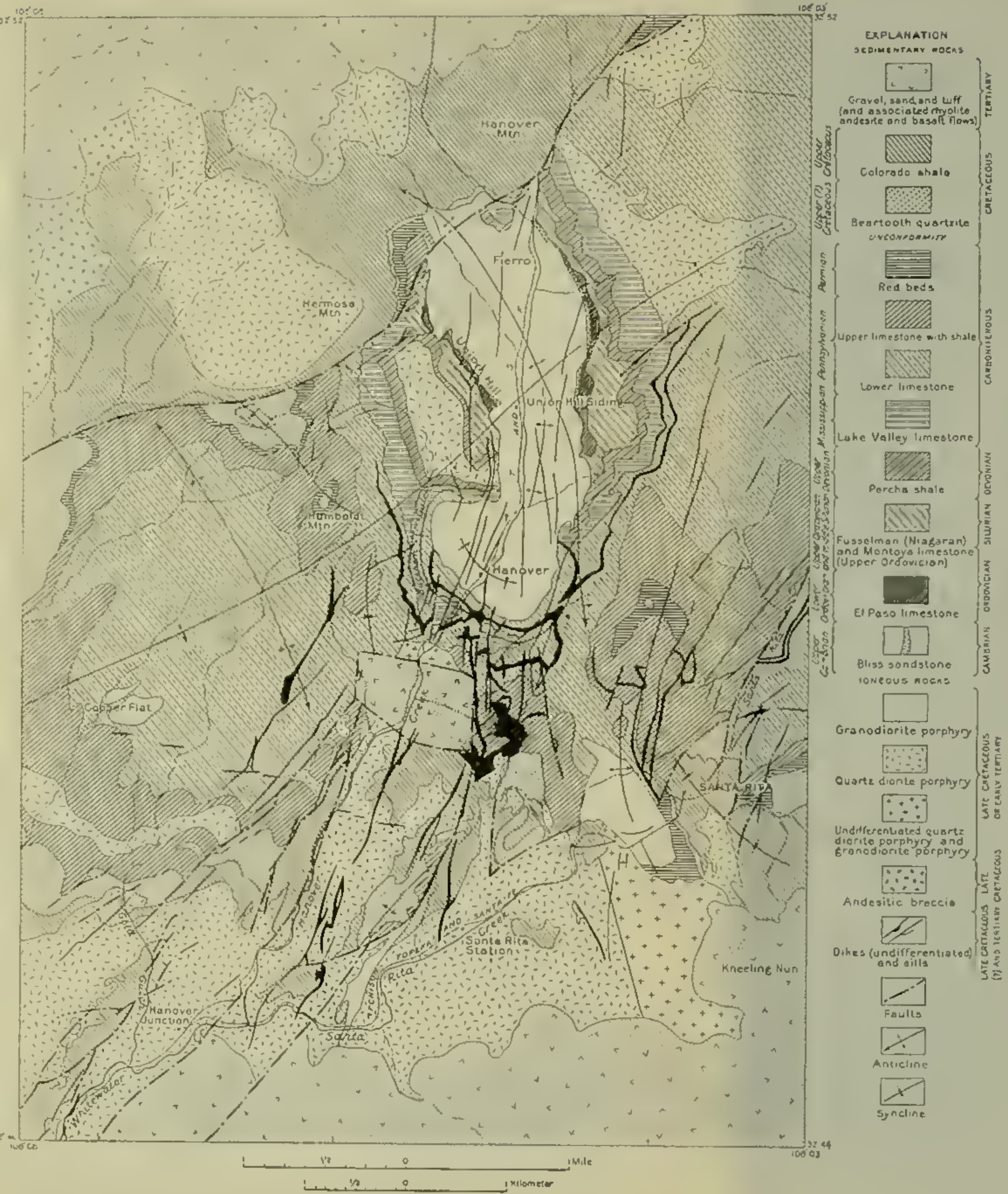
The precise dating of later igneous intrusions is not possible, but two invasions of outstanding economic importance are recognized. The first includes stocks and laccolithic and sill-like masses of quartz diorite porphyry; the second, somewhat later, stocks of granodiorite porphyry and associated dikes. The quartz diorites invade the andesitic complex; the granodiorites cut the quartz diorites.

The quartz diorite porphyry occurs as laccolithic and sill-like masses. Sills are found in the Percha shale, a weak member of the Paleozoic, and in the Pennsylvanian limestones, where shaly members are present. Also, as if in response to a lesser weight of superincumbent beds, a laccolithic mass of substantial proportions invaded Colorado shale at various horizons within a few hundred feet of the top of the Beartooth quartzite. The nature of these invasions implies domal warping of the beds that lay above the invading masses, but within the area of Paleozoic rocks this warping was of minor amount, for here are found only the wedgelike edges of the intrusions. On the other hand, there is reason to believe that to the south the Cretaceous formations were substantially domed above the laccolithic mass in the region now covered by lavas, and it may be supposed that the invasion of the quartz diorite mass of Hermosa Mountain, near the northern border of the Santa Rita quadrangle, produced a similar effect on overlying beds. However, the sharp folding about to be described and displayed by the formations around the later granodiorite masses was due entirely to these later invasions, and not to the laccolithic invasions of diorite porphyry.

Broad upwarping is conceived to have begun at an early stage of the granodiorite invasion, before the magma had penetrated the Bliss sandstone. At this stage an anticlinal arch arose, its crest extending N. 60° E. from a point near Central and corresponding with the crest of the fold in the quartz diorite sill that lies a mile or so to the northeast of Hanover Creek. That this arch plunges to the southwest is clearly displayed by outcrops of Beartooth quartzite that partly encircle the Paleozoic formations. (See pl. 2.)

Superimposed upon this broad arch are two transverse anticlinal folds of which the more prominent is related to the Hanover-Fierro mass of granodiorite, and the other lying to the west, is presumed to be related to a buried mass that connects with the granodiorite cropping out at Copper Flat. Between these transverse anticlinal folds there is a synclinal depression that indents the opposite limbs of the major arch but does not appreciably depress its crest. (See pl. 5.) There are several folds in the southern part of the Santa Rita quadrangle that also appear to be related in time and origin to the invasion of the granodiorites there. Thus there was an arch over the intrusive mass at Santa Rita, and the Cretaceous beds immediately to the


108°08
32°52'
Herm
Mt
Hum
Mtn
Copper Flat
Gold
Gulch
Hanover
Hanover
Junction
Cr.

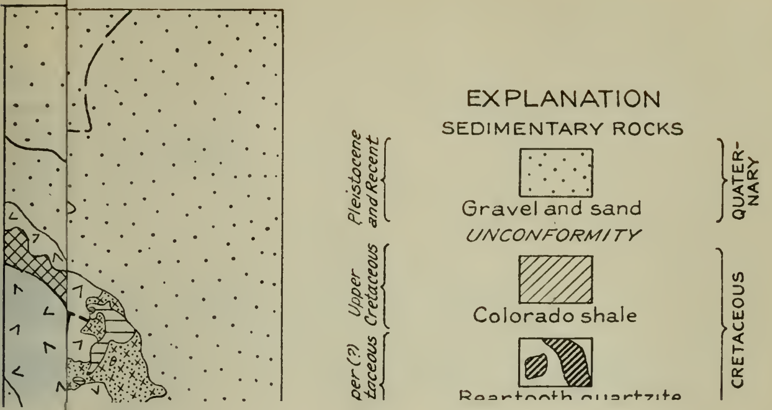


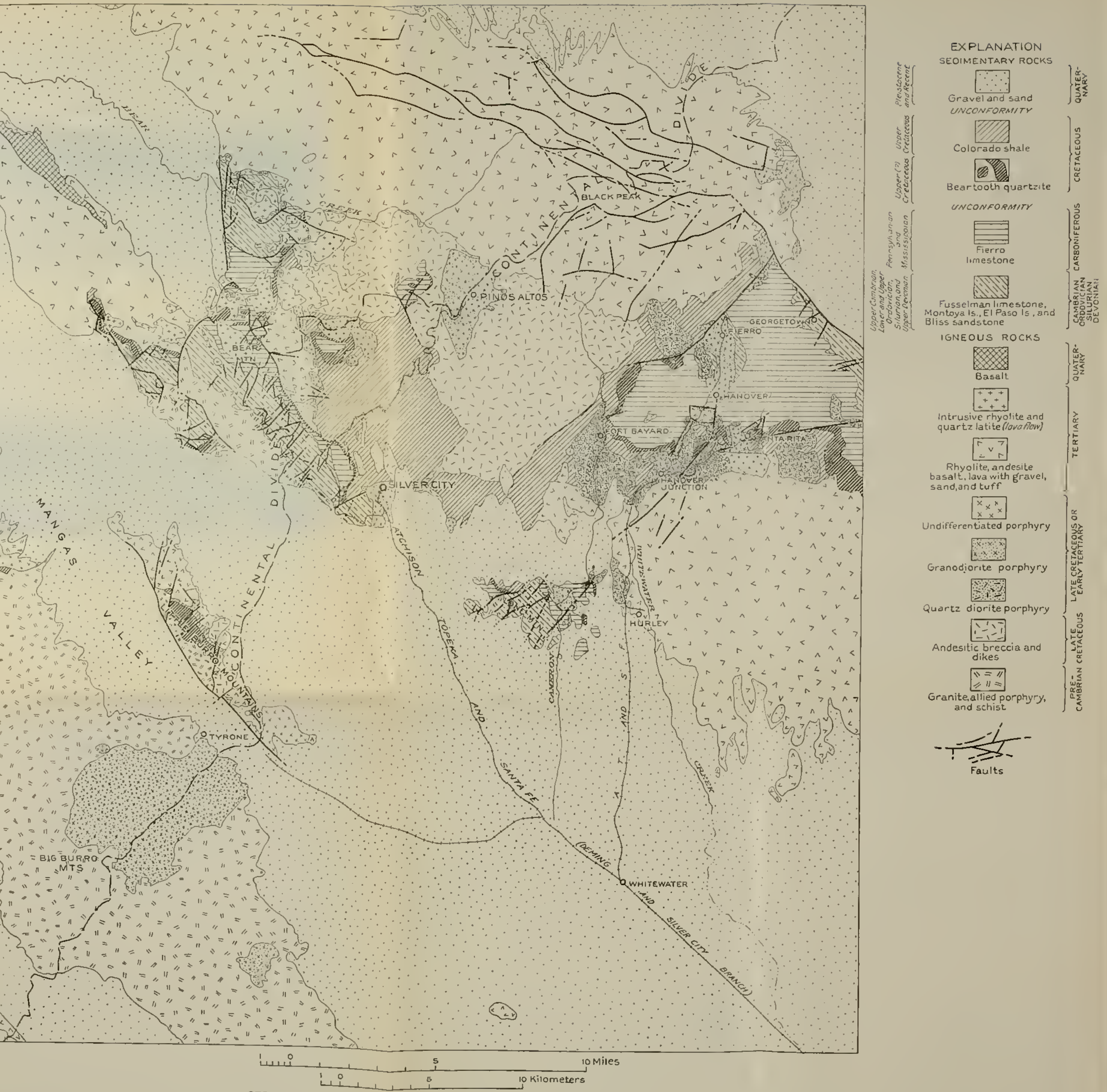
GEOLOGIC MAP OF THE SANTA RITA QUADRANGLE, NEW MEXICO

Geology by A. C. Spencer.

ORE

PLATE 6


EXPLANATION
SEDIMENTARY ROCKS
Pleistocene and Recent
Gravel and sand
QUATERNARY
UNCONFORMITY
Upper Cretaceous
Colorado shale
CRETACEOUS
per(?) taceous
Beartooth quartzite



GEOLOGIC MAP OF THE SILVER CITY QUADRANGLE, NEW MEXICO

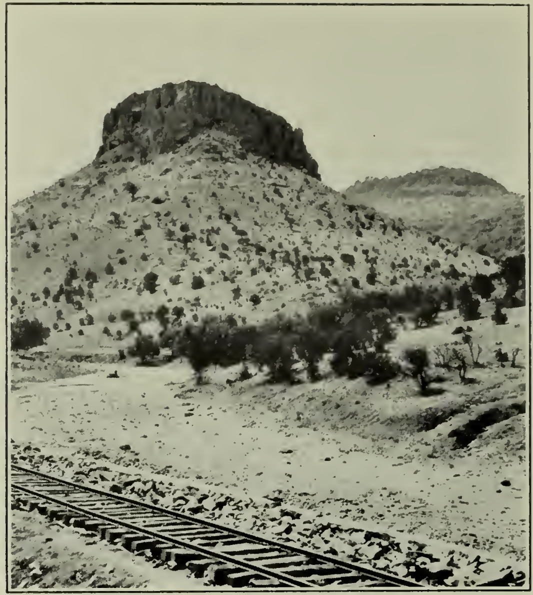
eneralized from U. S. Geol. Survey Geol. Atlas, Silver City folio (No. 199), 1916. The geology of the Santa Rita quadrangle, a part of this area, is shown in greater detail on Plate 5, which is based on later mapping and differs in some respects from this map.

A. TYPICAL RECENT TRENCHING OF VALLEY FILL

Initiated within the last century and proceeding vigorously to-day.

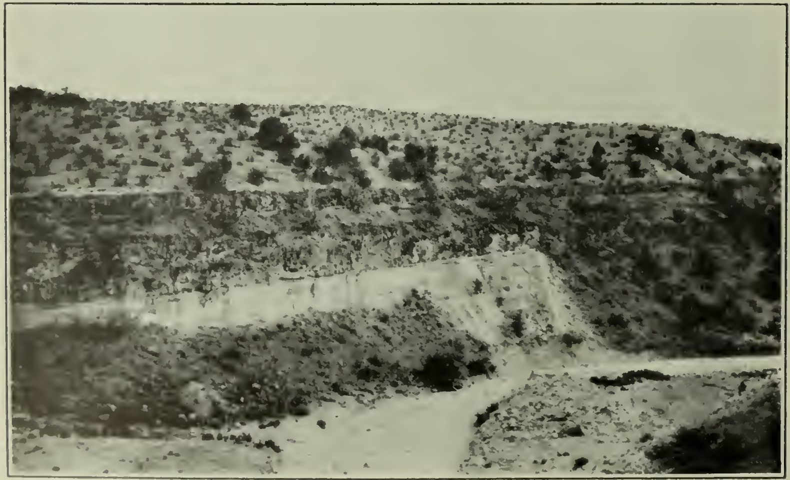
B. ANCIENT TERRACE IN VALLEY FILL

Marking a stage in the degradation of Quaternary gravel and sand.

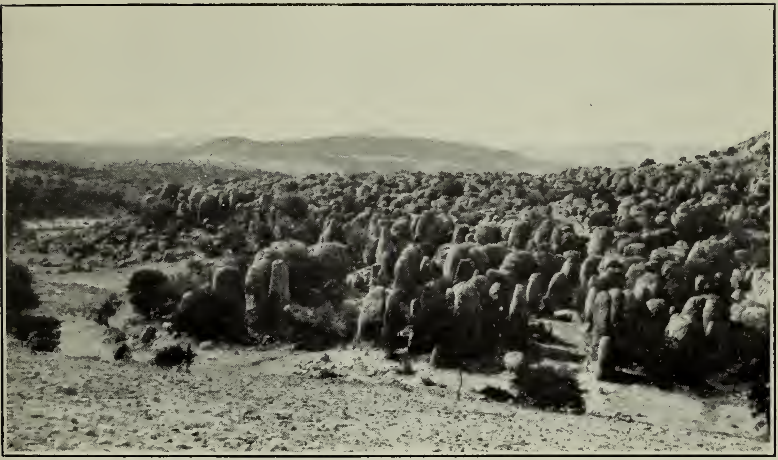


A. LAVA CAPPING HILLS SOUTH OF SANTA RITA, NEW MEXICO

Underlain by Tertiary gravel, sand, and tuff.



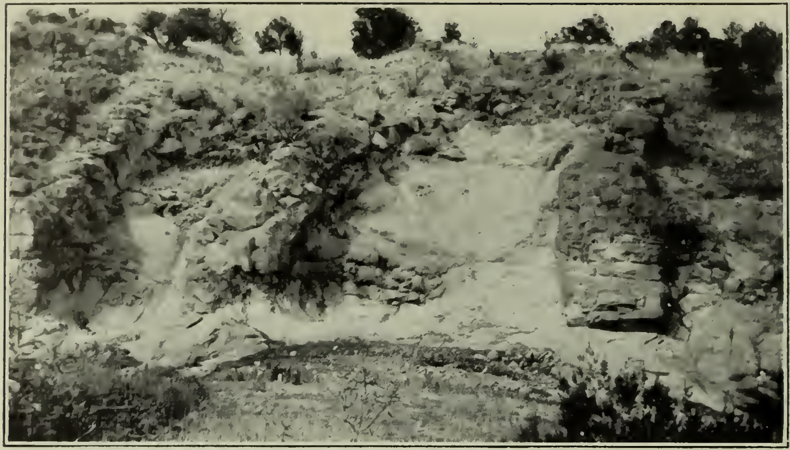
B. BASALT FLOWS INTERBEDDED WITH QUATERNARY SAND AND GRAVEL



A. FANTASTIC FORMS OF WEATHERING IN RHYOLITE FLOWS, IN MOUNTAINS SOUTH OF SANTA RITA, NEW MEXICO

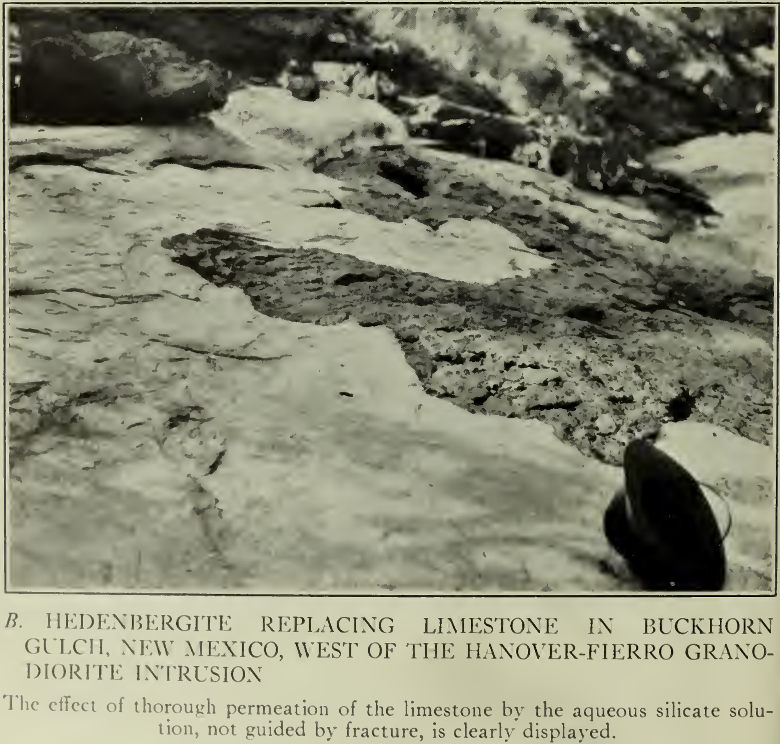
B. VIEW LOOKING NORTH OVER EROSION SURFACE BETWEEN SILVER CITY AND FORT BAYARD, NEW MEXICO

Surface is cut across dikes, Cretaceous shale, and andesitic breccias; not etched greatly beneath the ancient pre-lava erosion surface. Lava ranges in the distance.



A. CRETACEOUS ANDESITIC BRECCIA-DIKE COMPLEX

Covers many square miles between Fort Bayard and Silver City, New Mexico.



B. HEDENBERGITE REPLACING LIMESTONE IN BUCKHORN GULCH, NEW MEXICO, WEST OF THE HANOVER-FIERRO GRANODIORITE INTRUSION

The effect of thorough permeation of the limestone by the aqueous silicate solution, not guided by fracture, is clearly displayed.

Stratigraphic section in th

System and series		Formation	Thickn	
			Feet	
Quaternary Recent and Pleistocene).		Gravel and sand with interbedded basalt flows.	1,000 ±	
Tertiary.		Lava flows and interbedded sediments---	3,000 ±	
Cretaceous.		Colorado shale (Upper Cretaceous)-----	800 ±	
		Beartooth quartzite (Upper? Cretaceous) —Unconformity—	80 ±	
Carboniferous.	Permian.	----------------------------------	200	
	Pennsylvanian.	----------------------------------	400 ±	
		----------------------------------	420	
	Mississippian.	Lake Valley limestone----------------	500	
Devonian.		Percha shale------------------------	250–300	7
Silurian and Ordovician.		Fusselman (Silurian) and Montoya limestones.	225	
Ordovician.		El Paso limestone-------------------	500	
Cambrian.		Bliss sandstone---------------------	180	
Pre-Cambrian.		Complex of granites, allied intrusives, and schists.	180	

Stratigraphic section in the Silver City region

System and series		Formation	Thickness		Character of rocks
			Feet	Meters	
uaternary Recent and leistocene)		Gravel and sand with interbedded basalt flows.	1,000 ±	305 ±	Gravel and sand, in places partly consolidated, with interbedded breccia flows.
Tertiary.		Lava flows and interbedded sediments---	3,000 ±	914 ±	Rhyolites, andesites, and basalts with interbedded partly consolidated sand, gravel, and tuff.
Cretaceous.		Colorado shale (Upper Cretaceous)-----	800 ±	244 ±	Chiefly shale, in places calcareous, with numerous thin sandstones.
		Beartooth quartzite (Upper? Cretaceous) –Unconformity–	80 ±	24 ±	Quartzite and thin beds of shale.
Carboniferous.	Permian.	----------------------------------	200	61	Red calcareous and argillaceous bands.
	Pennsylvanian.	----------------------------------	400 ±	122 ±	Limestone and shale.
		----------------------------------	420	128	Limestone and shale and lenticular sandstone beds.
	Mississippian.	Lake Valley limestone----------------	500	152	White crinoidal limestone at top (120). Blue limestone and shale (250 ±). Siliceous limestone (130).
Devonian.		Percha shale----------------------	250–300	76–91	Green to black shale.
Silurian and Ordovician.		Fusselman (Silurian) and Montoya limestones.	225	69	Gray and pink limestone with prominent beds of chert near base.
Ordovician.		El Paso limestone------------------	500	152	Gray dolomite or magnesian limestone with chert.
Cambrian.		Bliss sandstone---------------------	180	55	Quartzose and glauconitic sandstone, calcareous near top.
Pre-Cambrian.		Complex of granites, allied intrusives, and schists.	180	55	Granites, allied intrusives, schists, etc.

east were depressed into a syncline. To the west, also beyond a poorly defined syncline, lies a clearly marked anticline.

The causal relation between intrusion and folding is best displayed by the structural features surrounding the Hanover-Fierro mass of granodiorite. This narrow intrusive mass broke through the pre-Cambrian basement and in the early stages of its advance assumed the form of an elongate symmetrical laccolith, the position of which has been established by direct observation at the surface. Its principal axis is shown in Plate 5. The further upward movement of the magma, however, was not directed symmetrically with respect to this dome. On the contrary, as it violently forced its way through each successive higher stratum, dragging along a part of the Bliss sandstone moving upward and southward, the crest of the intrusion shifted progressively toward the southwest, deflected from the south end of the earlier dome. (See pl. 5.) At a stage in its progress which preceded the penetration of the Percha shale, two folds developed within the beds surrounding the south end of the intrusion—one a synclinal downwarp adjacent to the magma, the other an anticline immediately beyond it. Because the invading mass was narrow these folds were sharply arcuate in plan.

The progressive advance of the magma forced the northern limb of the syncline to a nearly vertical position and in fact locally overturned it, and the magma, finally penetrating it en masse, nearly destroyed the structure. The dip of the contact of the granodiorite as revealed to-day suggests that the magma then rose at a steep angle upward and outward on the northern limb of the anticlinal ridge. The cuplike form of the synclinal downwarp is regarded as due in part to the merging of the arcuate folds with the dip slope of the ancient arch and possibly in part to circumferentially directed hydrostatic pressure within the magma. The roughly circular lobe that characterizes the south end of the intrusion supports this view. Thus the entire history of the invasion as interpreted from field observations emphasizes this relation—namely, that structural features were formed by the advance of the magma only to be later modified by its continued forward progress.

The emplacement of such granodiorite masses as those at Hanover-Fierro, Copper Flat, and Santa Rita did not quite close this period of intrusion. Narrow dikes of granodiorite porphyry invaded the Hanover-Fierro mass as well as the surrounding sedimentary rocks. Some of these dikes crossed the main igneous boundary and are thus, in a measure, dated. Though many more, found to the southeast, south, and southwest of the main mass, are of the same type, it is recognized that among them are a number that are related to a much later period of intrusion—the post-lava Tertiary.

About this time, during the period of dike intrusion, the igneous mass at Santa Rita and the adjacent invaded rocks were intensely shattered, subjected to hydrothermal metamorphism, and mineralized; and the rocks bordering the Hanover-Fierro mass, though not so intensely shattered, suffered intense contact metamorphism.

A prolonged period of erosion next stripped the Cretaceous cover from the Hanover-Fierro and Santa Rita masses, and though accurate estimate is possible of the depth of this erosion, it seems certain that enrichment of the copper deposits at Santa Rita had begun before the succeeding flood of Tertiary lava brought this process to a temporary standstill.

The outpouring of the lavas was followed by a period of very widespread normal faulting. During this interval of dislocation the Little Burro Mountains, west of Silver City, assumed their monoclinal position, the Silver City Range and its related fault blocks were tilted, and Lone Mountain was raised to approximately its present position. In the Santa Rita region a number of northeastward-trending faults cut the southern lava range and passed as far north as the downfaulted block of Tertiary sand, gravel, and tuff so conspicuously out of place about a mile (1.6 kilometers) south of Hanover. Several faults east of Santa Rita are regarded as of the same age. Displacement also occurred at this time on the Barringer fault, which bounds the Paleozoic area on the north and cuts squarely across folds of earlier date. As an effect of all this faulting the Paleozoic area was raised en bloc and thus exposed to accelerated erosion, in consequence of which the lavas were stripped from the underlying rocks in advance of such stripping from the blocks to the north and south. The erosion surface thus formed has already been described.

ORE DEPOSITS

GENERAL FEATURES

The ore deposits of the Santa Rita quadrangle were formed during a period of mineralization that may have accompanied but in the main followed the emplacement of the granodiorite stocks. These masses and the invaded rocks around them, in consequence of forces that may reasonably be assigned to final upward movements of the cooling solid intrusives, were intensely fractured. To the widespread hydrothermal alteration which immediately followed and which may be regarded as an end effect of the intrusions the ore deposits are in large measure due.

Dikes of granodiorite porphyry invaded the stocks and the surrounding rocks about this time. It is clear that mineralization preceded and followed the emplacement of these dikes. Thus fracturing, hydrothermal metamorphism, the ore deposits, and the dikes may all be regarded as elements of an episode of magmatic invasion.

All the ores were precipitated from heated aqueous solutions. Their mineralogic make-up, the place in which they were deposited, and the form that they assumed depended on the temperature and pressure of the solutions and on the character of the rocks that were available to receive them. Inasmuch as a great variety of rocks, variously disposed, adjoin the stocks, and inasmuch as fracturing in places occurred at long distances from the intrusives, there resulted a variety of ore deposits—contact deposits, disseminated copper ores, and veins.

Sedimentary rocks, chiefly calcareous or dolomitic, surround the Hanover-Fierro stock. During and after the intrusion high temperatures prevailed along the contacts, and solutions circulated freely. In consequence there was formed around the intrusive mass a rude shell, varying in mineral make-up from place to place, consisting of lime, magnesium and iron silicates, iron oxides, and sulphides.

The magnesian limestones in the lower part of the Paleozoic succession contain very little garnet and epidote, the only abundant silicates being wollastonite and serpentine. In places the Percha shale has been converted into hornstone with epidote. Epidote is also developed within the sill west of the granodiorite mass, where it is hydrothermally altered.

The nonmagnesian limestones above the Percha shale, on the other hand, are replaced by the lime-iron garnet, andradite, with which epidote is characteristically found. A bed of shale at the base of the Pennsylvanian section was particularly susceptible to epidotization and garnetization, but though this alteration in places extended beneath the shale into the crinoidal limestone member of the Lake Valley limestone, it is always possible to distinguish the metamorphic shale, because of a marked difference in texture of the metamorphic mineral.

The development of silicate minerals in the Pennsylvanian and Permian formations bears no obvious relation to the proximity of the granodiorite masses, but there appears to have been a structural control of the paths followed by the circulating solutions. Thus these solutions in many places moved through limestone strata much as water is absorbed by or driven through a porous medium, but the replacement, proceeding pari passu with this movement, was evidently directed by beds of relatively impervious shale. Igneous sills played a similar part, and the calcareous argillite of the Permian formation, overlain by dense Beartooth quartzite, was particularly susceptible to alteration, as may be observed at Humboldt Mountain and on the high ridge north of Santa Rita. As a rule the Permian is altered to dense hornstone, but in the ore pits at Santa Rita it is converted to a mixture of pyrite and chlorite.

Hedenbergite and ilvaite, of somewhat sporadic occurrence, are usually found with zinc sulphide, characteristically in places somewhat more distant from the intrusive masses than garnet and epidote. Fine examples of replacement by hedenbergite may be seen in Buckhorn Gulch, west of the Hanover mass of granodiorite. (See pl. 10, *B*.) The rocks exposed at the surface between the south end of the Hanover mass of granodiorite and the Santa Rita mass exhibit a degree of alteration that suggests a connecting body of igneous material beneath the surface.

CONTACT-METAMORPHIC DEPOSITS

Iron ores.—The mine of the Hanover Bessemer Iron & Copper Co., at Fierro, the only operating iron mine in the southwest, has produced 200,000 tons annually in recent years. The property is noteworthy on account of the long rail haul of its product—nearly 700 miles (1,127 kilometers)—to the smelters of the Colorado Fuel & Iron Co. at Pueblo, Colorado, and the economical mining methods that have made the operation profitable. The Hanover Bessemer Iron Ore Association was organized in 1899; the Hanover Bessemer Iron & Copper Co. was incorporated in 1914. A controlling interest was acquired by the United States Smelting, Refining & Mining Co. in 1919, and several years later a magnetic-cobbing mill was installed.

On both sides of the Hanover-Fierro stock, in places where the contact of the igneous mass is parallel with the invaded strata, are commercially important deposits of magnetite which obviously have been formed by replacement. Along the east side of the intrusive mass the ore persists throughout a distance of 6,000 feet (1,829 meters); on the west side for about 5,000 feet (1,524 meters). On both sides the formations stand at high angles, and from place to place there is strong evidence of plastic deformation of the limestones, as a result of which the El Paso limestone has suffered a reduction in thickness. The magnetite ores of high grade occur in the lower part of this formation, and in general it may be said that the replacement ceases at a definite horizon, which is everywhere recognizable because of the presence of serpentine. The serpentine is a metamorphic mineral, and the zone in which it occurs represents a chert horizon of the El Paso limestone, a characteristic feature of this formation throughout the Silver City region. The Bliss sandstone also carries ore but of a distinctly lower grade. The ore bodies follow the stratification in the main, but there are a few places where veins in each border extended out into the limestone above the serpentine.

The magnetite deposits occurring in the lower Paleozoic section have replaced magnesian formations, and the principal silicates are wollastonite and serpentine with minor amounts of garnet and epidote.

On the east side the magnetite ores are found along the contact between the Bliss sandstone and the El Paso limestone, replacing both formations. The thickness of the ore averages about 40 feet (12 meters) but in places may be as great as 200 feet (61 meters). Locally alternate beds of unreplaced limestone occur; in general the ore shows a rude lenticularity. The Bliss sandstone merges upward by gradual increase of calcareous layers with the El Paso limestone, and no clear-cut boundary between the ores of the two formations is to be expected. On the west side of the intrusive mass the El Paso limestone is thin, either because of strike faults or because of plastic flowage. The ore zone occupies the full thickness of such of the Bliss sandstone as remains along the igneous contact and all of the El Paso formation up to and partly including the serpentined chert layer (low grade).

In a few places veinlike bodies of magnetite cut across the serpentine zone into the Montoya limestone, which lies stratigraphically above the El Paso limestone.

Pyrite, chalcopyrite, and chalmersite are noteworthy constituents of the magnetite ores and are clearly in part of later date, as proved in places by their veinlike distribution through the massive magnetite. Sphalerite likewise occurs sporadically in the magnetite.

The average partial analysis of the concentrates shipped is as follows:

Fe	51.00	CaO	1.41
P	.058	MgO	13.38
SiO	7.28	Cu	.37
Mn	.72	S	.38
Al_2O_3	1.42		

Magnetite ores occur also at the south end of the intrusive mass near Hanover, where they replace nonmagnesian limestone of Pennsylvanian age. Here ore has been mined for a thickness of 50 feet (15 meters) and over a distance of 1,500 feet (457 meters) along the contact.

North of Santa Rita is a considerable area in which nonmagnesian limestones of the middle part of the Pennsylvanian succession have been converted into magnetite. In this locality the ore is not confined to the contact of the granodiorite.

Zinc ores.—The mines of the New Jersey Zinc Co. at Hanover, which have been worked more or less continuously since 1902, are credited with an output of approximately 500,000 tons of sphalerite ore, with an average content of 15 per cent of zinc, and in addition considerable amounts of high-grade carbonate ore, most of which was produced prior to 1916. The ores were particularly desirable because they are essentially free of lead. An average analysis representing several thousand tons of mill heads is as follows:

Zn	17.49	MgO	1.81
Pb	.13	CO_2	3.37
Fe	6.19	S	10.19
Mn	.94	Insoluble	49.77
CaO	8.09		

The ore was milled at Hanover; the first mill was a magnetic concentrator, the later mill of the flotation type. The mines are south and west of the Hanover-Fierro intrusive mass, all within a zone of intense alteration, 800 to 1,000 feet (244 to 305 meters) wide, that adjoins the intrusive.

The typical ore bodies occur in the upper part of the Mississippian Lake Valley limestone and are essentially confined to a massive limestone member about 120 feet (37 meters) thick, locally known as the white crinoidal limestone. The Lake Valley limestone appears at the surface on the crest of a curving anticline that closely parallels the southern lobelike intrusive mass.

The ore bodies are typical replacement deposits in limestone, either tabular masses following steeply inclined fractures, some of which correspond with pre-ore dikes, or rude blanketlike deposits developed at the top of or throughout the crinoidal limestone beneath a bed of garnetized shale, which constitutes the lowermost member of the Pennsylvanian. The blanket deposits reach a maximum thickness of 120 feet (37 meters) and are of considerable extent. Some of the upright tabular ore bodies are on the west side of the dikes which they accompany. The largest of these bodies was 120 feet (37 meters) high and 1,000 feet (305 meters) long, with a maximum width of 30 feet (9 meters).

The sphalerite is found in the outer part of the metamorphic aureole, associated with hedenbergite, ilvaite, and manganese-bearing calcite. Magnetite, on the other hand, is found next to the contact of the granodiorite, and between the magnetite and the zinc ores are masses of garnet and epidote. The zinc ores carry greater proportions of lead as distance from the intrusive mass increases.

Zinc ores are not confined to the Lake Valley limestone but have been mined from deposits in the overlying Pennsylvanian formations on the property of the Peru Mining Co. east of Hanover and on that of the Black Hawk Mining Co. about a mile (1.6 kilometers) south of Hanover.

Disseminated copper ores of Santa Rita.—The following notes on production are quoted from a paper by Thorne (43). In the same paper will be found a brief history of the mines, which date back as early as 1800, when, it is stated, an Indian chief showed native copper to Colonel Carasco, of the Spanish military service.

> The Nevada Consolidated Copper Co., Chino mines, operates an open-cut copper mine at Santa Rita. The ore is transported in standard railroad cars by the Atchison, Topeka & Santa Fe Railway Co., approximately 10 miles [16 kilometers] to Hurley, where it is milled. The concentrates are shipped, approximately 70 miles (113 kilometers), over the same railroad to the smelter of the American Smelting & Refining Co., at El Paso, Texas.

According to Butler (38, p. 320), "From 1845 to 1912 New Mexico has a recorded output of 124, 353, 963 pounds (56,405,725 kilograms) of copper, or 0.71 per cent of the output of the country since 1845. The principal production has been from the districts in Grant County." The "districts in Grant County" may practically be interpreted as the Santa Rita district.

> No recorded figures are available for the years previous to 1845, but from the various works in which the Santa Rita del Cobre grant is mentioned, it is estimated that previous to 1845 there were produced not less than 41,000,000 pounds [18,597,290 kilograms] of copper, which would make the production to 1912 165,353,963 pounds [75,003,051 kilograms]. Accurate data are available since 1912, so that, except for a small percentage of error, the production of the Santa Rita mines can be placed at 1,204,000,000 pounds [546,122,370 kilograms] of copper up to the year 1930.

At Santa Rita a granodiorite porphyry stock invades Paleozoic and Mesozoic sediments and a mass of quartz diorite porphyry. The southern boundary of the granodiorite where it cuts the quartz diorite porphyry is obscure, for widespread hydrothermal metamorphism has destroyed many of the distinguishing characteristics of the invading and invaded rocks, both igneous and sedimentary. The granodiorite where unaltered is similar petrographically to the larger mass at Hanover and also to the smaller masses at Copper Flat, though the latter are somewhat finer grained. The thorough alteration of limestone to silicates, found at the surface between Hanover and Santa Rita, suggests that the two granodiorites are connected at moderate depth.

The quartz diorite porphyry is regarded as part of the Fort Bayard laccolith. The crosscutting relations that this rock displays south of Santa Rita, where it breaks across the Permian red beds, the Beartooth quartzite, and the Colorado shale, suggest that here or somewhat farther to the south beneath the lavas may be the position where the magma arose through the basement rocks. Churn drilling indicates that the quartz diorite porphyry is at least 945 feet (288 meters) thick.

The granodiorite deformed the sedimentary rocks that it invaded. Two cross sections (43, p. 4) across the Santa Rita mass, one directed N. 26° E. and the other N. 72° W., show dips away from the intrusive. At the northeast side this dip is very local, for the regional dip of the Pennsylvanian formations is southward, toward the stock. The axis of the anticline indicated by these dips trends northwest. A short distance to the east a synclinal depression trends in the same direction. These folds and comparable folds farther west may be due to the intrusion of the magma.

After the emplacement of the granodiorite, in late Cretaceous (?) time, and owing perhaps to waning upward movements of intrusion, the borders of the rigid mass, as well as the adjoining wall rocks, were intensely fractured. There ensued a period of thorough hydrothermal metamorphism, with sulphide mineralization and dike intrusion. Where sulphides are abundant there has been intense fracturing, but where fracturing was relatively slight mineralization has occurred to only a minor degree. The ringlike dispositon of the ore bodies at Santa Rita strikingly illustrates this relationship, for the core of relatively unfractured granodiorite is relatively unmineralized. (See fig. 1.)

Much ore was formed in the sedimentary rocks adjoining the granodiorite mass. This is particularly true with respect to the ore body on the east side of the stock, where Permian limestone, Beartooth quartzite, and Colorado shale contained ore, and at the south end, where Permian limestone and diorite porphyry contained ore. Considerable Colorado shale was excavated on the southwest side of the stock, and the smaller ore bodies along the northwestern border lie next to the contact. These facts serve to emphasize the conclusion that mineralizing solutions discovered those places where fracturing was highly developed—namely, the borders of the intrusion—irrespective of the host rock.

Thorne says (43, p. 6):

> The thickness of the overburden (above the ore bodies) is extremely variable and ranges from nothing over the northwestern and northeastern portions of the ore body and small areas in other sections to about 150 feet [46 meters] over the southern portion. * * * The contours of the top and bottom of the ore are very irregular. In the main part of the ore body the thickness of the ore reaches 600 feet [183 meters], feathering along the margins to 300 feet [91 meters] and less. None of the ore bodies have been delimited by drilling either vertically or horizontally.

The value of the ore at Santa Rita is due directly and almost entirely to enrichment. Primary mineralization by pyrite and chalcopyrite accompanied the thorough silicification and sericitization of the fractured rocks. Thus Colorado shale was altered to a porcelainlike siliceous rock, distinguishable from altered porphyry only by painstaking examination with a hand lens, and quartz diorite porphyry in its altered facies is distinguished with difficulty fron altered granodiorite.

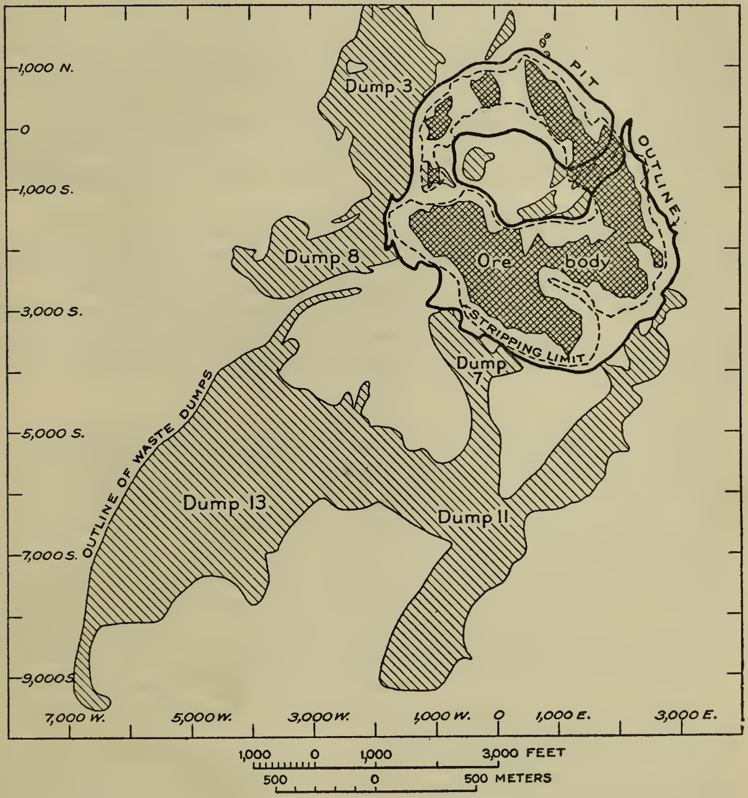


FIGURE 1.—Ore body, stripping limits, pits, and waste dumps at Chino mine, Santa Rita, New Mexico. (After Thorne)

The minerals that have given and still give value to the deposits particularly in the upper zone, are chalcocite, pyrite, malachite, azurite, chrysocolla, cuprite, and native copper. The chalcocite and chalcocite-coated pyrite which are the most abundant, are generally disseminated through the rocks and also fill countless seams and stringers. Quartz, sericite, halloysite, and kaolin are common gangue minerals.

It is well established from regional studies that enrichment was interrupted by eruptions of lava but resumed after the erosion of the lavas in Quaternary time. The horstlike uplift of the area north of Santa Rita brought about the erosion of the lavas that covered the Hanover and Santa Rita intrusive stocks. East of Santa Rita are several faults that are believed to have played a part in this uplift. One, the Romero fault, approaches the stock from the northeast and meets a fault which trends southeast near and along the porphyry contact and which to the southeast either joins or intersects a fault (the Niagara fault) that cuts the lava series. These faults are downthrown on the east.

Another fault to the east, traced to the borders of the Santa Rita quadrangle and shown in the Silver City folio, and several faults west of Santa Rita also played a part in the uplift.

Whether there was a movement along the Romero fault system in pre-lava time can not be discussed here, but it is probable that post-lava faulting accelerated the progress of enrichment.

VEINS

The fracturing and hydrothermal metamorphism that followed the emplacement of granodiorite stocks was not confined to the immediate vicinity of the large masses now exposed at the surface. In the southwestern part of the Santa Rita quadrangle and extending to Central City the quartz diorite porphry and associated sediments are traversed by numerous mineralized fractures. As a group they trend northeast and are characterized by wall-rock alteration and by minerals that strongly suggest an origin related to the granodiorite intrusions; and the presence of numerous granodiorite dikes supports this view. It is not unreasonable to suppose that in depth there are larger masses to which the dikes are related.

Although the region has been prospected for many years, there are only a few of these veins that have been worked with profit. Of these the most productive occur in the vicinity of Hanover Junction. Here a mineralized fracture zone trending northeast has been developed throughout a length of approximately 4,000 feet (1,219 meters). The first development was near the north end of the zone, on the San Jose claim, located in 1875, from which copper, lead, and silver were produced, for the most part prior to 1895. Work on the Lucky Bill claim, at the south end of the zone, began about 1900, when lead carbonate and vanadate ores were discovered. In value this production amounted to several hundred thousand dollars. The Ground Hog claim, in the central part of the zone, with the original San Jose claim, is now owned by the Asarco Mining Co.

The net smelter returns of shipments from the Ground Hog claim up to 1917 were about $50,000, derived from 2,000 tons of lead-copper ore. Between 1917 and 1920, 6,430 tons was produced. Idle from 1920 to 1924, the mine was taken over in 1924 by the Hayward Richmond Leasing Co., and after courageous prospecting an extensive ore shoot was discovered in 1928, when a controlling interest was sold to the present owner, a subsidiary of the American Smelting & Refining Co. The total production of the mine to November, 1930, was approximately 123,260 tons of ore, the net value of which is estimated at $2,250,000 (39).

Lasky (39) has discussed in detail the geologic features of the Ground Hog mine. What follows is a summary of the important geologic relations.

Granodiorite dikes have invaded the quartz diorite porphyry (Fort Bayard laccolith) along a fracture zone trending N. 35° E., approximately 200 feet (61 meters) wide. The quartz diorite porphyry here, as at many other places, contains slices and masses of in-faulted or "included" Colorado shale. This is not surprising in view of the nature of the laccolithic intrusion. The slices and blocks may be regarded as fragments of displaced roof or floor, engulfed during the advance of the magma, the relation of which at many places was crosscutting, at least in detail. Lasky finds that there has been subsequent faulting along most of these shale-diorite contacts, the precise date of which it is difficult to establish but which in the main certainly antedated the Tertiary lavas. The invading granodiorite dikes and the adjacent wall rocks have in turn been fractured, and it is within these fracture zones that the ore occurs. Many of the dike contacts are now fault planes.

This vein system, after deep erosion and burial by Tertiary lava, was subsequently faulted and again eroded and exposed at the surface. The principal post-lava fault practically parallels the vein system, dips about 45° E., and is downthrown on the east about 300 feet (91 meters). The vein system is cut off by this fault, to the southwest, on the Lucky Bill claim.

Four classes of ore have been mined—lead carbonate ore with a little copper and silver, secondary copper ore, argentiferous zinc-lead-copper sulphides, and galena ore.

The main ore body occurs as a well-defined shoot within the vein, as thus far developed about 1,000 feet (305 meters) long, 40 feet (12 meters) wide, and opened to a depth of at least 600 feet (183 meters). The primary ore consists of a massive argentiferous mixture of sphalerite, galena, pyrite, and chalcopyrite of the following average composition: Silver, 8 ounces (248 grams) to the ton; lead, 8 per cent; copper, 4 per cent; zinc, 16.5 per cent. The gangue, which is scarce in the ore shoot, consists mainly of quartz and sericite in veinlets cutting the ore. The origin of the ore body is regarded as related to the period of mineralization that followed the emplacement of the granodiorite stocks at Santa Rita and Hanover-Fierro.

The Ivanhoe mine, on the extension of this fracture zone about 3,000 feet (914 meters) to the northeast, has been worked for lead and copper ores. The ore bodies are of the same general type as those just described. The lode is the result of a combination of fissure filling and replacement along a contact between a granodiorite dike and shaly limestone.

BIBLIOGRAPHY, SANTA RITA AND HANOVER

38. Butler, B. S., U. S. Geol. Survey Mineral Resources, 1912, pt. 1, pp. 275–334, 1913.

39. Lasky, S. G., Geology and ore deposits of the Ground Hog mine, Central district, Grant County, New Mexico: New Mexico Bur. Mines Circ. 2, 1930.

40. Lawson, A. C., The epigene profiles of the desert: California Univ. Dept. Geology Bull., vol. 9, pp. 23–48, 1915.

41. Paige, Sidney, U. S. Geol. Survey Geol. Atlas, Silver City folio (No. 199), 1910.

42. Paige, Sidney, Rock-cut surfaces in the desert ranges: Jour. Geology, vol. 20, pp. 442–450, 1912.

43. Thorne, H. A., Mining practice at the Chino mines, Nevada Consolidated Copper Co., Santa Rita, New Mexico: U. S. Bur. Mines Information Circ. 6412, 1931.

THE BISBEE MINING DISTRICT

By J. B. Tenney

ABSTRACT

Although work in the Bisbee district commenced in 1880, the major developments have taken place since 1902. The district has produced nearly $750,000,000, chiefly in copper, and will eventually pass the $1,000,000,000 mark.

The Mule Mountains, in which the district is located, were formed by compressive stresses acting during late Cretaceous or early Tertiary time, probably a part of the Laramide orogenic disturbances. The early Mesozoic uplift was of the plateau type, accompanied by normal faulting of great magnitude. The Laramie folding was influenced very greatly during the early Mesozoic uplift by the faulting and consequent unequal erosion, which stripped the Paleozoic sediments from a large part of the area.

The porphyry intrusion and accompanying mineralization are placed in late Cretaceous or early Tertiary time, bringing the district into harmony with most of the Rocky Mountain mining districts. As the age relations are controversial, the evidence is analyzed in considerable detail.

The ore deposits are intimately associated with apical stocks of porphyry, the largest of which is that of Sacramento Hill. There are probably other independent apices and ore centers.

The general type of ore bodies is that of limestone and porphyry replacement under conditions of intermediate temperature.

Oxidation was governed by the varying water levels which existed in the past in the bordering tectonic valleys, and deep oxidation below the present water level is postulated as having been effected during early stages in the aggradation of the valleys.

The metamorphism and mineralization are discussed, and little new material is introduced except where differences are noted in independent centers developed since early descriptions of the district.

The importance of the development of a prospecting technique in the search for ore extensions and new ore in the district is emphasized.

HISTORY OF MINING

Prospecting for copper in Arizona was not active until the late seventies, after the Territory was surveyed for the two transcontinental rail routes which are now the Atchison, Topeka & Santa Fe and the Southern Pacific. Copper production started after the completion of the two railroads in the early eighties.

The rich copper outcrop opposite the Copper Queen Hotel at Bisbee was discovered in 1877 by army officers and scouts. In 1879 the first company, known as the Copper Queen Mining Co., was organized to exploit the deposit. In the following year Phelps, Dodge & Co., through the advice of Dr. James Douglas, entered the district and purchased ground adjoining the Copper Queen. In 1884 the two companies were merged into the Copper Queen Consolidated Mining Co. under the control of Phelps, Dodge & Co.

During the next 16 years the Copper Queen Consolidated absorbed most of the ground surrounding the original outcrop and gradually expanded the scale of operations. It was not until the late nineties that the growth of the electric industry had progressed far enough to be reflected in the copper market. Prices began to soar in response to the demand. Phelps, Dodge & Co. decided to build a separate smelter town in the Sulphur Spring Valley, 20 miles (32 kilometers) east of Bisbee, and to build a railroad from El Paso, Texas, to the new smelter town of Douglas, Arizona, on into Bisbee, and beyond to Benson, making connections there with the Southern Pacific Railroad. On the completion of this road the company purchased the El Paso & Northeastern Railroad, which extended the line from El Paso to the Chicago, Rock Island & Pacific Railroad terminus at Tucumcari, New Mexico. The work was completed by the end of 1903, and the annual output of copper was more than doubled.

Until 1900 the Copper Queen Consolidated Mining Co. was the only operator in the camp. In 1900 large groups of claims were purchased by capitalists from the copper and iron districts of the Great Lakes, and the Calumet & Arizona and subsidiary companies were organized to exploit the ground. By the end of 1902 high-grade ore had been developed and a smelting plant had been erected at Douglas. Other smaller ventures were also started at this time, notably the Shattuck-Arizona and Denn-Arizona companies.

The Copper Queen and the later companies continued mining and developing in the camp without interruption during the next 25 years, and the Copper Queen Co. increased its scale of operation still further by the exploitation of two large bodies of disseminated ore in the central porphyry core of Sacramento Hill.

At the end of 1931 the two largest companies, the Copper Queen and the Calumet & Arizona, were consolidated under the control of the pioneer company as the Phelps Dodge Corporation, Copper Queen branch. The Shattuck mine had previously been consolidated in 1925 with the Denn mine by the Shattuck-Denn Mining Corporation. At the present time (1932) there are thus two operating companies in the camp, both of them with large reserves of high-grade ore, insuring a profitable life of many years to the district.

The Bisbee district has produced very considerable amounts of other metals besides copper. The most valuable are gold and silver, which occur with the copper ore and are recovered from the copper bullion in refining. A considerable tonnage of lead-silver ore has been mined in the district in the past, but such ore is now nearly exhausted. Smaller tonnages of lead-zinc ore have been mined, and during periods of favorable market conditions high-grade manganese ore is mined and shipped to Bessemer plants on the Atlantic coast.

PRODUCTION AND DIVIDENDS

The production of the several metals to the end of 1929 is stated below.

Copper:		
Early production, 1880–1901	pounds	338,568,058
Copper Queen, 1902–1929	do	2,121,665,023
Calumet & Arizona, 1902–1929	do	1,261,190,224
Shattuck and Denn, 1906–1929	do	152,464,825
Miscellaneous, 1909–1920	do	14,641,142
		3,888,529,272
Lead, 1908–1929	do	148,425,188
Silver, 1895–1929	ounces	41,524,193
Gold, 1895–1929	do	1,110,058
Zinc, 1917–1926	pounds	14,169,579
Manganese ore, 1918–1929	tons	42,397
Total value, 1880–1929		$704,421,404
Normal annual production rate		$25,000,000
Maximum annual production (1917)		$47,880,400
Dividends paid, 1885–1929, approximately		$222,500,000

SURFACE FEATURES

The Bisbee district is in the southeast end of the Mule Mountains, in the southeast corner of Arizona. The range starts at the Mexico-Arizona line, 6 miles (9.6 kilometers) east of Bisbee Junction, as a narrow low-lying ridge, and continues in a northwesterly direction with gradually ascending altitude to a point 3 miles (4.8 kilometers) east of the settlement of Warren, where it spreads out as a mountain mass 12 miles (19 kilometers) wide. Thence it extends, with this width, a distance of 15 miles (24 kilometers) northwest to a depressed alluvium-covered pass between Sulphur Spring Valley and San Pedro Valley, northwest of which are the Tombstone Hills and the foothills of the Dragoon Mountains. The range is bounded on the northeast by the broad Sulphur Spring intermont plain and on the southwest by the narrower plain drained by the San Pedro River.

The range is formed of two distinct parts separated by a deep, narrow valley. This valley heads in the center of the mountains at Mule Pass, 6,038 feet (1,840 meters) above sea level. Northwest of this pass is the northwestward-draining Tombstone Canyon, and southeast of it is the southeastward-draining Mule Gulch. It is in this depression that the main highway runs from Douglas to Tombstone. Northeast of the depression the range is a wide dissected cuesta carved from gently northeastward-dipping Comanche (Lower Cretaceous) sandstones, shales, and limestones. Southwest of the depression is the bold, rugged Escabrosa Ridge, carved from an intricately folded and faulted complex of indurated pre-Cambrian and Paleozoic rocks and large masses of intrusive porphyry and rhyolite.

The highest point in the range is on Escabrosa Ridge, southwest of the pass, where Mount Ballard reaches an altitude of 7,400 feet (2,256 meters) above sea level. The lowest points are at the two ends, where the altitudes are 4,800 feet (1,463 meters) at the northwest and 4,400 feet (1,341 meters) at the Mexican border.

The boundaries between the range and the alluvium-filled plains on its northeast and southwest sides are sharp. The plains slope away from the mountains at the rate of 25 to 30 feet to the mile (4.8 to 5.7 meters to the kilometer), as contrasted with rock slopes in the range, which reach 100 to 500 feet to the mile (19 to 95 meters to the kilometer) on the northeast side and 500 to 1,000 feet to the mile (95 to 190 meters to the kilometer) on the southwest side.

GEOLOGY

The Mule Mountains (see pls. 11, 12) are made up of a thick series of sedimentary rocks which lie on a basement of metamorphic schists and intrusive granite. Intrusive into the whole are large masses and smaller dikes and sills of granite porphyry and rhyolite. A generalized stratigraphic section is shown in Figure 2.

BASEMENT ROCKS

The oldest rock exposed is a metamorphic schist, known as the Pinal schist, composed of thinly laminated silica and sericite, generally with steep dips. It is of unknown thickness and is separated from the overlying Upper Cambrian beds by a profound unconformity. It is probably derived from argillaceous sandstones, and the schistosity has developed along the original bedding. The schist is a widespread formation and is probably of Archean age.

Intrusive into the Pinal schist is a large mass of coarse to medium grained granite composed of quartz, orthoclase, microcline, and a little biotite and plagioclase, with microscopic apatite, magnetite, zircon, and tourmaline. It is exposed in the center of the range but does not crop out in the productive area.

SEDIMENTARY ROCKS

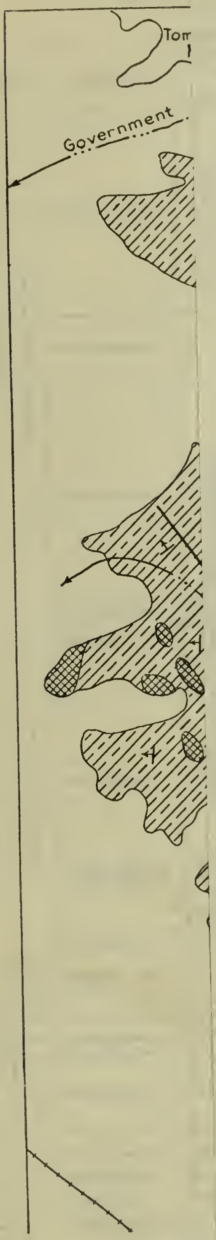
Above a peneplaned surface of Pinal schist is a thick series of Paleozoic rocks, starting with 440 feet (134 meters) of quartzite known as the Bolsa quartzite, somewhat arkosic at its base and with a basal conglomerate of variable thickness. Conformably overlying the quartzite is the Upper Cambrian Abrigo limestone, shaly at the base and increasingly sandy toward the top. The maximum measured thickness is 798 feet (243 meters). The age of the greater part of the limestone has been determined from fossils found in it as Upper Cambrian, of the *Crepicephalus texanus* zone. The topmost beds in one section, however, yield fossils of the *Maladia* zone.

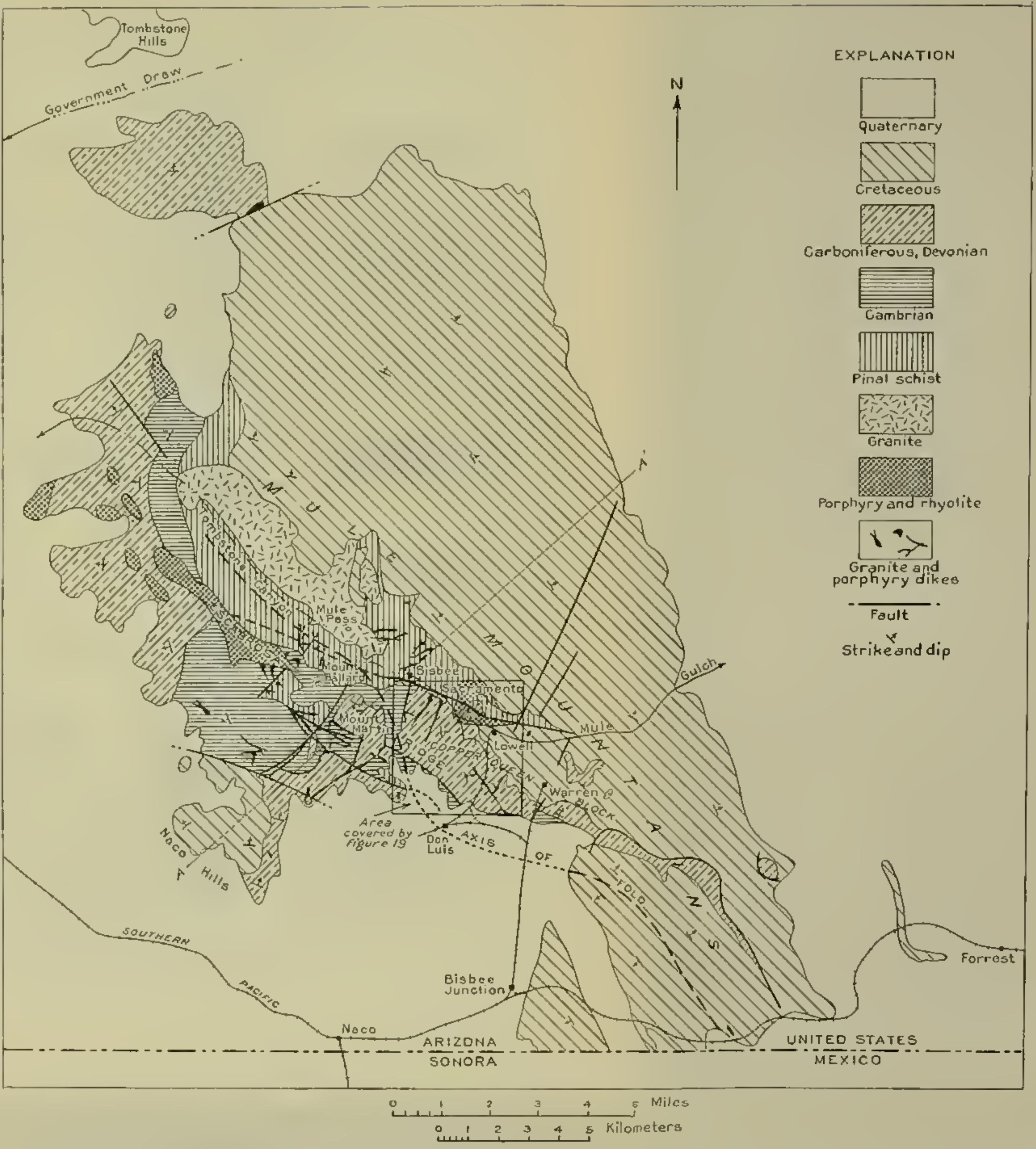
Ordovician, Silurian, and Lower and Middle Devonian rocks are not present in the Mule Mountains, the Cambrian Abrigo beds being overlain disconformably by the lower shaly beds of the Upper Devonian Martin limestone. No angular unconformity exists between the Martin and the underlying Abrigo, and the two formations are in most places separated by a pure quartzite bed, 20 feet (6 meters) in maximum thickness, locally known as the capping quartzite, which was included by Ransome (52)[5] in the Abrigo. It may, however, represent detritus that accumulated on the Cambrian surface and was reworked by the waves before the deposition of the Martin shales. The Martin limestone is very persistent in character and in thickness, which ranges from 300 to 350 feet (91 to 107 meters). It is overlain

---

[5] Numbers in parentheses refer to bibliography, pp. 66–67.

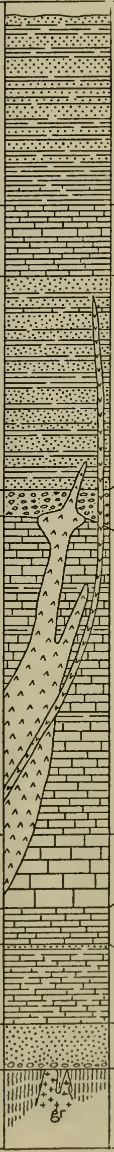
ORE DEPOSITS OF





GEOLOGIC SKETCH MAP OF MULE MOUNTAINS, ARIZONA

For section along line *A–A'* see Figure 3.



System	Series	Formation		Thickness		Character
				Feet	Meters	
Cretaceous	Comanche (Lower Cretaceous).	Cintura formation.	Kc	1,800+	549+	Red nodular shales with cross-bedded buff, tawny, and red sandstones; a few beds of impure limestone near base.
		Mural limestone.	Km	650	198	Thick-bedded hard gray fossiliferous limestone. Thin-bedded arenaceous dark fossiliferous limestone.
		Morita formation.	Kmr	1,800– 2,000+	549– 610+	Buff, tawny, and red sandstones and dark red shales, with an occasional thin bed of impure limestone near the top.
		Glance conglomerate.	Kg	25– 1,000	7.6– 305	Bedded conglomerate with rather angular poorly assorted pebbles of schist, quartzite, and limestone. Rests on irregular surface of erosion.
		–Unconformity–				
Carboniferous.	Pennsylvanian, Permian.	Naco limestone.	Cn	3,000+	914+	Principally light-gray compact limestone in beds of moderate thickness, with very subordinate shale. Contains abundant fossils.
		Granite porphyry and andesite porphyry.	ǥp Pa			Erupted into all formations.
		–Disconformity–				
	Mississippian.	Escabrosa limestone.	Ce	700	213	Thick-bedded white and light-gray granular limestone. Contains abundant crinoid stems.
Devonian.	Upper.	Martin limestone.	Dm	340	104	Dark-gray fossiliferous limestone in beds of moderate thickness, with subordinate pink calcareous shale.
		–Disconformity–				
Cambrian.	Upper.	Abrigo limestone.	Ꞓa	770	235	Thin-bedded epidote-banded limestones with some calcareous shales, sandy toward the top, capped by 8 to 15 foot bed of white quartzite.
		Bolsa quartzite.	Ꞓb	430	132	Moderately thick cross-bedded quartzite and arkosic grits with basal conglomerate. Rests on peneplaned surface of schist and granite.
		–Unconformity–				
Archean.		Pinal schist.	ps			Sericite-quartz schist.
		Granite and granite porphyry.				Intrusive in the schist.

FIGURE 2.—Columnar section of the Bisbee district, Arizona

conformably by lower Mississippian pure massive limestone, from 500 to 700 feet (152 to 213 meters) thick, known as the Escabrosa limestone. No fossils of upper Mississippian or lower Pennsylvanian age have been found in the district, but there is no apparent unconformity between the lower Mississippian limestone and the overlying upper Pennsylvanian Naco limestone, formed of less massive and somewhat shaly limestone. The thickness of the Naco is at least 3,000 feet (914 meters) with the top removed by erosion.

Resting on a very uneven erosion surface of all the earlier rocks is a thick section of Comanche (Lower Cretaceous) sediments. Although the sedimentary contact is uneven, there is little difference in attitude of the beds of the two series. At the base of the Comanche is a coarse conglomerate, known as the Glance conglomerate, which ranges in thickness from 8 feet (2.4 meters) up to at least 1,500 feet (457 meters) and is composed of poorly assorted material with predominant partly rounded fragments of Pinal schist and Bolsa quartzite. Its prevailing color is dark brown. Overlying the conglomerate is 1,800 feet (549 meters) of the Morita formation, composed of light-brown sandstone and arenaceous shale. Overlying the Morita is 650 feet (198 meters) of the Mural limestone, of upper Comanche age, replete with fossils. The top of the series is the Cintura formation, composed of sandstone, quartzite, and shale, with a thickness of 1,800 feet (549 meters) plus an unknown thickness removed by erosion. The formation names were all given by Ransome (52, pp. 24–73), who first worked out the stratigraphy in detail.

INTRUSIVE ROCKS

Cutting the Paleozoic and underlying formations in Escabrosa Ridge are a great number of small stocks, dikes, and sills of granite porphyry. The Comanche sediments have been completely eroded. In the northeast side of the range there has been very little disturbance, and no porphyry dikes occur. In the southeast end of the range, where the extension of Escabrosa Ridge is partly covered by the basal members of the Comanche, a few dikes of granite porphyry and small dikes of andesite porphyry cut the Comanche beds. The Sacramento Hill mass of porphyry, one of the largest outcropping igneous masses, is bounded on the north and east by Glance conglomerate and Morita sandstone. The relations of the porphyry and conglomerate are here somewhat obscure. Ransome's original interpretation (52, p. 106) was that the conglomerate overlies an eroded surface of the porphyry. Subsequent underground exploration has shown that a large sill of porphyry extends several thousand feet to the east under the conglomerate. It is probable that the contact is intrusive, as no boulders of altered porphyry of the Sacramento Hill type have been found in the conglomerate. The conglomerate is here from 500 to 1,000 feet (152 to 305 meters) thick and is cut by numerous tight, iron-stained siliceous fractures, in part copper-stained. The north contact of the porphyry mass was interpreted by Ransome as a fault contact. The conglomerate and overlying sandstones and shales are here red and, in places, copper-stained. The conglomerate, here a few feet thick, is made up of boulders of highly metamorphosed schist and quartzite, so that subsequent contact-metamorphic effects would have been almost negligible.

The porphyry when fresh is a light-gray rock, which weathers light salmon-colored or red. It has abundant phenocrysts, as much as 12 millimeters in diameter, of feldspar, quartz, and biotite. The groundmass, which makes up one-half to eight-tenths of the rock, is fine grained to nearly glassy. The composition varies from granite porphyry to basic monzonite porphyry, the acidic phase predominating. The feldspars are chiefly orthoclase, with oligoclase and albite in the more basic phases.

There are numerous dikes of rhyolite porphyry with a glassy groundmass and flow lines, and some of the larger stocks of porphyry at the northwest end of the range have rhyolite borders. The age relations vary, some porphyry dikes cutting rhyolite, but most of the larger masses of rhyolite are distinctly of the last phase of igneous activity, and a surface flow over an eroded surface of porphyry occurs at the northwest end of the range, together with a few remnants of rhyolite tuff.

Closely associated with the granite porphyry are small later dikes of hornblende andesite. Several dikes of andesite cut the Sacramento Hill mass at its northern edge and extend beyond the porphyry into the Comanche sediments.

GEOLOGIC HISTORY

Pre-Cambrian geology has been very little studied in Arizona. The Pinal schist, the basal rock in Bisbee, is a fissile, compact quartz-sericite schist, probably derived from sandstones. The schistosity has been developed, for the most part, along the bedding planes, as is shown by a few darker bands derived, probably, from contemporaneous lava flows. It varies in strike and dip but strikes on the average northeast and dips at steep angles. The schistosity is much more pronounced on the edges of a large intrusion of granite, and, to the north of the granite, the schist is represented by less metamorphosed thin-bedded quartzites. The schistosity was well developed prior to the deposition of the Cambrian basal conglomerate, in which rounded boulders of schist are found. The unconformity between the two is therefore profound. The last known event in pre-Cambrian time was the intrusion of a large mass of granite now exposed in the center of the range. Subsequent to this intrusion the whole complex was reduced to a very even peneplain of low relief, on which was deposited the Middle Cambrian Bolsa quartzite, followed by farther off-shore Upper Cambrian Abrigo shales and sandy limestones.

At the end of Cambrian time a gentle upwarp took place throughout southern Arizona, resulting in a land mass of very low relief. Erosion of this land mass was probably very slight, in spite of its long duration (Ordovician, Silurian, and Lower and Middle Devonian time). The next younger sediments represented are the Upper Devonian shaly limestone beds. The Devonian beds throughout southern Arizona rest on Abrigo or older Cambrian formations with no angular unconformity and no observed channeling in the Cambrian surface. It is possible that extremely arid conditions prevailed, and that locally the Capping quartzite, which consists of pure-white quartzite with well-rounded grains, may represent the reworked sand-dune covering of the Cambrian surface.

From Upper Devonian time until at least late Pennsylvanian time the area was subjected to nearly continuous sedimentation with probable shoaling of the seas in late Mississippian and early Pennsylvanian time.

During the interval between Permian and Comanchean (Lower Cretaceous) time the whole of southeastern Arizona and southern New Mexico was elevated. Very little is known of this diastrophic period. In general, the lack of marked differences of attitude between the underlying Paleozoic beds and the overlying Comanche and Upper Cretaceous beds indicates that the uplift was probably of the plateau type with little folding. Normal faulting, however, took place, probably on a grand scale. One of the faults occurs in the Bisbee district—the Dividend fault, which strikes west to northwest and has a throw of 1,500 to 5,000 feet (457 to 1,524 meters) down to the southwest. Almost all the Paleozoic beds were stripped from the northeast, exposing Pinal schist and intrusive granite and leaving deep channels in the Paleozoic surface on the southwest.

The subsequent depression to sea level took place rapidly, as the débris was only partly reworked by the waves, and the surface was very irregular. During all of Comanchean and probably a large part of Upper Cretaceous time the whole of southeastern Arizona was repeatedly invaded by the sea, with the accumulation of a great thickness of sediments, partly continental. Most of these sediments have been stripped from the Bisbee area, but to the northwest and west, in the Tombstone Whetstone, Patagonia, Santa Rita, Empire, and Tucson Mountains, from 10,000 to 18,000 feet (3,050 to 5,490 meters) of Upper Cretaceous sediments have been measured.[6]

At the end of Cretaceous time or in early Tertiary time the Mule Mountain area was involved in the Laramide revolution. The range was subjected to compressive stresses, resulting in doming around the resistant core of pre-Cambrian granite. The doming was followed by overthrusting from the southeast, and this in turn by shattering and intrusion of granite porphyry and rhyolite.

In the southeast end of the range the intrusion of magma was followed by ore-bearing solutions, resulting in the metamorphism of the sediments and invading porphyry and the deposition of sulphides of iron, copper, and minor amounts of lead and zinc, together with gold and silver.

From the time of ore formation to the present, the area has been subjected to continued erosion, oxidation, and enrichment.

STRUCTURE

The present structure of the range (see fig. 3) shows the effect of the inherited pre-Comanche structure. The stripping of at least 5,000 feet (1,524 meters) of Paleozoic beds from the northeast side of the Dividend fault left the area at the dawn of the Laramide revolution in an unbalanced condition as regards competency. The attitude of the sediments indicates that at a period subsequent to the Comanche the range was subjected to intense compressive stresses, which resulted in folding and doming. The axis of folding, as shown by the dips of the sediments, did not coincide exactly with the strike of the preexisting Dividend fault. The strike of the axis is about N. 60° W., and that of the fault averages N. 75° W. The two cross each other about in the center of the range, as shown in Plate 11. North of the crossing the fold was essentially a dome against the resistant core of pre-Cambrian granite, the directions of stress being from the west, northwest, and north. South of the crossing, which coincides with the southeast end of the granite intrusion, the range was folded into a southeastward-pitching anticline, the axis of which strikes N. 10°–30° W., as shown in Figure 3 and Plate 11.

---

[6] Personal communications from W. H. Brown, Roy A. Wilson, A. A. Stoyanow, R. J. Leonard, Carl Lausen, and others.

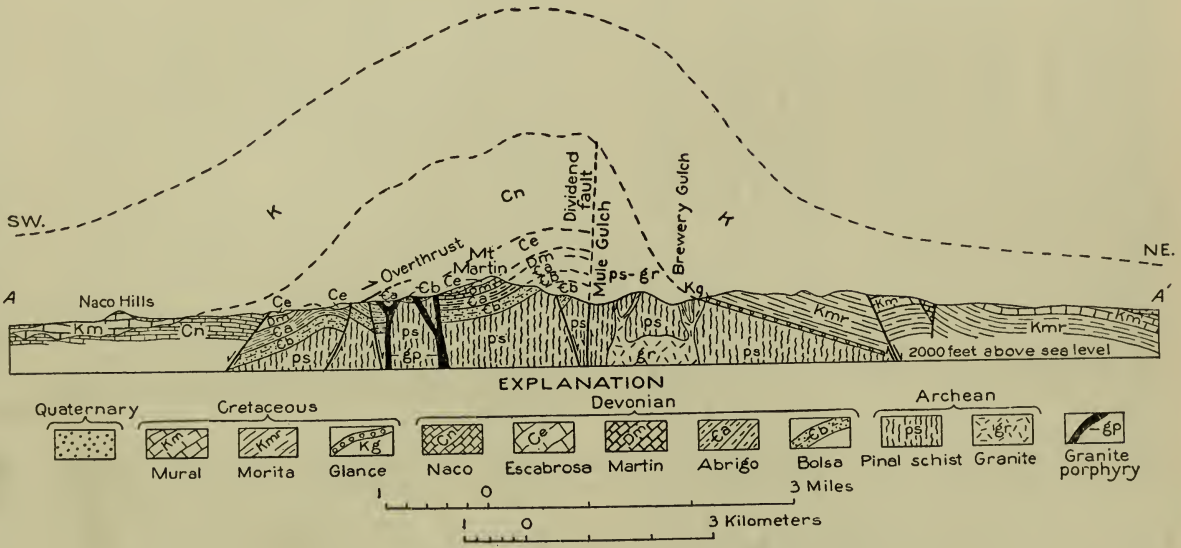
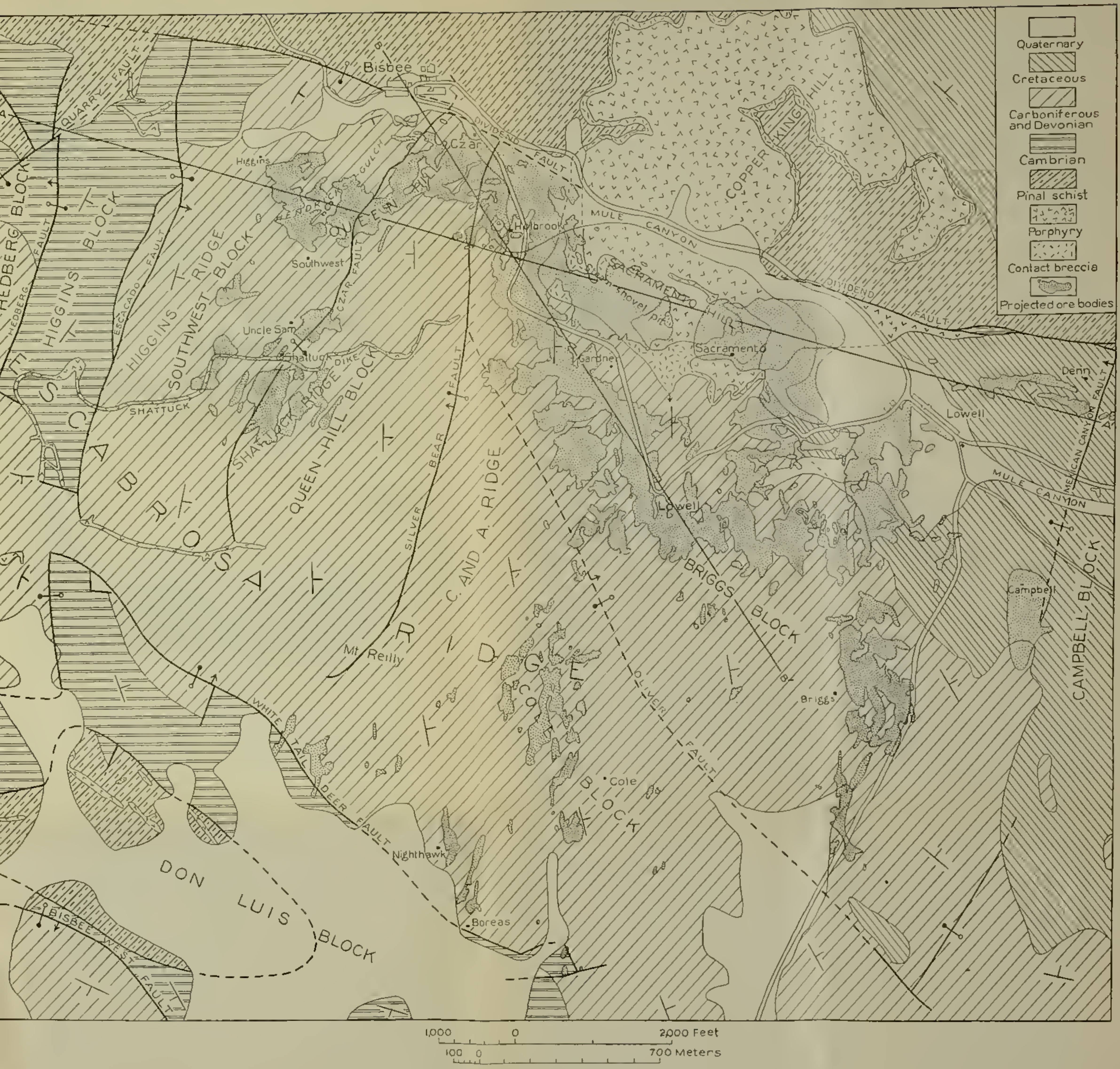


FIGURE 3.—Geologic section along line *A–A'*, Plate 11

In general, the massive Paleozoic beds left on the south side (hanging-wall side) of the Dividend fault resisted folding to a marked extent, and the doming and folding resulted in the development of large fault blocks. The slopes on all sides of the range are dip slopes, modified to a large extent on the southwest side of Escabrosa Ridge by local faulting. The productive area is in one of these blocks, known as the Copper Queen block, which is bounded on the north by the Dividend fault, on the northwest by the Escacado fault, and on the south by the Whitetail Deer fault. This block is on the northeast limb of the main structural fold. The prevailing dips are to the east and northeast.

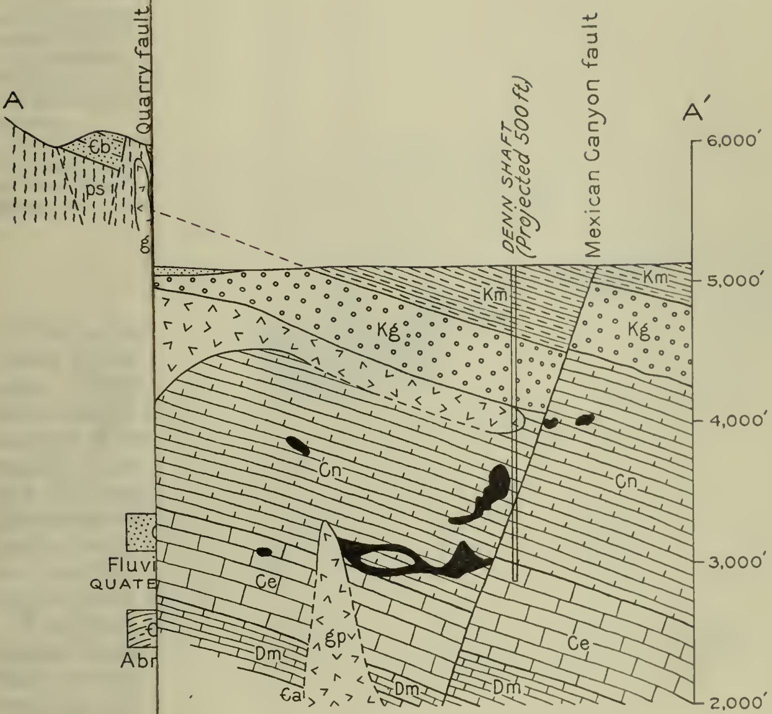
Block faulting was followed by the development of further compressive stresses, which acted from the west to the east and produced low-angle overthrust faults. Owing to the preceding folding, the overthrust blocks usually slid over older instead of younger beds. Where the thrust plane extended considerably beyond the crest of the fold, older beds were thrust over younger beds. In the Gold Hill-Naco overthrust block, at the southeast end of the area, upper Paleozoic limestones were thrust over Pinal schist and lower Paleozoic quartzite and limestone at the southwest and finally over Comanche conglomerate, sandstone, and limestone at the northeast, the direction of thrusting being from the southwest to the northeast. Overthrusting was general throughout the range. In Escabrosa Ridge it commonly produced overthrust fingers or wedges, each wedge bounded by steep faults. These wedges are easily mistaken for grabens. Their true relations in the productive area were revealed by underground exploration. The more prominent wedges found there are the Queen Hill block, opposite the Copper Queen Hotel, and several smaller blocks to the southwest over the Southwest ore bodies.

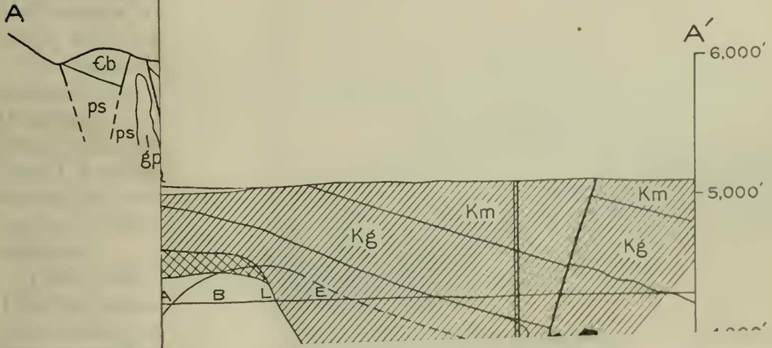
Subsequent to the overthrusting the crest of the fold at Escabrosa Ridge was intensely shattered by normal faults. Intrusion of stocks, dikes, and sills of porphyry accompanied the shattering, and the introduction of metallized solutions in one small area produced the ore bodies. Subsequent erosion has stripped all the Comanche and Upper Cretaceous sediments from the crest of the fold and has exposed the underlying Paleozoic and pre-Cambrian complex. The lower northeast slopes have been relatively less attacked by erosion, although it is probable that only small remnants of the original Comanche and Upper Cretaceous sediments remain anywhere in the area.

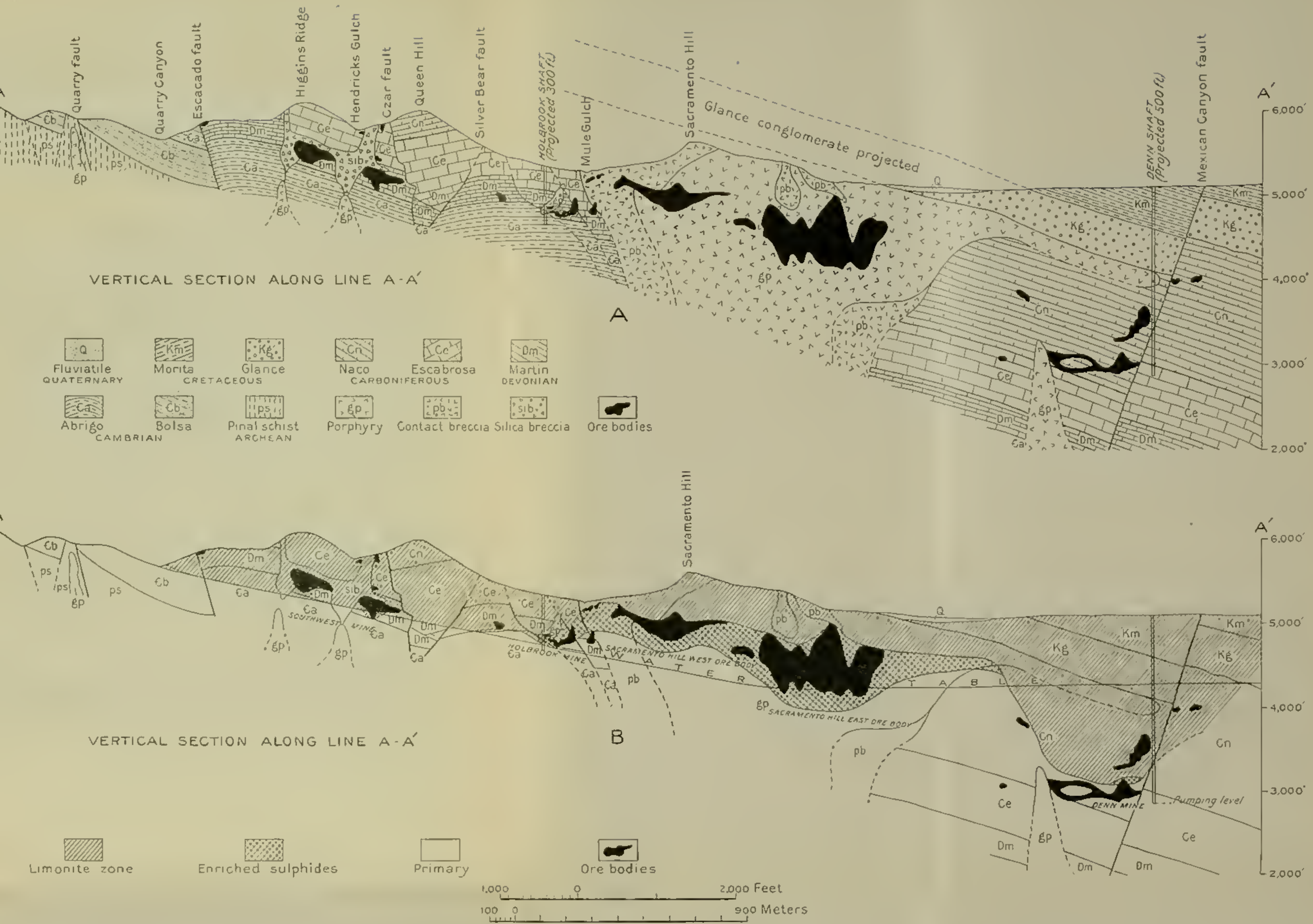


GEOLOGIC MAP OF THE BISBEE DISTRICT, ARIZONA

A–A′, Line of sections in Plate 13; B–B′, line of vertical projection in Figure 4.


A
A′
Quarry fault
DENN SHAFT (Projected 500 ft)
Mexican Canyon fault
Ꞓb
ps
g
Km
Kg
Cn
Ce
gp
Dm
Ꞓa
6,000′
5,000′
4,000′
3,000′
2,000′
Fluvi
QUATE
Abr


A
A′
Ꞓb
ps
ps
gp
Km
Kg
A
B
L
E
6,000′
5,000′



GEOLOGIC SECTIONS ALONG LINE A-A′, PLATE 12

Showing (A) position of the ore bodies and (B) depth of oxidation and enrichment.

7. Six miles (9.6 kilometers) southeast of the productive area small dikes of quartz monzonite porphyry of the same type as the Sacramento Hill and other masses of porphyry of the district cut Comanche beds.

8. Andesite porphyry dikes, although admittedly later than the porphyry, definitely cut Comanche beds.

9. Mineralization in a district is rarely repeated in two so widely separated periods.

10. The Bisbee district is surrounded on all sides by districts in which the age of intrusion and mineralization is late Cretaceous or early Tertiary. It would be truly remarkable to have as violent faulting, intrusion, and mineralization segregated in one small area during the pre-Comanche uplift.

OCCURRENCE OF ORE

STRUCTURAL RELATIONS

The ore bodies of the district are confined areally to the Copper Queen block, one of the major fault blocks of the Mule Mountains. There are no known reasons why the mineralizing solutions should have confined themselves to this one area. The amount of faulting is no greater here than elsewhere. There are equally large porphyry intrusions in other parts of the range, and the porphyry elsewhere is associated with those Paleozoic limestones which have been the most favorable hosts for mineral replacement in the productive area. Whatever the reasons, it is a fact that mineralization and ore deposition to an appreciable extent occur only in the Copper Queen block.

The block is bounded on the north by the Dividend fault, the largest single dislocation in the productive area. North of the fault, on the footwall side, all the Paleozoic beds except a few remnants of Bolsa quartzite were removed by pre-Comanche erosion, leaving the Pinal schist exposed. South of the fault the western part of the block is composed of a faulted complex of Paleozoic limestones and intrusive porphyry. The eastern part of the block is largely covered by the Comanche Glance conglomerate, with a few erosional windows of Paleozoic limestone.

The prevailing dip of the sediments is easterly and ranges from southeast to northeast. The block has been subjected to overthrusting in the form of overthrust wedges from the southwest toward the northeast. Owing to previous tilting, a part of the initial doming of the range, the overthrust blocks were thrust over older instead of younger strata. Subsequent normal faulting and intrusion have rendered the relations very complex and obscure.

There has been extensive porphyry intrusion in the block. The intrusion occurred at several centers, the largest of which is the Sacramento Hill-Lowell stock and associated dikes and sills. Other smaller known centers are those of the Shattuck-Uncle Sam, a series of closely spaced dike-connected sills a mile (1.6

kilometers) south of Sacramento Hill; the Southwest Higgins mass of porphyry of unknown extent (as it lies below the ore horizon), half a mile (0.8 kilometer) west of Sacramento Hill; the Campbell dike, 4,000 feet (1,219 meters) east of Sacramento Hill; the Sacramento-Briggs dike and sills, southeast of Sacramento Hill; and probably deep-lying masses south of Sacramento Hill below the ore bodies in the Boras, Night Hawk, Whitetail Deer, and Cole mines.

The Sacramento Hill-Lowell stock was intruded as a plug in the plane of the Dividend fault. It dips on its south side about 45° SE. and crops out on both sides of the fault. Little is known of its shape north of the fault, because of lack of exploration. The average diameter of the plug at the surface is about 1 mile (1.6 kilometers). The mass has numerous dike and sill apophyses, of which the largest are the Junction-Denn sill, to the east, overlain by Glance conglomerate; the Shattuck dike, to the southwest; and the Sacramento-Briggs dike, to the south. Surrounding the mass, south of the fault, is a semicircular halo of contact breccia composed of rounded and angular fragments of Pinal schist, Bolsa quartzite, porphyry, and intensely altered limestone. The thickness of this shell ranges from a few feet up to 1,000 feet (305 meters).

It is probable that the whole range is underlain by a large batholithic mass, the cupolas of which are now being exposed by erosion. Erosion of the batholith has reached the stage of apical truncation regarded by Butler[7] as exposing the most favorable zone of related ore deposits. The structure of the Copper Queen block is illustrated in Plate 12, which shows the different ore centers, the horizontal projection of the ore bodies, and the porphyry outcrops. The vertical section in Plate 13 shows the eastward-extending sill of Sacramento Hill underlying Glance Conglomerate.

METAMORPHISM AND MINERALIZATION

Regional metamorphism.—The pre-Cambrian Pinal schist is the only intensely regionally metamorphosed rock in the district. The later sediments have been somewhat indurated and the limestones slightly recrystallized away from igneous contacts, but the amount of alteration is slight. The greatest regional metamorphism is exhibited in the deepest and more shaly sediments of Cambrian age. The Bolsa sandstone was metamorphosed into a quartzite, and the thin shale partings of the Abrigo limestone were altered into epidote. Considerable

---

[7] Butler, B. S., and others, The ore deposits of Utah: U. S. Geol. Survey Prof. Paper 111, pp. 198–201, 1920.

induration took place in all the overlying beds and resulted in some recrystallization of the calcite of the limestones and the silicification of the sandstones of the Comanche.

Contact metamorphism.—The effects of the porphyry intrusion vary considerably. In general where the porphyry itself was not altered by subsequent mineralizing solutions the effect on the intruded sediments was relatively slight. On the other hand, where the porphyry was attacked and altered by solutions the sediments were greatly altered. The principal alteration, in and surrounding the Sacramento Hill stock, was effected by hydrothermal solutions.

The most pronounced change in the highly altered Sacramento Hill mass of porphyry and connecting Lowell stock was the attack of the feldspars and groundmass by siliceous, alumina-bearing solutions which produced a mass of sericite and quartz. The solutions also carried considerable sulphur and iron and some magnesia, which produced veinlets and disseminated grains of pyrite and, in places, chlorite and serpentine. The quartz phenocrysts largely escaped alteration.

The Pinal schist was only slightly altered. Pyrite was introduced, and the original schistosity was partly destroyed.

The effect on the limestones depended in great measure on their purity. Close to the borders of the larger masses of porphyry, such as Sacramento Hill, even the purest limestones were altered to fine-grained sericite, wollastonite, and diopside, very sparse, usually microscopic garnet, abundant pyrite, and, in places, abundant specularite and magnetite. When the pure Escabrosa limestone was subjected to less intense attack, it was marmarized only and was replaced only in fractures with silica, chlorite, serpentine, pyrite, magnetite, etc. The most intense metamorphism took place in the less pure Cambrian and Devonian limestones. The purer limestone members of these formations often remain as marble, and the impurities were segregated as grains and veinlets of garnet in the marble. The shaly and sandy members were thoroughly altered to sericite, chlorite, serpentine, massive pyrite, and often magnetite and specularite.

Where the solutions were rich in silica, intense silicification resulted. Alteration of this type was more common in association with smaller porphyry centers. The most common result was the development of intensely brecciated pipes of quartz and chalcedonic silica. The solutions of this type attacked all formations with equal intensity, regardless of their original composition. Accompanying the siliceous solutions were considerable iron and less sulphur than in the normal solutions, which resulted in the development of considerable specularite in the pipes.

The bare hill slope opposite the Copper Queen Hotel has numerous outcrops of large and small pipes of this type. The largest of these silica breccia pipes are associated with the copper and lead-silver ores of the Southwest and Shattuck-Uncle Sam mines, south and southwest of Sacramento Hill. The mineralizing solutions of this type were very intense and far-reaching.

In the treatment of contact metamorphism in the district, the separation of "contact" effects from "hydrothermal" effects is in great measure arbitrary. Both were caused by hydrothermal solutions, and those described above as contact-metamorphic effects were caused by the earliest and hottest emanations from the magma chambers.

Hydrothermal metamorphism.—The solutions that followed the earliest emanations, in general, carried large amounts of sulphur and iron and relatively little silica and alumina. Within the largest porphyry centers and in the contact breccia surrounding the Sacramento Hill-Lowell mass these solutions were virtually contemporaneous with the earlier emanations. Farther from the hot centers the two waves tended to be more widely separated. A common result of the solutions in the less altered limestones was the production of pyrite replacement pipes. Owing to the more thorough oxidation of the ore bodies in the western shallower part of the camp, the pyrite has been largely altered to limonitic "ledge matter" (46, p. 532). The pipes are well preserved in the east end of the camp, in the Junction, Briggs, and Sacramento mines, where the ground has been little touched by oxidation. The more usual effect of the first wave of hydrothermal solutions was the partial replacement of the limestone by pyrite, silica, and, frequently, magnetite and specularite.

The last wave of hydrothermal solutions carried copper, sulphur, and some silica, which replaced all the previously formed minerals. The pyrite deposited in the earlier waves was as a rule intensely shattered, and the chalcopyrite and bornite replaced it along the cracks developed, in addition to replacing the gangue minerals—quartz, sericite, chlorite, and serpentine in the intensely altered rocks and calcite in the less altered limestones. In addition to copper, the last waves of this general period in places carried zinc, lead, and silver. In general, the ore-bearing solutions chose paths through the less altered rocks. No ore bodies of commercial importance have been found in the Pinal schist, and relatively few ore bodies have been discovered in the thoroughly altered contact breccia and contact zone surrounding the Sacramento Hill-Lowell mass. The greater bulk of the ore is found in the outer fringe of relatively less altered limestone. The only exceptions to this generalization are the large ore bodies in the Sacramento Hill mass of porphyry. These ore bodies differ from those in the limestone in that the prevailing hypogene copper mineral formed was bornite. Where bornite and chalcopyrite occur together in the limestone ore bodies, the bornite was the last to form and is more extensive. It is possible that the last copper-bearing waves were more intense than the first, as well as more cupriferous.

Where the earlier siliceous solutions produced silica breccia pipes, the later iron-copper-lead-silver solutions followed in channels in the limestone bordering the pipes. Here again the last waves of mineralization, which carried more abundant lead and silver and less iron, were apparently stronger, as they replaced many of the pipes themselves with lead-silver ore and smaller bodies of bonanza copper ore. This type is well exemplified in the Shattuck and Southwest mines and to a less extent in the upper levels of the Howell claim of the Gardner mine. A good description of the contact and hydrothermal metamorphism of the district is given by Bonillas (44, pp. 318–323).

ORE ZONES

Before the effects of oxidation and enrichment are discussed the position of the zones of alteration and metallization will be given. Previous descriptions of the Bisbee ore deposits were written at a time when the major developments in the camp were in the one ore zone surrounding the largest porphyry center, the Sacramento Hill-Lowell stock. The ore deposits developed elsewhere were assumed to have been under the influence of this stock. A careful analysis of the situation in view of later developments distant from the Sacramento Hill center has shown that not only are there other porphyry centers, but that many of these centers have also been centers of hydrothermal solutions, each one independent of the others and of the Sacramento Hill center. One of the most definite of the independent centers is that of the Boras, Night Hawk, and Whitetail Deer mines, on the southwest side of the Copper Queen block. The ore bodies found there are not associated with exposed bodies of porphyry, although small dikes of porphyry crop out in the vicinity. There is not much doubt, however, in the light of past experience in the camp, that an underlying porphyry body does exist. The Shattuck-Uncle Sam ore center is associated with a large mass of porphyry, which, however, has a narrow dike connection with Sacramento Hill. There is no corresponding connection of mineralization, although thousands of dollars have been expended in trying to find a connection that does not exist. The Southwest Higgins ore zone, associated with a large mass of silica breccia, which is connected in turn with a deep-lying root of porphyry of unknown size, has a narrow connection of weak mineralization with Sacramento Hill. The ore zone is, however, practically independent in its development. The same may be said of the Briggs and Cole centers. The largest ore body now being mined in the camp is the Campbell, separated from the edge of the Sacramento Hill zone by about 2,000 feet (610 meters) of nearly unaltered sediments. The ore body is associated with a large dike of porphyry that has no known connections with Sacramento Hill. In each of these separate centers the ore occurrences are, to a large extent, a law unto themselves as to shape of ore bodies, favorable limestone beds, and even ore minerals developed. The relations of the different ore centers are shown in Plate 12, on which the horizontal projection of the ore bodies is plotted.

The two authoritative publications on the district (44, 52) described in detail the occurrences in the one major ore zone that surrounds the Sacramento Hill-Lowell stock. The stock on the hanging-wall side of the Dividend fault is bordered by a semicircular ring of highly metamorphosed sediments and an outlying ring, with a frayed outer boundary, of ore bodies. The ore bodies form a virtually continuous chain from the contact of Pinal schist and porphyry on the west side of the stock to the same contact on the east side, in Denn ground. In this large ore zone the individual ore bodies vary in size and in shape to a considerable extent but are predominantly tabular and replace limestone, following the bedding planes. The zone of more intense metamorphism is also tabular and confined to a certain more or less definite zone. The thickness of this zone of metamorphism is approximately 700 feet (213 meters), with relatively less altered sediments below and above than in the zone itself. The zone is inclined, following the dip of the sediments, as shown in Figure 4. The general inclination is about 15° SE. The ore bodies are found scattered within the metamorphic zone and on its outer edge. The location of individual ore bodies is governed to a large extent by the position of porphyry dikes and sills and

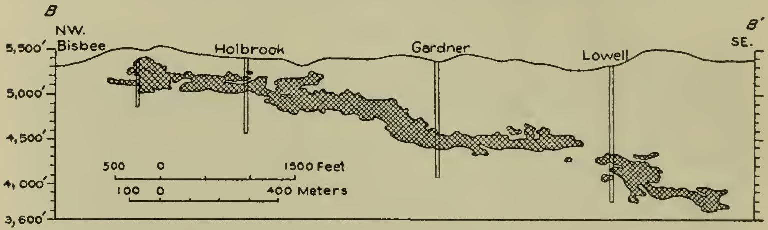


FIGURE 4.—Vertical projection of ore bodies on line *B–B'*, Plate 12

by faults and other structural features. The metamorphic zone and the ore-body chain crop out west of Sacramento Hill, owing to erosion of the overlying less altered sediments. The stratigraphic position of the zone is roughly from the top of the Abrigo limestone to the middle of the Escabrosa limestone, and the most favored ore horizons are the upper half of the Martin limestone and the bottom 200 feet (61 meters) of the Escabrosa limestone. Some ore is found, however, as deep as middle Abrigo and as high as top Escabrosa and bottom Naco. The greater bulk of the ore in this zone, which has furnished most of the past production of the camp, is exhausted. The favored stratigraphic horizon tends to rise in the east end of the zone, in Junction, Denn, and Sacramento ground, where the ore bodies replace Escabrosa and Naco limestones, as contrasted with preponderant replacement of the Martin limestone around the southern and southwestern margins.

The usual types of metamorphism are sericitization, chloritization, and serpentinization. Very few examples exist of intense silicification to silica breccia pipes. The predominant hypogene ore minerals are pyrite and chalcopyrite, with subordinate bornite, zinc blende, and galena and very subordinate tennantite. The ore bodies within the porphyry itself are found as thick tabular deposits with very irregular outlines, which also dip to the east at about the same inclination as the limestone ore. The horizon is several hundred feet higher than that of the limestone ore, and the two zones have no ore connections. The east end of the porphyry chain of ore bodies replaces the large eastern sill apophysis of Sacramento Hill. The preponderant hypogene ore minerals are pyrite and bornite, although chalcopyrite is also present at the east end. The bottom and side boundaries of the ore bodies are sharp and are in contact with sparsely metallized porphyry. The average grade of hypogene ore found in the limestone ore of the Sacramento Hill-Lowell ore zone is about 4 per cent of copper. The grade of hypogene porphyry ore is unknown, as it has been enriched. It was probably high compared to that of other protores of this type. The grade was at least 1 per cent of copper and possibly higher.

In the Uncle Sam-Shattuck ore center the ore bodies are associated with a silica breccia pipe, and silicification has affected both the porphyry and the limestone. The silicification was followed by intense but less far-reaching pyritization. The ore is found both as bedded deposits in the limestone on the margins of the pyrite core and as irregular replacement bodies in limestone and breccia. The bedded deposits consist chiefly, where unoxidized, of pyrite-chalcopyrite ore. The replacement deposits are now thoroughly oxidized and consist of both copper and lead-silver-gold ore. The ore bodies are veinlike in form, in that their major dimensions are vertical and do not extend far beyond the breccia contacts. The ore and breccia zone extends from the top of the Abrigo limestone up to a horizon several hundred feet above the top of the Martin limestone.

The Southwest ore zone is, like the Shattuck-Uncle Sam zone, associated with a large pipe of silica breccia that connects with a porphyry mass of unknown extent, only the top of which has been cut in the lowest extraction drifts. The ore occurrence is very similar to that of the Shattuck-Uncle Sam zone except that there is very little pyrite. All the ore is thoroughly oxidized, so that the grade of the protore can be inferred only from the fact that rich cores of chalcocite exist with a few residual kernels of bornite. Here also there are large bodies of lead-silver-gold ore. The favorable horizon is about the same as that of the Shattuck-Uncle Sam zone.

In the Briggs zone the ore bodies occur as replacement deposits along the margins and within large pyritic pipes. The grade of the hypogene ore is not known, as the ore is all enriched. It was probably about the same as that of the Sacramento Hill center, about 4 per cent of copper. The ore zone here extends from the middle of the Martin limestone up to a horizon several hundred feet above the Martin-Escabrosa contact.

In the Cole ore zone the ore bodies are intimately associated with a zone of closely spaced steeply dipping faults of small throw. The ore bodies are generally in the form of steeply inclined lenses which replace Martin limestone. They are not in close association with porphyry.

In the Boras-Night Hawk-Whitetail Deer ore zone the ore bodies occur as tabular deposits replacing limestone in association with weak silica breccia pipes. The ore zone extends from a horizon 400 feet (122 meters) below the Abrigo-Martin contact to the top of the Abrigo. The tenor of the hypogene ore is low, the average being about 4 per cent, although rich cores of nearly pure bornite are found. The low tenor of the ore is due largely to the impurity of the replaced limestone, the silica and epidote gangue being unreplaced.

In the Campbell ore zone the ore bodies occur as large, steeply inclined lenses following fracture zones near the contact of a large porphyry dike. The hydrothermal metamorphism preceding the introduction of the ore consisted of silicification and sericitization with some introduction of magnesia, but with less iron and sulphur than in the ore surrounding the Sacramento Hill-Lowell center. The ore solutions were richer in copper and in silver and gold than elsewhere. The bottom of the favorable zone has not yet been reached by underground exploration, but it extends at least as far down as the top of the Martin limestone and extends up to the top of the Escabrosa limestone.

To summarize, the ore deposits in the camp were formed by metasomatic replacement of Paleozoic limestone beds and of porphyry by iron, copper, lead, and zinc sulphides in close association with porphyry apices, the largest of which is the Sacramento Hill-Lowell stock. The succession and composition of the solutions that produced the metamorphism and ore bodies varied for each center and within each of the larger centers. The mode of replacement also varied widely, depending on the type of rocks invaded, the presence or absence of porphyry dikes and sills, and the structure of the invaded rocks. In general the metamorphism was effected in a definite stratigraphic zone, which varied with each center both in thickness and in position.

OXIDATION AND ENRICHMENT

General features.—The ground-water table west of Sacramento Hill is a southeastward-dipping plane which starts at the Czar shaft at an altitude of 5,000 feet (1,524 meters) (300-foot level) and reaches an altitude of 4,350 feet (1,326 meters) at the Lowell mine (1,000-foot level), a drop of 650 feet (198 meters) in 1 mile (1.6 kilometers). East of the Lowell mine the table is nearly horizontal and stands at an average altitude of about 4,300 feet (1,310 meters).

The bottom of the oxidized zone is very irregular in detail but in general corresponds west of Sacramento Hill to the ground-water table and to the east is much deeper. The greatest depth of oxidation found is in Campbell ground, where thorough oxidation occurs in deep roots to the 2,200-foot (670-meter) level, 1,200 feet (366 meters) below the water level. West of Sacramento Hill the terrane slopes steeply to the southeast, the fall from the town of Bisbee at the Czar shaft to the settlement of Lowell, northeast of the Lowell shaft, being about 200 feet (61 meters). East of Sacramento Hill the surface slopes gently to a broad basinlike depression at the town of Warren, 3 miles (4.8 kilometers) southeast of Bisbee. The surface at Warren is approximately 5,000 feet (1,524 meters) above sea level, about 300 feet (91 meters) lower than that at Bisbee. The ground-water level at Warren, as determined by shafts sunk before it was lowered by deep pumping, stood at the same altitude as at the Lowell shaft, about 700 feet (213 meters) below the surface of the ground.

Both the intermont valleys bordering the Mule Mountains are tectonic depressions filled with many thousands of feet of débris. In the San Pedro River valley, to the west, the river is now actively degrading the débris. The Sulphur Spring Valley, to the east, is still virtually an inclosed basin with degradation in the initial stages at each end. Degradation in both valleys started in very recent geologic time. It is probable that before degradation began the ground-water level tended to rise continually as aggradation progressed. The ground-water level in internal mountain basins like that from Sacramento Hill to Warren would probably stand at a higher level than that in the valleys but would have enough connecting underground channels to move with the changing levels established in the valleys. At the present time the ground-water table east of Sacramento Hill stands 4,300 feet (1,310 meters) above sea level. The altitude of the San Pedro River to the west, at Hereford, is 4,150 feet (1,265 meters). The ground-water level at Douglas, in the Sulphur Spring Valley, stands at 3,600 feet (1,097 meters) above sea level in wells and at 3,900 feet (1,189 meters) at Whitewater Draw. There is no reason why the Bisbee deep oxidation should not be related to a former deep water table established at an early stage of the history of the two valleys. The correspondence of the present water table and bottom of oxidation in the steep mountain front west of Sacramento Hill is normal, as the water table would always have been inclined there, and the elevation of the general water table would have been compensated there by the rapid lowering of the surface by erosion. The absence of deep oxidation roots west of Sacramento Hill and their presence in the basin to the east do not fit the theory of pretilting oxidation postulated by Bonillas (44, p. 339).

The variations in detail in the depth of oxidation have been well described by Bonillas (44, pp. 340–341), and the relations are illustrated in Plate 13, which shows the rapidity of attack by oxidizing solutions in the various formations of the district. In general, circulation was active in the purer, competent limestones (Naco and Escabrosa), was less active through the impure, thin-bedded, incompetent limestones (Martin and Abrigo), and was still less rapid in the zone of metamorphic limestones and sericitized porphyry. In many of the ore bodies that replace the purer limestones thorough oxidation extends to the primary ore contact, with little development of secondary sulphide. Sulphide enrichment between overlying gossan or oxide ore and underlying protore is much more common in the Martin limestone. In the more thoroughly metamorphosed limestones and sericitized porphyry, oxidation lags behind that in adjacent less altered limestone. Massive pyritic ore withstands oxidation to a marked degree, and in places massive primary sulphide relicts are surrounded by and overlie thoroughly oxidized ore bodies derived from originally less massive sulphide protore.

Under the same conditions the different sulphides are attacked by oxidizing waters at different rates. Pyrite is less readily attacked than chalcopyrite and bornite and is usually almost untouched in the enrichment of the better-grade protores. It does not usually start to oxidize until after the complete transformation of chalcopyrite and bornite to chalcocite or covellite. Where the circulation is retarded by sericite or kaolin, pyrite is attacked and replaced by chalcocite, usually the sooty variety.

Of the two copper-iron sulphides, bornite is slightly more readily attacked than chalcopyrite, but both are vulnerable and are quickly dissolved. The deeper chalcopyrite and bornite are replaced by chalcocite and, rarely, by covellite. Except where circulation is much retarded, pyrite is not materially replaced by chalcocite.

Owing to the abundance of unaltered limestone above the blanket of mineralization, chalcocite where once formed is fixed by the development of films of copper carbonate. Where circulation is retarded, especially where the overlying gossans and gangue are rich in kaolin, chalcocite is oxidized to cuprite and the cuprite reduced to native copper. Ore of this character was mined in great abundance in the shaly Martin limestone replacement deposits of the older parts of the camp. Much of the chalcocite that has survived the downward migration of the acid-rich solutions remains above the ore bodies as cores surrounded by a protective shell of malachite and even crops out in small vein feeders.

In the thoroughly oxidized ore the usual copper mineral end product is malachite. Azurite is often found, but usually in association with abundant kaolin.

Gossans.—In the less metamorphosed limestones the gossans usually represent those parts of the original primary sulphide deposits that were lean in copper and high in pyrite. In places in the west end of the camp, where oxidation was most complete, gossan of this type completely envelops cores of oxidized ore. Owing to the fixation of the limonite by abundant lime, the pyrite-gangue structure may be retained in the gossans as corresponding limonite-gangue structure. In the more intensely metamorphic zone in the limestone and porphyry, where circulation was not so active, gossans derived from formerly rich protore are found. Such gossans usually do not retain their former structure but present the appearance of limonite-kaolin-silica breccia or rubble.

Oxidation collapse.—The phenomenon of oxidation collapse, described by Locke (47, pp. 76–80), is common in the Bisbee district, especially in the more intensely metamorphosed zones. It is caused by the oxidation and removal of sulphides in solution, and the subsequent collapse of the overlying rocks. This does not take place to a great extent in the pure limestones, because of limonite fixation by calcite. The result of collapse is best shown in the moatlike depression that surrounded Sacramento Hill before it was filled by waste material from the steam-shovel operations. Remnants of the depression are still to be seen on the eastern margins and in the basinlike depression to the west, from Sacramento Hill to the Czar shaft.

Efficiency of enrichment.—Bonillas (44, pp. 341–342) has discussed the "efficiency or lack of efficiency" of enrichment and oxidation in the district. Enrichment was most efficient in the metamorphic zones and least so in the less altered limestones, where oxidation of the leaner hypogene copper minerals to the richer oxidation products tended to occur in place, with little migration of the copper. Even where migration and enrichment occurred, the oxidation of the abundant pyrite to limonite compensated for the enrichment by reducing the specific gravity of the resulting ore. It is probable that as much or more metallic copper would have been produced from the camp if no oxidation or enrichment had taken place.

Siderite formation.—Siderite is formed by the attack of ferrous sulphate solutions on calcium carbonate. In the Bisbee district it was very commonly formed at the chalcocite-forming horizon in the zone of more intense metamorphism. Any residual limestone left unmetamorphosed was transformed to an open boxwork of siderite. Siderite was also formed abundantly where much metamorphosed pyritized limestone and ore were underlain by relatively pure limestone. The calcium sulphate was largely removed in the ground water but remained as gypsum where protected by kaolin. The siderite formed in the chalcocite zone is rapidly attacked by oxidizing solutions and never survives in the oxide ore or gossan. Its former existence is indicated in places by the inherited boxwork structure of the resulting limonite. Where oxidation has been complete, as in many localities in the west end of the camp, siderite formed below ore is frequently found completely oxidized to a pseudogossan.

APPLICATION OF GEOLOGY TO THE DISCOVERY OF ORE

Until recent years the greater part of the production of the Bisbee district came from the Sacramento Hill-Lowell ore center. Prospecting for extensions of ore bodies in this center was simple, as isolated ore bodies were rare. The extensions of the ore were ultimately found by the normal development of the ore bodies by mining operations.

During the 20 years from 1880 until 1900 there was little economic urge to study the geology of the district, as the ore bodies near the surface and actually outcropping in the west end of the camp were all mined by one company, and the limited production rate was easily maintained by following the virtually continuous chain of ore bodies. With the entrance of new companies into the district and the necessity of greatly increasing the production rate, ore had to come from a great number of separated centers in the zone in order to keep pace with the increased scale of operations. Geologic study then became of great importance in delimiting the favorable and unfavorable areas and ore horizons. The technique developed since 1900 has been based largely on the search for ore in the largest ore center. During this time, however, other ore centers were found and developed, although not always recognized as such. The technique applicable to the old zone was found to apply, with modifications, to the independent centers. As more of these new centers have been found, some preconceived ideas based on the old center have had to be abandoned or considerably modified.

The ore bodies in each center occur in a roughly tabular zone of relatively intense metamorphism. The overlying limestone, though relatively fresh, is usually more highly altered than the underlying sediments. In most occurrences the overlying feeders from the mineralized blanket have been oxidized, whereas the underlying pyritic roots have not. It is therefore desirable to do the initial work in unknown areas in the ground overlying the unknown ore zone and to judge the depth of the ore zone from the strength of the feeders and the minerals found in them. If the initial work is done below, it is very difficult to judge the height of the ore zone above the insignificant pyritic roots encountered.

In appraising the overlying feeders as cut by the initial prospect drifts and as outcropping on the surface, silica alone, without appreciable limonite, manganese oxide, or copper carbonate stain, is of little significance because of its great range. The extent of the fracturing and the relative abundance of limonite, manganese oxide, and copper carbonate are the chief valuable criteria in judging the proximity of the ore.

Structure maps are of extreme importance as guides to fractured areas favorable as possible ore channels. Porphyry contacts along which mineralization has occurred are worthy of prospecting, but the presence of mineralized rock is of much greater significance than the presence of porphyry.

Oxidation collapse, as shown by concentric and radial fractures, has been a valuable guide in many places, but the collapse of solution caverns produces similar fractures. Here again the presence or absence of mineralized rock is the governing factor.

If, of necessity, the initial work has to be done below the ore zone, it is important to map carefully all pyritized fractures, no matter how insignificant, and to note the minutest changes in general metamorphism and the degree of fracturing. The degree of alteration of porphyry, if cut, is important in the judgment of the overlying zones. If siderite boxwork is cut, the presence or former presence of oxidized iron sulphide is indicated. Considerable associated chalcocite, native copper, or cuprite increases the probability that the siderite is derived from the leaching of pyritic copper sulphides.

The most difficult area to prospect is that lying east and southeast of Sacramento Hill. Here the Paleozoic limestones are largely covered by a variable thickness of Glance conglomerate. The imperviousness of this formation to the upward penetration of mineralizing solutions makes the search for surface outcrops of mineral feeders very difficult. The prevailing brown color of the formation adds to the difficulty Mapping has to be done on a minute scale, and all mineralized fractures noted.

In prospecting for possible new centers of mineralization it is important to bear in mind that all favorable ore zones are not necessarily at the same stratigraphic horizon as that of the Sacramento Hill-Lowell center, and their positions depend on the depth of the unexposed porphyry apex, the intensity of the solutions, and the degree of fracturing. It is quite within the possibilities that comparatively shallow zones at high stratigraphic horizons may be found in the east end of the district.

ACKNOWLEDGMENTS

The foregoing paper is largely a summary of the two principal publications on the district (44, 52) frequently referred to in the text, and the writer wishes to acknowledge the inestimable value of the work of the authors of those publications.

The hearty cooperation of the officials of the Phelps Dodge Corporation, Copper Queen branch, and the helpful suggestions of Carl Trischka, chief geologist, and of Milton Lindholm, assistant geologist, are gratefully acknowledged.

Special thanks are extended to B. S. Butler, of the geological department of the University of Arizona; F. L. Ransome, of the geological department of the California Institute of Technology; and Augustus Locke for valuable criticisms of the paper.

BIBLIOGRAPHY, BISBEE DISTRICT

44. Bonillas, Y. S., Tenney, J. B., and Feuchère, Léon, Geology of the Warren mining district: Am. Inst. Min. Eng. Trans., vol. 55, pp. 284–355, 1916.

45. De Kalb, Courtney, Sacramento Hill disseminated copper deposit: Min. and Sci. Press, vol. 116, pp. 549–554, 578–583, Apr. 20 and 27, 1918.

46. Douglas, James, The Copper Queen mine, Arizona: Am. Inst. Min. Eng. Trans., vol. 29, pp. 511–546, 1900.

47. Locke, Augustus, Leached outcrops as guides to copper ore, Baltimore, Williams & Wilkins Co., 1926.

48. Mitchell, G. J., Ore deposition in the Warren district, Arizona: Eng. and Min. Jour., vol. 109, pp. 874–875, Apr. 10, 1920.

49. Mitchell, G. J., Vertical extent of copper ore minerals in the Junction mine, Warren district, Arizona: Eng. and Min. Jour., vol. 109, pp. 1411–1412, June 26, 1920.

50. Mitchell, G. J., Replacement copper deposits in the Warren district: Eng. and Min. Jour., vol. 112, pp. 246–250, Aug. 13, 1921.

51. Notman, Arthur, The Copper Queen mine and works, pt. 2: Inst. Min. and Metallurgy Trans., vol. 22, pp. 550–562, 1913.

52. Ransome, F. L., The geology and ore deposits of the Bisbee quadrangle, Arizona: U. S. Geol. Survey Prof. Paper 21, 1904.

53. Ransome, F. L., U. S. Geol. Survey Geol. Atlas, Bisbee folio (No. 112), 1904; revised, 1914.

54. Tenney, J. B., The Bisbee mining district: Eng. and Min. Jour., vol. 123, pp. 837–841, May 21, 1927.