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THE GEOLOGY AND ORE DEPOSITS OF THE BISBEE QUADRANGLE, ARIZONA

BY

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THE GEOLOGY AND ORE DEPOSITS OF THE BISBEE QUADRANGLE, ARIZONA.

By FREDERICK LESLIE RANSOME.

INTRODUCTION.

GEOGRAPHY.

The Bisbee quadrangle lies in Cochise County, in the southeastern part of Arizona, within what has been called in a previous paper[a] the mountain region of the Territory. It is inclosed between meridians 109° 45′ and 110° 00′ and parallels 31° 30′ and 31° 20′, the latter being locally the Mexican boundary line. The area of the quadrangle is about 170 square miles, and includes the southeastern half of the Mule Mountains, one of the smaller of the isolated ranges so characteristic of the mountain region of Arizona. The Mule Mountains, while less markedly linear than the Dragoon, Huachuca, Chiricahua, and other neighboring ranges, have a general northwest-southeast trend. They may be considered as extending from the old mining town of Tombstone to the Mexican border, a distance of about 30 miles. On the northeast they are separated by the broad flat floor of Sulphur Spring Valley form the Chiricahua Range, and on the southwest by the similar broad valley of the Rio San Pedro from the Huachuca Range (Pl. V, *A*).

The town of Bisbee (Pl. V, *B*), with an estimated population of about 6,000,[b] is crowded into a few narrow confluent ravines near the heart of the range, 7½ miles north of the international boundary. It is connected by the El Paso and Southwestern Railroad to the east with the new town of Douglas in Sulphur Spring Valley, with Deming, and with El Paso. To the west, branches of the same road run to Naco on the Mexican boundary, to Tombstone, and to Benson on the main line of the Southern Pacific Railroad. At Douglas connection is made

[a] Ransome, F. L., Geology of the Globe copper district, Arizona: Prof. Paper U. S. Geol. Survey No. 12, 1903.
[b] Population not given in Twelfth Census, as town is not incorporated.

with the Nacosari Railroad to Cos and at Naco with the Cananea, Yaqui River and Pacific Railroad to Cananea, thus bringing the new smelting town of Douglas within reach of the important mines at Nacosari and Cananea in the State of Sonora.

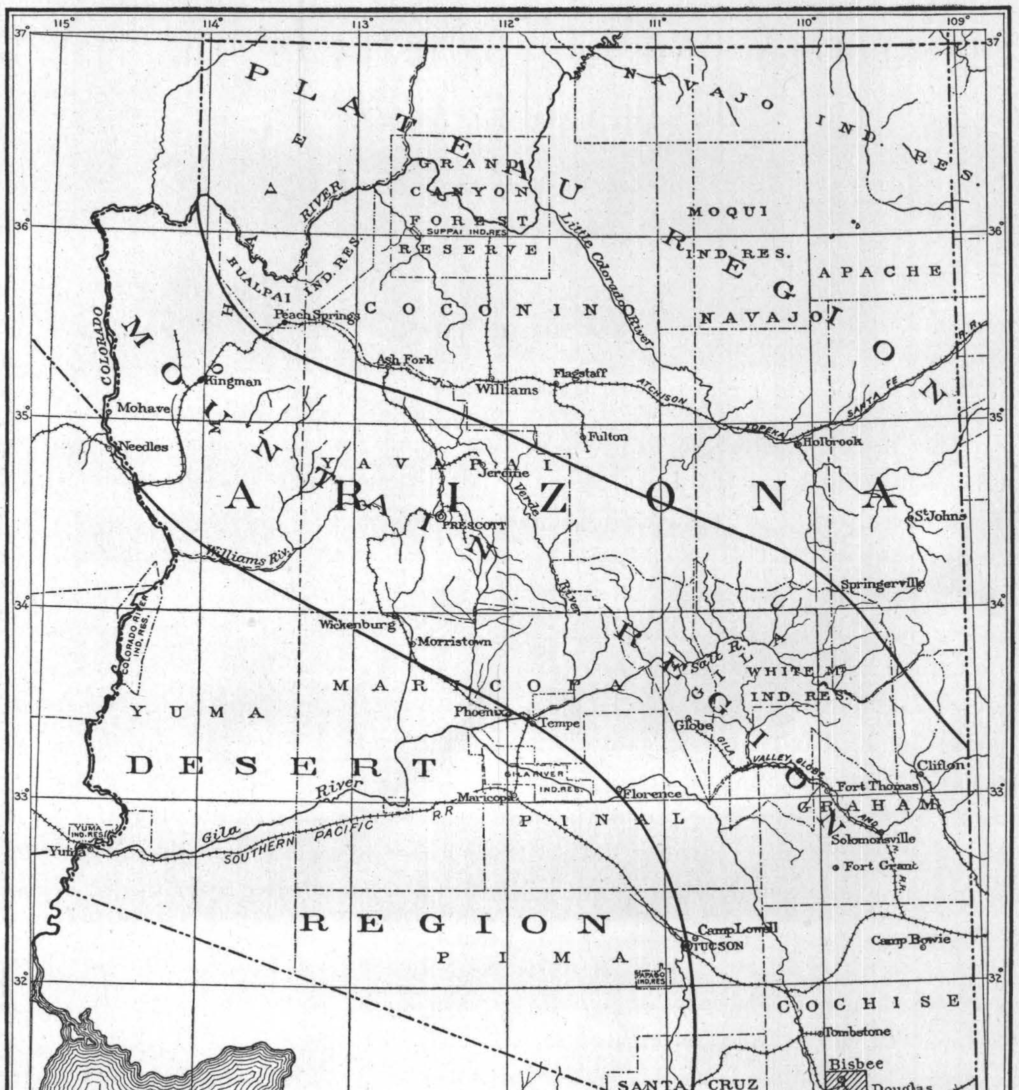
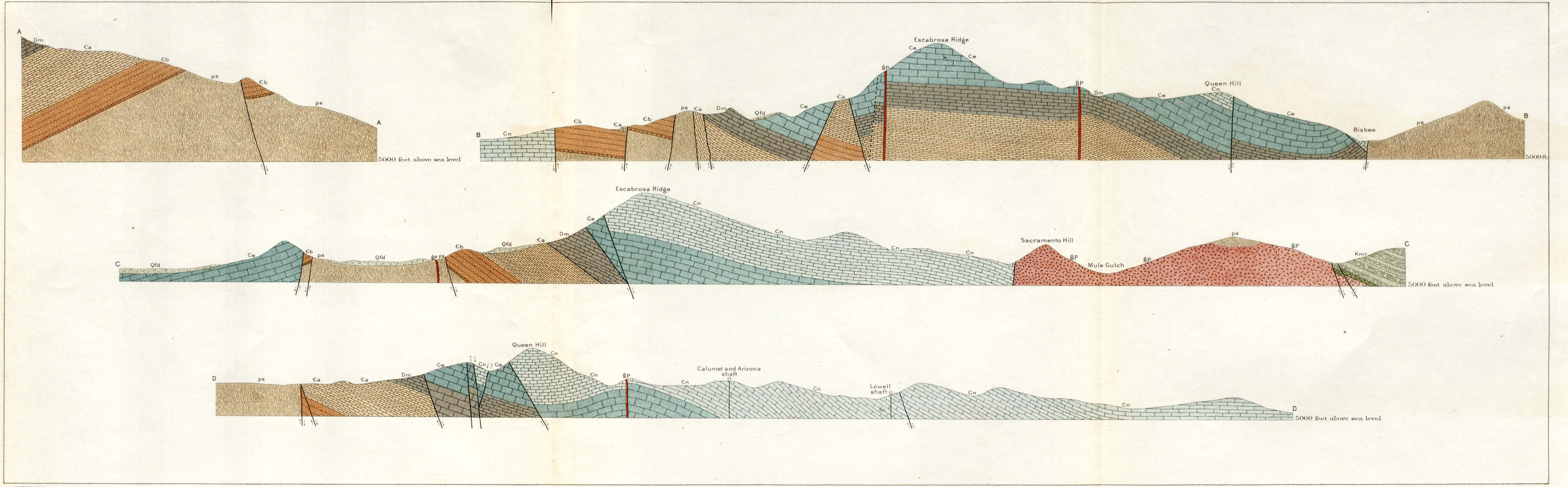


FIG. 1.—Index map showing position of the Bisbee quadrangle.

The position of the Bisbee quadrangle is shown in the accompanying index map (fig. 1).



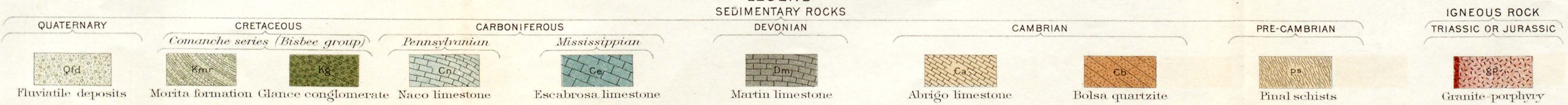
SECTIONS ALONG THE LINES A-A, B-B, C-C, AND D-D ON PLATE III

Scale $\frac{1}{12000}$

0 — $\frac{1}{8}$ — $\frac{1}{4}$ — $\frac{1}{2}$ — $\frac{3}{4}$ — 1 mile

1000 — 500 — 0 — 1000 — 2000 — 3000 — 4000 feet

LEGEND



FIELD WORK AND ACKNOWLEDGMENTS.

The geological field work upon which this report is based was begun in the middle of September, 1902, and finished late in December of the same year. Throughout this period efficient assistance was rendered by Dr. J. Morgan Clements and Mr. Alfred M. Rock. Mr. Clements is chiefly responsible for the careful mapping of the Cretaceous beds and of the Juniper Flat granitic area.

After a reconnaissance of the quadrangle had been made, Dr. George H. Girty joined the party and devoted five days to an examination of the local Paleozoic sections and faunas. The results of his brief examination were highly fruitful in suggesting the most natural divisions of the Paleozoic sequence. Without his aid and the patience with which he, after his return to Washington, examined over twenty collections of Carboniferous fossils, sent him from time to time by mail, it would have been impracticable to have separately mapped the Pennsylvanian and Mississippian limestones. Much of the geological structure would, in such case, have received no cartographic expression.

Mr. Girty, after the close of the field season, reviewed all of the Carboniferous collections from the Bisbee quadrangle, selected the Carboniferous fossils for illustration, and furnished the paleontological note that is elsewhere included in this report. Prof. H. S. Williams, of Yale University, and Dr. T. W. Stanton, of this Survey, have placed me under similar obligations with regard to the Devonian and Cretaceous fossils, respectively, while Dr. Charles D. Walcott kindly examined the small collection of Cambrian forms that determine the age of the Abrigo limestone.

To Dr. W. F. Hillebrand, Dr. H. N. Stokes, and Mr. George Steiger, of this Survey, I am indebted for chemical analyses, tests, and criticism.

To name all of those in Bisbee who in various ways lent cheerful aid during the progress of the work would make too long a list. Each one who opened to us his records and gave generously of his time may be sure that his courtesy is not forgotten. May he also feel that he is in some degree a contributor to so much of this report as deserves his approval.

LITERATURE.

Publications treating of the geology and ore deposits of the Bisbee district are surprisingly few when it is considered that the Copper Queen mine has long been one of the largest producers of copper in the Territory of Arizona. But the Mule Mountains lie to the south of the routes of the earlier geological explorers who accompanied the expeditions of the Pacific Railroad and Wheeler surveys, and even after the presence of ore was ascertained in the late seventies, the region was for some time difficult and dangerous of access.

The first attempt to describe the geological environment of the ores was that of Wendt, in 1887, followed thirteen years later by the more comprehensive account by Douglas. Both of these papers, however, touch on the geology and structure of the Mule Mountains in the very briefest way, being concerned mainly with the ore bodies and with the process of ore extraction. Dumble's reconnaissance notes, published in 1902, although necessarily fragmentary, are really the first step toward any general knowledge of the broader geological features, and to him is due the first recorded recognition of the extensive Cretaceous deposits of the Bisbee region.

The papers just referred to, with some mineralogical notes, and two other works of general nature which have been drawn upon for historical data, are included in the following brief bibliography:

List of publications on the Bisbee district.

HINTON, R. J. The Handbook to Arizona. San Francisco and New York, 1878.

General description and early history of region about the Mule Mountains. Records the then recent discovery of ore in these mountains.

HAMILTON, P. The Resources of Arizona. Prescott, Ariz., 1st ed. 1881. San Francisco, 2d ed. 1883, 3d ed. 1884.

Contains notes on the early history of mining near Bisbee.

WENDT, ARTHUR F. The copper ores of the Southwest. Trans. Am. Inst. Min. Eng., vol. 15, 1887, pp. 25–77.

Sketches briefly the geological occurrence of the ores. Describes the latter as filling fissures and caves in Carboniferous limestone, and concludes that they were originally deposited as carbonates and oxides and not derived from sulphides by oxidation practically in situ.

KOENIG, GEORGE A. On paramelaconite and the associated minerals. Proc. Philadelphia Acad. Sci., 1891, pp. 284–291.

Describes paramelaconite, footeite, and malachite from the Copper Queen mine.

DOUGLAS, JAMES. The Copper Queen mine. Trans. Am. Inst. Min. Eng., vol. 29, 1900, pp. 511–546.

Sketches the history of the mine and describes the character and geological occurrence of the ores. Discusses the origin of the ore bodies.

DUMBLE, E. T. Notes on the geology of southeastern Arizona. Trans. Am. Inst. Min. Eng., vol. 31, 1902, pp. 696–715.

Describes particularly the Cretaceous deposits in the Mule Mountains and names them the Bisbee beds. Estimates their total thickness at about 3,000 feet. Notes the occurrence of Carboniferous limestones and suggests that Devonian is also represented. Correlates the quartzite (Bolsa quartzite) underlying the Paleozoic limestones with the quartzite of the Dragoon Mountains (Dragoon quartzite). Refers to it as pre-Devonian. Notes the occurrence of mica-schists, to which he assigns a thickness of 300 feet. States that they rest upon granite, although in some cases an intrusive porphyry intervenes.

KOENIG, GEORGE A. On the new species melanochalcite and keweenawite; with notes on some other known species. Am. Jour. Sci., 4th ser., vol. 14, 1902, pp. 404–410.

Describes melanochalcite from the Copper Queen mine.

HISTORY OF MINING DEVELOPMENT.

The presence of ore in the southern part of the Mule Mountains was probably known as early as 1876, but it was not until four years later that there was discovered the first of the great bodies of copper ore whose subsequent exploitation has caused the steady development of the Warren mining district and the growth of the towns of Bisbee and Douglas. Prior to 1880 Bisbee was an insignificant mining camp, dependent upon lead-carbonate ore mined from the Hendricks claim just south of the present town, and smelted in a single small furnace situated upon what is now Main street. As Douglas[a] has pointed out, the increased activity in prospecting in the year 1880 was due primarily to the construction of the Southern Pacific and Atchison, Topeka and Santa Fe railroads, and was stimulated by a rise in the price of copper and a general revival of business prosperity.

The Copper Queen mine, whose history is practically that of the Bisbee district, is said to have been discovered in 1877 by Hugh Jones and to have been relocated in 1878 by George Warren (from whom the mining district derives its name) and others.[b] Warren is reported to have shortly afterwards staked and lost his share in the property upon the result of a foot race.

In 1880 Messrs. Martin, Ballard, and Reilly bonded the mine and began active operations. Very little work was required to reveal the existence of a large body of unusually rich copper ore. This, the famous Queen ore body, was at first quarried from an open cut, and afterwards worked by an incline down to the 300-foot level. Two 36-inch water-jacket furnaces were erected in 1881, and with wood as fuel were able to turn out half a million pounds of copper a month from ore averaging 23 per cent. There were no sulphides, and the smelting was direct. The Copper Queen mine continued to produce ore steadily from the original ore body up to 1884. The Neptune mine, just east of the Copper Queen mine, began work about the same time as the latter, and had a furnace at Hereford, on the Rio San Pedro.

The success of the Copper Queen soon brought other companies into the field, particularly the Atlanta, whose claim was southeast of the Copper Queen, and the Copper Prince, which lay northwest of the same mine. A prominent member of the Atlanta Company was Dr. James Douglas, now president of the Copper Queen Consolidated Mining Company.

Benson, on the Southern Pacific Railroad, was at first the nearest railway station. Between this point and Bisbee supplies and bullion were transported by teams over the comparatively level floor of San Pedro Valley. After the completion of the Sonora Railroad between Benson and Nogales, the Copper

[a] Douglas, J., The Copper Queen mine: Trans. Am. Inst. Min. Eng., vol. 29, 1900, p. 512.

[b] Hamilton, P., The Resources of Arizona, 2d ed. (San Francisco), 1883, p. 85.

Queen Company built a toll road over Mule Pass to the railway at Fairbanks, and in 1884 freight was hauled over this road by 18-mule teams, at a rate of $7.25 per ton.

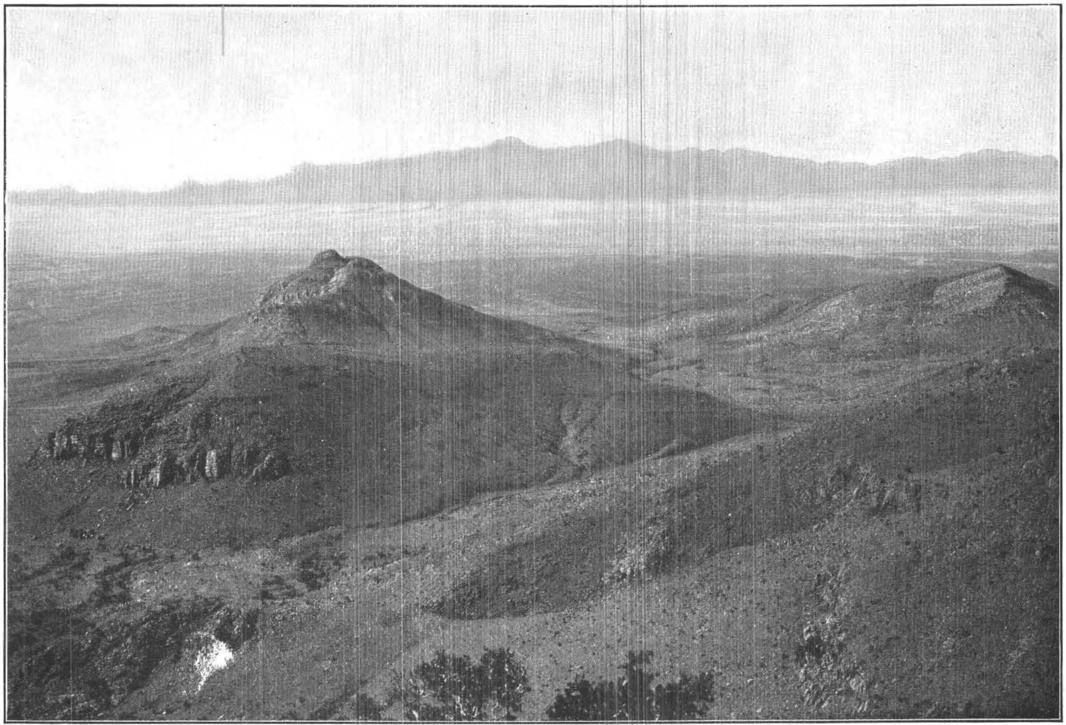
In this same year the first ore body of the Copper Queen, after having been worked down to the bottom of a 300-foot incline, suddenly gave out, and the principal companies were almost on the point of abandoning further search when a second large body of ore was encountered simultaneously in the Copper Queen and Atlanta properties. Litigation was wisely avoided by consolidation of the rival interests into the present Copper Queen Consolidated Mining Company. Shortly after this combination the holdings of the Copper Prince Company, which had been for some years waging bitter legal war with varying success against its prosperous neighbor, were acquired by purchase, followed in succeeding years by the amicable absorption of the Holbrook, Neptune, and other mines formerly under separate ownership.

The average tenor of the ore in 1884 was about 12 per cent, copper being then worth about 18 cents per pound.

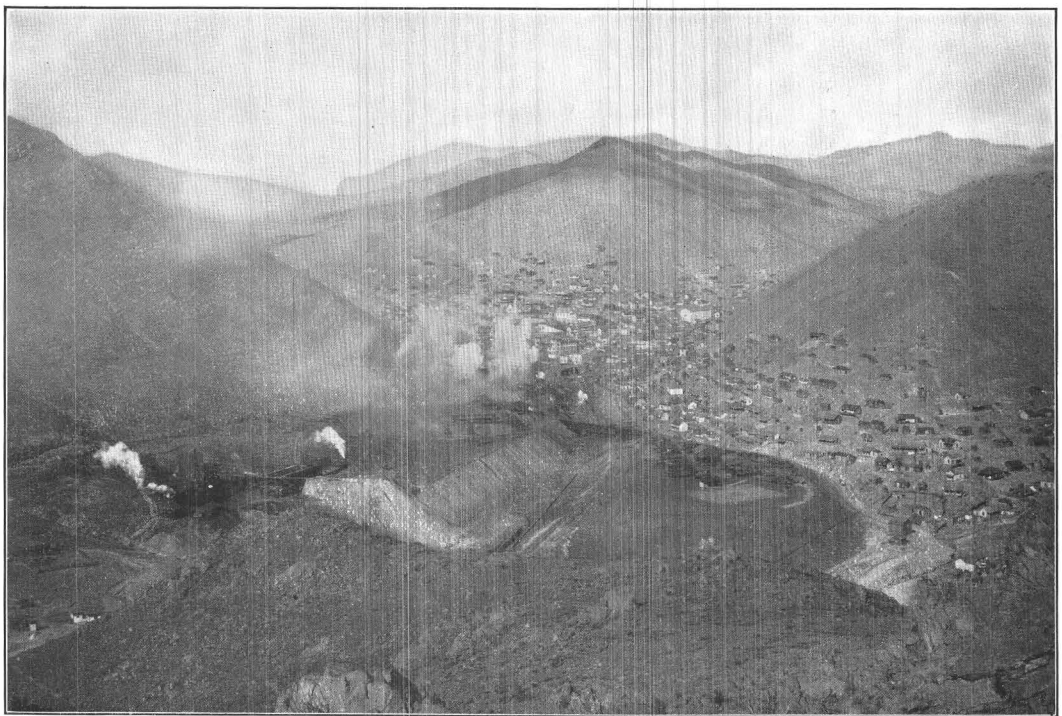
The original smelting plant became inadequate in 1886 and was replaced by three 36-inch furnaces, to which there was soon added an 80-inch furnace. The small furnaces were gradually abandoned during succeeding years and replaced by larger ones. Water was never abundant at Bisbee, and the quantity was sometimes insufficient to supply the jackets of even these small furnaces. The project of pumping water from the Rio San Pedro was seriously considered at this time. A concentrating plant was installed in connection with the remodeled smelter, and used with some success, but the jigs were afterwards abandoned.

With the growth of the Copper Queen mine transportation became a problem of increasing importance. A traction engine was used for a time over the Mule Pass grade, but was not satisfactory, and in 1887 grading was begun for a railroad to connect Bisbee with the Southern Pacific system at Fairbank. The average tenor of the ore had by this time fallen to about 8 per cent, rendering the demand for more efficient transportation imperative.

In the early nineties it became evident that sulphide ores were becoming an important factor in the development of the mine, and as the working of such ores was commonly supposed at that time to be impracticable in Arizona, the situation was grave. The application of the Bessemer process to the metallurgy of copper was, however, already successful at Butte, Mont., and after a trip of investigation to Europe in 1892, Mr. Douglas introduced a modification of the horizontal barrel type of converter, and began the reduction of mixed sulphide and oxide ores by the matte process still in use.



A. SAN PEDRO VALLEY AND HUACHUCA RANGE FROM THE MULE MOUNTAINS.



B. BISBEE FROM SACRAMENTO HILL.

Holbrook shaft in foreground; Czar shaft in middle.

Up to about 1900 the Copper Queen, maintaining a steadily increasing output, continued to be the only important mine in the Bisbee quadrangle. Within the last three years, however, the Calumet and Arizona Company has opened extensive workings in the Irish Mag and neighboring claims, and has shown that large bodies of high-grade copper ore are by no means confined to the ground quietly developed for over twenty years by the Copper Queen Company. The opening of a second large mine has increased the activity of an already flourishing district.

Simultaneously with the entrance of the Calumet and Arizona Company, Phelps, Dodge & Co., who control the Copper Queen Company, having become dissatisfied with the existing railway transportation by way of Benson and the Southern Pacific, with characteristic boldness and energy set about securing better facilities for their large freight traffic. They built the El Paso and Southwestern Railroad, connecting Bisbee directly with El Paso, 240 miles away. This line, which was completed in 1902, promises, with its various branches and connections, to become a very important factor in the economic development of southern Arizona and northern Mexico.

The present smelting plant of the Copper Queen Company, situated in the town of Bisbee, is cramped for room and necessarily unsystematic in arrangement. The new railroad has made possible the erection of more commodious modern works near the rapidly growing town of Douglas, situated 26 miles from Bisbee, in the middle of the broad Sulphur Spring Valley. The new smelter was in course of construction in 1902, and the smelter of the Calumet and Arizona Company, also at Douglas, began reduction with one furnace in December of the same year. Probably ere this report appears all the ore mined at Bisbee will be smelted at Douglas, much to the improvement of the former town as a place of abode.

The business portion of the town of Bisbee consists for the most part of unsubstantial buildings, crowded into the bottoms of narrow ravines, with reckless disregard of the occasional flood which sooner or later will inevitably claim its own. (Pl. V, *B*.) The enterprise and public spirit of the Copper Queen Company is shown by an excellent general store, a public library, a large gymnasium building of brick and stone, a handsome and well-appointed hotel, and a pipe line through which pure water is pumped from a well 118 feet deep near Naco. The town, however, is badly in need of public waterworks and a sewerage system. Shallow wells open to obvious contamination are largely used as sources of drinking water, and typhoid fever still finds victims among the careless and ignorant.

PRODUCTION.

The annual production of the Copper Queen mine from the beginning of operations to the close of 1902 is as follows, the figures being taken from those furnished by the company and published in successive volumes of the Mineral Industry, beginning with 1893:

Annual production of the Copper Queen mine in pounds of "black" (crude) copper.

1880	1,379,940	1889	12,152,910	1898	33,749,390
1881	3,866,581	1890	13,120,934	1899	36,901,684
1882	7,744,278	1891	13,022,957	1900	34,382,309
1883	7,523,981	1892	12,916,416	1901	39,781,333
1884	7,668,617	1893	13,795,618	1902	35,831,755
1885	6,663,782	1894	12,968,372	Total	378,047,210
1886	[a] 3,797,256	1895	15,741,732		
1887	[a] 5,707,728	1896	23,298,150		
1888	12,031,614	1897	23,999,873		

If there be added to the above total 2,066,647 pounds, the product of the newly opened Calumet and Arizona mine in 1902, there is obtained a total recorded output for the Bisbee quadrangle of 380,113,857 pounds of copper.

There will undoubtedly be a notable increase in production during 1903, owing to the active operation of the Calumet and Arizona mine, and a still further increase may be expected when the new smelter of the Copper Queen Company at Douglas is running at its full capacity.

CLIMATE AND VEGETATION.

The climate of Bisbee offers no marked exception to the prevailing aridity of central and southern Arizona. Owing to the altitude of the town, 5,300 feet, a maximum temperature of 99° is rarely exceeded in summer. The minimum temperature seldom falls below 15°, and the annual mean is about 60.5°. As shown by the reports of the United States Weather Bureau from 1891 to the end of 1900, the average annual precipitation is about 17 inches, so that the aridity, while pronounced, is not extreme. The hottest period, in June and July, is closely followed by the rainy season, usually beginning in July and lasting until September. During this season the greater part of the precipitation falls as heavy showers, which are often very local in extent and of short duration. Occasional showers of rain and flurries of snow may occur at other times during the year, but they are rarely enough to tint with green the brown landscape or

[a] Works closed during portions of these years for remodeling.

to lend any effective aid in washing detritus from the mountain slopes into the valleys. The quadrangle contains no permanent streams, and but few perennial springs.

Junipers and oaks of some size were formerly abundant in the Bisbee quadrangle, particularly on Juniper Flat and Escabrosa Ridge. But with the demand for firewood these have disappeared. Such trees as still grow on some of the northern hill slopes are little more than bushes. Prior to 1893 oak trees stood in the streets of Bisbee, and the neighboring hill slopes were dotted with shrubs. But this vegetation was destroyed soon after the introduction of the matte process in the Copper Queen smelter with its attendant sulphurous fumes.

Once each year, just after the summer rains, the country awakes for a brief period from its long drought to a belated spring. Grasses wave over many of the hill slopes and gay-colored flowers nod among the rocks. But this change in the face of the country is as transient as it is beautiful, and the fresh verdure soon fades into the neutral tints of hopeless aridity.

GENERAL GEOLOGY.

TOPOGRAPHY.

TOPOGRAPHIC NAMES.

The Bisbee quadrangle, like many other western mining districts, is curiously lacking in appropriate names for its topographic features, while such names as have become fixed suggest, but too often, minds untouched by imagination and ears untuned to musical sound. This want of good names becomes a real obstacle when any attempt is made to describe in detail the topography and geology of such a district. To overcome this difficulty, new names have been given in this essay to such hitherto unnamed topographic features as require frequent mention. In most instances these have been derived from the Spanish language, which is not only an historically appropriate source but is rich in euphonious terms. The purist may perhaps object to such a combination of Spanish and English as Escabrosa Ridge, but experience shows that this usage merely anticipates the almost inevitable transformation undergone by names of Spanish origin in the attrition of familiar use. It is only necessary to cite such well known names in Arizona as Santa Rita Range, Huachuca Mountains, Colorado River and Tonto Basin to illustrate this tendency. Whether the names here proposed will ever transcend their present employment as a literary expedient and come into popular use, must depend of course upon their filling a local need.

The new names employed in this report are as follows:

Abrigo Canyon (Spanish, shelter).

Mount Ballard
Mount Martin
Mount Reilly } (from Messrs. Ballard, Martin, and Reilly, who opened the Copper Queen mine in 1880).

Bolsa Canyon (Spanish, purse or pouch).

Cintura Hill (Spanish, waist).

Escabrosa Ridge (Spanish, cliffy).

Escacado Canyon (Spanish, checkered).

Espinal Plain (Spanish, place full of thorns).

Mural Hill.

Naco Hills (from town of Naco).

Soto Canyon (Spanish, bushy).

GENERAL CONFIGURATION OF THE MULE MOUNTAINS.

As the boundaries of the Bisbee quadrangle have been determined without regard to physiographic or geological unity, it is desirable that a brief general account of the topography of the Mule Mountains should precede the more detailed description of a smaller area. For the still broader relations of the quadrangle to the Territory as a whole, the reader is referred to the physiographic outline of Arizona included in the report on the Globe copper district, to which reference has already been made.

Topographically, the Mule Mountains are less imposing than the neighboring Huachuca and Chiricahua mountains, lacking both the striking linear plan and the bold serrate form of these ranges. They are a compact group of ridges and peaks and, like other mountain masses in this part of Arizona, rise abruptly from broad valley plains floored with Quaternary deposits. If the relatively low and rathered scattered hills southeast of Tombstone be considered as a part of Mule Mountains, the length of the range is about 30 miles. The maximum width, in the vicinity of Mule Pass, 2 miles northwest of Bisbee, is about 12 miles. The length of the range is thus about two and one-half times its breadth. Its trend is northwest and southeast. The greatest elevation, 7,400 feet, is attained by Mount Ballard, one of the peaks of Escabrosa Ridge (see Pl. I), 1½ miles southwest of Mule Pass and 2½ miles west of Bisbee. The general height of the range decreases both to the northwest and southeast of Mule Pass. About 5 miles northwest of the pass the road to Tombstone enters more open country. The hills become relatively low, and before Tombstone is reached, are divided into semidetached clusters by broad embayments of Quaternary alluvium, continuous with that flooring San Pedro or Sulphur Spring valleys. Just southeast of

Tombstone, these island-like hills connect the main mass of the Mule Mountains with the southern end of the linear Dragoon Range, and form a low divide between Sulphur Spring and San Pedro valleys.

Five miles southeast of Mule Pass the width of the range contracts rather abruptly to about 5 miles and this narrowed portion decreases in general altitude toward the Mexican border, where the range terminates in a low, broad pass through which the international boundary line runs from Sulphur Spring Valley to the valley of the San Pedro. The geological structure of the southeastern end of the Mule Mountains continues across this pass, however, and the Morita Hills[a] in Mexico, just south of the boundary line, are made up of rocks similar to those composing the southern end of the Mule Mountains.

On their northeast side the Mule Mountains present a fairly straight front, their slopes rising with moderate steepness from the gently inclined detrital plain forming the southwestern part of Sulphur Spring Valley. The line separating the mountains from the San Pedro Valley on the southwest is much more sinuous and the mountain front more variable in slope and height. Gently sloping plains, continuous with the floor of the main valley, extend, bay-like, into the mountain mass. The town of Naco lies in such an embayment, which in this case not only extends into the Mule Mountains as Espinal Plain (see Pl. I), but separates this range from the San Jose Mountains in Mexico, just southwest of Naco.

Within the Mule Mountains may be distinguished two topographic divisions, based upon geological structure, and roughly separated by a northwest-southeast line passing through Bisbee, through Mule Pass, and down Tombstone Canyon. Northeast of this line the mountains are sculptured from comparatively soft Mesozoic beds, striking approximately with the trend of the range, and dipping at generally moderate angles toward Sulphur Spring Valley. The slopes of these hills are comparatively smooth, although the occurence of a hard fossiliferous limestone in the middle of the generally arenaceous group of sediments has occasioned a conspicuous and persistent cliff of erosion (Pl. IX, *B*).

Southwest of the divisional line Paleozoic and older rocks prevail. These are generally more resistant to erosion and more heterogeneous in character than the Mesozoic beds, and have a far more complicated structure. Their degradation has consequently resulted in a more rugged and less regular topography. These older rocks have their greatest development west of Bisbee, and it is here that the range is highest and broadest. With the gradual disappearance of the Paleozoic rocks to the northwest and southeast, the Mesozoic rocks make up an increasing part of the mountain mass, and the general height of the range diminishes. Thus the low hills for some distance toward Tombstone, and the

[a] See Atlas of the International Boundary Commission between the United States and Mexico: Senate Doc. No. 247, 55th Cong., 2d sess., Atlas Sheets 13 and 14.

insignificant ridges into which the range subsides at its southeast end, are made up principally of these less durable Mesozoic beds.

The comparatively simple northeast front of the Mule Mountains conforms to the general strike of the Mesozoic strata. The more irregular southwest front is likewise conditioned by structure, but of a more complex character. For while the dominant structures of the Paleozoic rocks to a recognizable extent conform to the trend of the range, the minor and less uniform structures resulting from transverse faulting, complex folding, and irregular intrusions have deeply impressed their own character upon the topography.

RELIEF AND DRAINAGE OF THE BISBEE QUADRANGLE.

With this preliminary survey of the topography of the Mule Mountains as a whole, attention may now be given more particularly to the Bisbee quadrangle, which embraces practically the southeastern half of the range.

Probably the most marked topographic feature apparent in the map of the quadrangle is the sharp contrast between mountain and plain—a contrast which, while in no way exaggerated, is perhaps even more striking in a map than on the ground; for the traveller, passing through the arid portions of New Mexico and Arizona, has usually had the same feature repeated before his eyes again and again long ere he reaches the Mule Mountains. In the eastern part of the quadrangle, the floor of Sulphur Spring Valley, rising gently to the southwest from the valley axis, with a grade of less than 100 feet per mile, ends abruptly at the Mule Mountains, whose northeast front rises with an average grade of about 800 feet per mile.

There is a slight increase in the inclination of the plain as the mountains are approached, owing to the accumulation along their front of coarser fluviatile material in low coalescing detrital fans. This increase, however, is not enough to detract materially from the abrupt change in slope, which corresponds in general with the boundary between the Quaternary wash and the older rocks. The difference in altitude between the lowest part of Sulphur Spring Valley included within the quadrangle and the highest point in the Mule Mountains is about 3,300 feet.

In the southwestern part of the quadrangle, Espinal Plain, which surrounds the town of Naco and is really an embayment of the San Pedro Valley, exhibits a similar contrast to the mountains north of it. To the east of the plain the change is less marked, as this part of the Mule Mountains just east of Gold Gulch, composed of Mesozoic conglomerate, is well worn down by erosion. Espinal Plain, as may be seen from the geological map (Pl. I), is not entirely a constructional plain, but is in minor part floored by Mesozoic and Paleozoic rocks eroded to the general slope of the plain surface.

The two-fold topographic division of the Mule Mountains, already referred to, is well shown in the Bisbee quadrangle. Northeast of a line drawn about half a mile northeast of Tombstone Canyon, Mule Pass, Bisbee, and extending southeast to Gold Hill, there is, broadly speaking, a monoclinal ridge composed of Mesozoic strata, with general northeasterly dip, resting upon pre-Cambrian schist and intrusive granite-porphyry. The back of this ridge is deeply furrowed by numerous consequent intermittent streams flowing northeast into Sulphur Spring Valley. When considered in detail, however, the strata composing the ridge are found to be folded and to be cut by several faults.

Southwest of this dividing line are the Paleozoic and pre-Cambrian rocks. On the whole, the Paleozoic beds have a northwest-southeast strike, which finds topographic expression in Escabrosa Ridge and in the chain of hills extending past Black Gap to Gold Hill. On the southwest slope of Escabrosa Ridge numerous faults and dikes of porphyry, in general parallel with the strike, have cooperated in maintaining the dominant northwest-southeast trend of the main ridge. Inspection of the map (Pl. I), however, shows that the complex deformation of this portion of the quadrangle has led to a much more irregular topography than that characterizing the Mesozoic terrane to the northeast.

Southeast of Gold Hill the general topographic division just described does not exist. The Paleozoic rocks are here for the most part buried beneath the Cretaceous beds, and the latter extend farther to the southwest than elsewhere in the quadrangle.

Two river systems compete for the drainage of the Bisbee quadrangle. One is that of the northward-flowing San Pedro, whose waters find their way through the Gila and Colorado rivers into the Gulf of California. The other is that of the southward-flowing Yaqui River, which also enters the Gulf of California after traversing the Mexican state of Sonora. The divide between these two drainages enters the quadrangle at boundary monument No. 91, and runs north across Espinal Plain to a low saddle about half way between Black Gap and Gold Hill; thence it turns northwest across the open basin just north of Black Gap, and coincides with the crest of Escabrosa Ridge as far as Mount Ballard. From this peak it swings northeast across Mule Pass to the broad ridge known as Juniper Flat. The country lying northeast of this tortuous water parting drains into Sulphur Spring Valley, and during the wet season such water as is not evaporated on the way reaches White River or the Agua Prieta, a headwater tributary of the Yaqui River. The country southwest of the divide has a similar intermittent and partly underground drainage into the San Pedro.

Not only is the annual precipitation in this region as a whole insufficient to maintain vegetation of such character as might serve as a protective covering to the hill slopes, but it falls in a manner to accentuate this deficiency. The violent summer rains descend as a rule upon hills that have been parched by months of burning sunshine, during which all herbaceous plants have become shriveled and brown. The bare ground is directly exposed to the wash of the rains, and the finer particles of disintegrated rock that might, if undisturbed, have ultimately become soil, are swept down to join the turbid floods in the arroyos and by them borne valleyward.

The prevailingly fitful action of erosion in arid countries has received attention from various observers, without, however, losing its latent power of impression upon all who are brought into direct contact with its work. As regards erosive processes, southern Arizona presents many points of likeness to the Great Basin, of which Gilbert writes[a]:

"As in other desert regions precipitation here results only from cyclonic disturbance, either broad or local, is extremely irregular, and is often violent. Sooner or later the 'cloud-burst' visits every tract, and when it comes the local drainage-way discharges in a few hours more water than is yielded to it by the ordinary precipitation of many years. The deluge scours out a channel which is far too deep and broad for ordinary needs, and which centuries may not suffice to efface. The abundance of these trenches, in various stages of obliteration, but all manifestly unsuited to the every-day conditions of the country, has naturally led many to believe that an age of excessive rainfall has but just ceased—an opinion not rarely advanced by travelers in other arid regions. So far as may be judged from the size of the channels draining small catchment basins, the rare, brief, paroxysmal precipitation of the desert is at least equal while it lasts to the rainfall of the fertile plain."

The usual behavior of the intermittent torrents of southern Arizona and northern Sonora, as they issue from their confined channels upon the broad valley plains, has been graphically described by McGee.[b] The water, no longer held within canyon walls, spreads out as a sheet which becomes rapidly thinner as it advances into the valley, deposits its burden of sediment as a thin wash of bowlders, gravel, and sand, and, unless the shower be unusually prolonged, soon sinks out of sight within the porous accumulation of earlier floods. Thus it is, that even the larger arroyos issuing from the Mule Mountains into the Sulphur Spring Valley as a rule loose their identity before they have proceeded more than 3 or 4 miles from the mouths of their ravines (Pl. I). The energetic showers which are capable of performing considerable erosional work within the mountains are too transient to cut permanent stream ways out to the axis of the main valley, and so each intermittent stream has in ordinary years its own local base-level, defined by the low detrital apron in front of its ravine. This feature in the drainage, together with the frequent occurrence in the rainy season of very local downpours whereby one stream may be swelled to much greater extent than others in its immediate neighborhood, tend to prevent the delicate adjustments to load, volume, grade, and structure that characterize the continuously acting streams of more humid regions, and which not only render the whole of a river

[a] Gilbert, G. K., Lake Bonneville: Mon. U. S. Geol. Survey, vol. 1, 1890, p. 9.

[b] McGee, W J, Sheetflood erosion: Bull. Geol. Soc. America, vol. 8, 1897, pp. 100–101.

system sensitive to a change in any of its parts, but make for permanence of drainage plan. Material that is swept along with ease through the narrow channels of the mountains becomes suddenly unwieldy when laterally unconfined, and is soon dropped. Thus the vigorous erosion of the mountains is out of all proportion to that of the arid intermontane valleys, and but a small portion of the material carried from the mountains to the valleys is thence in turn borne to the sea. The valley floors thus become burdened with detritus, and their feeble drainage may be diverted or ponded and evaporated. As the mountains are encroached upon by the growing waste slopes, the latter tend more and more to become geographically important albeit somewhat unstable divides, subject to change through the capricious action of some cloud-burst in the mountains.

It is probable that at some time during the early Quaternary the drainage from the upper part of Mule Gulch escaped southward through Black Gap, and was afterwards diverted to its present channel, which enters Sulphur Spring Valley at Forrest's ranch. The primary cause of the diversion was probably the difference of about 500 feet in the local base-levels determined by Sulphur Spring Valley and Espinal Plain. Thus, while the stream issuing from Black Gap was hindered in its downward cutting by the apron of waste which it and other arroyos had deposited upon Espinal Plain and were powerless to sweep into the Rio San Pedro, the eastward-flowing stream had a decided advantage in the delivery of its burden into the lower and broader Sulphur Spring Valley. It was thus enabled to cut back into the mountains until some freshet probably gave it possession of the water that formerly flowed out through Black Gap.

A somewhat similar change of drainage is indicated by the topography near Gold Gulch. Examination of the map suggests that the drainage of upper Gold Gulch formerly flowed southwest toward the Rio San Pedro, and that the present course of the arroyo past Johnson's and Christianson's ranches into Sulphur Spring Valley, and the resultant shifting of a part of the main divide to the Quaternary deposits of Espinal Plain, is due to diversion by the more active arroyos tributary to the Agua Prieta.

PRELIMINARY OUTLINE OF THE GEOLOGY.

The fundamental rocks of the Bisbee quadrangle are crystalline schists of pre-Cambrian age, separated by a profound unconformity from the overlying Paleozoic beds. The latter comprise a basal Cambrian quartzite 430 feet in thickness, succeeded by over 4,500 feet of limestones representing portions of Cambrian, Devonian, and Carboniferous time. The Silurian, so far as known, has no lithological representation in the quadrangle.

At the close of the Carboniferous period the rocks of the Bisbee quadrangle were deformed by faulting and folding, and were cut by intrusions of granitic magma. The principal mineralization of the district probably dates from this time of revolutionary disturbance. The region as a whole was elevated above sea level and subjected to erosion until the beginning of the Cretaceous period.

During the Cretaceous the land again sank beneath the sea, and over 4,500 feet of sandstones, shales, and limestone, representing the earlier part of this period, were accumulated.

Subsequently, elevation brought these sediments above sea level and exposed them to erosion. The quadrangle contains no rocks of Tertiary age, and there are no known facts from which to determine the exact date of the post-Cretaceous uplift. It was accompanied or followed by faulting and folding.

During the Quaternary, and probably during a part of the Tertiary, the higher parts of the Bisbee quadrangle have been undergoing erosion, and have shed their waste into the flat-floored valleys surrounding the Mule Mountains.

PRE-CAMBRIAN METAMORPHIC ROCKS.

PINAL SCHIST.

Name.—In a previous report[a] the name Pinal schist was applied to the fundamental crystalline metamorphic rocks of the Pinal Range. These were shown to be essentially quartz-muscovite or quartz-sericite-schists formed by metamorphism of arenaceous sediments, and to be separated from the oldest Paleozoic rocks by a profound unconformity. The Pinal Range lies about 90 miles north of the Bisbee quadrangle, and no occurrence of Pinal schist has yet been identified within the intervening country. Nevertheless, the lithological similarity of the schists of the Pinal Range and Mule Mountains, and their identical relation to the great unconformity at the base of the Paleozoic, are considered as justifying the application of the name Pinal schist to the basal schistose rocks of the Bisbee quadrangle.

Distribution and general structure.—The Pinal schist is the ancient crystalline foundation upon which rest all the Paleozoic and younger sediments of the region, and through which have broken the granite and intrusive porphyries exposed in various parts of the district. It is probable that it underlies the entire quadrangle but for the most part is buried beneath hundreds or thousands of feet of later rocks. At present it is exposed only in the northwest quarter of the quadrangular area, where the geological structure has led to the stripping off by erosion of the beds which formerly covered it.

The largest area of Pinal schist, if interruptions due to intrusive bodies be disregarded, is that which underlies the town of Bisbee. This area, which, so far as present exposures go, is divided by the porphyry mass of Sacramento Hill, extends

[a] Ransome, F. L., Geology of the Globe copper district, Arizona: Prof. Paper U. S. Geol. Survey No. 12, 1903.

southeast of the town for about 3 miles and finally disappears beneath the Cretaceous rocks in Mule Gulch. Northwest of Bisbee the area becomes much broader, and the Pinal schist forms most of the slope between Tombstone Canyon and the crest of Escabrosa Ridge. It is the rock in which Brewery Gulch and Dubacher Canyon have been excavated north and east of Bisbee, passing, near the heads of these ravines, beneath the Glance conglomerate which marks the base of the Cretaceous sediments. It is exposed also by the erosion of the overlying Cretaceous in the upper part of Soto Canyon, east of Juniper Flat.

Along Escabrosa Ridge, northwest of Mount Martin, the Pinal schist is well exposed, sometimes forming the crest of the ridge and sometimes capped by outliers of Paleozoic strata. It also extends down the southwest slope of the ridge, as in Moore and Bolsa canyons, but is there intersected by an elaborate network of dikes and faults. The most southerly exposures of the Pinal schist are in a few small fault blocks near the mouth of Escacado Canyon, a mile and a half northwest of Don Luis.

In general, the main exposed area of schist may be described as limited on the southwest partly by passage beneath the unconformably overlying Bolsa quartzite but chiefly by faults and igneous intrusions, and on the northeast by the irregular line defining the base of the Cretaceous beds, under which the schist extends for an unknown distance as the eroded basement upon which these Mesozoic sediments were laid down.

The Pinal schist has a typical schistose structure. The planes of schistosity are usually more nearly vertical than horizontal and are so contorted and so variable in dip and strike from point to point as to preclude in the present stage of regional denudation any unraveling of general pre-Cambrian structure. The dominant trend of the schistosity appears to be about east-northeast and west-southwest, but wide departures from this direction are encountered on every hand. The schists sometimes exhibit an inconspicuous banding, which is not always parallel with the planes of schistosity, and is suggestive of an original bedded structure.

Neither the original base of the rocks which have been transformed by metamorphism to the Pinal schist nor the present bottom of the latter terrane is exposed in the Bisbee quadrangle. Accordingly, the thickness of the Pinal formation prior to recrystallization and the present depth to which the schists extend remain unknown.

Lithology.—The Pinal schist varies in color from light to dark gray, often with a slight tinge of green. The cleavage, as in most crystalline schists, is imperfect and the surfaces have commonly a satin-like sheen. In texture and general appearance the schist is monotonously uniform. It is very fine grained throughout, and the naked eye can rarely distinguish any mineral constituents other than small glittering scales of sericite and occasional granules of quartz.

The microscope shows that the essential constituents are quartz and sericite, which form a crystalline aggregate of minute interlocking grains and tiny foliated wisps. The sericite shows a tendency toward arrangement in parallel bands, and thereby gives to the rock its imperfectly fissile character. With these preponderant minerals are commonly associated a few small prisms of tourmaline up to a quarter of a millimeter in length, occasional red garnets of about the same diameter, a few nests or shreds of chlorite, small crystals of zircon and granules of magnetite or ilmenite. An occasional grain of sodium-calcium feldspar, probably oligoclase, can sometimes be microscopically detected among the quartz grains which make up most of the rock. Amphibole was not observed in any of the specimens studied, and biotite is certainly a rare constituent, although it was noted in a bleached and decomposed state in a single thin section.

Origin.—In mineralogical and chemical composition, the schist of the Mule Mountains is very similar to the Pinal schist of the Pinal Range described in a recent report,[a] and there shown to have been derived by metamorphism from arkose sediments. The evidence of original sedimentary character is less satisfactory in the Bisbee quadrangle, as there is no decisive indication of former bedding and no real proof of original clastic texture. Nevertheless the general character of the schists in the Bisbee region renders it highly probable that they too were at one time arkose sands and silts. The metamorphism has been more uniform than in the Pinal Mountains of the Globe district without the development of any such coarsely crystalline facies as there make up part of the schist. The difference is undoubtedly connected with the absence of pre-Cambrian granitic intrusives in the Mule Mountains and their abundance in the Pinal Range. Much of the metamorphism of the Pinal schist in the Globe quadrangle is due to the obvious contact action of large intrusive masses. While it can not be said that concealed bodies of intrusive rock have had no part in the recrystallization of the Pinal formation in the Bisbee quadrangle, the process seems to have been more nearly a simple case of what is known as regional metamorphism. For this alteration deep subsidence and burial under later deposits, intense folding and squeezing, and time for the completion of slow crystallization and chemical rearrangement are considered efficient causes.

Age and correlation.—The crystalline Pinal schist, in which almost all original structure has been obliterated by metamorphism, underlies Cambrian beds in which the ordinary change from loose cross-bedded sands to hard sandstones or quartzites constitutes the only noticeable alteration. The Cambrian beds rest with a basal conglomerate upon the eroded edges of the contorted schists. The Pinal schist is

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[a] Ransome, F. L., Geology of the Globe copper district, Arizona: Prof. Paper U. S. Geol. Survey No. 12, 1903, pp. 23-27.

therefore not only pre-Cambrian but is separated from the Cambrian strata by a profound unconformity. This unconformity, considered in connection with the train of geological events implied by the complete metamorphism of the Pinal schist prior to the deposition of the earliest Cambrian sediments of the region, presents no less vividly to the imagination "the long result of time" than do all of the up-piled beds of the Paleozoic. There can be no question but that the Pinal schist is vastly older than the Cambrian sediments.

The Pinal schist of the Mule Mountains, and of the Pinal Range, and possibly also the Vishnu schist of the Grand Canyon probably belong to the same geological period and present somewhat different aspects of the fundamental crystalline complex of Arizona, upon which have been laid down the Algonkian Grand Canyon group (embracing the Unkar and Chuar terranes of Walcott), the Cambrian sediments represented by the Tonto group of the Grand Canyon section, the Bolsa quartzite and Abrigo limestone of the Mule Mountains, and the Apache group of the Globe district, which has not yet been definitely assigned to either the Algonkian or Cambrian.

Shall the Pinal schist of the Bisbee region, in view of its probable sedimentary origin and in spite of the tremendous unconformity that separates it from the Algonkian beds of the Grand Canyon group, also be considered as Algonkian? If the original definition of the Algonkian as including all pre-Cambrian sedimentary rocks be accepted, the Pinal schist belongs in that period, which must then be considered as embracing rocks above and below the most significant unconformity known in Arizona. In view of this fact, it seems best, in the absence of definite correlation, to refer to the Pinal schist simply as pre-Cambrian, leaving it to future investigation to determine whether the Algonkian is to be represented in Arizona by the "Grand Canyon series," or by the "Vishnu series," or by both of these series separated by an unconformity apparently as profound as any described in geological literature.

PALEOZOIC SEDIMENTS.

GENERAL STATEMENT.

The Paleozoic rocks of the Bisbee quadrangle are divisible into five formations. At the base, resting upon the Pinal schist, is the unfossiliferous Bolsa quartzite. Overlying the quartzite is the Abrigo limestone, carrying middle Cambrian fossils. Succeeding the Abrigo is the Martin limestone, of Devonian age, which in turn is overlain by the Mississippian ("Lower Carboniferous") Escabrosa limestone. The youngest of the Paleozoic formations is the Naco limestone, which overlies the Escabrosa and belongs in the Pennsylvanian ("Upper Carboniferous").

CAMBRIAN.

BOLSA QUARTZITE.

Name.—In a recent paper[a] E. T. Dumble gave the name *Dragoon quartzite* to some pre-Devonian arenaceous beds, about 400 feet in thickness, occurring in the Dragoon Mountains. He describes these beds as separated from the pre-Cambrian schists by 100 feet of "andesitic rock" and 40 feet of limestone. The actual stratigraphic relation of the rocks is by no means evident from his description, although in a summary at the end of his paper the Dragoon quartzite is said to be underlain by limestone. Continuing his reconnaissance into the Mule Mountains, Dumble noted the presence of the Dragoon quartzite beneath Devonian limestone, and mentions also a "bed of porphyritic andesite" (?) between the quartzite and the underlying schists.

It is probable that the so-called Dragoon quartzites of the Dragoon and Mule mountains are stratigraphically the same, but Dumble has not only omitted to establish this correlation, but has rather obscured it by several statements revealing misconceptions of geological structure not altogether surprising considering the rapid character of his reconnaissance.

If, for example, the two Dragoon quartzites are properly correlated by Dumble, the reported occurrence of 40 feet of limestone underlying the quartzite in the Dragoon Mountains seems, in the light of stratigraphic work in the Mule Mountains, to require confirmation, since in the latter range the so-called Dragoon quartzite rests with a basal conglomerate upon pre-Cambrian schists. As the base of these schists is nowhere exposed and as the only granitic rocks in the Bisbee quadrangle are of post-Carboniferous age, Dumble's statement that the schists have a thickness of only 300 feet and rest upon granite is misleading.

It was at first intended to use in this report the term Dragoon quartzite for the basal sedimentary formation of the Bisbee quadrangle, but for reasons just indicated this name has been reluctantly abandoned and that of Bolsa quartzite adopted in its stead. The latter designation is derived from the newly named Bolsa Canyon, on the southwest side Escabrosa Ridge (Pl. I), where these beds are well exposed.

Distribution, thickness, and general stratigraphy.—The principal exposures of the Bolsa quartzite are in Escabrosa Ridge, west of Bisbee. In the northeast corner of the quadrangle, this formation is represented by small residual outliers resting here and there along the crest of the ridge upon the pre-Cambrian schists. These remnants of once continuous strata become larger toward the southeast, and near Bisbee the quartzite makes up a considerable part of Escabrosa Ridge. Owing to the prevalent faulting, however, the Bolsa quartzite is not found in extensive areas nor in continuous belts of more than a mile in length. About three-quarters of a

[a] Dumble, E. T., Notes on the geology of southeastern Arizona: Trans. Am. Inst. Min. Eng., vol. 31, 1902, pp. 713–714.

mile west of the center of town the quartzite, which has been quarried for silica, is well exposed as the basal formation of the faulted syncline of Paleozoic rocks to be described in subsequent pages. Half a mile west of the quarry and separated by a great fault from the syncline just referred to is the most typical and instructive exposure of the Bolsa quartzite to be found in the quadrangle. The beds, with a total thickness of 430 feet, are continuously exposed in the line of strike for a distance of a little less than a mile along the northeast slope of Mount Martin (Pl. I). They rest with a very conspicuous unconformity upon the pre-Cambrian schists, and dip to the southwest at an angle of about 25°. They are conformably overlain by the Abrigo limestone (Cambrian), succeeded by the Martin limestone (Devonian) and the Escabrosa limestone ("Lower Carboniferous" or Mississippian), the last named forming the summit of Mount Martin. As this section (Pl. VI, *A*) is a typical one not only for the Bolsa quartzite but for the overlying Paleozoic limestones, it will be frequently referred to in the following pages and may be conveniently designated the Mount Martin section.

Between Mount Martin and the western edge of the quadrangle are many small areas of the Bolsa quartzite bounded on one or more sides by faults.

As may be seen from the geological map (Pl. I) all of the exposures of the Bolsa quartzite occur in the northwest quarter of the Bisbee quadrangle. The formation undoubtedly underlies other portions of the area studied, but is there buried beneath younger beds. The present distribution of the exposed areas is determined by deformation and erosion, not by original deposition.

Lithology.—The Bolsa quartzite is constant in its lithological character, and is readily recognized wherever it occurs.

The base of the formation is exposed at many places along Escabrosa Ridge. It is invariably marked by a bed of conglomerate from 6 inches to a foot in thickness, resting upon the eroded edges of the pre-Cambrian schists. Most of the pebbles of this basal conglomerate are composed of white vein quartz, and are rarely over 3 inches in diameter. This conglomerate is overlain by hard pebbly grits in beds from 10 to 20 feet in thickness, the change from conglomerate to grit being, as a rule, not very definitely marked. The scattered pebbles in these thick-bedded grits are usually white quartz, but their matrix frequently contains abundant small fragments of pink feldspar mingled with the predominant quartz grains. Cross bedding is often a conspicuous feature in the lower part of the formation. The pebbly grits in turn pass upward into thinner bedded, more vitreous, fine-grained quartzites showing no feldspathic material, which are conformably overlain by the Abrigo limestone.

Conditions of deposition.—The Bolsa quartzite was deposited during an advance of the sea over a subsiding basement of pre-Cambrian crystalline rocks which had been worn down by long-continued erosion to a nearly level plain. The arkose character of some of the lower beds of the quartzite shows that this ancient crystalline basement is composed in part of granitic rocks. None of the latter, however, are exposed in the Bisbee quadrangle, where fine-grained sericitic schists are the only pre-Cambrian rocks known. The basal conglomerate of the Bolsa formation is a littoral deposit made up of the most durable materials of this schist terrane, chiefly fragments of quartz derived from the numerous irregular veins that occur within the schists, while the finer particles of quartz and flakes of mica were probably transported by currents into deeper water and contributed to the formation of the overlying quartzite beds. The general nature of the Bolsa formation, particularly the pebbly and cross-bedded character of its lower portion, indicate that deposition took place in comparatively shallow water, with probably a gradual increase in depth as the upper beds were laid down. The conditions were apparently not favorable to marine life, as no organic remains have yet been found in the Bolsa quartzite.

Age and correlation.—As no fossils have been found in the Bolsa quartzite, its exact geological age is not directly determinable. It will presently be shown, however, that the Bolsa formation is conformably overlain by the Abrigo limestone which contains a middle Cambrian fauna. It is thus without very much doubt, the stratigraphic equivalent of the Tonto sandstone of the Grand Canyon section, considered by Walcott[a] as also included within the middle Cambrian, the lower Cambrian being there represented by the unconformity between the Tonto and the Grand Canyon series. It is possibly the equivalent of at least the lower part of the thicker and more varied Apache group of the Globe district in central Arizona, about 110 miles north-northwest of the Bisbee quadrangle, and also correlated provisionally with the Tonto group.[b]

In the Mule Mountains as in the Globe district the absence of Algonkian beds equivalent to the Grand Canyon group renders the unconformity at the base of the middle Cambrian even more pronounced than in the Grand Canyon. At Bisbee the Bolsa quartzite rests directly upon the Pinal schist, which is correlated with the Pinal schist of the Globe region and is regarded as probably the equivalent of the Vishnu schist of the Grand Canyon section. The relation of the Bolsa quartzite to the Dragoon quartzite of Dumble has already been pointed out.

ABRIGO LIMESTONE.

Name.—The Abrigo limestone is named from Abrigo Canyon, 3 miles southwest of Bisbee, where the beds composing the formation are well exposed.

Distribution, thickness, and general stratigraphy.—Like the Bolsa quartzite, the Abrigo limestone occurs principally in the northwestern part of the quadrangle,

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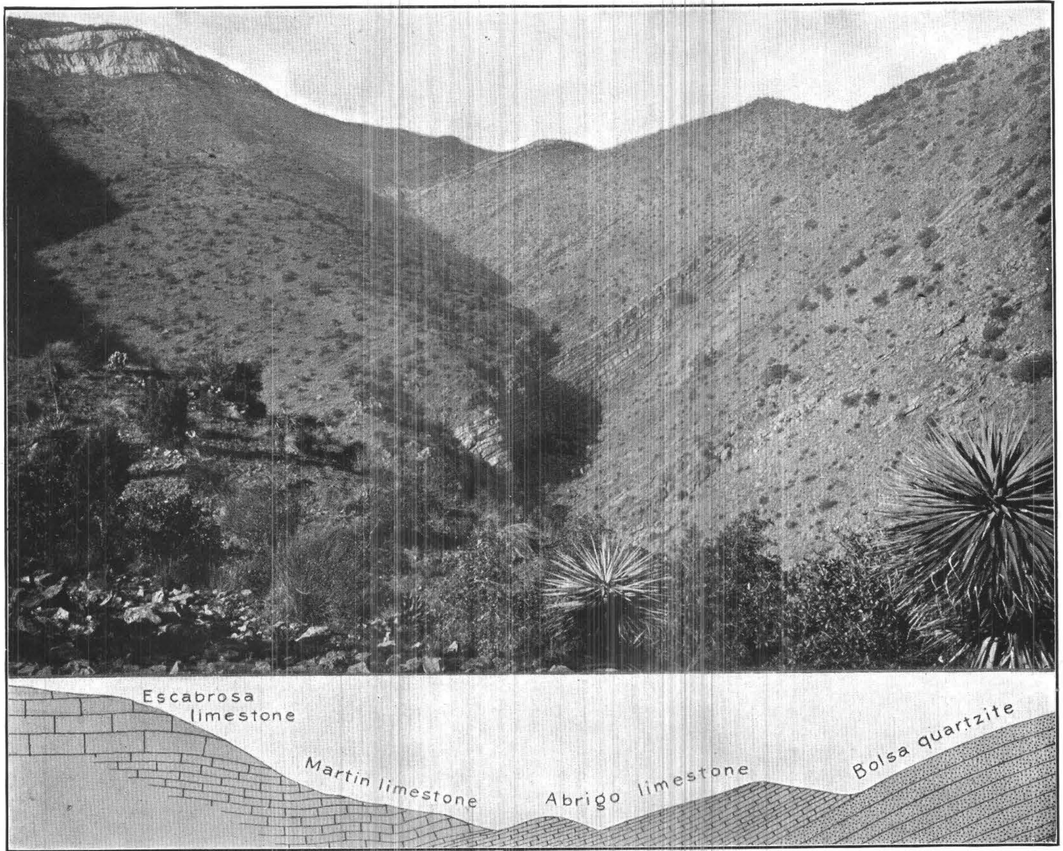
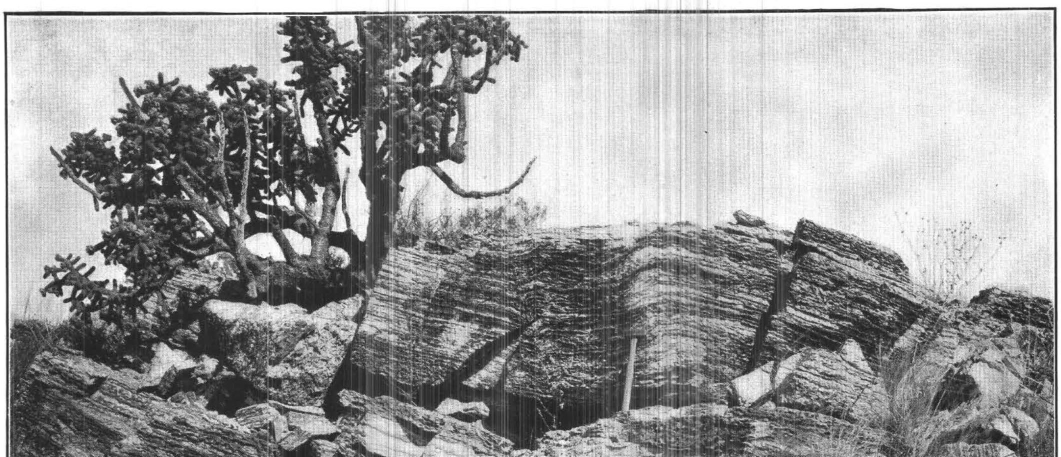
[a] Walcott, C. D., Algonkian rocks of the Grand Canyon of the Colorado: Jour. Geol., vol. 3, 1895, p. 328.

[b] Ransome, F. L., Geology of the Globe copper district, Arizona: Prof. Paper U. S. Geol. Survey No. 12, 1903, p. 38.



A. THE MOUNT MARTIN PALEOZOIC SECTION ON THE NORTHEAST SLOPE OF ESCABROSA RIDGE, WEST OF BISBEE.



B. CHERTY BANDING OF ABRIGO LIMESTONE.

although a few small areas are found within the attenuated belt of Paleozoic rocks extending southeastward past Gold Hill toward Glance Creek. The most satisfactory occurrence, and the only one in the quadrangle where the entire sequence of the beds from base to top may be studied in a single continuous exposure, is that of the Mount Martin section, 1½ miles west of Bisbee.

As measured in this section the Abrigo limestone is 770 feet thick. It rests conformably upon the Bolsa quartzite and is overlain by the Martin limestone (Devonian). The beds strike nearly northwest and southeast, and dip southwest at an angle of 25°.

Many smaller areas of the Abrigo formation occur along the crest of Escabrosa Ridge, usually bounded on two or more sides by faults or by dikes of granite-porphyry. The most extensive exposures, however, are found on the southwest slope of the ridge, where the Abrigo limestone underlies a practically continuous area about 1 mile in width and 4 miles in length, stretching northwest from Abrigo Canyon to about 1 mile beyond Moore Canyon. The boundaries of this area are in most cases faults or intrusive contacts. The prevailing strike of the beds is northwest and southeast and they dip in general to the southwest.

As the Abrigo limestone is more readily eroded than the granite-porphyry, Bolsa quartzite, and younger Paleozoic limestones, the larger areas of this rock are found associated with topographic features of relatively slight prominence. The area just described as stretching northwestward from Abrigo Canyon is characterized by gentle slopes, broad open arroyos, and low ridges in marked contrast with the more rugged topography of the main Escabrosa Ridge. (Pl. I.)

Lithology.—The Abrigo limestone is distinguished from the other calcareous formations of the local Paleozoic section by its prevailing thin bedding, and particularly by a conspicuous laminated structure produced by the alternation of thin irregular sheets of chert with layers of gray limestone. (Pl. VI, *B*.) The layers of limestone may be 2 or 3 inches in thickness, while those of chert are usually less. This cherty lamination is eminently characteristic of the Abrigo limestone in the Mule Mountains and serves as a ready means of identifying the beds belonging to this formation within the various fault blocks into which the region is dissected. Chert also occurs occasionally in the Devonian and Carboniferous limestones of the Bisbee quadrangle, but as irregular bunches, never in the form of the thin, more or less anastomosing sheets peculiar to the Cambrian Abrigo limestone illustrated in Pl. VI, *B*.

The beds are commonly from 1 to 2 feet in thickness. Their dominant color as seen in large exposures is dark greenish-yellow, whereas the prevailing tint of the overlying Martin limestone is dark gray, and of the still higher Escabrosa and Naco limestones, white or light gray.

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In the typical Mount Martin section the Bolsa quartzite is immediately overlain by about 40 feet of thin-bedded, very cherty limestones, which break up, on weathering, into thin rusty plates. Above this occur a few beds of gray limestone up to 2 feet in thickness, alternating with fissile yellowish calcareous shales, and with laminated cherty beds, such as have just been described. The upper 100 feet of the formation is made up of rather soft, sandy, thin-bedded gray limestone, with one bed of harder gray limestone 6 feet in thickness about 40 feet from the top. The upper limit of the Abrigo formation is defined in the Mount Martin section by a bed of pure white quartzite about 8 feet in thickness.

This quartzite is a persistent stratum and is always found immediately underlying the Martin limestone, which carries Devonian fossils. Its thickness, however, is variable and it sometimes grades downward into the upper sandy limestones of the Abrigo formation. It apparently records the consummation of an increasing supply of sandy sediments during the later phases of the deposition of the Abrigo limestone and contrasts with the more purely calcareous beds of the overlying Devonian formation.

The large area of Abrigo limestone stretching northwest from Abrigo Canyon exhibits the general lithological character of the Mount Martin section. In Abrigo Canyon, however, the soft sandy limestones below the white quartzite are represented by calcareous grits, which are darker and harder than the corresponding beds farther north, and these grits, sometimes associated with hard, dark-gray, dolomitic beds containing abundant quartz grains, as just north of Don Luis, continue to characterize the upper part of the Abrigo limestone as far as the formation can be traced to the southeast. They are rather hard, thin-bedded, sandy limestones, usually dark gray in tint, and occasionally rusty on weathered surfaces. They frequently show cross bedding, particularly just north of Don Luis.

Very fissile, greenish-yellow, calcareous shales, often showing fossil worm trails, and glistening with minute scales of mica, are generally a characteristic feature of the lower half of the Abrigo formation where this part is exposed. Such beds usually form smooth topographic slopes and weather to fragments often superficially resembling those resulting from the disintegration of the pre-Cambrian schists.

Partial chemical analyses of the usual nonmagnesian Abrigo limestone and of the dolomitic phase near Don Luis are given under I and II on page 55.

Conditions of deposition.—The Abrigo limestone records increasing subsidence of the Bisbee region following the deposition of the Bolsa quartzite, and a change from comparatively coarse littoral sediments to the accumulation of fine calcareous muds in somewhat deeper water. That these muds contained abundant silica as well as calcium carbonate is shown by the characteristic cherty banding of the Abrigo limestone. The occurrence of shales containing minute mica scales indicates that the area of deposition was still within reach of current-borne detritus from some land mass and the water was probably of moderate depth only.

Marine life makes its first appearance in this region in the Abrigo formation and is represented by trilobites, linguloid brachiopods, pteropods, and other early forms.

As the accumulation of the beds proceeded, the sea appears to have become shallower, and the calcareous muds received an increasing proportion of detrital quartz grains. The deposits became, locally at least, more magnesian. Finally this epoch of deposition was closed by the laying down of a bed of pure, white, quartz sand.

Age and correlation.—The fossils collected from the Abrigo limestone were submitted to Dr. Charles D. Walcott, who kindly examined them and reported that they are middle Cambrian, indicating a fauna closely resembling that of the middle Cambrian of Texas.

It would be presumptuous to attempt in this paper a discussion of the general correlation of the Abrigo limestone with the Texan beds or with the Cambrian of the Colorado Canyon and of southeastern California. But it may be appropriately pointed out that this phase of Cambrian deposition was not recognized in the Globe district in central Arizona, where no limestones are known older than the Devonian. It is possible, however, that the upper portion of the Dripping Spring quartzite, the top member of the arenaceous Apache group, may be in the Globe district the stratigraphic equivalent of the Abrigo limestone in the Mule Mountains.

DEVONIAN.

MARTIN LIMESTONE.

Name.—The Martin limestone is named from Mount Martin on Escabrosa Ridge, where the formation is typically developed and well exposed.

Distribution, thickness, and general stratigraphy.—In the Mount Martin section the Martin limestone has a thickness of 340 feet. The beds overlie the Abrigo limestone and underlie the Escabrosa limestone (Mississippian), both relations being those of apparent conformity.

Other small areas of the Martin limestone are involved in the faulted structure of Escabrosa Ridge from the northwest corner of the quadrangle to Don Luis, and thence southeastward past Black Gap and Gold Hill to Glance. The formation is typically developed north of Moore Canyon, being exposed from top to base at several localities. It is also well exposed in the vicinity of Abrigo Canyon, but the stratigraphic relations are here complicated by overthrust faulting.

The conspicuous turreted crag overlooking Main street in Bisbee and known as Castle Rock, is composed of Martin limestone. Extending southwestward from Castle Rock to Escacado Canyon, and thence southeastward to Glance, is a curved chain of small areas of this limestone, which, as will later be more fully shown, form part of a much faulted syncline. Although the areas are separated by faults, the beds dip and strike in conformity with the general synclinal structure. Those between Castle Rock and Escacado Canyon dip to the southeast, while those between Escacado Canyon and Glance dip to the northeast. (See Pl. I.)

Owing to its medial position within the Paleozoic sequence and its comparative thinness, 300 to 350 feet, the Martin limestone is more generally distributed, and is more often present in its entirety than are the overlying or underlying beds. It is rarely topographically conspicuous, however, usually outcropping on slopes below cliffs of Escabrosa limestone and above lowlands floored with Abrigo limestone.

Lithology.—The beds most characteristic of the Martin formation are dark-gray, hard, compact limestones which are generally well provided with fossils. Small brachiopods (*Atrypa reticularis* and *Spirifer hungerfordi*, Pl. VII) of rounded outline are particularly abundant in some of the beds and give to the weathered surfaces of the limestone a nodular appearance which in the Bisbee quadrangle is peculiar to the Martin formation. A few of the beds are richly provided with corals, some of which weather out as distinct and often beautifully silicified fossils, while others produce rather ill-defined, white dendritic blotches in the dark limestone, an appearance that experience has shown to be a local criterion of some value in identifying small masses of the Martin limestone when faulted in among other beds.

Associated with the preponderant dark limestones are occasional beds of lighter hue, and sometimes calcareous shales of a decided pinkish tint. These shales, which flake and crumble upon exposure, are well exposed in the saddle just northeast of Mount Martin, where they carry abundant characteristic Devonian fossils. They occur also in several of the other areas of the Martin limestone, particularly on the southwest slopes of Escabrosa Ridge, but owing to their softness are seldom conspicuous except where revealed by prospecting pits and tunnels. They belong in the lower half of the formation.

The upper limit of the Martin limestone is not always sharply defined. In general, it corresponds with the decided change from the dark compact limestones characteristic of this formation to the nearly white granular limestones, made up largely of crinoid stems, which characterize the Escabrosa formation. The actual plane of division is, however, rarely visible, owing to the tendency of the Escabrosa limestone to form cliffs and the consequent accumulation of talus over the contact. Even when no detritus conceals the relation of the two formations, there may be an intermediate zone 10 to 20 feet in thickness which contains no characteristic fossils, and which it is impossible to assign with confidence, on purely lithological grounds, either to the Martin or Escabrosa limestones.

The beds of the Martin limestone are usually less than 4 feet in thickness. They are thicker, on the whole, than those of the underlying Abrigo limestone, but thinner than those of the overlying Escabrosa limestone next to be described.

Chemically, the typical dark limestone of the Martin formation is a fairly pure calcium carbonate, containing a little silica but practically no magnesia, as may be seen from the partial analysis under III, p. 55.

Conditions of deposition.—The fairly pure calcareous material of the Martin beds, the absence of dolomite and of all but the finest terrigenous sediments, and the abundant remains of marine organisms, all indicate accumulation in an open sea at some distance from shore, and presumably in water of moderate depth. In these respects the Martin limestone seems to represent conditions of deposition intermediate between those under which the Abrigo limestone and the succeeding Escabrosa limestone were laid down.

Age and correlation.—Collections of fossils were made from the Martin limestone at several points within the Bisbee quadrangle and submitted to Prof. H. S. Williams, of Yale University, for identification. Mr. Williams has very kindly furnished the following note, which embodies all that need here be said concerning the age and paleontological affinities of this formation. The fauna is of the same general character but more abundant and varied than that already described from the Globe quadrangle, Arizona.[a] A few of the most characteristic species, selected by Mr. Williams, are illustrated on Pl. VII.

Note on the Devonian Fossils.

By Henry S. Williams.

The fossils from the Bisbee quadrangle, Arizona, submitted for examination by Mr. F. L. Ransome, were collected from several localities and are labeled as follows:

Bi I to VI. Northeast side of Escabrosa Ridge, 1½ miles west of Bisbee. Various horizons in the Martin limestone. Collected by Girty and Ransome.

Bi VII. Limestone hill on western edge of quadrangle, just north of Moore Gulch. Various horizons in the Martin limestone. The strophomenas occur rather low down in the series, associated with *Atrypa reticularis*. Collected by Girty and Ransome.

Bi 11a. Same locality as Bi VII. Collected by A. M. Rock.

Bi 11b. Same locality as Bi VII. Collected by A. M. Rock.

Bi 12a. Same locality as Bi VII. Near base of Martin limestone. Collected by Ransome.

Bi 12b. Same locality as above. About 100 feet stratigraphically above Bi 12a. Collected by Ransome.

Bi 22d. Same locality as Bi I to Bi VI. About halfway between base and top of the Martin limestone. Collected by Ransome.

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[a] Ransome, F. L., Geology of the Globe copper district, Arizona: Prof. Paper U. S. Geol. Survey No. 12, 1903, pp. 40–42; note on Devonian fossils, by Prof. H. S. Williams.

Bi 22e. Same locality as above. A little higher in the section. Collected by Ransome.
Bi 22f. Same locality as above, but a few feet higher in section. Collected by Ransome.
Bi 42. Western edge of quadrangle, 2.4 miles due south of Brown's ranch. Collected by Ransome.
Bi 44. Same locality as 42. Collected by Ransome.
Bi 45. Same general locality as 42. Collected by Ransome.
Bi 46. Abrigo Canyon, 2¾ miles WSW. from Bisbee. Collected by Ransome.
Bi 52. Bed of Abrigo Arroyo, 3 miles WSW. from Bisbee. Collected by Ransome.
Bi 53. West slope of isolated limestone hill near head of Abrigo Canyon, 3½ miles N. 33° E. from Naco Junction. Collected by Ransome.
Bi 58. North side of Abrigo Canyon, 2.7 miles N. 25° E. from Naco Junction. Collected by Ransome.
Bi 67. Three miles northeast of Naco Junction. Pink shales forming subordinate part of the Martin formation. Collected by Ransome.
Bi 84. Prospect pit in saddle on Escabrosa Ridge, 1½ miles WSW. from Bisbee. In soft sandy phase. Collected by Ransome.
Bi 98. Three-quarters of a mile north of Don Luis. In pinkish shaly phase of the Martin formation. Collected by Ransome.
Bi 102a. Same locality as Bi VII. Collected by J. M. Clements.
Bi 102b. Same locality as Bi VII. Higher bed. Collected by J. M. Clements.
Bi 102c. Same locality as 102b. Higher bed. Collected by J. M. Clements.
Bi 125a. Southwest front of ridge between Black Gap and Gold Hill. Collected by J. M. Clements.
Bi 125b. Same locality as above. Collected by J. M. Clements.
Bi 128. South slope of Gold Hill. Collected by J. M. Clements.

The following species have been identified in the foregoing collections, viz:

1. Acervularia davidsoni (Ed. & H.).
2. Pachyphyllum woodmani (White).
3. Cladopora prolifica (Hall & Whitfield).
4. Stromatopora erratica (Hall).
5. Cyathophyllum cæspitosum (Goldfuss).
6. Atrypa reticularis (Linn.).
7. Cyrtia cyrtiniformis (Hall & Whitfield).
8. Dielasma calvini (Hall & Whitfield).
9. Schizophoria striatula (Schlotheim).
10. Productella speciosa Hall.
11. Delthyris consobrina (d'Orbigny).
12. Sp. cf. jeremejevi (Tschernyschew).
13. Sp. hungerfordi Hall.
14. Sp. orestes Hall & Whitfield.
15. Sp. cf. euryteines (small specimen).
16. Sp. whitneyi Hall.
17. Stropheodonta demissa (Conrad).
18. Str. (fragilis) perplana (Hall).
19. Strophonella cælata Hall.

The following species are too imperfect for specific determination, viz:

20. Coral, several species.
21. Crinoid stem.
22. Bryozoa.
23. ? Terebratula (small.)
24. ? Minute brachiopod.
25. Loxonema.
26. Platyceras.
27. Pleurotomaria.
28. Bellerophon.
29. Leperditia.

The distribution of the various species among the different localities at which collections were made in the Bisbee quadrangle is shown in the following table:

Table showing distribution of Devonian species in the Bisbee quadrangle.

	Species.	Localities.														
		I.	II.	III.	IV.	V.	VI.	VII.	11a.	11b.	12a.	12b.	22d.	22e.	22f.	42.
1	Acervularia davidsoni							×		×		×				×
2	Pachyphyllum woodmani								×	×		×				
3	Cladopora prolifica	×								×						
4	Stromatopora erratica							×		×						
5	Cyathophyllum cæspitosum															
6	Atrypa reticularis		×			×	×	×	×	×	×	×	×	×	×	×
7	Cyrtia cyrtiniformis							×								

Table showing distribution of Devonian species in the Bisbee quadrangle—Continued.

	Species.	Localities.														
		I.	II.	III.	IV.	V.	VI.	VII.	11a.	11b.	12a.	12b.	22d.	22e.	22f.	42.
8	Dielasma calvini															
9	Schizophoria striatula							×								
10	Productella speciosa															
11	Delthyris consobrina															
12	Sp. cf. jeremejevi															
13	Sp. hungerfordi		×					×		×	×	×			×	×
14	Sp. orestes			×											×	
15	Sp. cf. euryteines															
16	Sp. whitneyi				×			×							×	×
17	Stropheodonta demissa													?		
18	Str. (fragilis) perplana							×								
19	Strophonella cælata															
20	Coral, several species	×						×	×							
21	Crinoid stem									×						
22	Bryozoa															
23	? Terebratula (small)															
24	? Minute brachiopod															
25	Loxonema															
26	Platyceras															
27	Pleurotomaria											×				
28	Bellerophon															
29	Leperditia															

	Species.	Localities.														
		44.	45.	46.	52.	53.	58.	67.	84.	98.	102a.	102b.	102c.	125.	125b.	128.
1	Acervularia davidsoni			×			×							×		
2	Pachyphyllum woodmani			×												
3	Cladopora prolifica			×	×		×							×		×
4	Stromatopora erratica			×												
5	Cyathophyllum cæspitosum	×												×		
6	Atrypa reticularis	×	×	×	×	×	×	×	×	×	×	×			×	×
7	Cyrtia cyrtiniformis					?	?	×								
8	Dielasma calvini								×							
9	Schizophoria striatula	×	×			×										
10	Productella speciosa	×														
11	Delthyris consobrina	×	×											×		
12	Sp. cf. jeremejevi											×				
13	Sp. hungerfordi								×			×		×	×	
14	Sp. orestes			×								×		×		
15	Sp. cf. euryteines					×										
16	Sp. whitneyi	×							×					×	×	
17	Stropheodonta demissa	?	×													
18	Str. (fragilis) perplana															
19	Strophonella cælata			×				×								
20	Coral, several species	×	×	×		×							×	×		×
21	Crinoid stem			×		×										
22	Bryozoa					×										
23	? Terebratula (small)	×														
24	? Minute brachiopod					×										
25	Loxonema							×								
26	Platyceras							×								
27	Pleurotomaria	×	×					×			×					
28	Bellerophon											×				
29	Leperditia	×														

The species *Atrypa reticularis* is present in 25 of the 30 faunules. Some one or more of the corals are found in 11 of the faunules. The faunules marked 11b, 12b, 46, 58, 125, and VII contain several species of the reef-building corals and probably represent a common fauna.

Associated with these corals are the following species, viz:

1. Atrypa reticularis.
2. Cyrtia cyrtiniformis.
3. Schizophoria striatula.
4. Dethyris consobrina.
5. Sp. hungerfordi.
6. Sp. orestes.
7. Sp. whitneyi.
8. Stropheodonta (fragilis) perplana.
9. Strophonella cælata.

These species indicate distinctly the fauna so well developed in the Devonian rocks at Rockford, Iowa. On the supposition that *Spirifer hungerfordi* and *Spirifer whitneyi* are characteristic species of that fauna, the following species, associated with them in the Bisbee quadrangle, are now added to it, i. e., 10, *Dielasma calvini;* 11, *Productella speciosa;* 12, *Spirifer* cf. *jeremejevi.* These twelve species, at least, are therefore probably present in a common fauna of this Arizona region, which is also represented in Iowa, and is certainly of Devonian age.

Its comparison with New York and Northern Appalachian faunas indicates close affinity with a fauna occurring at the base of the Chemung formation of New York, above the typical Ithaca formation. In the High Point zone of Naples, Livingston County, N. Y., the species of the genus *Strophonella* reported is *S. reversa.* The form reported in the above list is *S. cælata*, which occurs in the *Stropheodonta cayuta* fauna of the southern counties of New York and across the border in Tioga and Bradford counties, Pa., but not, so far as I have observed, in the High Point fauna. In this southern extension it is associated with typical *Spirifer disjunctus.* The *Productella* of the Arizona region is also of the same type as that represented in this upper (Chemung) zone rather than in the underlying typical Ithaca zone of *Productella speciosa.* The evidence is therefore confirmatory of the opinion that this western American fauna did not reach the upper Appalachian region, in its full complement, until after the deposition of the zone of the Ithaca formation.

It is to be observed, however, that in Russia, the fauna with which this Arizona fauna shows closest affinity is classed by Tschernyschew[a] as middle Devonian rather than upper Devonian and occurs below the *Cuboides* fauna. It is also regarded by him as equivalent to the *Stringocephalus* fauna, which in western Europe is strictly Mesodevonic. This is further correlated by Tschernyschew (p. 192) with the Hamilton group of North America.

The species occurring in "zone D 2 2b," at Kirchdorfe Sserpeewka in the lower bituminous limestone (b1) and in the overlying shaly limestone (b2) are as follows: In b1, *Pleurotomaria melnikovi* n. sp., *Platyschisma uchtensis* Keyserling,

[a] Die Fauna des mitteleren und oberen Devon an West-abhange des Urals: Mém. du Comité Géol., vol. 3, 1887, No. 3, p. 207.

PLATE VII.

PLATE VII.

DEVONIAN FOSSILS CHARACTERISTIC OF THE MARTIN LIMESTONE IN THE BISBEE QUADRANGLE.

ATRYPA RETICULARIS.

FIG. 1. Dorsal view.
1*a*. Side view.
2. Ventral view of larger specimen.

SPIRIFER HUNGERFORDI.

FIG. 3. Ventral view.
3*a*. Side view.
4. Dorsal view of larger specimen.

SCHIZOPHORIA STRIATULA.

FIG. 5. Dorsal view.
5*a*. Front view.
5*b*. Ventral view.

PACHYPHYLLUM WOODMANI.

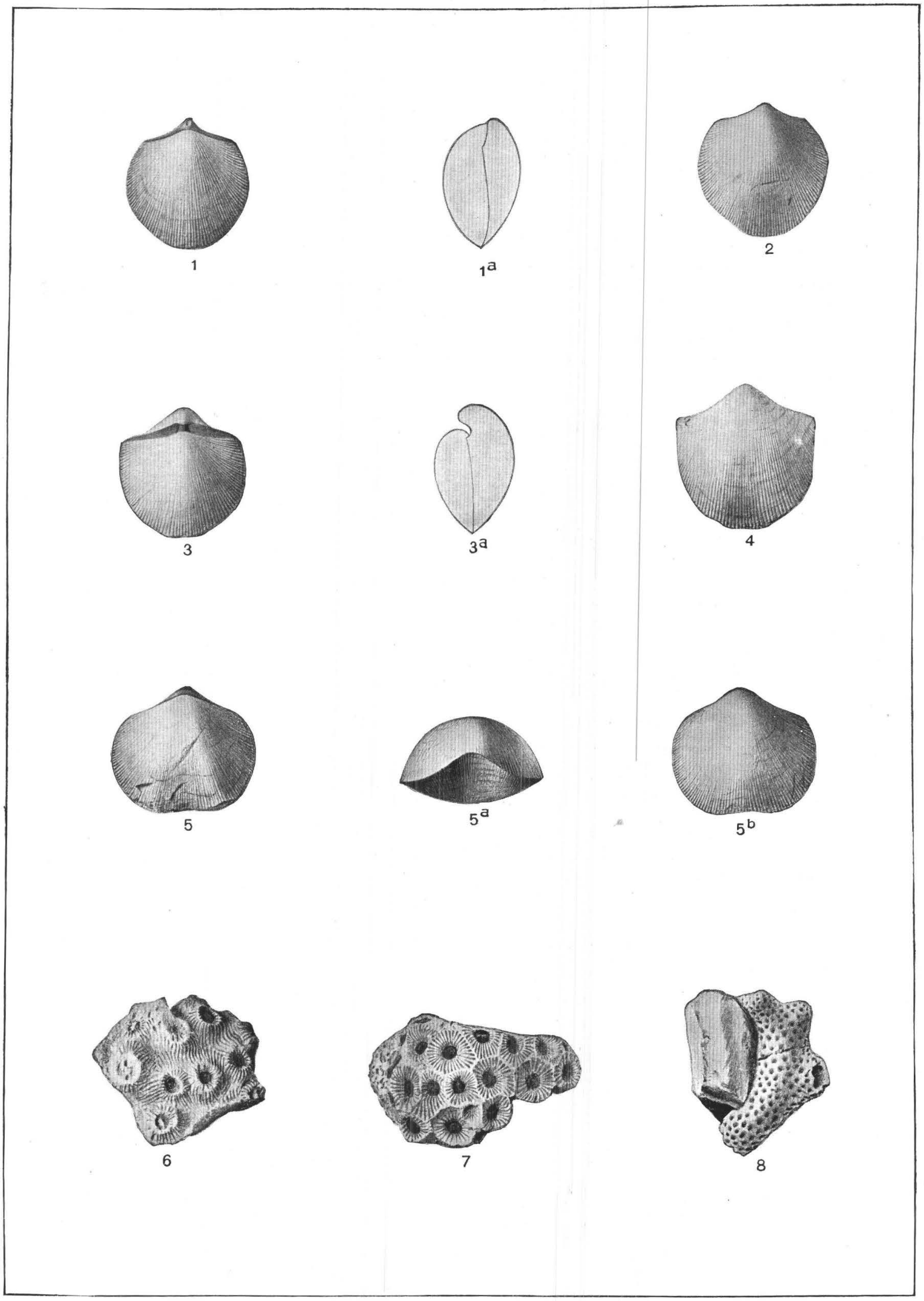
FIG. 6. Composite corallum showing several corallites, natural size. From locality Bi 11a (Martin limestone, north of Moore Gulch).

ACERVULARIA DAVIDSONI.

FIG. 7. Colony showing wall separating individual corallites, natural size. From locality Bi 125a (ridge between Black Gap and Gold Hill).

CLADOPORA PROLIFICA.

FIG. 8. Branching corallum, natural size. From locality Bi 125a (ridge between Black Gap and Gold Hill).



DEVONIAN FOSSILS CHARACTERISTIC OF THE MARTIN LIMESTONE IN THE BISBEE QUADRANGLE.

Phanerotinus serpula De Kon., *Actinopteria boydi* Conrad, *Cypricardinia lamellosa* Sandb., *Aviculopecten exactus* Hall, *Mytilarca* cf. *dimidiata* Goldfuss, *Dielasma sacculus* Mart., *Athyris helmerseni* Buch, *Athyris concentrica* Buch, *Spirifer elegans* Stein, *Spirifer anossofi* Vern., *Reticularia urii* Flem., *Reticularia lineata* Mart., *Rhynchonella livonica* Buch, *Rhynchonella acuminata* Mart., *Atrypa reticularis* Linn., *Atrypa desquamata* Sow., *Atrypa aspera*, Schloth., *Grünewaldtia latilinguis* Schnur, *Pentamerus galeatus* Dalm, *Schizophoria striatula* Schloth., *Orthis bistriata* n. sp., *Strophomena interstrialis* Phill., *Streptorhynchus umbraculum* Schloth., *Productus hallanus* Walcott, *Favosites cervicornis* Blainv., *Cyathophyllum cæspitosum* Goldfuss.

(From b2) *Dielasma sacculus* Mart., *Athyris concentrica* Buch, *Spirifer anossofi* Vern. (in great abundance), *Spirifer jeremejevi* n. sp. (in extraordinary abundance), *Atrypa desquamata* Sow., *Atrypa aspera* Schloth., *Productus subaculeatus* Murch., and a number of corals (p. 161).

There can be little doubt as to the close affinity of the Arizona and Russian faunas here referred to. Comparison of *Spirifer hungerfordi*, as it occurs both in Iowa and Arizona, with Russian specimens of *Spirifer anossofi*, demonstrates the two to be closely related, as Tschernyschew maintained; but the rounded cardinal angle as well as coarser radiating striæ mark the figures of *S. anossofi* of Tschernyschew (as well as actual specimens seen by me), from the *Sp. hungerfordi* as it is seen both in Iowa and Arizona. There are figures in the original description of d'Verneuil,[a] which have the angular terminations of the cardinal area. Also some young specimens from Iowa in my collection show distinctly rounded cardinal angles.

Associated with that species are *Productus hallanus* and rhynchonellas of the *Pugnax* type (*R. acuminata*), which distinctly belong to this fauna as developed in America.

As I have reported in other places, this *Pugnax pugnus* fauna occurs in the New York section, both in Ithaca and High Point zones, which are both above the representative of the Cuboides zone (Tully limestone) of that region, and before the appearance there of the typical *Spirifer disjunctus* fauna. But in New York the species which dominates in the Iowa, Arizona, and Russian faunas (*Spirifer hungerfordi* and *Spirifer anossofi*) is entirely absent, or certainly very rare even if eventually it should be discovered. From this and other similar peculiarities presented by the New York faunas, I am inclined to think that the horizon at which the *Pugnax* fauna enters the New York sections is later chronologically than that of the formations holding the fauna in Russia, and possibly also appreciably later than the zone marked by it in Iowa and Arizona.

Although *Spirifer whitneyi* presents many characters of the general *Spirifer disjunctus* type, its range in the Russian and also in the west European Devonian confirms this same view. The Arizona fauna does not present any very close affinity with the distinctly Chemung (*Spirifer disjunctus*) fauna of New York.

This earlier age for the *Spirifer hungerfordi* fauna is also indicated by the development of *Productus*. All the representatives of that genus reported from Arizona, and from the same fauna as expressed in Iowa, indicate an earlier stage of

[a] Russia and the Ural Mountains, Geology, vol. 2, p. 153, pl. iv, fig. 32 and f.

its development than that exhibited by the productellas of the Chemung formation of New York.

From these and other considerations it seems reasonable to adopt Tschernyschew's view that the zone in Russia containing the *anossofi* fauna is the equivalent of the *Stringocephalus* zone of western Europe as well as of the Hamilton formation of North America; and therefore that the fauna is properly a Mesodevonian rather than Neodevonian fauna. On these grounds we should place the formation bearing this fauna in Arizona in the Mesodevonian, although its representatives do not appear in the New York fauna until the opening of Neodevonian time.

CARBONIFEROUS.

ESCABROSA LIMESTONE.

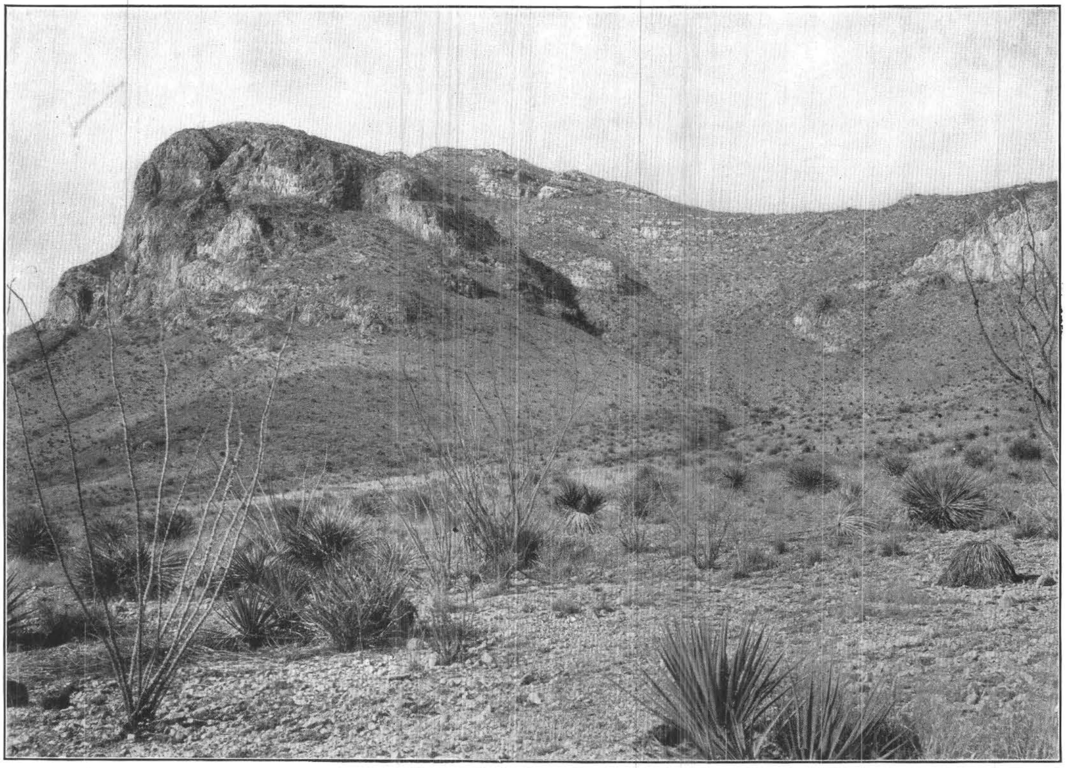
Name.—The Escabrosa limestone takes its name from Escabrosa Ridge, where the thick white beds belonging to this formation are conspicuously displayed.

Distribution, thickness, and general stratigraphy.—The distribution of the Escabrosa limestone is practically that of the Martin limestone which underlies it. But its lighter hue, thicker beds, and greater power of resisting erosion make it a much more marked feature in the landscape than any of the limestones yet described. The summit of Mount Martin, the prominent light-colored scarps visible from Bisbee along the northeast side of Escabrosa Ridge, and the bold cliffs (Pl. VIII) which the same ridge presents toward Espinal Plain and Naco on the south are due to this formation.

The most northern occurrence of the Escabrosa limestone is a small area 5 miles west-northwest of Bisbee on the edge of the quadrangle, resting with apparent conformity and gentle westerly dip upon the Martin formation. Other areas north of Moore Canyon extend the distribution of the beds in a series of fault blocks westward beyond the bounds of the quadrangle to the edge of the San Pedro Valley. Between Moore and Abrigo canyons the Escabrosa limestone has been removed by erosion. Nearly the whole thickness of the formation, however, is preserved on Mount Martin, and several faulted blocks of these beds occur to the southwest and south of this peak within a radius of 2½ miles.

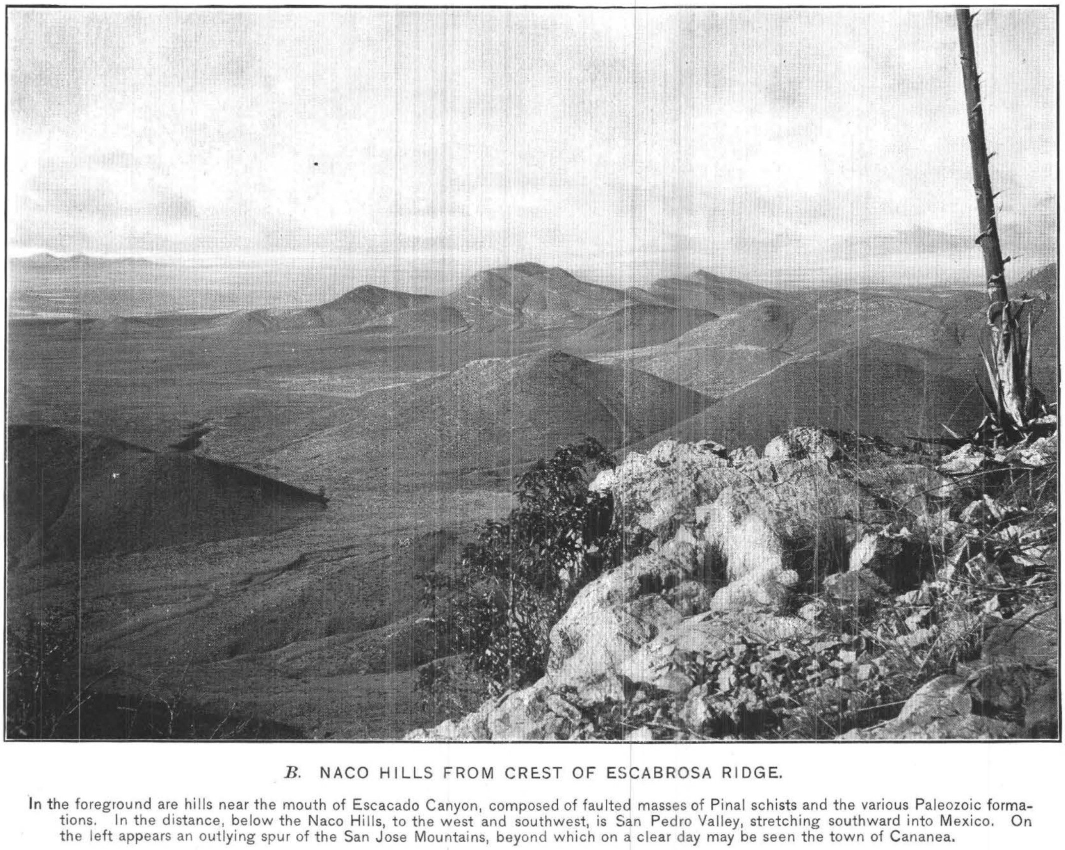
The Escabrosa limestone is also exposed in Hendricks Gulch, just southwest of Bisbee, and, like the Martin limestone, extends in a curved belt, broken by many faults, southeastward past Gold Hill as far as Glance Creek.

The formation appears in most places to lie conformably above the Martin limestone, but the contact is not always well exposed and has in some cases been modified by faulting. This faulting, chiefly along planes forming small angles with the bedding, is a particularly noticeable feature in the structure near Abrigo Canyon and will be fully described in later pages. The upper part of the Escabrosa passes without any stratigraphical break or marked lithological change (Pl. IX, *A*) into the overlying Naco limestone. The distinction between these two



A. CLIFF OF ESCABROSA LIMESTONE NORTHWEST OF DON LUIS.

Structure is complicated by faulting. Some Naco limestone occurs on crest of ridge in background. Martin and Abrigo limestones underlie slopes in foreground.



B. NACO HILLS FROM CREST OF ESCABROSA RIDGE.

In the foreground are hills near the mouth of Escacado Canyon, composed of faulted masses of Pinal schists and the various Paleozoic formations. In the distance, below the Naco Hills, to the west and southwest, is San Pedro Valley, stretching southward into Mexico. On the left appears an outlying spur of the San Jose Mountains, beyond which on a clear day may be seen the town of Cananea.

formations was based primarily upon paleontological evidence, and they have accordingly been mapped in different colors but with no definite dividing line, except in the case of faults.[a] There are indeed certain lithological differences between the Escabrosa limestone and the Naco limestone, as will be pointed out when the latter is described, but it is only after an intimate knowledge of the beds is gained that these lithological criteria can be utilized as a basis of separation. They would hardly in themselves have suggested the two-fold division of the Carboniferous limestones here adopted.

The thickness of the Escabrosa limestone in the Bisbee quadrangle can not be determined with the same accuracy as in the case of the Devonian and Cambrian limestones. Although the overlying Naco limestone has been eroded from the summit of Mount Martin, there is good reason to conclude that the Escabrosa limestone is still present in this section in very nearly its original thickness, which measurements and calculation give as approximately 800 feet. Another section just west of Black Gap, where apparently the whole of the Escabrosa limestone is represented in conformable sequence between the Martin and Naco limestones, affords a thickness of a little more than 600 feet. A third section was measured 1¾ miles south of Bisbee, near the Whitetail mine, and intermediate in position between the two already referred to. This afforded a minimum thickness of 775 feet. It thus appears that the Escabrosa limestone has a maximum thickness of about 800 feet, and that it probably thins out toward the southeast to about 600 feet. For general purposes 700 feet will be taken as the average thickness of the formation.

Lithology.—The characteristic rocks of the Escabrosa formation are rather thick-bedded, nearly white to dark-gray, granular limestones, which close examination often shows to be made up very largely of fragments of crinoid stems. Near the base the beds are commonly 10 or 15 feet in thickness, but above the first hundred feet thicknesses from 1 to 5 feet are the rule, with occasional occurrences of more massive strata. The formation, as a whole, may be characterized as a pure nonmagnesian limestone (see chemical analysis, under IV, p. 55), containing practically no arenaceous sediments and only occasional, irregular bunches and nodules of chert—usually in its upper part.

Fossils occur distributed from the bottom to the top of the formation, but, with the exception of small scattered corals and the abundant fragments of crinoid stems, are rarely conspicuous and seldom appear on weathered surfaces of the limestone. As a rule they must be carefully sought for with a liberal use of the hammer. The general appearance of the Escabrosa formation is white or light gray, but some dark-gray beds occur, particularly near the top.

[a] Through an oversight, Pl. I was printed without erasure of a temporary boundary line between these formations.

Conditions of deposition.—The absence of terrigenous sediments and dolomitic beds from the Escabrosa limestone indicates deposition in an open sea and in deeper water than had hitherto covered this region. But so many factors in the case—such as the distance and elevation of the nearest land from which detrital material might have been derived—are unknown that it is not possible to give even the approximate depth of this portion of the sea at that time. The Escabrosa limestone, however, is probably to be classed as a deep-sea deposit and may have been formed near the 100-fathom zone and 30 or 40 miles from shore.[a]

Age and correlation.—The Escabrosa limestone is of Mississippian or lower Carboniferous age. The paleontological evidence upon which this determination is based is presented by Mr. Girty in his note on the Carboniferous fossils. As this note is concerned with the Naco as well as with the Escabrosa limestone, its consideration is deferred until both of the formations comprising the local Carboniferous section shall have been described.

NACO LIMESTONE.

Name.—The name *Naco limestone* is derived from the Naco Hills, situated near the western edge of the quadrangle, and composed of the light-colored and regularly stratified beds belonging to this formation.

Distribution, thickness, and general stratigraphy.—The Naco Hills (Pl. VIII, *B*), surrounded on three sides by the Quaternary wash of Espinal Plain and San Pedro Valley and cut off from the older Paleozoic rocks on the north by the Abrigo fault (Pl. I), are carved from the Naco limestone and their steep southwest slopes afford exceptional opportunity for studying the lithological character of this formation. The broader stratigraphic relations of the beds are, however, not revealed in this relatively large but isolated exposure, where the only visible relation with the other Paleozoic rocks is that of faulting.

Between the Naco Hills and Bisbee are several smaller blocks of the Naco limestone involved in the intricate web of faults that characterizes the structure of this portion of the quadrangle, particularly in the vicinity of Escacado Canyon.

The largest area of Naco limestone within the quadrangle, and by far the most important from an economic standpoint, is that which stretches southeastward from Bisbee to Gold Gulch, and is thence continued by a series of smaller exposures extending past Glance to within a mile and a half of the Mexican boundary. The main area, between Bisbee and Gold Gulch, partly covered by the Cretaceous Glance conglomerate, constitutes the inner Paleozoic member of the faulted syncline which has been referred to several times, and which will be shown to have a very important connection with the great copper deposits of the district. Although

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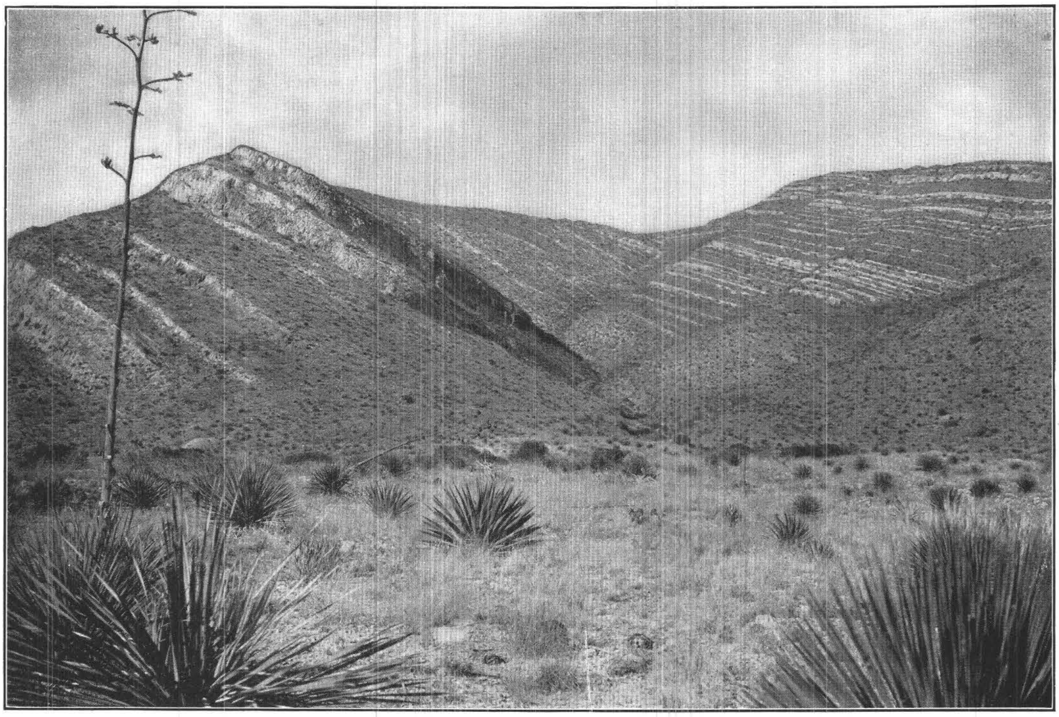
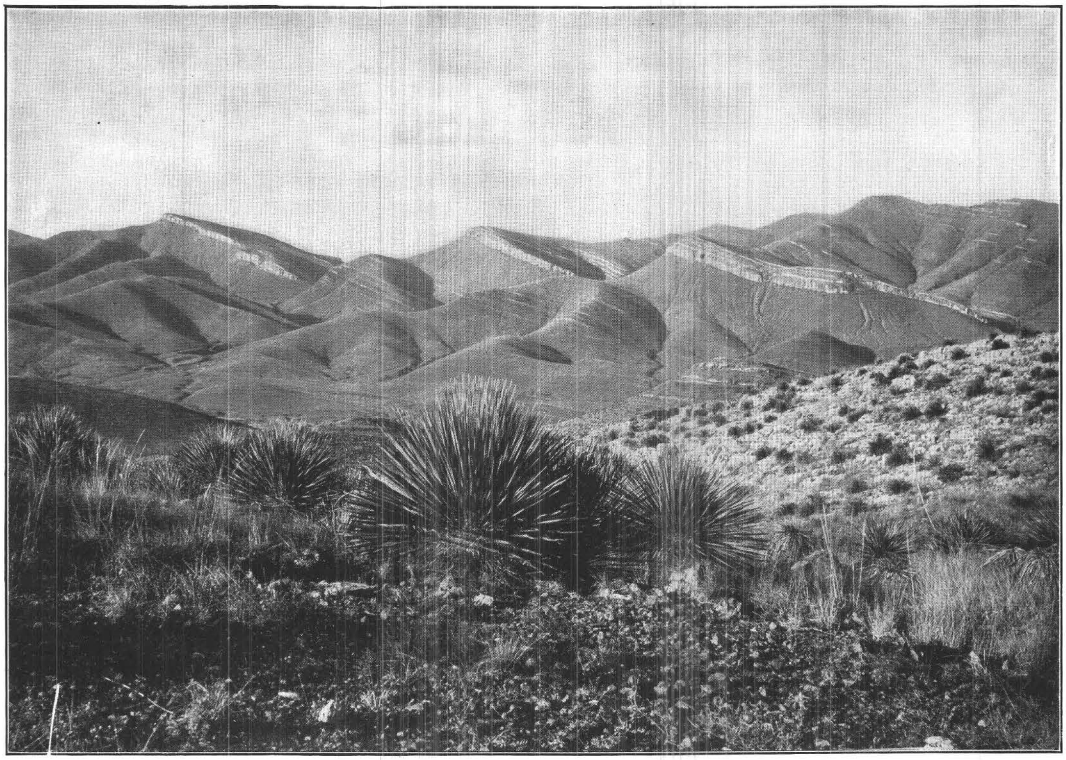
[a] Challenger Reports. Deep Sea Deposits, p. 186.



A. ESCABROSA LIMESTONE CONFORMABLY OVERLAIN BY NACO LIMESTONE, 1 MILE NORTH OF DON LUIS.

The hill on the left is formed of Escabrosa limestone. The base of the Naco limestone outcrops about halfway up the slope on the right.



B. HILLS CARVED FROM CRETACEOUS BEDS EAST OF BISBEE.

View is northward across Mule Gulch The prominent white band is the upper member of the Mural limestone, forming the top of Mural Hill on the left and showing the dislocation due to the Mexican Canyon fault.

much disturbed by faulting, the beds generally conform to the dominant synclinal structure, dipping southeasterly near Bisbee and then swinging around in a rather sharp curve until they dip to the northeast near Black Gap. The mass forming the summit of Gold Hill and the other areas to the southeast owe their positions to faults which have thrust them bodily over Cretaceous beds, as will be described in the section on geological structure.

The Naco limestone conformably overlies the Escabrosa limestone, as may be well seen at several points along Escabrosa Ridge, southeast of Mount Martin, and particularly in the excellent exposures (Pl. IX, *A*) a mile due north of Don Luis, where the rather thin beds immediately above and below the plane of division are continuously exposed for nearly a mile along a steep slope. The upper limit of the Naco formation is a rather irregular surface of erosion, upon which the basal conglomerate of the Cretaceous Bisbee group was deposited. The original thickness of the formation is thus unknown, but it undoubtedly greatly exceeds that of any other member of the local Paleozoic section. Measured sections in the Naco Hills show that the formation, as there exposed, has a present thickness of at least 1,500 and probably of as much as 2,000 feet, plus an unknown thickness removed by erosion and an unexposed portion concealed by Quaternary deposits. Unless there are important faults which have escaped the careful examination given to the synclinal area of Naco limestone just south of Bisbee, 3,000 feet is a very moderate estimate for the thickness of the Naco beds involved in this structure. It is probably fairly safe to conclude that the original thickness of the Naco limestone was more than 3,000 feet.

Lithology.—The Naco limestone, like the Escabrosa formation, is made up chiefly of light-colored beds, which consist essentially of calcium carbonate. The beds range in thickness from a few inches to 10 feet, but are usually thinner than those of the Escabrosa limestone. They differ from the latter also in texture, the typical Naco limestone being compact and nearly aphanitic, ringing under the hammer, and breaking with a splintery fracture, whereas the Escabrosa limestone is usually more granular and crystalline, and crumbles more readily when struck. There are, however, exceptions to this rule, dense aphanitic beds occurring rarely in the Escabrosa formation and granular crinoidal beds being not uncommon in the Naco limestone.

Fossils, particularly brachiopods, are much more abundant in the Naco than in the Escabrosa limestone, sometimes making up a considerable part of individual beds, and weathering out conspicuously upon exposed surfaces.

While the greater part of the 3,000 feet or more of the Naco formation is made up of fairly pure gray limestone (see chemical analysis under V, p. 55), certain thin beds of a faint-pink tint occur at several horizons, and are often a

PLATE X.

PLATE X.

MISSISSIPPIAN ("LOWER CARBONIFEROUS") FOSSILS CHARACTERISTIC OF THE ESCABROSA LIMESTONE.

RHIPIDOMELLA THIEMEI.

FIG. 1. Ventral valve, with side view and outline.

2. Ventral valve of a different shape.

Locality: Bisbee quadrangle. Very characteristic of the Escabrosa limestone.

LEPTÆNA RHOMBOIDALIS.

FIG. 3. Ventral valve, with side view and outline.

Locality: Cuyahoga shale, Bagdad, Ohio. No species at all like this is known from the Pennsylvanian.

CHONETES LOGANENSIS.

FIG. 4. Ventral valve.

Locality: Logan Canyon, Wasatch Range, Utah. From U. S. Geol. Explor. 40th Par., vol. 4, Pl. IV, fig. 9. This species is also very characteristic of the Escabrosa limestone.

SPIRIFER CENTRONATUS.

FIG. 5. Ventral view.

6. Dorsal view.

7. Side view.

Locality: Mountain Spring, old Mormon road, Nevada. From U. S. Geog. Surv. W. 100th Mer., vol. 4, Pl. V, figs. 8a, 8b, and 8c. This species is common in the Escabrosa limestone. Forms similar to it, however, are also found in the Pennsylvanian.

SPIRIFER PECULIARIS?

FIG. 8. Ventral valve.

Locality: Mountain Spring, old Mormon road, Nevada. From U. S. Geog. Surv. W. 100th Mer., vol. 4, Pl. V, fig. 7a. This species is found only in the Escabrosa limestone, but not in the Naco limestone.

SYRINGOTHYRIS CARTERI.

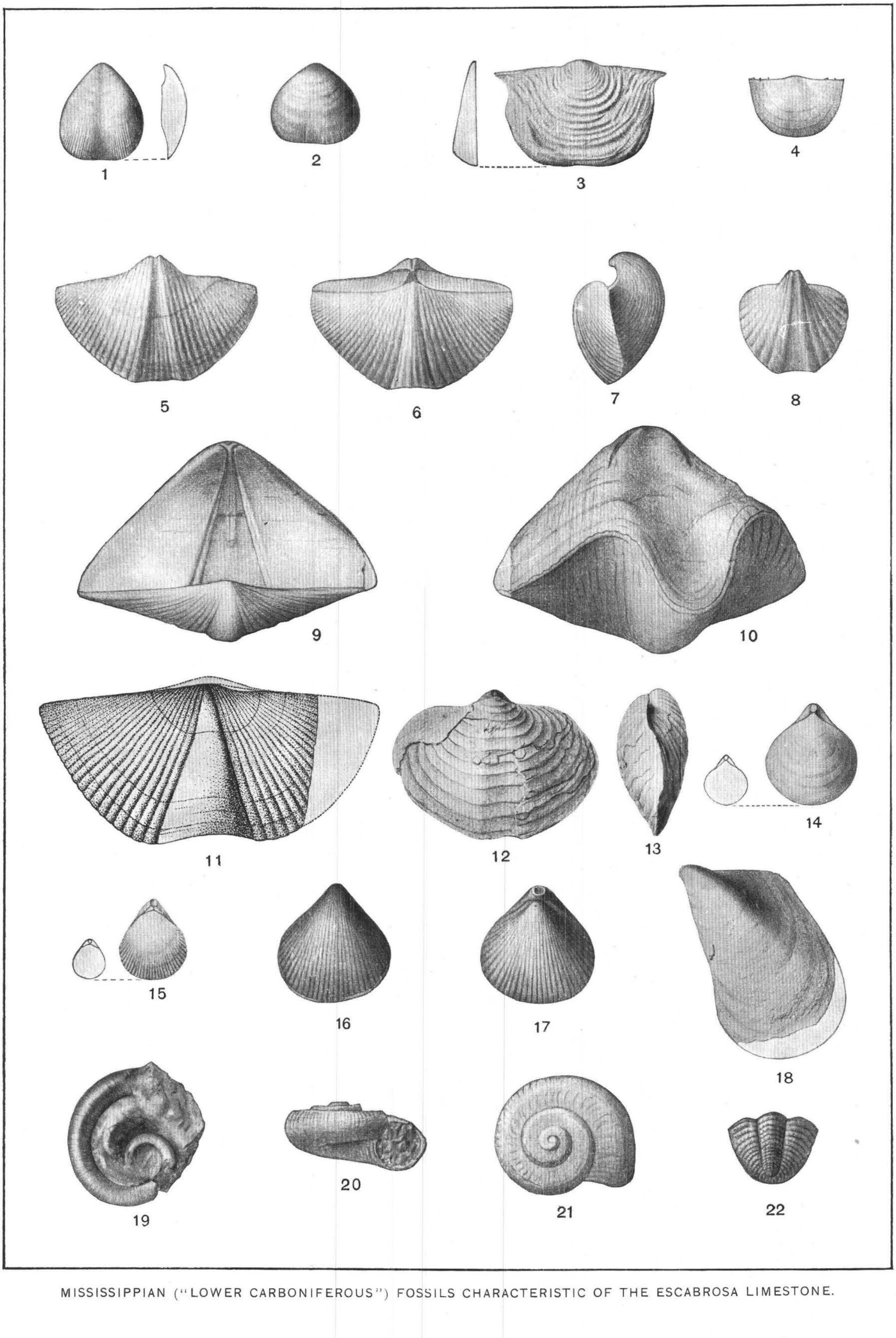
FIG. 9. Posterior view.

10. Anterior view.

Locality: White Pine Mountains, Treasure Hill, Nevada. From U. S. Geol. Explor. 40th Par., vol. 4, Pl. III, figs. 11, 11*a*.

11. Dorsal valve.

Locality: Yellowstone National Park. From Mon. U. S. Geol. Survey, vol. 32, pt. 2, Pl. LXXI, fig. 1*a*. Nothing resembling this species is found in the Pennsylvanian. Note the unplicated fold and sinus.



MISSISSIPPIAN ("LOWER CARBONIFEROUS") FOSSILS CHARACTERISTIC OF THE ESCABROSA LIMESTONE.

ATHYRIS LAMELLOSA.

FIG. 12. Dorsal view.

13. Side view in outline.

Locality: Lake Valley, New Mexico. No form like this found in the Pennsylvanian.

SEMINULA sp.

FIG. 14. Dorsal view, natural size in outline. Enlargement of 2 diameters.

Locality: Bisbee quadrangle. The genus *Seminula* is rare in the Escabrosa limestone at Bisbee. Specimens are mostly of small size, but are not readily distinguished from those occurring in the Naco limestone.

EUMETRIA MARCYI.

FIG. 15. Dorsal view, natural size in outline. Enlarged 3 diameters.

Locality: Bisbee quadrangle. No species quite like this occurs in the Pennsylvanian; the Pennsylvanian representatives have far fewer ribs.

16. Ventral view.

17. Dorsal view.

Locality: Little Belt Mountains, near Clendenin, Mont. From Mon. U. S. Geol. Survey, vol. 8, Pl. VII, figs. 5, 5*a*. This is probably the same species as fig. 15, but the specimens are much larger and of more nearly mature size.

MYALINA KEOKUK.

FIG. 18. Left valve.

Locality: Bisbee quadrangle. The genus is better represented in the Pennsylvanian (though apparently not at Bisbee), but the same species does not occur in the higher beds.

PHANEROTINUS PARADOXUS.

FIG. 19. Seen from above.

Locality: Bisbee quadrangle. Nothing at all like this known from the Pennsylvanian.

STRAPAROLLUS LUXUS.

FIG. 20. Side view.

21. Seen from above.

Locality: Dry Canyon, Oquirrh Mountains, Utah. From U. S. Geol. Explor. 40th Par., vol. 4, Pl. IV, figs. 24 and 25. This is a small specimen. The genus occurs in the Pennsylvanian, but not the same species.

PHILLIPSIA PEROCCIDENS.

FIG. 22. Tail.

Locality: Ogden Canyon, Wasatch Range, Utah. From U. S. Geol. Explor. 40th Par., vol. 4, Pl. IV, fig. 21. This genus also is found in the Pennsylvanian, but the species are different. *P. peroccidens* is rather characteristic of the Escabrosa limestone.

519—No. 21—04——4

Menophyllum excavatum.
Syringopora aculeata.
Rhipidomella thiemei.
Rhipidomella michelini.
Leptæna rhomboidalis.
Orthothetes inequalis.
Chonetes loganensis.
Productus lævicostus.
Productus semireticulatus var.
Spirifer centronatus.
Spirifer mysticensis.
Spirifer cf. peculiaris.
Reticularia pseudolineata?
Syringothyris carteri.
Athyris lamellosa.
Eumetria marcyi.
Entolium aviculatum.
Myalina keokuk.
Phanerotinus paradoxus.
Straparollus luxus.
Platyceras sp.
Phillipsia peroccidens.

Associated with some of the species in the above list were found others which probably indicate a slightly higher horizon than the Osage; in other words, basal Genevieve. There are such forms as *Lithostrotion* sp., *Meekopora* sp., *Archimedes* sp., *Productus* cf. *biseriatus*, and *Spirifer* cf. *tenuistriatus*. On the other hand, no fossils of a well-marked Chester type have been found, so that so far as the evidence at hand is concerned the upper Mississippian is missing. It is also true that many of the striking Osage forms have not been found, e. g., *Schizophoria swallowi*, *Derbya keokuk*, *Spirifer grimesi*, *Spirifer logani*, etc., nor the wealth of crinoids which characterize this horizon in certain areas in the Mississippi Valley. I am disposed to regard the absence of these Osage forms as due to local conditions, but also to believe that upper Mississippian time is really in large part unrepresented.

The earlier of the Pennsylvanian faunas is largely composed of species which characterize the "Upper Carboniferous" faunas of the Mississippi Valley. Some of the common species are the following:

Fusulina cylindrica.
Chætetes radians.
Derbya crassa.
Productus semireticulatus.
Productus cora.
Productus inflatus?.
Productus nebraskensis.
Productus punctatus.
Marginifera wabashensis.
Spirifer rockymontanus.
Spirifer cameratus.
Squamularia perplexa.
Spiriferina kentuckyensis.
Seminula subtilita.
Hustedia mormoni.
Dielasma bovidens.
Phillipsia major.

Some of the local faunas have a facies which I believe to indicate very early Pennsylvanian time.

The upper Pennsylvanian fauna comprises many species which are as yet undescribed, and its general character only can be indicated. The following forms have been discriminated:

Fusulina cylindrica.
Michelinia? sp.
Lophophyllum cf. proliferum.
Archeocidaris, several sp.
Productus, semireticulatus type.
Productus cf. norwoodi.
Marginifera cf. wabashensis.
Martinia sp.
Seminula subtilita.
Dentalium cf. canna.
Worthenia sp.
Murchisonia? several sp.
Euomphalus sp.
Omphalotrochus, several sp.
Cyclonema sp.
Orthonema sp.
Polyphemopsis sp.
Belleriphon cf. crassus.
Euphemus sp.

PLATE XI.

PLATE XI.

PENNSYLVANIAN ("UPPER CARBONIFEROUS") FOSSILS CHARACTERISTIC OF THE NACO LIMESTONE.

FUSULINA CYLINDRICA.

FIG. 1. A block of limestone containing a number of specimens partly weathered. Enlarged two times.

Locality: Bisbee quadrangle. These forms sometimes occur in great abundance in the Naco limestone, but are not known in the Mississippian.

CHÆTETES MILLEPORACEUS.

FIG. 2. A fragment of a coral belonging to this species. Locality: Virgin Range, southwest of St. George, Utah. From U. S. Geog. Surv. W. 100th Mer., vol. 4, Pl. VI, fig. 2a. This form is somewhat abundant in the Naco limestone, but nothing similar to it is found in the Escabrosa limestone.

DERBYA CRASSA.

FIG. 3. Ventral valve.

Locality: Bisbee quadrangle. The specimen is weathered, so that the vertical plate on the inside of this valve is shown. This form is often abundant in the Naco limestone, but does not occur at all in the Mississippian. A form resembling it very closely is found in the Escabrosa limestone, but it is without the vertical plate, which of course does not show on the outside of the shell.

PRODUCTUS SEMIRETICULATUS.

FIG. 4. Ventral valve with side view in outline.

Locality: Bisbee quadrangle. This species is common in the Naco limestone, but does not occur in the Mississippian.

PRODUCTUS INFLATUS?

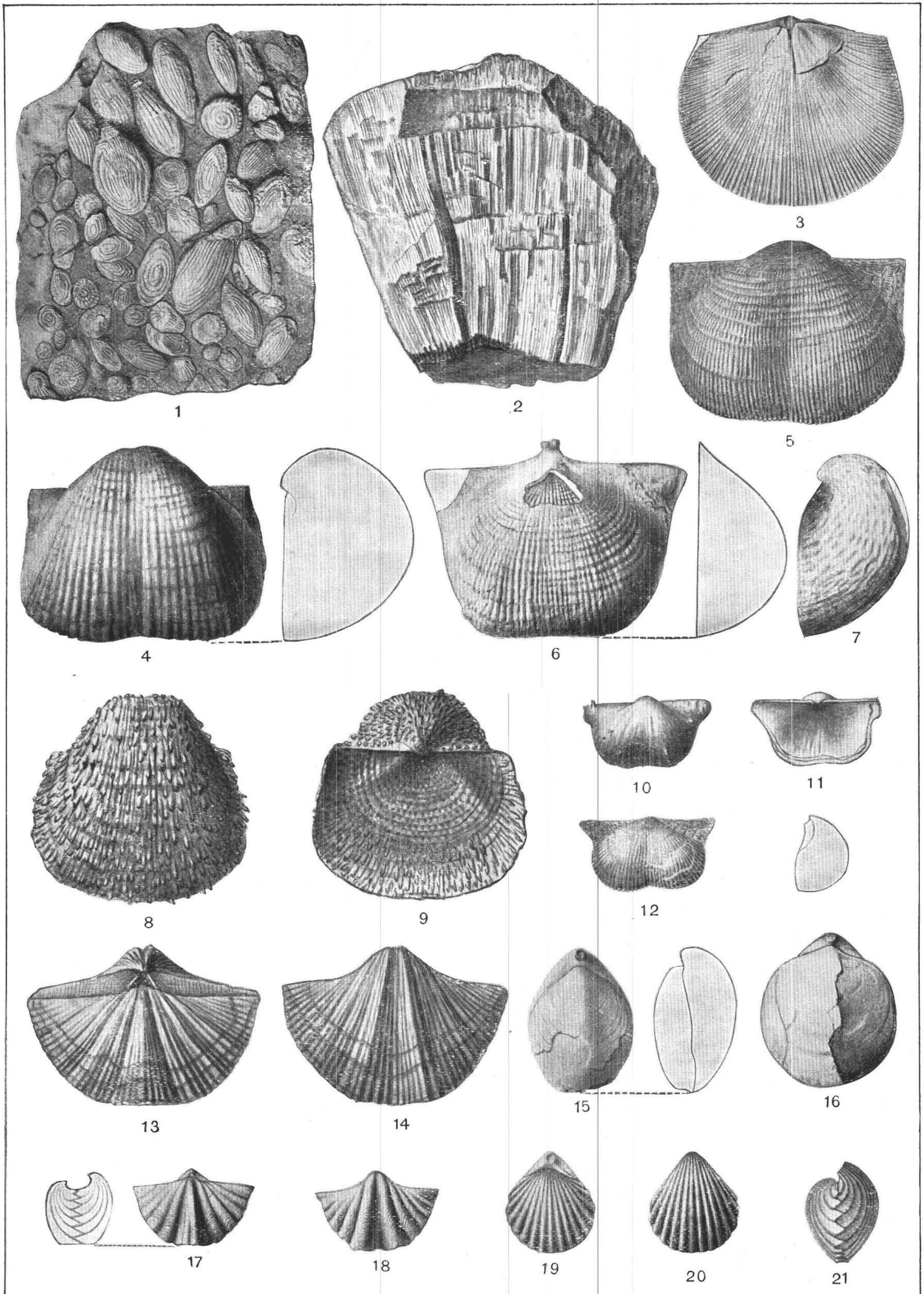
FIG. 5. Ventral valve.

Locality: Bisbee quadrangle.

6. Dorsal valve with side view in outline.

N. B.—The dorsal valve is concave, and this is the interior surface. The shell has been in part exfoliated.

Locality: Bisbee quadrangle. This species resembles the previous one, and the same remarks are true regarding it.



PENNSYLVANIAN ("UPPER CARBONIFEROUS") FOSSILS CHARACTERISTIC OF THE NACO LIMESTONE.

PRODUCTUS NEBRASKENSIS.

FIG. 7. Ventral valve, side view.

Locality: Bisbee quadrangle. Specimen is somewhat exfoliated and imperfect.

8. Ventral view.

9. Dorsal view.

Locality: Coal Measures of Nebraska. From the U. S. Geog. Surv. W. 100th Mer., vol. 4, Pl. VIII, figs. 3a and 3b. Better preserved and more perfect examples from Nebraska. This species is distinctive of the Pennsylvanian, and nothing similar to it is known from the Escabrosa limestone.

MARGINIFERA WABASHENSIS.

FIG. 10. Ventral view.

11. Dorsal view.

Locality: Coal Measures, southern Iowa. From U. S. Geog. Surv. W. 100th Mer., vol. 4, Pl. VIII, figs. 5a and 5b.

12. Dorsal valve with side view in outline.

Locality: Bisbee quadrangle. This form is peculiar to the Pennsylvanian.

SPIRIFER CAMERATUS.

FIG. 13. Dorsal view.

14. Ventral view.

Locality: Santa Fe, N. Mex. From U. S. Geog. Surv. W. 100th Mer., vol. 4, Pl. X, figs. 1b and 1c. This species is peculiar to the Naco limestone at Bisbee. The distinctive character consists in the grouping or bundling of the ribs.

SEMINULA SUBTILITA.

FIG. 15. Dorsal view with side view in outline.

Locality: Bisbee quadrangle. An elongated specimen of medium size.

16. Dorsal view.

Locality: Bisbee quadrangle. A more rotund specimen of the usual sort. This species is often extremely abundant in the Naco limestone. Forms not different materially from it are found in the Escabrosa limestone at Bisbee, but they are usually rare and for the most part small.

SPIRIFERINA KENTUCKYENSIS.

FIG. 17. Dorsal view with side view in outline. Enlarged $1\frac{1}{2}$ times.

18. Ventral view with side view in outline. Enlarged $1\frac{1}{2}$ times.

Locality: Howard, Elk County, Kans. Museum No. 33139. This species is not rare in the Naco limestone. A form not greatly different occurs also in the Escabrosa limestone. The shell in this genus is characteristic, being rather coarsely porous or spongy. This can be seen with an ordinary hand lens.

HUSTEDIA MORMONI.

Fig. 19. Dorsal view. Enlarged $1\frac{1}{2}$ times.

20. Ventral view. Enlarged $1\frac{1}{2}$ times.

21. Side view.

Locality: Coal Measures, Kansas, station 2474. This is a rather rotund specimen. Others are considerably elongate. This form is peculiar to the Pennsylvanian. Its representative in the Mississippian is *Eumetria marcyi*, illustrated on Pl. X. Externally the two species are distinguished by the much greater number of ribs in *Eumetria*. The shell structure in both species is porous or punctate, as in *Spiriferina*.

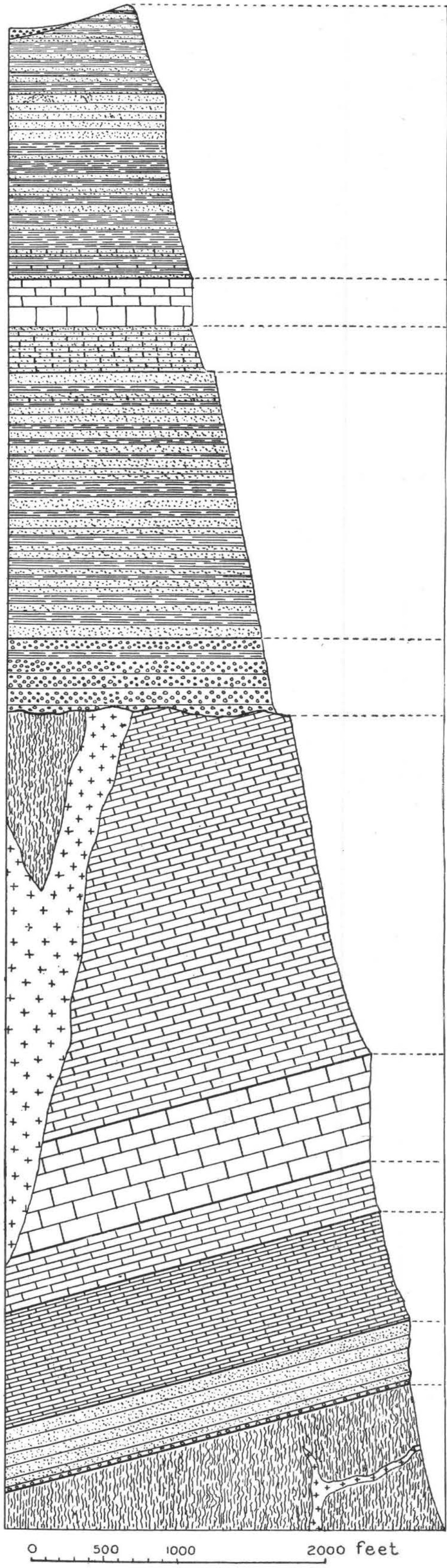
There appear to be two species of *Productus* of the *semireticulatus* type. They are not rare, yet are in no instance very perfect. One is related to *P. ivesi* and the other to *P. occidentalis*. The genus *Omphalotrochus* is well represented. One species appears to be the same as *O. whitneyi* Meek. Another is related to *O. obtusispira* Shumard, described as *Trochus obtusispira*, while several forms appear to be new. *Archeocidaris* is also represented in great variety and abundance. Species related to *ornata*, *megastylus*, *cratis*, *biangulata*, *aculeata*, etc., have been noted. Very few of these species have exact representatives in the Mississippi Valley Pennsylvanian, and few, if any, are found in the fauna below. *Productus ivesi*, *Productus occidentalis*, and *Archeocidaris ornata* are suggestive of the Aubrey limestone of the Grand Canyon section, just as the abundance of *Omphalotrochus* suggests the "Permo-Carboniferous" of California. The whole fauna is closely related to that of the limestones of the Hueco Mountains in western Texas. I shall later describe this fauna, and employ for it the name Hueconian. Its age seems to be late in the Carboniferous, perhaps about the same as the series just referred to. The fauna has at the same time a very different facies from that of the Guadalupe fauna, as well as from that of the so-called "Permo-Carboniferous" of the Mississippi Valley.

The close relationship, pointed out by Mr. Girty, between the Carboniferous fauna of Bisbee and that of western Texas is particularly interesting in view of the fact that the Cambrian faunas of the two regions show a similar affinity. More than this, it will be shown in the following pages that the Cretaceous fauna of the Bisbee group finds its nearest analogue in portions of the Comanche series as developed in Texas.

Some of the characteristic fossils of the Escabrosa and Naco limestones are illustrated on Pls. X and XI. These fossils were selected by Mr. Girty, who very kindly supplied the brief annotations to the plates. As the object of the plates is to enable those who are not paleontologists to recognize the typical forms and distinguish thereby the different limestones in the field, specifically identical specimens from other localities have been utilized whenever the Bisbee specimens were not sufficiently well preserved to furnish good illustration material.

RÉSUMÉ OF THE PALEOZOIC SECTION.

From the preceding descriptions it appears that Paleozoic time is represented in the Bisbee quadrangle by beds having a total thickness of a little over 5,000 feet. Of these the lower 430 feet are quartzites, while the remaining 4,570 feet are so predominantly calcareous that they may be collectively designated as limestones. The Pennsylvanian is represented by at least 3,000 feet of strata (the Naco limestone), while only 340 feet (the Martin limestone) can be assigned to the Devonian, and the Silurian is wholly without stratigraphic representation, unless the unfossiliferous quartzite at the top of the Abrigo limestone belongs in this period. No unconformity has been discovered to account for the absence of recognizable



Red nodular shales with cross-bedded, buff, tawny, and red sandstones. A few beds of impure limestone near base. Unconformably overlain by fluviatile Quaternary deposits.	Cintura formation, 1,800 feet plus unknown thickness, removed by erosion.	Bisbee group (Comanche series).	Cretaceous.
Thick-bedded, hard, gray, fossiliferous limestone.	Mural limestone, 650 feet.		
Thin-bedded, arenaceous fossiliferous limestones.			
Buff, tawny, and red sandstones and dark-red shales, with an occasional thin bed of impure limestone near top.	Morita formation, 1,800 feet.		
Bedded conglomerate with rather angular pebbles, chiefly schist and limestone. Rests on irregular surface produced by erosion.	Glance conglomerate, 25 to 500 feet. Great unconformity.		
Chiefly light-gray, compact limestone in beds of moderate thickness. Contains abundant fossils. Cut by granite-porphyry.	Naco limestone, 3,000 feet plus unknown thickness, removed by pre-Cretaceous erosion.	Pennsylvanian series.	Carboniferous.
Thick-bedded, white and light-gray limestone. Contains abundant crinoid stems. Cut by granite-porphyry.	Escabrosa limestone, 700 feet.	Mississippian series.	
Dark-gray fossiliferous limestone in beds of moderate thickness. Cut by granite-porphyry.	Martin limestone, 340 feet. Unconformity?		Devonian.
Thin-bedded, impure, cherty limestones. Cut by granite-porphyry.	Abrigo limestone, 770 feet.		Cambrian.
Moderately thick, cross-bedded quartzites, with basal conglomerate. Cut by granite-porphyry.	Bolsa quartzite, 430 feet. Great unconformity.		
Sericite-schists. Cut by granite and granite-porphyry.	Pinal schist.		Pre-Cambrian.

GENERALIZED COLUMNAR SECTION OF THE ROCKS OF THE BISBEE QUADRANGLE.

Silurian strata, but unless the quartzite just mentioned is of that age and represents the whole of the period the region was probably a land area during at least a part of the interval between the Cambrian and the Devonian.

The sequence and relative thicknesses of the various Paleozoic formations are shown in the generalized columnar section of Pl. XII.

For the purpose of determining whether the limestones belonging to the various divisions of the Paleozoic section possess any marked chemical individuality, such as might indicate essentially different conditions of deposition or influence the subsequent deposition of ores, typical specimens from each of the calcareous divisions were subjected to partial chemical analysis. The results are shown in the following table:

Partial analyses of Paleozoic limestones.

[W. F. Hillebrand, analyst.]

	I.	II.	III.	IV.	V.
SiO_2	11.80	12.53	8.52	0.06	2.52
Al_2O_3	a2.15	a1.04	a.64	a.12	a.24
Fe_2O_3 / FeO b	1.08	1.26			
MgO	.48	17.41	.55	.13	.46
CaO	45.86	27.28	50.07	55.80	53.68

a Includes TiO_2 and P_2O_5, if present. b Calculated as Fe_2O_3.

I. Representative specimen of Abrigo limestone.
II. Dolomitic phase of Abrigo limestone.
III. Representative specimen of Martin limestone.
IV. Representative specimen of Escabrosa limestone.
V. Representative specimen of Naco limestone.

Evidently the foregoing analyses do not give the average composition of each formation as a whole. The determination of such an average would require elaborate and extensive sampling with that special end in view. The specimens utilized, however, were selected with care as illustrating the preponderant and characteristic lithological aspect of each formation. The greatest difference between analysis given and average composition would probably be found in the case of the Abrigo formation, which contains a considerable bulk of chert and shale unrepresented in the present comparison.

It appears from the analyses that the typical white crinoidal limestone of the Escabrosa formation is very nearly pure, containing over 99 per cent of calcium carbonate. The Naco, Martin, and Abrigo limestones are successively more siliceous and contain more alumina and iron oxides, but they consist essentially of calcium carbonate, and the latter two are less impure than might have been expected from their color and appearance. Although the Abrigo limestone locally exhibits dolomitic phases, it, like the other Paleozoic limestones of the quadrangle, is in the main practically free from magnesia.

MESOZOIC SEDIMENTS.

GENERAL STATEMENT.

The Mesozoic era is represented in the Bisbee quadrangle by a thick accumulation of conglomerate, sandstone, shale, and limestone which has been named the Bisbee group, and is of Cretaceous age. It is probable that Jurassic and Triassic strata are entirely absent.

BISBEE GROUP.

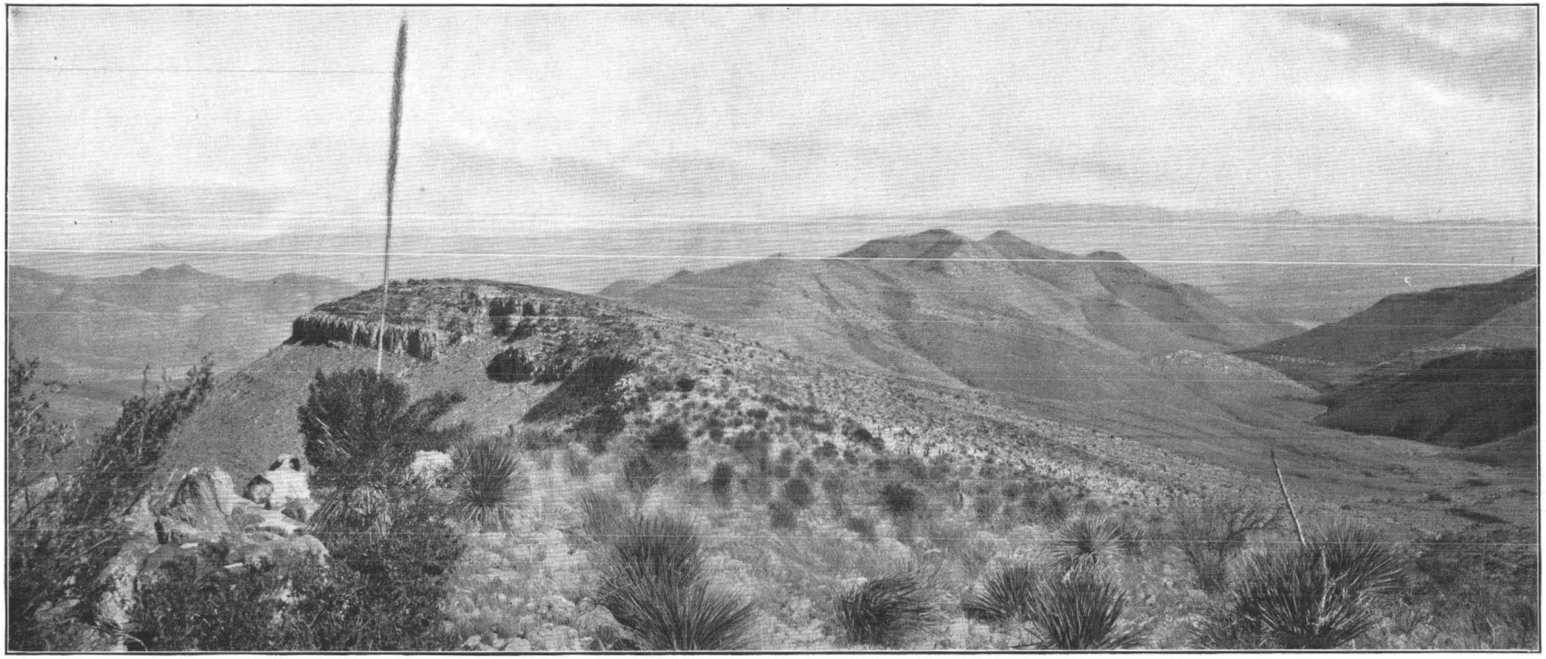
NOMENCLATURE AND SUBDIVISIONS.

In 1902 Dumble[a] described under the name *Bisbee beds* an assemblage of arenaceous and calcareous strata near Bisbee, assigning to them a thickness of about 3,000 feet and referring them on satisfactory paleontological evidence to the Cretaceous. This, so far as I am aware, was the first recognition of Cretaceous beds in the Mule Mountains. In the present report Dumble's name has been retained as the *Bisbee group*, a group divided into four formations. The lowest of these, the Glance conglomerate, derives its name from Glance, a station on the El Paso and Southwestern Railroad, near the Glance mine. The overlying Morita formation is named from the Morita Hills, lying just south of the international boundary, between longitudes 109° 45′ and 109° 50′. The Mural limestone, overlying the Morita formation, is so called from Mural Hill, east of Bisbee. The topmost member of the group, the Cintura formation, derives its name from Cintura Hill, near the northern edge of the quadrangle. The local upper limit of the Cintura formation and of the Bisbee group is a surface of Quaternary erosion. The definition of the group is therefore left somewhat elastic as concerns its upper part, in the hope that future work in southeastern Arizona will discover the relation of the Bisbee group to possible stratigraphic representatives of upper Cretaceous or Tertiary time.

Beds belonging to this group are known to enter largely into the structure of the Mule Mountains, north of the area here studied; they have been noted in great thickness by Dumble[b] south of Rucker Pass, in the Chiricahua Range, and very probably occur in the San Jose Mountains, southwest of Naco.

The sequence and thickness of the various formations making up the group as it occurs in the Bisbee quadrangle are graphically represented in the generalized columnar section of Pl. XII. As there shown the total thickness of the Cretaceous beds in the Mule Mountains probably exceeds 4,750 feet.

[a] Dumble, E. T., Notes on the geology of southeastern Arizona: Trans. Am. Inst. Min. Eng., vol. 31, 1902, pp. 696–715.
[b] Ibid., p. 706.



VIEW NORTHEAST FROM RIDGE EAST OF BISBEE, SHOWING THE TOPOGRAPHY ASSOCIATED WITH THE BISBEE GROUP.

On the right is Mexican Canyon, on the left Dixie Canyon. In the foreground is the Mural limestone, which appears also in the distant hills to the left, and, as the result of faulting, low down in Mexican Canyon. Overlying the Mural limestone is the Cintura formation. In the distance is the broad Sulphur Spring Valley, bounded on the east by the Chiricahua Range.

GENERAL DISTRIBUTION.

The rocks of the Bisbee group outcrop in a broad belt, of generally northwest and southeast trend, occupying much of the northeastern and eastern portions of the quadrangle. From Juniper Flat to Gold Hill this belt is bounded to the southwest by the sinuous line defining the unconformable contact of the Glance conglomerate with the pre-Cretaceous rocks, while on the east the beds pass unconformably beneath the Quaternary detritus covering the floor of Sulphur Spring Valley. South of Gold Hill the Bisbee sediments are divided by overthrust faults into separate blocks, which together form a belt about 6 miles in width, bounded on the east, west, and in good part on the south by Quaternary deposits. The general aspect of the Bisbee group as exposed in the hills northeast of Bisbee is illustrated in Pl. IX, *B*, and Pl. XIII.

GLANCE CONGLOMERATE.

Distribution, thickness, and general stratigraphy.—The basal member of the Bisbee group is well exposed just north of Bisbee as a distinctly bedded red-brown conglomerate, from 50 to 75 feet in total thickness, resting upon a pre-Cretaceous surface of erosion carved upon the Pinal schist. This old surface is in this part of the quadrangle a nearly even plain which has been tilted about 15 degrees to the east, and which, as it emerges from beneath the Glance conglomerate, is recognizable as a well-marked topographic bench formed by the tops of the schist ridges north of Bisbee and by the gently inclined surface of Juniper Flat. (Pl. XIV, *A*.) The conglomerate continues northwestward, retaining a fairly constant thickness to within a mile of the northern edge of the quadrangle, where it rather suddenly thins out, and for a distance of about 1,500 feet is wanting, the Morita formation resting directly upon the granite. The conglomerate comes in again, however, toward the north and continues beyond the bounds of the quadrangle. Toward the southeast the conglomerate, interrupted by some faulting and becoming rather thinner, extends to Mule Gulch, where it is offset to the west by a series of post-Cretaceous faults.

South of Mule Gulch a marked change occurs in the formation. Instead of resting as a smoothly spread and rather thin deposit upon a nearly plane surface, the Glance conglomerate becomes exceedingly variable in thickness and fills the hollows in a buried topography scarely less diversified than that in the vicinity of Black Gap at the present day. North of the gap the conglomerate occupies an irregular basin. (Pl. XV, *A*.) It probably attains a local thickness of over 500 feet in the deepest part of this depression, and must formerly have been considerably thicker.[a] Hills of Paleozoic limestone project through the conglom-

[a] A diamond-drill hole put down by the Junction Development Company, 1½ miles southeast of Bisbee, since this report was written, is reported to have gone down 653 feet in the Glance conglomerate. It then penetrated mineralized granite-porphyry for 70 feet, when boring was temporarily suspended.

erate at several points, notably a mile northeast of Black Gap, where there is excellent opportunity of studying the relation of the Glance formation to the irregular pre-Cretaceous surface upon which it lies. (See Pl. XIV, *B*.) A similar conglomerate-filled depression forms the head of Gold Gulch, the conglomerate in all probability attaining here a local thickness of over 200 feet.

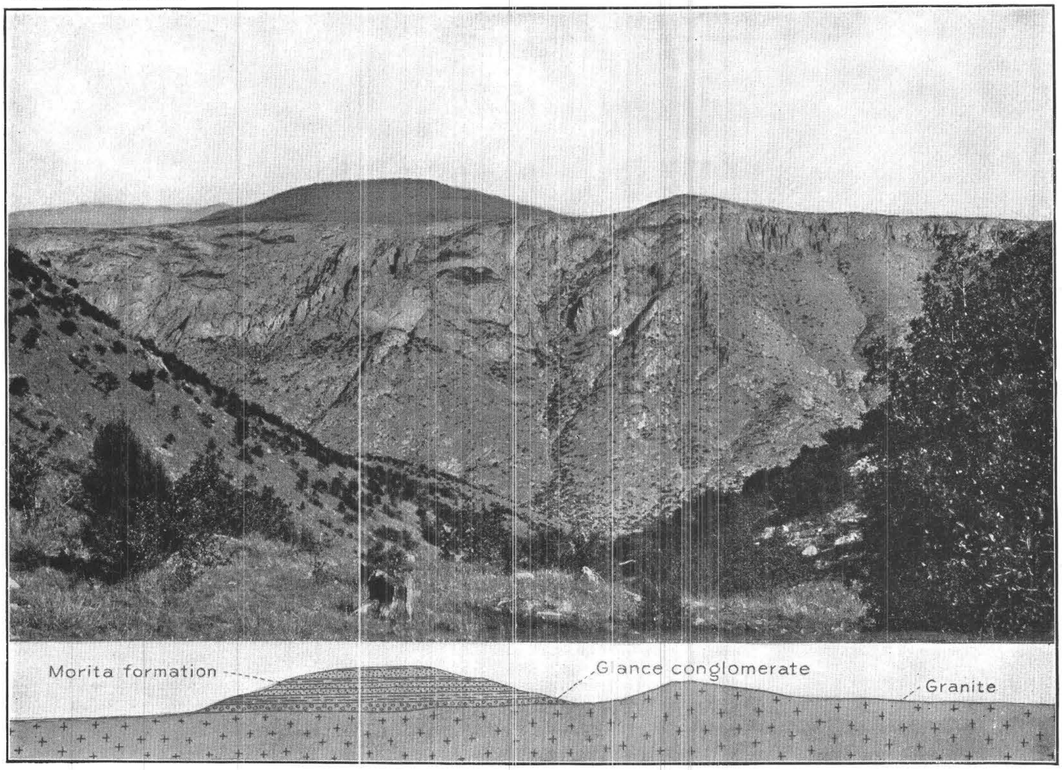
This contrast between the pre-Cretaceous topography north and south of Mule Gulch is a very striking feature, the origin of which will be discussed in succeeding pages.

Northwest of Gold Hill the conglomerate dips generally to the east or northeast, at angles ranging from 10° to 20°. At Gold Hill, however, the beds are overridden by an overthrust block of Paleozoic limestone (Pl. XXI), and are locally turned up to a nearly vertical position in a compressed and slightly overturned anticline.

About 1½ miles southeast of Gold Hill the belt of conglomerate thus far described is cut off by a fault.

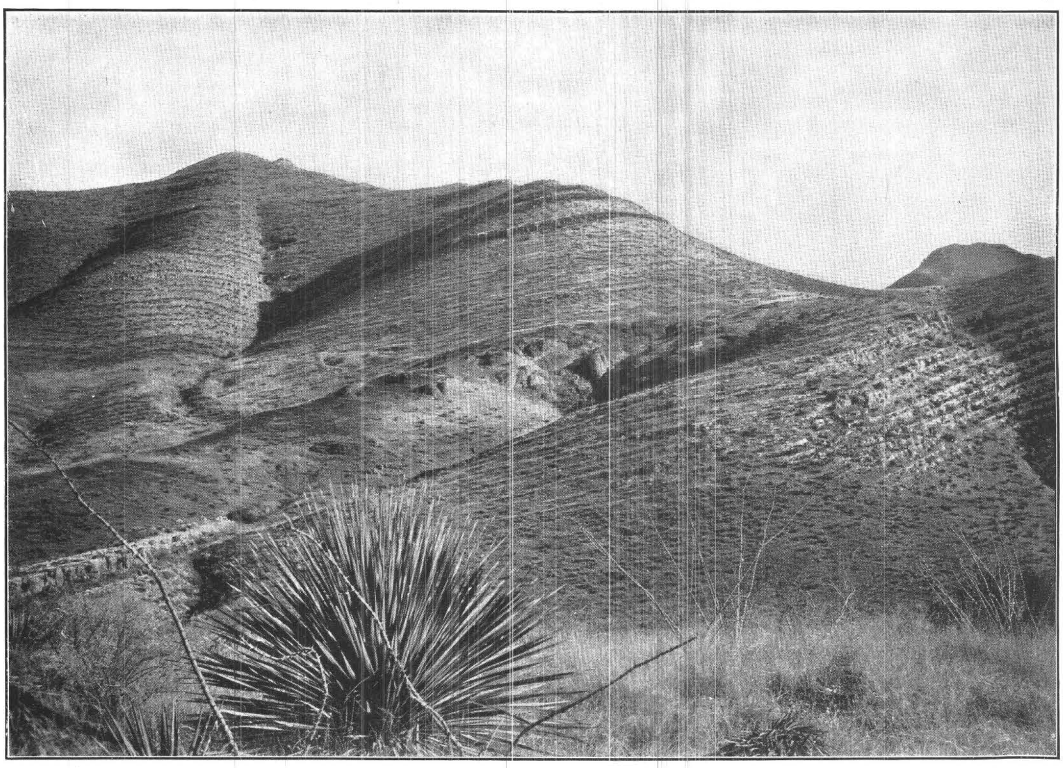
The area of Glance conglomerate stretching southward from Gold Hill into Mexico presents by far the most extensive exposure of this formation within the quadrangle. Like the areas at the head of Gold Gulch and north of Black Gap, it probably rests upon an unevenly eroded surface of Paleozoic limestones, which in turn form part of the great fault block that has been thrust bodily northeastward over the belt of Glance conglomerate and Morita formation lying on the northeast side of the dislocation. Toward the southwest, near Johnson's and Armstrong's ranches, the conglomerate passes with southwesterly dip beneath the conformably overlying Morita formation. On the northeast the contact between the conglomerate and the Paleozoic limestones is seldom exposed. In some places there appears to have been faulting between the Cretaceous and older rocks, while elsewhere the conglomerate apparently reposes undisturbed upon the slopes against which it was originally deposited. The thickness of the conglomerate is probably greater in this area than elsewhere in the quadrangle. At the Glance mine a shaft was sunk to a depth of 500 feet before reaching the bottom of the conglomerate, and as the same rock with gentle easterly dip forms a hill just west of the mine and rising 400 feet above the collar of the shaft, the total thickness of the formation is probably at least 600 feet. As a whole the conglomerate beds of this area form a gently flexed anticline (see the structure sections, Pl. I), with a nearly northwest-southeast axis. The two narrow exposures of Naco limestone between Johnson's ranch and the Glance mine are plainly old eroded ridges which formed part of the irregular surface upon which the conglomerate was laid down and which are now again exposed by erosion along the crest of the low post-Cretaceous anticline.

Near the overthrust fault, which is defined topographically by the open



A. GRANITE MASS OF JUNIPER FLAT FROM ESCABROSA RIDGE.

Shows outliers of Cretaceous strata resting upon an even surface of erosion.



B. GLANCE CONGLOMERATE RESTING UPON IRREGULARLY ERODED NACO LIMESTONE 1 MILE NORTHEAST OF BLACK GAP.

The conglomerate is thickest at the left side of the picture and thinnest in the saddle on the right. The summit of Gold Hill is visible through the saddle.

valley between Glance station and Christianson's ranch, the beds of conglomerate have a local southwest dip and are in places nearly vertical. They thus form a narrow syncline along the northeast border of the main anticline.

The only other area of Glance conglomerate that requires particular mention is a small one (superficially divided in two by a strip of Quaternary material) occurring about a mile notheast of Glance station, on the edge of Sulphur Spring Valley. This also lies upon the back of an overthrust block of Paleozoic (Naco) limestone, which has been shoved, in this case from the east, over the Cretaceous (Mural) limestone.

Lithology.—The pebbles and fragments that make up the Glance conglomerate have been derived from the pre-Cretaceous rocks of the region, and have, as a rule, undergone no considerable transportation. To a certain extent, therefore, the distribution of the derivative materials of the conglomerate corresponds with the areal disposition of the underlying rocks which supplied the conglomeratic detritus. It is thus rather difficult to characterize the formation as a whole, although its identification seldom presents any difficulty. The most constant features are fairly distinct bedding, imperfect rounding of the pebbles, considerable induration, and a prevalent reddish color—particularly of the matrix. The other and more variable lithological characters may best be exhibited by describing actual occurrences of the conglomerate and noting the changes that appear as the formation is followed across the quadrangle from its northern to its southern border.

At the northern edge of the quadrangle the Glance conglomerate rests upon granite and is composed of rather angular fragments of this rock mingled with bits of vein quartz. On Juniper Flat fragments of schist become abundant, and on the east side of Soto Canyon they make up by far the greater part of the conglomerate. With them, however, are associated occasional pebbles of granite, granite-porphyry, limestone, dark chert, and vein quartz. At the head of Brewery Gulch, just north of Bisbee, the Glance formation comprises several rather irregular beds of dark red-brown conglomerate containing lenses of red sandstone and shale. Imperfectly rounded pebbles of schist preponderate. These are occasionally as much as 8 inches in diameter, but are usually smaller—the average being perhaps 2 or 3 inches. These are embedded in a dark-red sandy matrix evidently derived from the disintegration of Pinal schist. The coarser material predominates in the lower part of the formation, while the increasing proportion of sandstone and shale in the upper part produces the effect of a partial transition into the overlying Morita formation.

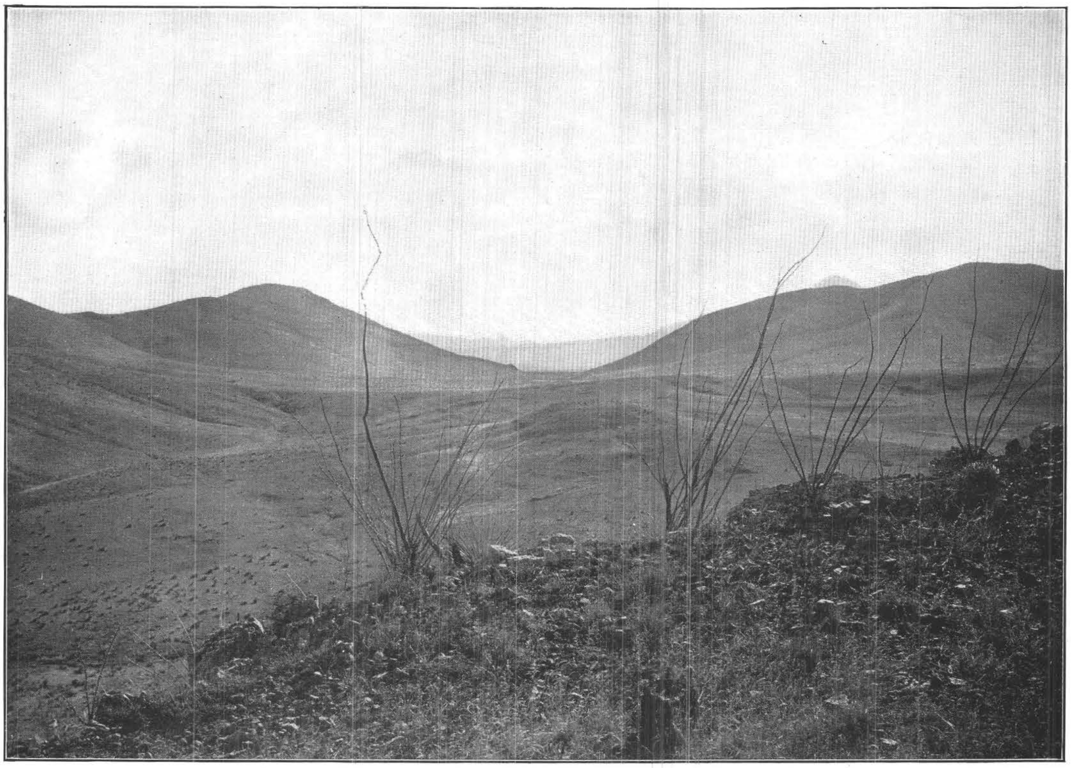
The conglomerate forming the area north of Black Gap and at the head of Gold Gulch is generally of a dull, dark-red color and is made up principally of schist fragments, as may be well seen along the various roads running south from

Bisbee, and in the excellent exposures on the divide a mile northwest of Gold Hill. (Pl. XV, *B.*) At the latter locality were observed several slightly waterworn blocks of the schist which were fully 18 inches across, and a few which measured 3 feet in diameter. As the rock underlying this mass of conglomerate is the Naco limestone, the schist fragments which compose the bulk of the material must have been derived from areas of Pinal schist lying immediately to the north and east, and now largely buried beneath the Cretaceous beds. Not all of the conglomerate, however, is of schist derivation, for wherever hills of limestone protrude through the Glance formation and along the southwestern border of the basin, it is found that the lower part of the deposit is composed of blocks of limestone firmly cemented with the usual reddish matrix. These angular fragments and imperfectly rounded limestone pebbles were evidently derived from the immediately underlying Naco limestone. They lay upon the limestone hill slopes, or formed talus heaps against small cliffs, as may be seen a mile northeast of Black Gap, and after slight reworking by the waves of the Cretaceous sea were buried beneath the abundant schist detritus carried into the basin from the north and east.

The belt of conglomerate which passes from the head of Gold Gulch through the saddle northeast of Gold Hill and thence eastward toward Black Knob contains some beds of grit and shale associated with the usual coarser conglomerate. The pebbles of the latter are principally schist and granite (or granite-porphyry) with some limestone.

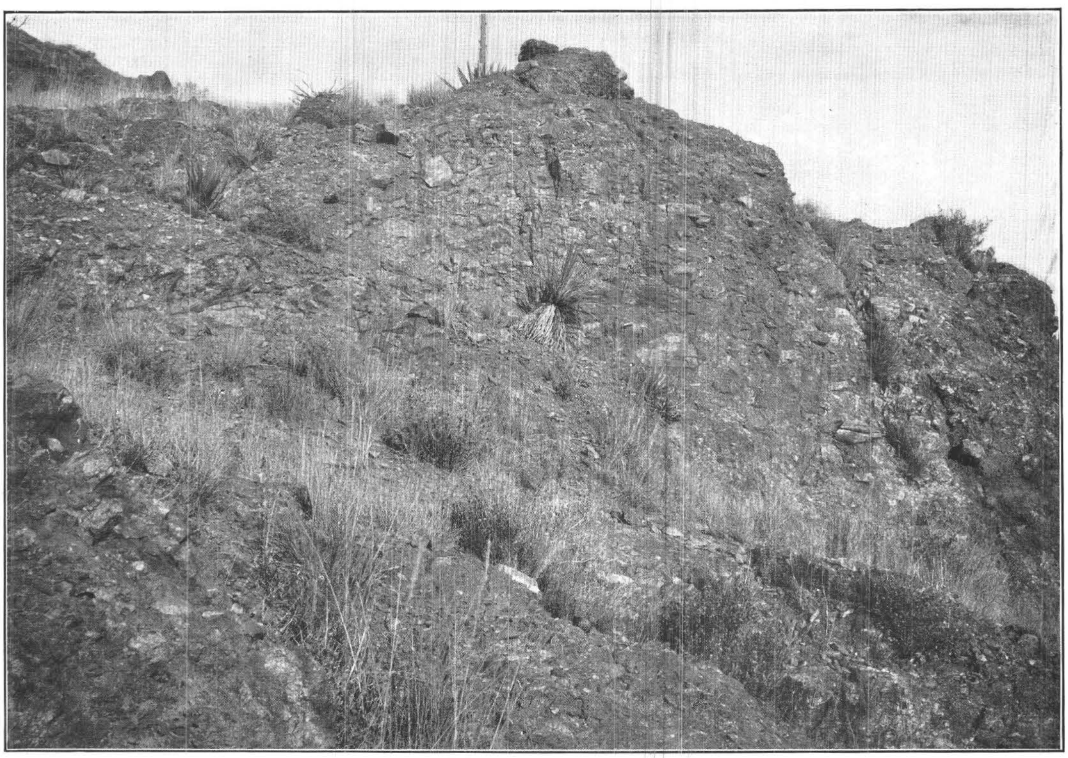
The low hills stretching southward from Gold Hill to the international boundary are carved from conglomerate similar in general appearance to that north of Black Gap. Pebbles of schist, quartzite, granite, granite-porphyry, and vein quartz were noted, and the fragments of schist in particular sometimes make up a considerable part of the upper beds, as in the vicinity of Johnson's ranch and in the lower part of Gold Gulch. But near the Glance mine and along the line of the El Paso and Southwestern Railroad the formation is mainly composed of beds made up almost exclusively of pebbles of limestone embedded in a reddish matrix which effervesces freely with acids and is evidently also composed of detritus derived chiefly from limestones. Good exposures of these limestone conglomerates are found in the railroad cuts and along the sand-scoured rocky bed of Glance Creek. It can be seen that these limestone conglomerates sometimes alternate with beds of schist conglomerate like those described north of Black Gap.

The calcareous pebbles of this area of the conglomerate have been derived mainly from the Carboniferous limestones, particularly the Naco limestone, which is known to underlie a portion of the beds. The schist fragments were



A. VIEW SOUTHWARD FROM MULE GULCH THROUGH BLACK GAP, SHOWING BASIN FLOORED WITH GLANCE CONGLOMERATE.

The hills on either side of the gap are formed from Paleozoic limestones. Beyond them stretches Espinal Plain to the foot of the San Jose Mountains, whose dominant peak appears on the sky line to the right of the gap.



B. GLANCE CONGLOMERATE AS EXPOSED 1 MILE NORTHWEST OF GOLD HILL.

The angular pebbles or fragments are mostly of schist, and range from a fraction of an inch to 3 feet in length.

undoubtedly supplied by the Pinal schist, but whether they came from the known areas north of Mule Gulch or from ancient exposures in the southern part of the quadrangle now concealed by Cretaceous or Quaternary deposits is not known. Similar uncertainty obtains in regard to the pebbles of quartzite and granite-porphyry. The Bolsa quartzite and the granite-porphyry intrusions of the northern half of the quadrangle could supply such materials, but it is not known whether the masses of these rocks now exposed were the actual sources of the conglomeratic material in the southern part of the quadrangle.

The small area of Glance conglomerate lying northeast of Glance station is composed almost exclusively of rather coarse fragments of Carboniferous limestone, sometimes containing fossils. These imperfectly rounded pebbles are firmly embedded in a compact, reddish, calcareous matrix of the same character as that cementing the conglomerates between Gold Hill and the Glance mine.

Conditions of deposition.—The Glance conglomerate is a coarse littoral deposit laid down along a marine shore line that rapidly encroached upon the land as a consequence of the latter's subsidence. The comparative rapidity of the submergence is shown by the variable size and very incomplete rounding of the pebbles. These were evidently subjected for a brief time only to the wear of the waves and were then buried beneath the fine gravels, sands, and muds of the Morita formation. Further evidence that the subsidence was, locally, at least, a geologically rapid movement is found in the hilly topography that underlies a considerable part of the Glance formation. The pre-Cretaceous surface sank beneath the waves before the latter could reduce its inequalities by planation or do more than slightly rework the stony detritus that littered its slopes and lay in its hollows.

The final result of the deposition of the Glance conglomerate was to level up the pre-Cretaceous topography, which must have exhibited differences in elevation amounting to at least 600 feet, to a smooth sea bottom upon which afterwards accumulated the regular beds of the Morita formation. The filling necessary to effect this leveling was, however, as has already been pointed out, much greater in the southern half than in the northern half of the quadrangle, and some explanation of the abrupt change which occurs along the line of Mule Gulch is demanded in order to fully understand the manner in which deposition proceeded.

If the Cretaceous beds could be restored to their original nearly horizontal position and then be entirely removed, we should see exposed the old surface upon which they were laid down. In the northern part of the quadrangle this surface would be a nearly level plain of erosion floored with Pinal schist, granite, and granite-porphyry. In the vicinity of the present Mule Gulch the plain would terminate, and one standing upon its edge would overlook to the south a lower country diversified by hills of light-hued Paleozoic limestones. What geological events, it may be asked, resulted in this association of elevated plain and hilly lowland? Was the plain formed prior to submergence by ordinary subaerial erosion at a generally lower level than the neighboring limestone hills, and was it subsequently elevated with reference to the latter by faulting? Or was it cut during the subsidence by the combined attack of rain, streams, and waves upon the highest portion of the land mass and the last to be covered by the sea?

Reference to the geological map of the quadrangle (Pl. I) shows that the line of abrupt change between the comparatively thin uniform layer of conglomerate on the north and the locally thick and variable conglomerate on the south coincides with a line of faulting which brings the Naco limestone against small remnants of the Bolsa quartzite resting upon the Pinal schist, and which is the easterly continuation of the great Dividend fault (see p. 85) which passes through the town of Bisbee. It is probable, therefore, that this fault had a direct influence upon the development of the pre-Cretaceous topography. As is elsewhere shown (p. 92) the main displacement along this fissure was accomplished before the intrusion of the porphyry and consequently before the Cretaceous submergence. But there has also been a revival of movement along the fault since the Glance conglomerate was deposited, as may be seen from the offsetting of the latter formation along Mule Gulch.

It seems probable, in the light of all the known facts, that the deposition of the Glance conglomerate was preceded and conditioned by the following train of events: After the main dislocation of the Dividend fault, subaerial erosion continued to degrade the region until nearly all of the Paleozoic rocks had been stripped from the up-faulted northeastern half of the quadrangle, and the pre-Cambrian schists, with their included granitic intrusives, laid bare as a broad and topographically simple ridge, whose upper surface was nowhere greatly above or below the surface of the denuded Cambrian peneplain upon which the Bolsa quartzite had been deposited. The southeastern half of the quadrangle, on the other hand, with its intricate structure of down-faulted Paleozoic beds, was carved into a complex hilly topography, standing as a whole somewhat lower than the schistose terrane to the northeast. The region was then rather rapidly submerged, until the schists and granite of the northeastern part of the quadrangle alone stood above the sea. During this subsidence the calcareous conglomerates of the Glance formation accumulated over the uneven surface of the Paleozoic rocks. Possibly, also, renewed movement along the Dividend fault may have somewhat accentuated the physiographic boundary between the northeastern and southwestern parts of the quadrangle. There was probably at this stage a retardation of the general subsidence, while the waves and streams attacked the still projecting schist mass, and gradually reduced it to sea level, the material derived from its degradation helping to level up the hollows in the region that had been carried down in the more rapid sinking, and finally accumulating as a relatively thin deposit over the last land to become sea bottom. With the entire submergence of the region embraced by the quadrangle the deposition of the Glance conglomerate came to an end and was succeeded by that of the Morita formation, whose materials were probably derived from a source outside of the district here described.

MORITA FORMATION.

Distribution, thickness, and general stratigraphy.—The Morita formation is exposed within the Bisbee quadrangle in two main areas—one an irregular belt traversing the quadrangle almost diagonally from its northern edge to its southeastern corner, the other a much shorter parallel strip lying west of Gold Gulch near Armstrong's ranch, 5 miles east of Naco.

In the former and larger area the beds dip generally east-northeast in the northern part of the quadrangle, at angles ranging from 15° to 20°. The strata, however, are not merely tilted, but frequently exhibit slight undulatory folds with northwest-southeast axes. In the neighborhood of Mule Gulch the strike of the beds becomes nearly northwest and southeast. The dip is generally to the northeast, but varies from about 15° in the lower beds near the Glance conglomerate to about 60° in the higher beds close to the Mural limestone.

The hills between Gold Hill and the Easter Sunday mine are carved from the Morita formation. Near the Gold Hill overthrust, the beds are upturned until they are practically vertical (Pl. XXII); but the normal dip of 20° to 25° to the northeast prevails along the main ridge and continues to within a short distance of the Easter Sunday mine, where the angle of dip again increases until an inclination of 55° is attained near the base of the Mural limestone. These relations are shown in structure-section CC, Pl. I.

At about the line of this section, the strike of the beds again swings into a nearly north-northwest to south-southeast direction, which is retained to the southern edge of the quadrangle. Northeasterly dips of from 20° to 35° prevail in this portion of the area, except along its southwest border, where the beds are locally disturbed in the vicinity of the Gold Hill overthrust fault.

The beds of the second area of the Morita formation—that surrounding Armstrong's ranch—have the same general strike as those between the Glance mine and Christianson's ranch. Their dip, however, is southwesterly, at an angle of about 15°. They conformably overlie the Glance conglomerate of Gold Gulch, and underlie the Mural limestone of the low hills 4 miles east of Naco. Were it not for the complication introduced by the Gold Hill overthrust they might be considered simply as the southwestern limb of a low anticline, of which the beds southeast of Glance form the northeastern limb.

The thickness of the Morita formation, as measured in the excellent exposures north and east of Bisbee, is 1,800 feet; but the beds thicken to the south.

Lithology.—The Morita formation comprises uniformly alternating beds of dull-red shales and red or tawny sandstones, with occasional layers of grit and lenses of impure limestone. Although some of the strata are 10 or 15 feet in thickness, the formation as a whole is characterized by beds of moderate thickness—usually less than 4 feet. The general landscape tints are dull red or yellowish brown, dependent upon the local predominance of the red or tawny beds. As a rule, the red color prevails near the base and the yellow tones in the upper part of the formation.

The red shales are finely arenaceous, and not particularly fissile. In fact, when they have not been exposed to the weather, they are tough, compact rocks with no distinct cleavage. The cementing material is calcite, as shown by the free effervescence of the shale in dilute acid. Little, light-gray, concretionary, calcareous nodules are a characteristic feature of the red shale. They are particularly conspicuous on weathered surfaces, and might readily be mistaken at first glance for pebbles of limestone. In the upper part of the formation the red shales become still more calcareous. The gray nodular concretions increase in abundance, and occasional thin beds or lenses of compact gray limestone appear within the shales, into which they grade above and below. The limestone lenses are not fossiliferous as a rule, although in some of the sections exposed northeast of Bisbee and in the little hills southwest of Armstrong's ranch they contain molluscan fossils of the same types as those occurring near the base of the overlying Mural limestone.

The sandstones alternating with the shales frequently show cross bedding, and range in color from reddish brown to buff. They are usually fairly hard, fine-grained rocks, in which the original sand grains have been cemented by calcite. In the upper part of the formation, however, are occasionally hard tawny to buff-colored beds, in which quartz is the cementing material. These might therefore properly be called quartzite. Microscopical examination of a representative specimen of the sandstone shows it to consist of incompletely rounded grains of quartz, frequently showing crystal enlargement by the growth of new quartz upon the worn particles, and a few fragments of plagioclase. The interstices between the detrital grains are filled with crystalline calcite.

About 1200 feet above the base of the Morita formation occurs a bed of reddish-brown grit from 10 to 15 feet in thickness, but otherwise there is no marked interruption in the monotonous repetition of sandstones and shales extending from the top of the Glance conglomerate to the bottom of the Mural limestone.

Between the Morita formation and the Mural limestone, next to be described, there exists no sharp natural boundary. The dominantly arenaceous Morita beds pass upward through transitional phases into the dominantly calcareous Mural limestone. The divisional plane chosen for descriptive purposes is that defined by the upper surface of a bed of hard buff sandstone or quartzite, which, as may be seen from the geological map (Pl. I), outcrops from beneath the Mural limestone to the east of Bisbee in such a manner as to find topographic expression in a series of little bench-like spurs, easily recognized by anyone looking along the general line of contact of the two formations. (See Pl. IX, *B.*) Immediately overlying this sandstone is a bed of dark impure limestone made up in considerable part of broken shells, chiefly *Ostrea.* The divisional plane marks practically the upper limit of the sandstones and red shales, although, as we have seen, it does not absolutely define the lowest appearance of fossiliferous limestones.

Conditions of deposition.—The Morita formation is clearly a shallow-water deposit, representing the transition during continued subsidence from the littoral conditions under which the Glance conglomerate accumulated to those of moderately deep water in which the medial beds of the Mural limestone were quietly deposited. Materials such as compose the Morita beds are rarely transported to greater depths than 600 feet, and, as the total thickness of the formation is 1,800 feet, it may be concluded that sedimentation kept fairly even pace with subsidence.

The actual source of the Morita sediments is unknown. It is evident that the Pinal schist contributed detritus to the basal beds, since the latter contain occasional visible fragments of schist, and are not to be sharply distinguished as regards lithological materials from the Glance conglomerate. But as it is probable that all of the schist within the limits of the quadrangle was covered by the Glance conglomerate before any considerable part of the Morita beds was laid down, the land mass that furnished the sands and muds now consolidated as the Morita formation evidently lay outside of the area under investigation. Paleontological evidence, as will be later seen, indicates that the general shore line at this time was to the west.

MURAL LIMESTONE.

Distribution, thickness, and general stratigraphy.—As one approaches Bisbee through the southern passes, particularly when the noonday glare has softened into the shadows of evening and the sculptured beauty of the hills is compensation for their barrenness, he is confronted by a prominent light-gray cliff crowning Mural Hill and stretching like a rampart along the face of the ridge northeast of town. (Pl. IX, *B.*) This cliff, giving scenic distinction to otherwise rather prosaic hills, is formed by a portion of the Mural limestone. Below the cliff,

weather out readily, and the tough, compact nature of the matrix renders their collection difficult. One or more species of *Ostrea*, in individuals up to 7 inches in length, are abundant, particularly in the very thick beds at the base of this upper member, while in the higher beds the little disk-like *Orbitolina texana* is very common and is associated with the so-called *Caprina occidentalis*, the large gasteropod *Lunatia pedernalis*, and a coral of the genus *Astrocœnia*. Casts were seen which suggested the occurrence of a large *Requienia*, but no distinct shells

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Distribution, thickness, and general stratigraphy.—As one approaches Bisbee through the southern passes, particularly when the noonday glare has softened into the shadows of evening and the sculptured beauty of the hills is compensation for their barrenness, he is confronted by a prominent light-gray cliff crowning Mural Hill and stretching like a rampart along the face of the ridge northeast of town. (Pl. IX, *B*.) This cliff, giving scenic distinction to otherwise rather prosaic hills, is formed by a portion of the Mural limestone. Below the cliff, which varies from 50 to 200 feet in height, is a smooth steep slope of about 200 feet from top to bottom, and at the foot of this slope a line of projecting spurs marking the outcrop of the topmost bed of the Morita formation. The cliff and slope are genetically related and are the topographic expression of the resistance to erosion of certain thick, hard beds composing the upper part of the Mural limestone, and the ready disintegration of some thin impure limestones in its lower part.

If we disregard local concealment by the Quaternary deposits and some irregularities due to faulting, the Mural limestone is exposed in a relatively narrow belt which, entering the quadrangle at about the middle point of its northern boundary, pursues a southerly course until it reaches the latitude of Bisbee. Thence it sweeps southeast to the edge of Sulphur Spring Valley, and again curving southward maintains a south-southeast course until it passes out of the southeast corner of the quadrangle into Mexico.

On the north the Mural limestone, like the beds of the Morita formation, dips generally to the northeast at angles ranging from 10° to 20°. The breadth of the outcrop in the vicinity of Dixie Canyon is due to this low angle of dip, to the presence of some shallow folds with northwest-southeast axes, and to minor faulting. At the point where the beds turn southeast toward Mule Gulch the dip becomes steeper, and where the limestones are crossed by the road to Forrest's ranch they attain a maximum dip of 65° to the northeast. Southeast of the Easter Sunday mine the dip decreases until it is from 20° to 30°. The unusually steep dip of the Mural limestone near Mule Gulch is associated with dips nearly as great in the adjacent Morita and Cintura beds. The inclination of these beds rapidly diminishes, however, both to the northeast and to the southwest, away from the Mural limestone, the latter exhibiting the maximum effect of this local upturning of the strata.

A mile northeast of Glance station the Mural limestone is partly covered by a fault block of Naco limestone that has been thrust over it from the east.

In addition to the principal area just described, the quadrangle contains several smaller exposures of the Mural limestone. Such are the small hills rising out of the Quaternary deposits near the eastern edge of the quadrangle, opposite the mouth of Glance Canyon. The beds forming these hills dip to the southwest and constitute the western limb of an anticline, the other limb being partly represented by similar hills projecting above the Quaternary deposits farther east. Another small area is that near Boundary Monument 91, 4 miles east of Naco. The strata here conformably overlie the Morita beds of the Armstrong's ranch area, and dip to the southwest. They continue southeastward into Mexico. The last area to which attention need be particularly directed lies a little less than a mile southeast of Gold Hill. It is a small block, bounded by faults. The interesting questions presented by the occurrence of a little isolated mass of Mural limestone at this place will be considered in the section devoted to geological structure.

Lithology.—Although mapped as a unit, the Mural limestone, with a thickness of 650 feet, is divisible into at least two stratigraphic members—a lower portion, about 300 feet in thickness, comprising thin-bedded impure limestones, and an upper portion 350 feet thick in which relatively thick-bedded and pure limestones predominate. The lower member is represented topographically by the smooth under-cliff slope. Its exposures are seldom conspicuous, and show subdued greenish-yellow, dark-green, brownish, or gray tints. The top beds of the lower member are usually buff sandstones, which may have a total thickness of 25 feet. Below these are rather soft thin beds of sandy limestone, sometimes grading into cross-bedded highly calcareous sandstone, with occasional thicker beds of dark-gray shell limestone, composed almost entirely of oyster shells (*Ostrea*). Molluscan remains are plentiful in certain of these beds, although not always well preserved. The genera most commonly represented are *Ostrea*, *Turritella*, *Lunatia*, *Cyprina*, *Trigonia*, and in one highly fossiliferous bed exposed just northeast of Monument 91, on the international boundary, well-preserved individuals of *Pecten stantoni* are abundant. Exceptionally favorable localities for making collections of representative fossils of the Bisbee group are found in the nearly isolated and faulted area of Mural limestone 2½ miles northeast of Bisbee, on the slopes beneath the cliffs in the vicinity of Mural Hill, and on the northeast side of the little group of hills 4 miles east of Naco.

The upper member of the Mural formation, unlike the lower beds just described, outcrops prominently, usually forming a cliff. The strata range from gray to white, and thus contrast strikingly with the sober red and tawny tints of most of the sediments composing the Bisbee group. At the bottom, resting upon the buff sandstone at the top of the lower member, are two or three beds of hard, gray limestone, which constitute practically a single massive stratum from 40 to 60 feet in thickness. This is the cliff-making portion of the Mural limestone. Above it lie beds of similar lithological character, but distinctly thinner—ranging usually from 6 to 10 feet in individual thickness.

The gray limestones are richly provided with fossils, but these do not weather out readily, and the tough, compact nature of the matrix renders their collection difficult. One or more species of *Ostrea*, in individuals up to 7 inches in length, are abundant, particularly in the very thick beds at the base of this upper member, while in the higher beds the little disk-like *Orbitolina texana* is very common and is associated with the so-called *Caprina occidentalis*, the large gasteropod *Lunatia pedernalis*, and a coral of the genus *Astrocœnia*. Casts were seen which suggested the occurrence of a large *Requienia*, but no distinct shells of this genus were found. Part of a well-preserved ammonite in the possession of Mr. W. G. McBride, of Bisbee, and said to have been picked up in Brewery Gulch, may have come from some portion of the Mural limestone exposed at the head of that gulch.

The little hills near the eastern edge of the quadrangle north of Hay Flat are composed mainly of the hard limestones of the upper member of the formation. Some of the beds here contain abundant corals (*Astrocœnia* and another form not collected), "*Caprina*," and a number of little brachiopods (*Rhynchonella*, *Terebratella*, and *Terebratula*) not seen at any other locality in the quadrangle.

The upper member of the Mural formation consisting almost, if not quite exclusively, of gray limestone, is conformably overlain, as a rule, by a bed of rather vitreous buff quartzite. The contact between these two rocks has been chosen as the boundary between the Mural limestone and the Cintura formation. But, as in the case of the Mural limestone and the Morita formation, the division so made is somewhat arbitrary. Limestone strata from 3 to 5 feet in thickness continue to occur in alternation with sandstones and shales throughout the lower 100 or 150 feet of the Cintura formation and occasionally contain *Turritella* and other fossils apparently identical with forms occurring in the Mural limestone.

Conditions of deposition.—The lower member of the Mural limestone represents a period of transition from the sands and muddy silts of the Morita formation to the gray fossiliferous limestones of the upper member of the Mural formation—that is, from terrigenous sediments to deposits formed more or less directly through the agency of marine organisms. The change may have been effected by an acceleration of the general subsidence whereby this portion of the sea became deeper and the shore line was transferred to such a distance as to prevent the influx of detritus derived from the land. But the abundance of *Ostrea* in the limestone, the general similarity of the fauna of the two members of the Mural formation, and the recurrence in the Cintura formation of beds lithologically identical with those of the Morita formation, all tend to indicate that the increase in depth was slight. It is quite possible that the change from arenaceous to calcareous deposition was dependent upon alteration of the configuration of the land of that time, or even upon climatic mutation. But the possible factors in the case are too many and variable to be determined merely from a consideration of the beds as we find them in the Bisbee quadrangle to-day.

CINTURA FORMATION.

Distribution, thickness, and general stratigraphy.—The occurrence of the Cintura formation within the Bisbee quadrangle is limited to a single area which lies along the edge of Sulphur Spring Valley, and extends northward from the vicinity of Forrest's ranch, past Cintura Hill, and beyond the northern boundary of the quadrangle. The beds form a generally very shallow syncline which pitches northeast under the Quaternary deposits of Sulphur Spring Valley, at an angle of about 20°. Near Mule Gulch, along the contact with the Mural limestone, the Cintura strata at the rim of the generally slightly hollowed syncline are locally upturned until they attain a dip of 50°, which, however, rapidly diminishes toward the north.

The total thickness of the beds belonging to the Cintura formation exposed in this syncline is at least 1,800 feet. The original thickness of the formation is unknown, its present upper limit being an irregular surface of Quaternary erosion.

Lithology.—In general lithological character, the Cintura formation is a repetition of the Morita formation. It is characterized by the same reddish, sometimes almost purplish shales, with gray nodular concretions, the same occasional bands of gray limestone, and the same tawny, buff or pinkish cross-bedded sandstones with quartzitic phases. The stratigraphic arrangement of the beds is different, however. Immediately overlying the Mural limestone, there is usually a bed of buff quartzite from 10 to 15 feet in thickness. Then follow from 100 to 150 feet of red shales, thin-bedded sandstones, and arenaceous, gray or greenish limestones. Some of the limestones contain fossils, particularly a *Turritella*, which is apparently identical with the form so abundant in the lower member of the Mural limestone. Upon these transitional beds repose red nodular shales with occasional strata of buff sandstone and very subordinate beds or lenses of impure, greenish nodular limestone, the whole having a thickness of from 700 to 800 feet. The individual sandstone beds sometimes attain a thickness of 6 feet, but are greatly surpassed in volume by the shales. Overlying these dominantly shaly beds are 300 feet of flaggy, cross-bedded gray and buff sandstones with occasional parting layers of red shale. These sandstones usually form a rough cliff or scarp along the hill slopes overlooking Mexican Canyon. They are succeeded in turn by about 600 feet of reddish nodular shales interbedded with flaggy cross-bedded sandstones. One of the latter beds, about 18 inches in thickness, occurring about 1,600 feet above the base of the Cintura formation (or about 200 feet below the present top) has a pale-cream tint and by contact with the darker hue of the rest of the formation is conspicuous as a light band near some of the hilltops east of Grassy Hill.

Conditions of deposition.—Whatever may have been the causes that led to the change from the Morita formation to the Mural limestone, the Cintura formation records a return to conditions similar to those obtaining during the deposition of the Morita sediments. The renewed incursion of terrigenous materials into this part of the Cretaceous sea may have resulted from a slight general uplift, from a local uplift of the land mass whence they were derived, or from a marked change in climate giving greater activity to the processes of erosion and transportation.

AGE OF THE BISBEE GROUP.

The various collections of fossils made during the progress of the field work, chiefly from the Mural limestone, were submitted to Dr. T. W. Stanton, who very kindly furnished the following note concerning them:

NOTE ON THE CRETACEOUS FOSSILS.

By T. W. STANTON.

The collection consists of a considerable number of small lots of fossils with seldom more than three or four species from one locality, and it includes a number of undescribed forms. The known species that are recognized, however, are sufficient to prove that only the fauna of the lower Cretaceous, or Comanche series, is represented in the collection. The identified species all occur in Texas, indicating that the waters in which the Arizona deposits were laid down were directly connected with the Comanche sea of Texas and Mexico, which probably did not extend much farther west than the Bisbee area.[a]

In the Texan region three principal divisions are recognized in the Comanche series, Trinity, Fredericksburg, and Washita. All of the identified species in this collection occur in the Glen Rose beds of the lowest, or Trinity, division and only one of them (*Lunatia pedernalis*) is known to pass up into the lower members of the Fredericksburg division. The following is the list of species referable to the Glen Rose:

Orbitolina texana (Roemer).
Glauconia branneri (Hill).
Lunatia pedernalis (Roemer).
Ostrea sp.
Pecten stantoni (Hill).
Trigonia stolleyi (Hill).
Trigonia n. sp.
Cyprina sp.

The following forms are suggestive of Fredericksburg horizons, possibly as high as the Edwards limestone:

Astrocœnia sp.
Rhynchonella sp.
Terebratella sp.
Terebratula sp.
"Caprina" sp. cf. *C.* occidentalis (Conrad).
Turritella sp. cf. T. seriatim granulati (Conrad).
Actæonella sp. cf A. dolium (Roemer).

The only forms in this list that have much weight are "*Caprina*" and *Actæonella* which are not known in the Texan region below the Fredericksburg division.

It is safe to conclude that the fossiliferous horizon represented by these collections corresponds in large part with the Glen Rose beds of Texas, and that possibly the upper portion is as high as the Edwards limestone; in other words, that they certainly belong to the Trinity division and possibly in part to the Fredericksburg division of the Comanche series.

Mr. Stanton's report thus definitely assigns the Mural limestone to the lower Cretaceous or Comanche epoch. Direct paleontological evidence for as satisfactory a determination of the three other members of the Bisbee group is not obtainable. The conformable sequence of the beds, however, considered in con-

[a] Mr. Stanton informs me that remarkably well-preserved fossils, apparently from horizons near those represented by the Bisbee collections, were obtained by Capt. E. A. Mearns of the Mexican Boundary Survey, in Guadalupe Canyon, about 50 miles east of Bisbee, in the extreme southeastern corner of Arizona.—F. L. R.

PLATE XVI.

PLATE XVI.

CRETACEOUS FOSSILS CHARACTERISTIC OF THE BISBEE GROUP.

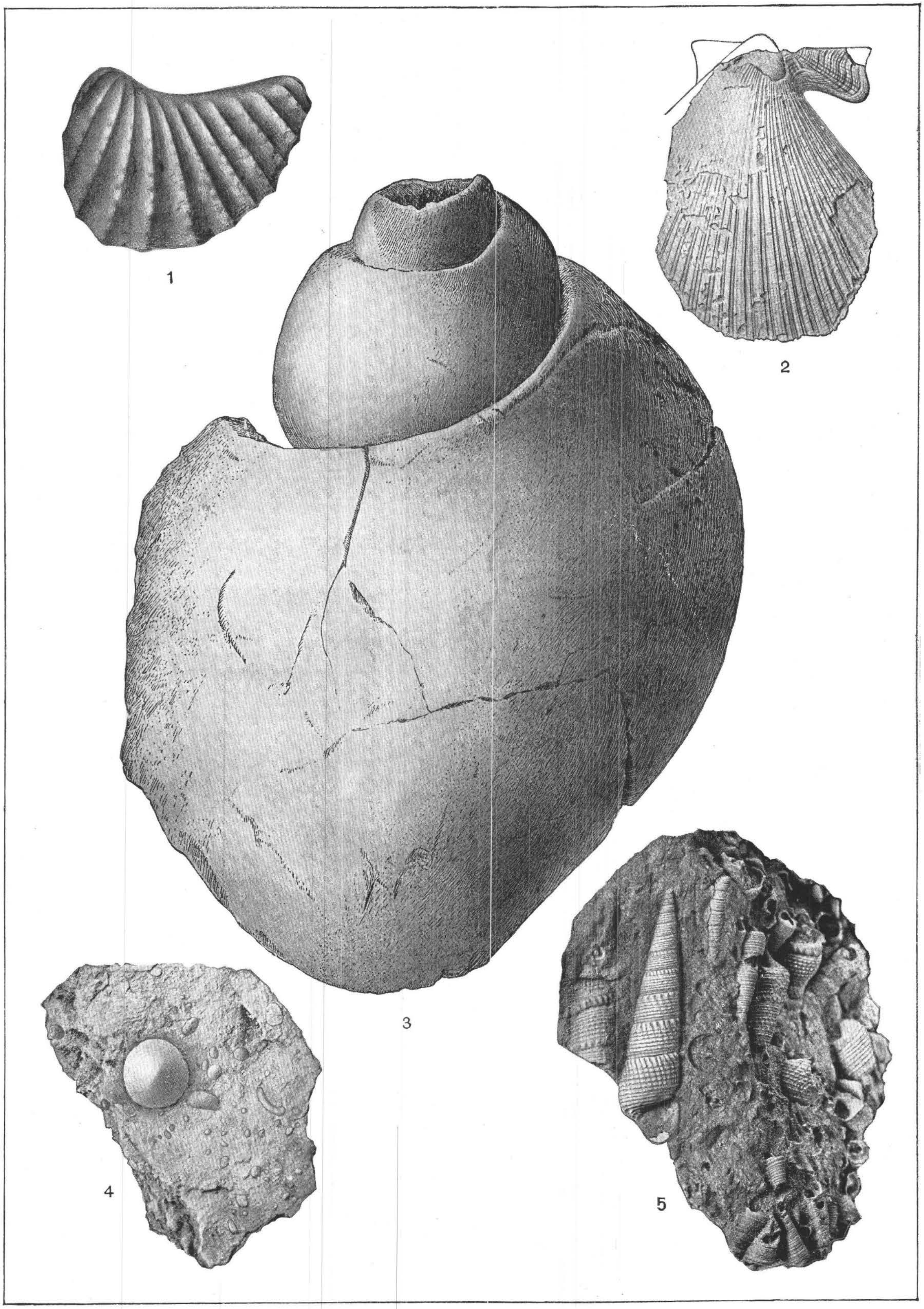
FIG. 1. Trigonia stolleyi (Hill). Natural size.

2. Pecten stantoni (Hill). Natural size.

3. Lunatia pedernalis (Roemer); cut taken from R. T. Hill's Geography and Geology of the Black and Grand Prairies, Texas: Twenty-first Ann. Rept. U. S. Geol. Survey, Pt. VII. Pl. XXV. Natural size.

4. Orbitolina texana (Roemer). Enlarged 2 diameters.

5. Turritella sp. Enlarged 1½ diameters.



CRETACEOUS FOSSILS CHARACTERISTIC OF THE BISBEE GROUP.

nection with the lithological transitions between the various stratigraphic units and the practical identity in character of the Morita and Cintura formations, below and above the fossiliferous Mural limestone, leave no room for any reasonable doubt of the Comanche age of the whole Bisbee group.

In Pl. XVI are illustrated a few characteristic fossils from the Mural limetones, kindly selected for this purpose by Mr. Stanton.

CENOZOIC ROCKS.

QUATERNARY DEPOSITS.

Distribution.—Deposits referable to the Quaternary period cover fully half of the Bisbee quadrangle. They are not deeply channeled, and natural sections of any but the superficial portions of the material do not occur.

The Quaternary deposits occupy the main floors and embayments of the larger valleys, such as Sulphur Spring Valley and Espinal Plain, and rise in gentle slopes toward the Mule Mountains. Against these they terminate in a very irregular line, which is nearly everywhere rather indefinite owing to the insensible passage of the slightly transported materials of the valley deposit into the loose stony detritus that cumbers the hill slopes.

Along the eastern front of the mountains the Quaternary of Sulphur Spring Valley buries the slopes of the older rocks up to an average altitude of about 4,600 feet. The boundary between the Quaternary of Espinal Plain and the southern front of the Mule Mountains attains a greater elevation but is so irregular as to render a general description difficult. Its average elevation may be roughly given, however, as about 5,250 feet, although in Escacado Canyon, northwest of Don Luis, characteristic Quaternary deposits extend to an elevation of 5,650 feet.

Lithology.—Near the mountains the Quaternary deposits consist, as a rule, of rather coarse and imperfectly rounded stony detritus which has evidently been derived from the adjacent slopes and rarely exhibits distinct bedding. Along the western edge of Sulphur Spring Valley the fragments have been supplied chiefly from the harder sandstone beds of the Bisbee group. Along the northern border of the Espinal Plain fragments of Paleozoic limestone greatly preponderate over those of any other rock, and are often found to be superficially consolidated into a hard conglomerate through the addition of a white travertine-like cement. Such cemented material is frequently not unlike certain phases of the Glance conglomerate, but may be distinguished by its white travertine-like matrix as contrasted with the reddish tint characterizing the matrix of the older rock. The maximum depth to which this cementation extends is unknown, but it is certainly in many cases slight. Prospecting pits less than 6 feet in depth frequently pass through the cemented crust into comparatively soft and loose material.

This calcareous matrix belongs to the class of deposits known in Mexico and southern Arizona as *caliche*, the general character of which has been recently described by Blake.[a] His explanation that "The formation is clearly the result of the upward capillary flow of calcareous water, induced by constant and rapid evaporation at the surface in a comparatively rainless region" is assented to. So far as seen, the deposition of caliche in the Bisbee quadrangle occurs only where the mountain slopes adjacent to the valley or plain are composed at least in part of limestones, and consequently where limestone detritus is abundant in the Quaternary accumulations. There is ample opportunity therefore for surficial waters to supply the calcareous material and to effect its deposition in a form that Blake aptly compares with the crusts of soluble salts, such as the "black alkali," which are familiar features of arid regions.

As the Quaternary deposits are followed away from the mountains, they become less coarse and exhibit more or less irregular cross-bedded stratification. The well west of Naco, from which water is pumped by the Copper Queen Company to Bisbee, is 118 feet deep, and is apparently wholly in Quaternary material. For a distance of 100 feet from the surface this was so soft as to need timbering. Apparently no record was kept of the exact nature of the material passed through, but the dump shows that it was principally a partly consolidated reddish sand containing occasional small pebbles. Similar soft sandy beds, containing fragile fresh-water shells of the genus *Unio*, have been encountered in a well at the new Copper Queen smelter near Douglas, in the middle of Sulphur Spring Valley.

According to Mr. W. M. Adamson, superintendent of machinery at the reduction works, the material encountered in this well was as follows:

Section of well near Douglas, Ariz.

	Feet.
Surface loam	15
Sand and gravel, containing abundant shells in its upper part, and affording 120 gallons of water per minute	22
Very white calcareous clay	15
Compact red clay	75
Sand, affording about 3 gallons of water per minute	1
Red clay	6
Very hard red clay	1
Red clay with considerable grit	36
Water-bearing sand and gravel	6
Total depth of well	177

[a] Blake, W. P., The caliche of southern Arizona: Trans. Am. Inst. Min. Eng., vol. 31, 1902, pp. 220-226.

At the above depth the well yielded 245 gallons of water per minute, and as this was all that the pump could raise, sinking was stopped for the time being.

A second well, sunk by the same company near the one just described, had reached a depth of about 400 feet in April, 1903. According to Mr. W. G. McBride[a] this well is all in unconsolidated material, chiefly sands, clays, and gravels. At 120 feet a good flow of water was tapped, and at 355 feet the drill, after penetrating a bed of compact clay, entered a thin layer of water-bearing gravel. The water from this stratum rose to within 3 feet of the surface and still maintained that level at the date of Mr. McBride's letter.

Origin.—The Quaternary deposits of the Bisbee quadrangle consist of the waste or "wash" shed from the Mule Mountains (and near Naco from the San Jose mountains also) into the surrounding valleys. Although they are undergoing some local dissection, they belong essentially to the present cycle of topographic development and are the work of streams similar in their mode of activity, and in some cases nearly coincident in position with those of the present day. No physical break has been detected in this region between the early Quaternary and the late Quaternary or Recent formations. Throughout the entire period the streams have been engaged in sculpturing the mountains and distributing the detritus over the valleys as fluviatile deposits, which range from coarse, imperfectly rounded gravels near the mountain fronts to pebbly sands and even fine silts near the valley axes.

There is no known evidence indicating that any part of the Bisbee quadrangle was covered by any considerable body of standing water during Quaternary time. But it seems highly probable that at least temporary lacustrine conditions obtained in portions of the broader valleys, such as San Pedro or Sulphur Spring. The presence of fresh-water shells in the Quaternary deposits beneath Douglas indicates the former presence of a lake, or at least of a perennial stream, in that quarter, neither of which could exist with the present scanty precipitation. It is probable therefore that the Quaternary has been marked by increasing aridity and that such dissection of its deposits as has taken place in the Bisbee region is an expression of that fact rather than of any differential changes of level.

IGNEOUS ROCKS.

GENERAL STATEMENT.

The eruptive or igneous rocks of the Bisbee quadrangle are for the most part intrusions of granitic magma ranging in form from small dikes and sills to stocks of considerable size, and in texture from rhyolite and rhyolite-porphyry to granite.

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[a] Personal letter.

In addition to these, are a few small dikes of monzonitic porphyry and occasional insignificant dikes of a decomposed greenish eruptive which was probably originally diabase.

GRANITE.

Definition.—Granite is a wholly crystalline, granular, eruptive rock consisting essentially of orthoclase (or some other member of the group of alkalic feldspars), quartz, and usually muscovite, biotite, or amphibole, with small quantities of various accessory minerals such as apatite, zircon, and magnetite or ilmenite. Chemically, the rock may contain from 70 to 78 per cent of silica, 11 to 16 per cent of alumina, rarely more than 4 per cent of the iron oxides, usually less than 1 per cent of magnesia, seldom over 3 per cent of lime, and commonly from 5 to 8 per cent of alkalies, the potash usually preponderating over the soda.

Occurrence and distribution.—The only granite found within the quadrangle is that composing the elongated intrusive stock which cuts the Pinal schist in the vicinity of Tombstone Canyon, northwest of Bisbee. The rock is well exposed both at Mule Pass and on Juniper Flat, and forms the bold cliffs overlooking from the northeast the road down Tombstone Canyon. Within the quadrangle the stock has a length of about 5 miles, and probably extends northwest for an additional mile or so beyond the northern boundary. Its width is at least 2 miles, but the northeastern contact of the mass is partly concealed by overlapping Cretaceous beds.

Petrography.—The granite of Juniper Flat and of the cliffs northeast of Tombstone Canyon has a typical granitic texture, and although sometimes exhibiting porphyritic phases it is without marked peripheral or contact modifications. The average diameter of the crystalline grains varies in different parts of the mass from about 7 millimeters in the coarser varieties down to a millimeter or less in those of finer texture. In color the rock is reddish gray, with a suggestion of pink when viewed in large masses. The minerals visible with the unaided eye in the coarser portions of the stock are a reddish-brown unstriated feldspar, quartz, a white feldspar showing distinct polysynthetic twinning lamellæ and a very little black mica in small flakes.

The microscope shows that the brown feldspar is microperthitic orthoclase, crowded with the usual minute dust-like inclusions. This mineral, with quartz, a smaller amount of sodic oligoclase, and a little biotite form an allotriomorphic aggregate, making up the greater part of the rock. The accessory minerals are tourmaline, muscovite, apatite, zircon, and magnetite or ilmenite. Of these the tourmaline is of most interest. It occurs in nests of small prisms, the latter being frequently embedded in muscovite, but penetrating also the quartz and orthoclase, showing that it is a primary constituent. The prisms show the characteristic strong absorption, rounded trigonal cross sections, and obtuse terminations characteristic of tourmaline.

A chemical analysis of the granite is given below in Column I, while an analysis of a similar granite from Norway is placed alongside in Column II, for comparison:

Analyses of alkali granites, granite-porphyry, and rhyolite.

	I.	II.	III.	IV.
SiO_2	75.86	76.05	76.81	76.78
Al_2O_3	12.17	11.68	10.96	
Fe_2O_3	.85	.34	1.18	
FeO	.36	1.05	.08	
MgO	None.	.29	.14	
CaO	.62	.42	None.	Trace.
Na_2O	3.60	3.79	.26	.30
K_2O	5.04	5.09	8.50	9.28
H_2O-	.27	1.36	.48	
H_2O+	.72		1.17	
TiO_2	.21	.05	.13	
ZrO_2	Not det.	.42	Not det.	
CO_2	None.		None.	
P_2O_5	Trace.		Trace.	
F		Trace.		
S		Trace.		
MnO	None.	Trace.	None.	
Li_2O		Trace.		
	99.70	100.54	99.71	

I. Tourmaline-bearing alkali granite; intrusive stock in Pinal schist, 5 miles northwest of Bisbee, Ariz. George Steiger, analyst.
II. Alkali granite; Drammen, Norway. Rosenbusch, Gesteinslehre, 1898, p. 78.
III. Granite-porphyry; sill in Bolsa quartzite, 3¼ miles north of Naco Junction. George Steiger, analyst.
IV. Rhyolite (aporhyolite); probable volcanic neck, 2½ miles northeast of Naco Junction. George Steiger, analyst.

As might be expected from the perthitic orthoclase and the presence of tourmaline, the rock is shown by the analysis to belong with the class of alkali granites, or, in accordance with a recent precise classification, to be a granoliparose.[a]

By calculation, the chemical analysis affords the following:

	Per cent.
Quartz	34.68
Orthoclase molecule	29.47
Albite molecule	30.39
Anorthite molecule	2.50
Biotite, tourmaline, zircon, magnetite, etc	2.96
	100.00

[a] Cross, Iddings, Pirsson, and Washington, Quantitative Classification of Igneous Rocks, Chicago and London, 1903.

Microscopical determinations indicate that the sodium-calcium feldspar present in the rock is oligoclase, having an approximate composition of 4 molecules of albite to 1 of anorthite (Ab_4An_1). The mineral composition of the granite may accordingly be given as—

	Per cent.
Quartz	34.68
Microperthitic orthoclase (Or_9Ab_2)	41.00
Oligoclase (Ab_4An_1)	21.36
Biotite, tourmaline, etc	2.96
	100.00

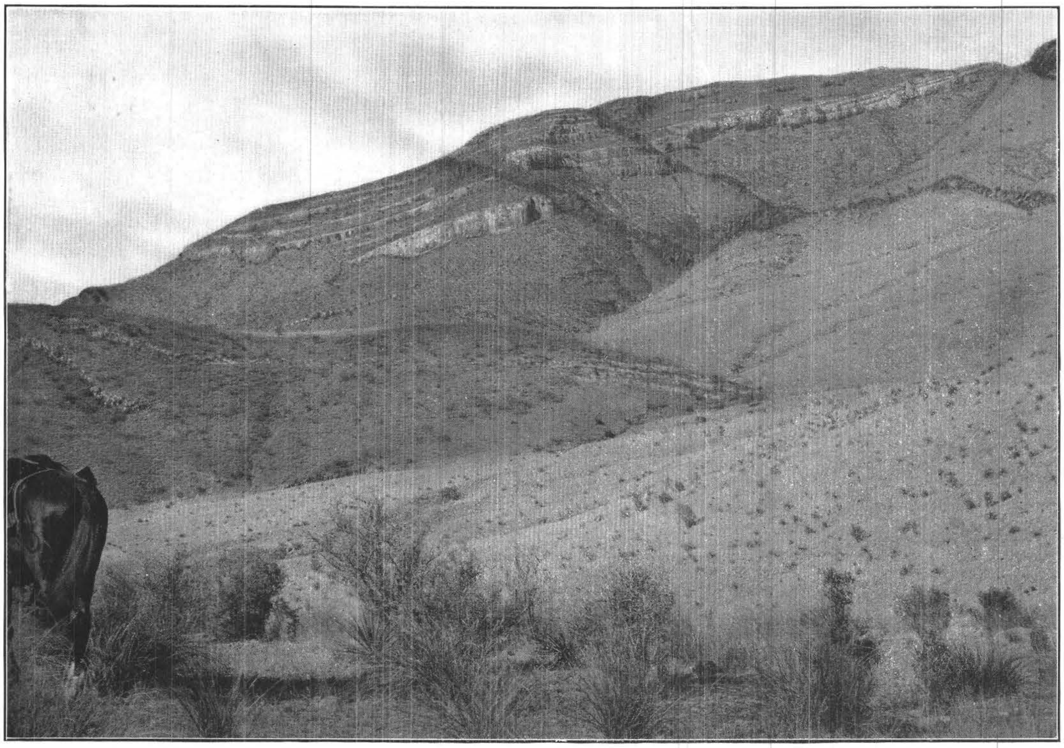
The coarser phase of the granite, to which the foregoing description particularly applies, is characteristic of the western portion of the stock in the vicinity of Cox's ranch. Finer-grained varieties, however, also occur, particularly on Juniper Flat and near the basal boundary of the Cretaceous beds. The evidence obtainable in the field indicated that the difference between these fine-grained facies and the coarsely crystalline type selected for chemical analysis was textural only. Microscopical study, however, shows that there is a mineralogical and chemical difference as well. The fine-grained pink granite from the northern part of Juniper Flat consists chiefly of quartz and orthoclase, with very little oligoclase, even less biotite, and as far as known, no tourmaline. The dominant minerals form an allotriomorphic aggregate, with a tendency on the part of the quartz to poikilitically inclose the orthoclase. In mineralogical composition and texture, therefore, the rock belongs with those aplitic granites for which Spurr[a] has proposed the name *alaskite*.

In chemical composition, the fine-grained granite just described corresponds more nearly than the coarser variety analysed to the granite-porphyries next to be considered, in which a similar mineralogical association is also connected with a marked preponderance of the potash molecule over that of soda (see analysis I, p. 77). Although there can be little doubt of the essential unity of the Juniper Flat granitic stock, and although additional analyses would probably show close agreement as regards silica, alumina, iron oxides, lime, magnesia, and total alkalies, yet the mass evidently exhibits considerable variation as regards the relative proportions of potash and soda, and it is accordingly unsafe to assume that the analysis given on page 77 is representative of the intrusion as a whole. There is good reason to suspect that the tourmaline-bearing granite analyzed contains less potash and more soda than the average rock of the stock.

GRANITE-PORPHYRY.

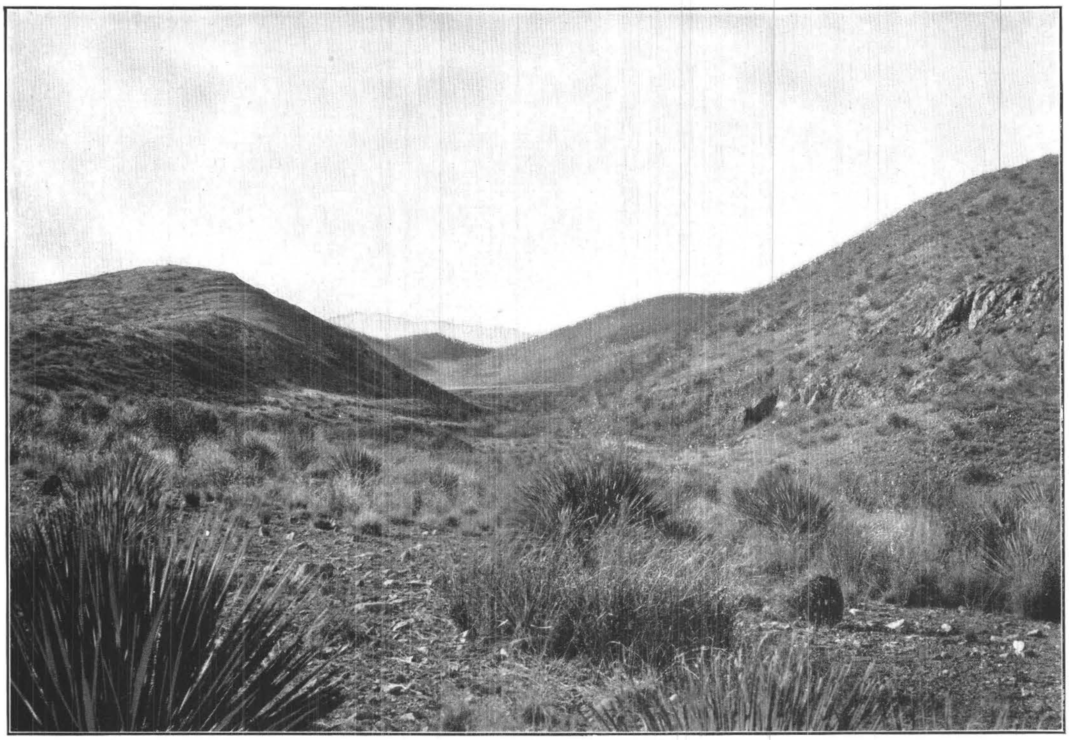
Definition.—Granite-porphyry is a wholly crystalline eruptive rock having the same chemical and mineralogical composition as granite, but distinguished

[a] Spurr, J. E., Classification of igneous rocks according to composition: Am. Geologist, vol. 25, 1900, p. 230.



A. PORPHYRY DIKES, ACCOMPANIED BY REVERSED FAULTS, CUTTING PALEOZOIC LIMESTONES.

Southwest slope of Escabrosa Ridge, north of Moore Gulch. The Escabrosa limestone forms the cliffs in the background, while the Martin limestone underlies the steep slope below the thick basal bed of the Escabrosa. The Abrigo limestone occupies the fore and middle ground.



B. VIEW WESTWARD ALONG THE ABRIGO FAULT.

The ravine in the foreground is eroded along the fault. On the right are Escabrosa and Martin limestones; on the left Naco limestone. The distant saddle is also determined by the fault which has there brought Bolsa quartzite on the right against Naco limestone on the left.

from the latter by a porphyritic instead of granular texture. That is, the quartz and feldspar occur as sharply bounded crystals or phenocrysts embedded in a distinctly finer-grained matrix or groundmass. This groundmass may be, and in the Bisbee quadrangle usually is, aphanitic, or so fine-grained as to show no crystalline texture to the unaided eye.

The granite-porphyries are divided by no definite line from the rhyolite-porphyries and rhyolites in which the groundmass is either originally obscurely cryptocrystalline, or is in part a devitrified volcanic glass. Both of these textural modifications of the granitic magma occur within the Bisbee quadrangle, but as they are of the same general geological age and derived from the same magma, their separate mapping would serve no useful purpose, and the rhyolite is accordingly included with the predominant granite-porphyry.

Occurrence and distribution.—Granite-porphyry occurs chiefly in the northwestern part of the quadrangle in the form of dikes and irregular intrusive masses cutting all of the formations from the Pinal schist to the Naco limestone, and less commonly as small sills intercalated between the beds of Bolsa quartzite. The rock is readily recognized by its usual pinkish or occasional buff tint, by its speckled appearance, due to the contrast of the porphyritic crystals of quartz and feldspar with the compact reddish groundmass, by its erratic occurrence within the limestones, quartzite, and schist, and by its clearly intrusive character.

Numerous small dikes of granite-porphyry occur within the pre-Cambrian schists between Bisbee and Juniper Flat. For the most part these dikes have no observable connection with the granite mass of Juniper Flat. One of them, however, cuts the latter a third of a mile southeast of Mule Pass, and is accordingly younger than the granite.

Similar dikes are found traversing the schists of Tombstone Canyon, on the southwest side of the granite stock, particularly near Brown's ranch in the extreme northwest corner of the quadrangle. While the relation of these dikes to the granite is not always clearly shown, they are in some cases undoubtedly direct offshoots from the latter, as may be well seen just north of Brown's ranch.

It is on the southwestern slope of Escabrosa Ridge, however, that the granite-porphyry dikes attain their most interesting development. They have a general northwest-southeast trend and are most abundant within a belt about a mile in width, stretching northwestward from the vicinity of Don Luis to the western edge of the quadrangle. Within this zone, the dikes, ranging in width from a foot to half a mile, branch and cross, forming an intrusive network of great complexity. (Pl. XVIII, *A*.) Many of the broader intrusions shown on the geological map (Pl. I) are so crowded with masses of schist, quartzite, or limestone as to be in reality complexes of many dikes, for which simplified representation is demanded by the scale of the map.

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As a rule, the dikes occupy fault fractures, along many of which it is evident that considerable displacement took place before the fissure was finally sealed by the intrusion and solidification of the granite-porphyry magma. Such a dislocation is well shown about 2 miles south of Brown's ranch, near the edge of the quadrangle, where the Escabrosa limestone on the nortwest side of the main dike has been dropped 500 feet below the base of the Bolsa quartzite on the northeast side of the dike-filled fissure, indicating a throw of more than 2,000 feet. Farther to the southeast the total throw has been distributed among the many branches composing the dike zone, but the aggregate displacement must be nearly or quite as great. These fissures are not always occupied by dikes for their whole lengths. It is not uncommon to find a dike becoming narrower and finally disappearing while the fault fissure can still be readily followed. An excellent example of this may be seen near the head of Abrigo Canyon (Pl. I).

Although some of the dikes on Escabrosa Ridge are nearly vertical, most of them dip steeply to the northeast. Consequently the displacement along their fissures corresponds in the greater number of cases to reversed faulting. This characteristic of the intrusion faulting is illustrated for two of the smaller dislocations by Pl. XVII, *A*.

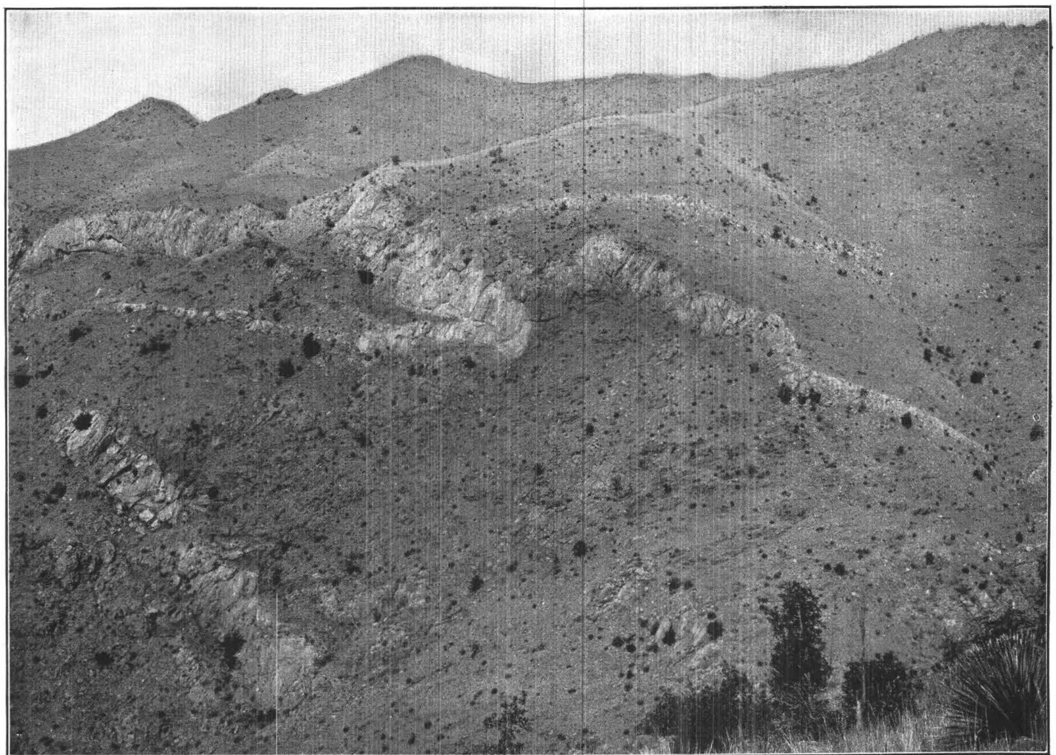
Occasionally the dikes, as they passed upward from the Pinal schist into the Bolsa quartzite, took advantage of the bedding planes of the latter to expand in the form of irregular sills, as may be seen in Bolsa Canyon and between Abrigo and Moore canyons.

That the dikes of Escabrosa Ridge were not all intruded at precisely the same time is proved by a few instances in which one dike clearly cuts others. Rhyolitic dikes have been observed cutting those of the more abundant granite-porphyry type, while in other cases the relation is reversed.

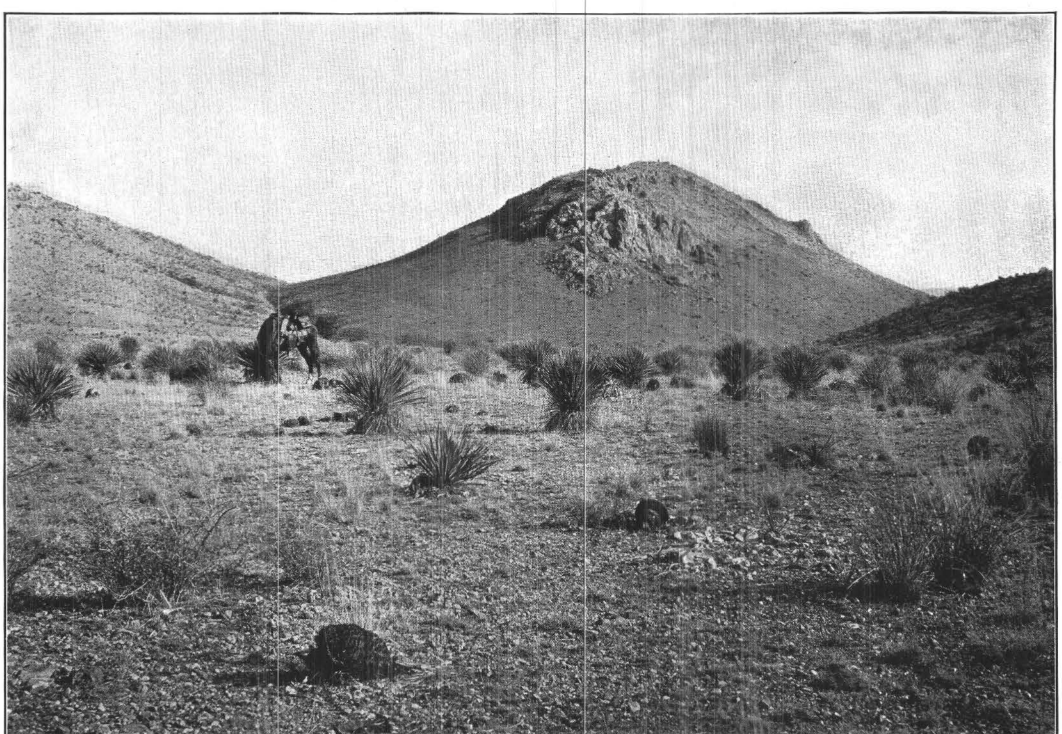
Although many of the granite-porphyry dikes exhibit no selvage modifications, others pass near their walls into rhyolitic facies showing flow banding.

One of the most important masses of granite-porphyry, on account of its relation to the ore bodies of the district, is that forming Sacramento Hill, just southeast of Bisbee. This is a stock, which, although of irregular outline, and partly concealed on the east by Cretaceous beds,[a] may be described as about a mile in diameter. Like most of the porphyry intrusions of the quadrangle it is closely related to a fault, but instead of following the fissure as a narrow dike, the magma has invaded the rocks on both sides of the fracture and formed a rudely cylindrical intrusive plug. On the northeast this plug or stock cuts the Pinal schist. On the southwest it cuts the Naco limestone and in all probability also the Escabrosa and older formations at greater depths.

[a] Recent prospecting with diamond drills shows that this porphyry mass probably extends for over 2,000 feet to the southeast beneath Glance conglomerate.



A. DIKES IN SCHIST ON SOUTHWEST SLOPE OF ESCABROSA RIDGE.



B. PROBABLE VOLCANIC NECK, 2½ MILES NORTHEAST OF NACO JUNCTION.

A much smaller plug-like mass occurs 2½ miles northeast of Naco Junction, forming a little conical hill (Pl. XVIII, *B*), which, owing to its shape and to the contrast of its dark-brown color with the surrounding limestones, is a conspicuous feature as seen from Espinal Plain. The rock composing the upper part of this hill is of much darker hue than the usual granite-porphyry of the quadrangle and has a pronounced vertical fluidal structure trending nearly north and south. It is more properly classed as a rhyolite or rhyolite-porphyry than a granite-porphyry. On the north side of the hill, poorly exposed and partly concealed by a talus of massive rhyolite derived from the top of the hill, is a rhyolitic breccia, which has the general appearance of a volcanic agglomerate. Unfortunately the relations of the rhyolite and breccia to each other and to the surrounding limestones are concealed, in this region of usually unrivaled exposures, by surficial detritus; but the form of the rhyolite mass, its vertical flow structure, and its association with an agglomerate-like rhyolitic breccia suggest that it is probably a small volcanic neck or plug through which rhyolitic lava ascended to a pre-Cretaceous surface.

About a mile northeast of Naco Junction is a small mass of white rhyolite intrusive in Naco limestone. The rock is remarkable for a very regular and pronounced flow banding, which stands nearly vertical and trends with the longer axis of the intrusion. This lamination is so pronounced as to give the eruptive rock much the appearance of a white schist or shale.

Petrography.—The granite-porphyry, as it occurs in most of the dikes of Escabrosa Ridge, is a pinkish or reddish rock, having a decidedly speckled appearance, which usually serves to distinguish it at a glance from the other rocks of the quadrangle. It contains corroded or idiomorphic phenocrysts of quartz up to a centimeter in diameter and generally smaller or less conspicuous phenocrysts of flesh-tinted orthoclase, embedded in a reddish groundmass that is nearly or quite aphanitic. Biotite in small scales is sometimes present, but as a rule quartz and orthoclase are the only minerals recognizable by the unaided eye.

There can be little doubt but that the reddish color of the porphyry, although characteristic of the freshest rock obtainable at the surface, is a result of incipient weathering and the formation of ferric oxide, for specimens obtained from deep mine-workings, away from oxidizing or mineralizing action, are light gray or pale green.

Under the microscope the dominant phenocrysts are found to be quartz, showing the usual embayed outlines, and orthoclase often rendered semi-opaque by minute ferritic inclusions. Much less abundant are crystals of sodic oligoclase, usually more or less altered to kaolin, and an occasional scale of bleached biotite. In the more coarsely crystalline rock of the larger dikes, the groundmass shows both micro-granitic and micropegmatitic textures. The micropegmatite usually envelops the phenocrysts and is commonly divided into somewhat irregular radial segments of different optical orientation. At a distance from the phenocrysts the groundmass is made up of quartz, orthoclase, and muscovite in a fine microgranitic aggregate. In the less coarsely crystalline rocks of small dikes and near the walls of the larger dikes the groundmass is often a minutely and rather obscurely crystalline aggregate of quartz and orthoclase in little micropegmatitic granules less than 0.1 millimeter in diameter. Such porphyries are not to be sharply distinguished from those of rhyolitic habit, in which the minutely crystalline felsitic groundmass may have resulted from devitrification of a glassy base subsequent to the solidification of the rock (aporhyolites).

A chemical analysis of a representative specimen of the granite-porphyry is given under III, on page 77. It will be seen that it differs from the analyzed specimen of the Juniper Flat granite in the great preponderance of potash over soda. In this respect it probably corresponds closely with the fine-grained granite described on page 78.

By calculation the following conventional composition is obtained from the chemical analysis:

	Per cent.
Quartz	42.78
Orthoclase molecule	50.04
Albite molecule	2.10
Hematite, magnetite, water, etc	5.08
	100.00

As no albite is visible in thin section under the microscope, the albite molecule is probably combined with the orthoclase molecule in the mineral orthoclase. The rock thus consists of 42.78 per cent of quartz and 52.14 per cent of orthoclase, with 1.65 per cent of water and 3.43 per cent of iron oxides, zircon, and indeterminable accessory minerals.

The rock with conspicuous flow banding, forming the little hill (Pl. XVIII, *B*) 2½ miles northeast of Naco Junction, shows in hand specimens minute phenocrysts of quartz and pink orthoclase in an aphanitic reddish-gray groundmass, within which may occasionally be seen little cavities lined with projecting crystals of quartz.

Under the microscope the texture is found to be very similar to that of the finer-grained granite-porphyries. Phenocrysts of quartz and orthoclase lie in a holocrystalline quartz-orthoclase groundmass. The crystallization of this groundmass is finely and obscurely granular, with patchy, shadowy extinctions between crossed nicols and occasional minute micropegmatitic intergrowths. It is such a texture as is known to result from the devitrification of an originally partly glassy groundmass, and, in view of the pronounced fluxion structure of the rock mass, this origin seems sufficiently probable to justify the classification of the rock as a rhyolite (or, more strictly, aporhyolite) rather than a granite-porphyry. But, as already pointed out, this distinction is unimportant in this region, where the rocks here called granite-porphyry are connected by direct transitions with rhyolite-porphyry and rhyolite.

A partial chemical analysis of the above-described rhyolite is given under IV, on page 77, and a comparison of this analysis with that of the granite-porphyry under III shows that both are products of the same magma.

The small intrusive mass a mile northeast of Naco Junction, already referred to, is a devitrified rhyolite in which the original flow structure, as seen under the microscope, has not been wholly obliterated by the subsequent crystallization of the glassy groundmass.

The important intrusive mass of Sacramento Hill was probably originally a granite-porphyry of the type common along Escabrosa Ridge; but it has been greatly altered in a manner that will be described when the mineralization of the region is discussed.

CONTACT METAMORPHISM.

If we disregard for the present the ore bodies and their possible relation to contact metamorphism, the effect of the intrusion of the granite-porphyry into the limestones has not been conspicuous, and in the case of many of the smaller dikes is inappreciable. In Uncle Sam Gulch, just above the old mine of the same name, the Naco limestone is cut by an irregular dike of granite-porphyry. The contact between the two rocks is well exposed in a prospect pit and the limestone preserves its usual color and compact texture up to the actual junction with the intrusive rock. In other words, it exhibits no apparent metamorphism to the naked eye. A thin section of the limestone at the contact shows, however, that it is nearly one-third altered into a granular aggregate of quartz forming an irregular web inclosing residual kernels of calcite.

In the vicinity of Sacramento Hill, the only place where a large body of granite-porphyry comes in contact with the limestones, the latter show considerable alteration, which, however, is to a large extent shared by the porphyry itself. As seen in surface exposures, the principal change in the limestone has consisted in the replacement of the calcium carbonate by granular aggregates of quartz containing chlorite and pyrite. The chlorite tends to form little ellipsoidal nests, and when the rock is exposed to the weather the chlorite is removed, the pyrite is oxidized, and the originally light-colored limestone becomes a rusty, cavernous, siliceous rock, looking superficially not unlike a weathered amygdaloidal lava. Rock of this character is abundant in the vicinity of the Gardner shaft and on the ridge extending from that shaft toward the ice factory (Pl. I).

The crest of this ridge corresponds roughly with the outer limit of the notably metamorphosed zone as visible on the surface. The boundary between altered and unaltered limestone is, however, extremely irregular and often indefinite. Certain beds retain nearly their original texture and composition close up to the porphyry, while others are obviously altered for long distances from the intrusive contact.

The Pinal schist in the vicinity of the porphyry of Sacramento Hill has lost its schistose structure and become a fine granular aggregate of quartz and sericite, containing abundant disseminated pyrite.

The porphyry itself exhibits throughout much of the mass a similar alteration, of which the extreme product, exemplified in the dump of the Copper King mine, is a fine granular aggregate of quartz, sericite, and pyrite, indistinguishable from certain altered forms of the schist. Less altered phases reveal traces of the original porphyritic texture, but the microscope shows that the quartz phenocrysts have recrystallized as granular aggregates, and that the former feldspar phenocrysts are now mixtures of quartz and sericite.

The nature of the metamorphic processes that have been active in the vicinity of the intrusive mass of Sacramento Hill will be considered at greater length in the discussion of metasomatic processes connected with ore deposition.

AGE OF THE GRANITIC INTRUSIONS.

As the granite and granite-porphyry have supplied pebbles to the Glance conglomerate and nowhere cut the beds of the Bisbee group, they are evidently pre-Cretaceous. Many of the granite-porphyry dikes and the stock of Sacramento Hill are intrusive into the Naco limestone and are therefore clearly post-Carboniferous. Although the granitic stock of Juniper Flat is in contact with no rocks younger than the pre-Cambrian Pinal schist, yet from the close connection of this granite with the granite-porphyry it is fair to conclude that all of the forms assumed by the granitic magma belong to one general period of intrusion, and are accordingly post-Carboniferous and pre-Cretaceous. The period of eruptive activity, however, extended over a sufficient length of time to allow the solidification of the granite, and of some of the granite-porphyry dikes, before they were cut by later intrusions of the same magma.

OTHER INTRUSIVE ROCKS.

At a few places within the quadrangle occur small dikes of a gray porphyritic rock cutting the Cretaceous beds, and therefore younger than the granite-porphyry just described. The best exposed of these dikes occurs at the Glance mine, cutting Glance conglomerate. It is less than 50 feet wide and runs nearly north and south through the little saddle just south of the mine. The dike is composed of a light-gray rock containing small phenocrysts of white feldspar and of biotite, and superficially resembles a mica-diorite-porphyry. The microscope shows phenocrysts of oligoclase partly altered to calcite, of some mineral (pyroxene?) now altered to aggregates of calcite, quartz, limonite, and other secondary products, and of biotite, all lying in a groundmass composed mainly of orthoclase which is crowded with minute inclusions and extinguishes in shadowy patches between crossed nicols. The rock is too much altered to repay thorough investigation, but is probably a monzonite-porphyry, approaching a syenite-porphyry in composition.

A decomposed greenish intrusive is occasionally met with in small dikes in the Paleozoic rocks southwest of Bisbee. These masses are of no structural importance and too small to map. Thin sections show complete alteration to aggregates of chlorite, quartz, calcite, sericite, and other secondary products, while such vestiges of original texture as remain suggest that the rocks were formerly fine-grained basalts or dolerites.

GEOLOGICAL STRUCTURE.

INTRODUCTORY STATEMENT.

Up to this point the rocks of the quadrangle have been considered chiefly as objects of description. They have been divided into natural assemblages or groups, and these groups subdivided into geological units. Finally the present distribution, form, and lithology of each unit have been described, and some conclusions reached as to age and origin.

All this, however, is preliminary. The rocks are merely the materials from which geological forces have fashioned a complex structure requiring further labor for its elucidation and comprehension.

In the development of this rocky fabric, faulting, folding, and igneous intrusion have cooperated, often so intimately that it becomes impossible to consider the part played by any one of these dynamic processes without at the same time referring to the others. The structure of the quadrangle, however, is preeminently characterized by faults, and to these some preliminary attention will now be given.

FAULTS.

Distribution.—The visible faults of the Bisbee quadrangle are most abundant within an irregular northwest-southeast zone that lies between Bisbee and Don Luis. This belt of dislocation is partly bounded on the northeast by the great Dividend fault which passes under Dividend Flat in the town of Bisbee and brings the Paleozoic rocks on the southwest against pre-Cambrian schists on the northeast. The southwestern limit of the belt is similarly defined by another important dislocation which passes about 2½ miles northeast of Naco Junction and may be called the Abrigo fault, since it is followed for a part of its course by the canyon of that name. Where it crosses the western boundary of the quadrangle the faulted tract has a width of about 4 miles, while between Bisbee and

Don Luis it is about 2½ miles. At Glance the width of the zone is about 1½ miles, while southeast of that point it is represented by a single fault—the continuation of that will presently be described as the Gold Hill overthrust. It is probable that in this southeastern portion of the quadrangle, much intricate faulting of the Paleozoic beds is concealed by the Cretaceous formations, and consequently that the faults visible at the surface and to which description is necessarily confined, may constitute but part of a belt of faulted structure as wide or wider than that west of Bisbee.

It will be noted that this tract characterized by abundant faults, is practically coincident with the present areal distribution of the Paleozoic rocks exclusive of the comparatively unfaulted Pennsylvanian limestones of the Naco Hills. (Pl. I.)

The only other faults of importance are a few that cut the Cretaceous beds northeast of Bisbee, and although of comparatively moderate displacement receive conspicuous expression on the geological map of the quadrangle (Pl. I) from the manner in which they offset the gently-inclined beds of the Mural limestone.

Expression in the topography.—The topographic expression of faults may be considered as of two general kinds, distinguished as *primitive* and *erosional*, the latter being further susceptible of elaborate analysis into many subtypes. In the primitive expression of a fault the upheaved block, or part of it, forms a ridge or hill while the downthrown block, or part of it, floors a valley, the top of the ridge and the bottom of the valley representing the displaced portions of the original surface as it existed before faulting occurred. Obviously, ideal primitive expression can be found only in connection with very recent faults or in regions so extremely arid that erosion has been able to make but slight progress. According to Russell's descriptions[a] it obtains in that part of the Great Basin included in southern Oregon. In somewhat less ideal sharpness it is probably exemplified in other regions of the Great Basin in those ranges which led Gilbert[b] to the recognition of the well-known and much discussed Basin Range type of orographic structure. As the normal progress of erosion must soon soften the primitive expression of a fault, in time greatly modify, and perhaps finally obliterate or reverse it, there is clearly no sharp distinction in nature between the evanescent condition of ideal primitive expression and the manifold stages of erosional modification. Consequently it may be difficult or impossible to determine whether the topographic expression of a given fault should be considered as essentially primitive or as erosional. Thousands of feet of overlying beds may have been removed and yet differences in elevation in the present topography, as determined by some identical hard stratum in the dislocated formations, may continue to topographically register the original displacement of the fault.

[a] A geological reconnaissance in southern Oregon: Fourth Ann. Rept. U. S. Geol. Survey, 1883, pp. 435-464.
[b] U. S. Geog. Surv. W. 100th Mer., vol. 3, Geology, 1875, pp. 21-42.

In the erosional expression of faulting in topography, on the other hand, the displacement is not directly recorded by differences in elevation of the present surface. The fault in the typical case has become a mere element of internal structure, introducing—just as do variations in the lithological character of beds, folds, and intrusive masses—factors of lithological diversity which are neither overlooked nor exaggerated in the impartial work of erosion. The topographic accentuation or subordination of the fault bears no necessary relation to the amount or character of its displacement, but is the accurate expression of the importance of the dislocation as one of many factors in determining that heterogeneity of material which, in most regions of erosion, is the essential condition of topographic variety.

In the Bisbee quadrangle the topographic expression of most of the faults is of a mature erosional type, such as is well exemplified in the Dividend and Abrigo faults.

When the Dividend dislocation occurred, the Pinal schist, near Bisbee, was surmounted by Paleozoic beds at least 5,000 feet in total thickness—the continuation of the strata now preserved in the downthrown block on the southwest side of the fault. Unless the movement along the fissure was so slow as not to outstrip denudation the now vanished beds were uplifted as a mountain ridge overlooking the downfaulted tract to the southwest. But these mountains have since succumbed to erosion, and the limestone hills of the depressed block look down over the upheaved and denuded schists upon which a few tiny remnants of Bolsa quartzite remain as witnesses of the former presence of the Paleozoic strata.

The Abrigo fault, which brings the Naco limestone against the Bolsa quartzite on the western edge of the quadrangle, corresponds to a throw of at least 3,000 feet. But of this great actual deformation of an older topographic surface the present topography retains no trace. (Pl. I.)

Many other illustrations of the erosional expression of faults might be given from the tract of faulted Paleozoic rocks west of Bisbee, but individual citation is hardly necessary, since the total disappearance of the primitive topographic expression of the faults may be readily verified by reference to the geological map and structure sections. (Pl. I.)

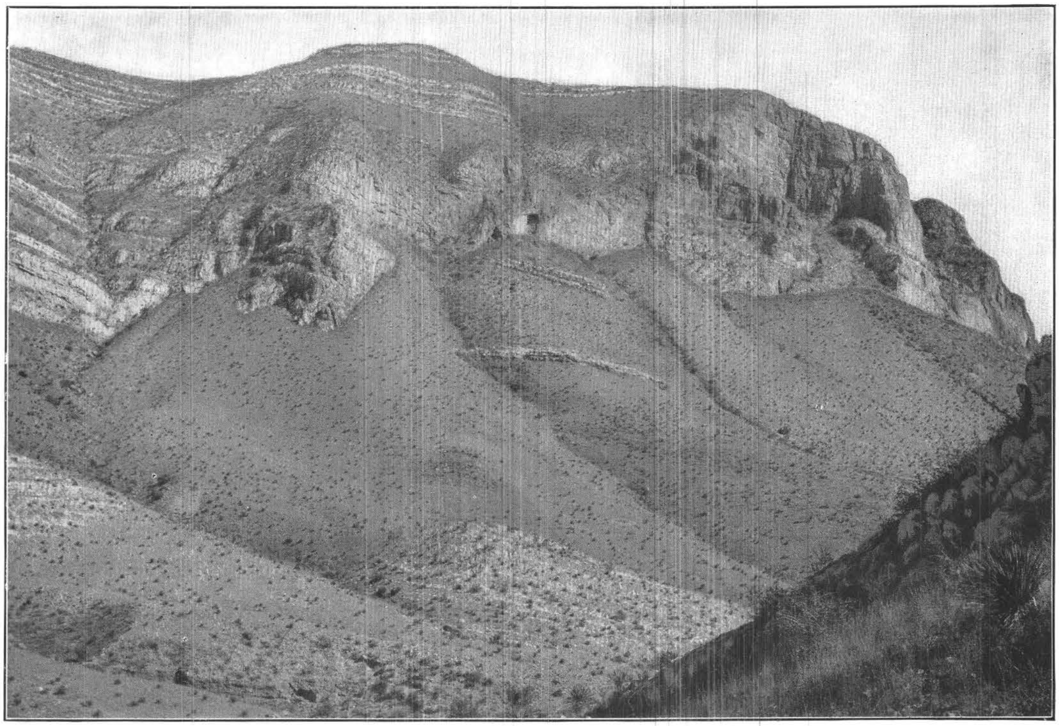
As regards the faults cutting the Cretaceous beds northeast of Bisbee the case is not so patent. The principal dislocation is here effected by a nearly vertical fissure which passes through the saddle at the head of Mexican Canyon and has elevated the beds on the southeast about 500 feet relative to those on the northwest. This fault is very evident to an observer looking up toward the head of Mexican Canyon from the conglomerate-filled basin north of Black Gap, since it interrupts the conspicuous white band of the Mural limestone (Pl. IX, *B*), and, as this limestone determines the outline of the ridge in this neighborhood, the displacement by the fault finds corresponding expression in the topography.

This, then, taken by itself, is an example of one of those less evident cases already referred to, in which the expression of the fault may at first sight be considered either as essentially primitive or as erosional. It is probable, however, that the Bisbee quadrangle has been considerably eroded since this faulting occurred and that the expression of the dislocation is erosional, owing its superficial resemblance to the primitive type to the control maintained over erosion by the resistant beds of the Mural limestone. This view is confirmed when study is made of the opposed Gold Hill and Glance overthrust faults (Pls. I and XXII), and it is seen that the relation of the present topography to the faults is such as to clearly demonstrate a subsequent origin for the topography.

It may be concluded, then, that notwithstanding the present aridity of climate and the many points of geological resemblance between this part of Arizona and the Great Basin, where the primitive topographic expression of faults has been described by careful observers, no trace of such primitive relationship is extant in the Bisbee quadrangle. The faults of the latter region are probably mostly much older than those which have been appealed to in explanation of the main topographic features of the typical Basin Ranges.

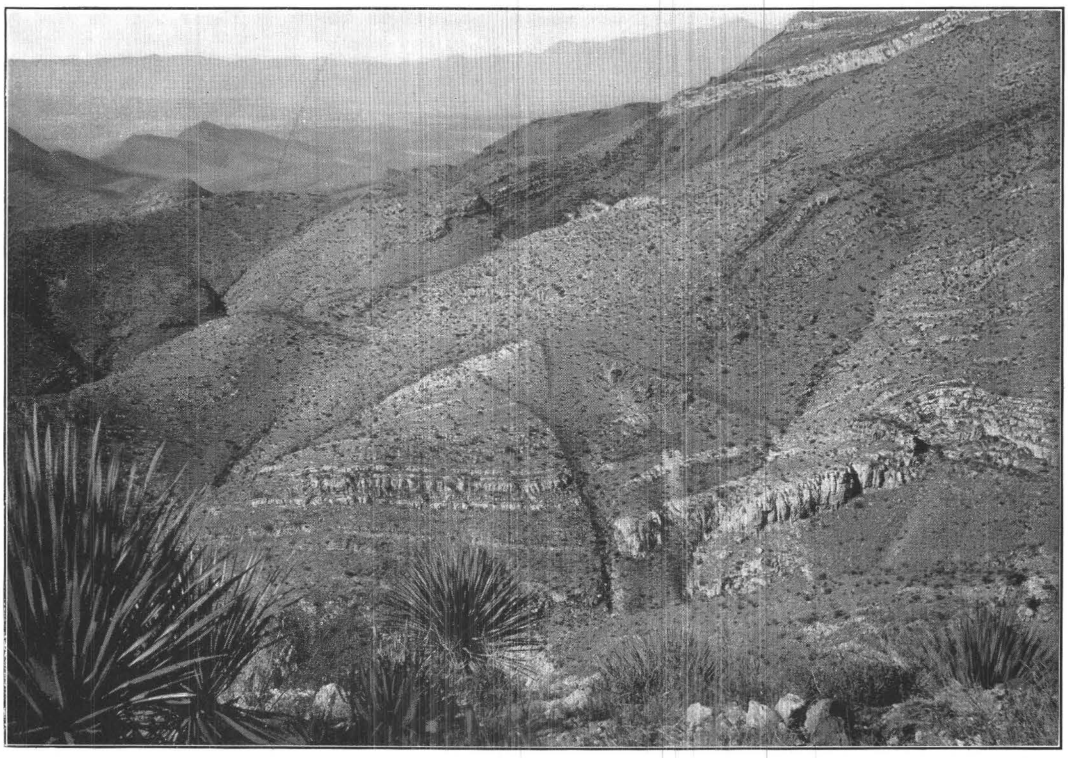
Looking a little more closely into the manner in which the faults of the Bisbee quadrangle have influenced erosion, we find considerable diversity, as is to be expected when the faults constitute but one factor in a complex process. As a rule, the structurally important faults are rather inconspicuous at the surface, considering the usual excellence of the rock exposures in this region. They rarely show any appreciable silicification and are not accompanied by the resistant siliceous breccias, which are so characteristic a feature of the faulting of the Globe quadrangle, where similar rocks are involved.[a] Instead of outcropping more or less boldly above the surface, as in that region, the comparatively unindurated fault breccias of the Bisbee quadrangle are commonly elements of weakness, and as such tend to find topographic expression as saddles, ravines, or valleys. For example, the Dividend fault has determined in part the course of Mule Gulch. The Abrigo fault is taken advantage of by Abrigo Arroyo for a distance of about half a mile (Pls. I and XVII, *B*), and near the western edge of the quadrangle determines a saddle between quartzite hills on the north and limestone hills on the south. Black Gap (Pl. XV, *A*) and the saddle of the head of Mexican Canyon owe their positions to the discovery by erosion of lines of weakness due to faulting. The course of the Gold Hill overthrust is marked by a curved line of ravines and saddles and by the straight open valley extending from Glance to Christianson's ranch.

[a] Ransome, F. L., Geology of the Globe copper district, Arizona: Prof. Paper U. S. Geol. Survey No. 12, 1903, pp. 101–102.



A. DETAIL OF FAULTED STRUCTURE ON THE EAST SIDE OF ESCACADO CANYON.

The cliffs are formed of Escabrosa limestone, overlain by Naco limestones. The slope below is underlain by Martin and Abrigo limestones, behind which the Escabrosa has been dropped by faults along the base of the cliffs. In the foreground are knolls of Escabrosa limestone which has been faulted down against the Abrigo.



B. FOLDED AND FAULTED ESCABROSA AND NACO LIMESTONES, AS SEEN FROM THE CREST OF ESCABROSA RIDGE, LOOKING WEST ACROSS THE HEAD OF ESCACADO CANYON.

Along a few of the fault planes the rocks have been developed by erosion into cliffs, occasionally 300 or 400 feet in height, of which the best examples occur on the east side of Escacado Canyon, about 1½ miles northwest of Don Luis (Pl. XIX, *A*). These bold white cliffs, which are visible from any part of the broad Espinal Plain, are composed of Carboniferous limestones which have been slightly downfaulted against Devonian and Cambrian beds.

Very frequently it is found that faults of much structural importance and with throws of several hundred feet have been impotent to impress their presence upon the topography, whose local development was, in such instances, controlled by other structural elements.

As will be later shown, many fault fissures in the Bisbee quadrangle have been filled by dikes of granite-porphyry. So far as the dike persists, such a fault can be followed with comparative ease. Other faults in the Paleozoic rocks may be accurately traced for long distances by one who looks carefully for evidence of fracturing and crushing and who has gained sufficient familiarity with the distinctive features of the local Paleozoic formations to recognize the particular abrupt lithological changes which are characteristic of faulted structure. But when the faults traverse the Carboniferous limestones, as they do southwest of Bisbee, their recognition demands close observation and patience. Even with good exposures it is not always possible in limestones to distinguish an important fault from an insignificant fissure—indeed, the brecciation, silicification, or mineralization may be far more pronounced in the case of the latter. In the Bisbee quadrangle the great thickness and uniformity of the Naco limestone and the lithological identity of certain of its beds with those of the Escabrosa limestone make the working out of the faulted structure a laborious processs, entailing the unremitting collection of the never too abundant fossils in order to check, step by step, the structural interpretations by the evidence of paleontology.

The obscurity of many of the faults in the limestones is well illustrated by the structurally and economically important Czar fault (Pl. III) which traverses the northwestern slope of Green Hill, separating the Naco limestone of the mass of the hill from the Escabrosa limestone of Hendricks Gulch. It has a throw of probably more than 500 feet and crosses a steep hillside upon which apparently every bed of limestone is exposed to view from the hotel in Bisbee. Yet so slightly does it affect the appearance of the bare, fume-swept hill that daily familiarity with the slope gives no hint of dislocation to one unaware of its existence.

Trends and dips.—The dominant faults of the Bisbee quadrangle have trends ranging from northwest to west-northwest. Such are the Dividend, Abrigo, and Gold Hill faults, the conspicuous dislocation near the Bisbee West mine (hereafter referred to as the Bisbee West fault), and most of the dike-filled faults along the southwest face of Escabrosa Ridge. Distinctly subordinate to the northwesterly fractures, but yet of much structural importance, are a number of faults with northeasterly strike. Some of the more prominent of these occur within an irregular zone of faulting stretching southwest from Bisbee, across Escacado Canyon and past the Bisbee West mine (Pls. I and II). One of the most interesting members of this belt of cross faults may be traced almost continuously from the vicinity of the quartzite quarry west of Bisbee to a point half a mile northwest of the Bisbee West mine—a distance of 2 miles (Pls. I, II, and III). As there will be frequent occasion to refer to this important dislocation, it may conveniently be called the Quarry fault. On the northeast, the Quarry fault apparently ends at the Dividend fault, while on the southeast it may terminate at the Bisbee West fault, although a tongue of Quaternary wash unfortunately conceals the junction of the two fractures. As a rule, the northeast faults in the Escacado zone (see Pl. II) are less persistent than the dominant northwest faults and frequently terminate at the latter. There are, however, several short northwest faults, which end against northeast faults, so that direction and persistency are not invariably related.

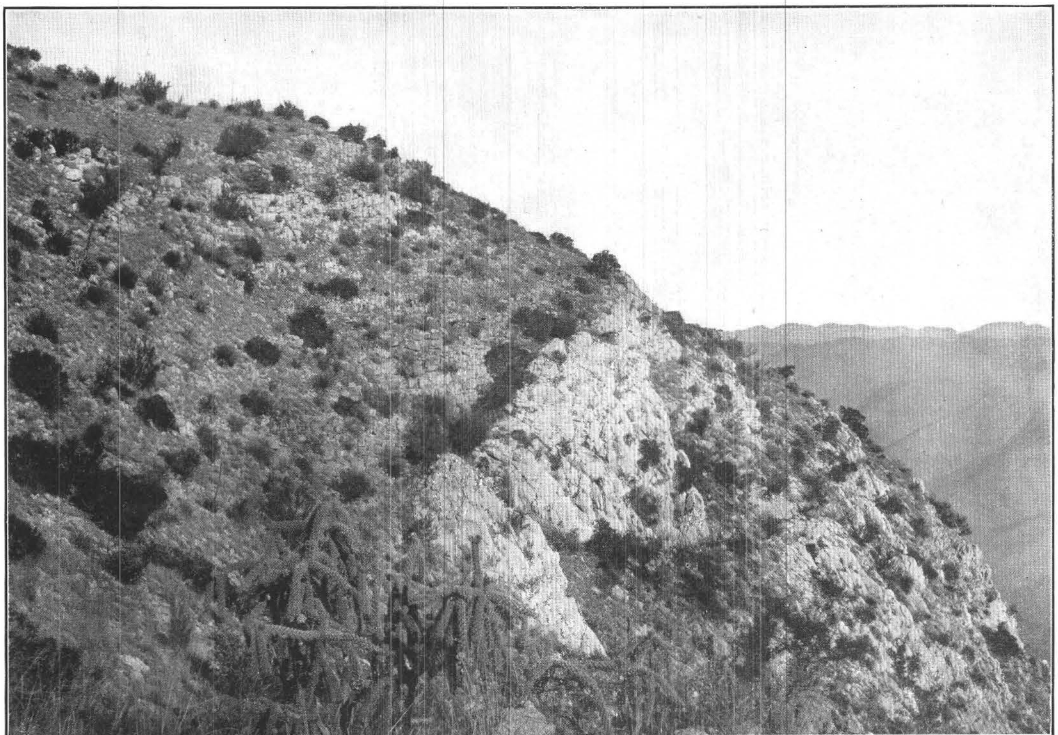
A northeast fault of considerable economic importance traverses the northwest slope of Queen Hill (Pl. III) and has been called the Czar fault. Others of similar trend occur in Uncle Sam and Silver Bear gulches, and still another dislocates the Paleozoic formations at Black Gap. The faults cutting the Cretaceous beds northeast of Bisbee are also to be classed with those of northeast trend.

In addition to the fissures of generally northwest or northeast trend, the quadrangle, as is to be expected, presents several examples of faults which do not conform to either of the principal directions. For example, Queen Hill is cut by a north-south fault, while a nearly east-west fault passes just south of the Cole shaft of the Lake Superior and Pittsburg mine (Pl. III). Such dislocations are structurally very subordinate, and are a necessary accompaniment of the general fissuring of the quadrangle in two main directions.

Character of dislocation.—Faults which are not vertical admit of a twofold classification based upon the relative movement of their walls. Those along which the hanging wall has slipped down (or the foot wall risen) are known as normal faults, while those in which the hanging wall has risen (or the foot wall gone down) are known as reversed, thrust, or overthrust faults.

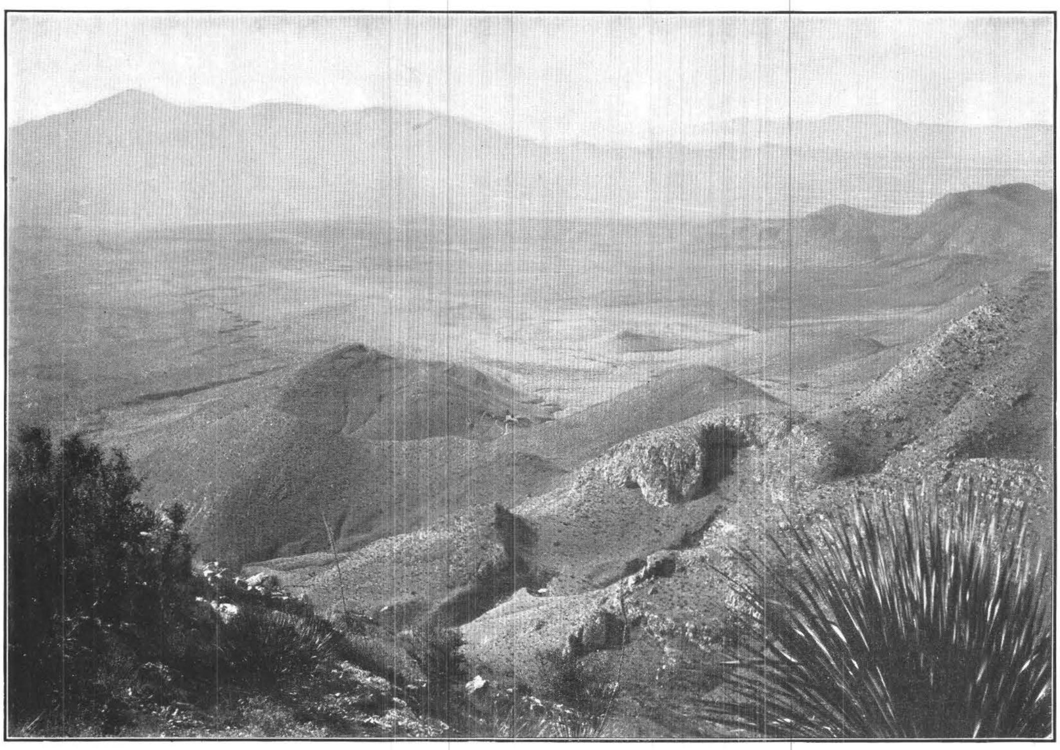
In the case of vertical faults the foregoing distinction vanishes, and the more nearly a fault approaches the vertical position the more difficult it may become to determine with surface exposures the character of the dislocation.

Both of the foregoing classes are represented in the Bisbee quadrangle. Faults of normal type are clearly exemplified by the Abrigo fault, several of the



A. FAULT BETWEEN NACO LIMESTONE, ON LEFT, AND ESCABROSA LIMESTONE, ON RIGHT.

Crest of Escabrosa Ridge west of Bisbee. The view is north, the canyon on the right being that extending from Bisbee up to Mule Pass.



B. VIEW FROM ESCABROSA RIDGE ACROSS ESPINAL PLAIN TO THE SAN JOSE MOUNTAINS, IN MEXICO.

In the foreground appear the faulted Paleozoic limestones near the mouth of Escacado Canyon. In the middle-ground is the Bisbee West mine. On the right are the Naco Hills and beyond them is faintly visible the Cananea Range.

fissures along the southwest slope of Escabrosa Ridge, particularly those not occupied by dikes, the Quarry fault, the Bisbee West fault, most of the faults in the vicinity of Escacado Canyon, most of those lying between Bisbee and Don Luis, and the faults in the Bisbee group northeast of Mule Gulch.

Faults of the overthrust type are remarkably well shown in the southeastern part of the quadrangle, where limestones, ranging in age from Cambrian to the Carboniferous, have been thrust from opposite directions over the Cretaceous formations by the Gold Hill and Glance faults. These, as will be fully shown in the following pages, are typical examples of this always impressive form of dislocation, in which older rocks have been thrust for considerable distances up gently inclined planes of fracture until they conspicuously overlie very much younger beds. Other cases of overthrust occur in the vicinity of Abrigo Canyon, about a mile west of the Bisbee West mine. Here the Escabrosa limestone rests discordantly upon the Martin and Abrigo limestones with an undulating, but, on the whole, nearly horizontal contact, which is apparently the result of faulting. If so, it represents a slightly inclined overthrust of unknown extent and direction.

The dike-seamed southwest face of Escabrosa Ridge presents several instances of reversed faults of a special kind. They are fissures now occupied by dikes of granite-porphyry, apparently intruded during the faulting. Such contemporaneous faulting and intrusion may conveniently be referred to as *intrusion faulting*, and the results of the action as *intrusion faults*. The best examples of this structure are to be found close to the western boundary of the quadrangle, about halfway between Moore Canyon and Brown's ranch, where two dikes may be seen cutting through the Abrigo, Martin, and Escabrosa limestones and displacing the beds of reversed throws of 75 and 150 feet (Pls. I and XVII, *A*). As most of the dikes along Escabrosa Ridge dip to the northeast, and as the general result of the faulting with which they are associated has been to depress the country on the southwest relatively to that on the northeast, the examples cited, although of very moderate throw, may be taken as typical of the intrusion faulting of the southwest slope of Escabrosa Ridge.

There still remain those faults for the classification of which the obtainable data are insufficient. Of these the most important, and the only one that need here be mentioned, is the Dividend fault. In spite of the extensive underground work accomplished in its vicinity this fault is not well exposed, and the direction of its dip is unknown. It is apparently nearly vertical, and as it is known that the southwest wall has gone down or the northeast wall up, the determination of the particular class of faults to which it belongs is perhaps a merely academic matter.

As a rule, only the relative movement of faults can be ascertained. We can very rarely determine, for instance, in a given normal fault whether the hanging wall actually moved down or the foot wall really moved up, or whether both walls moved in opposite directions. With this clearly understood once for all, to avoid circumlocution, the hanging wall of a normal fault will usually be described in the following pages as dropped or downthrown and the hanging wall of a reversed fault as upheaved or overthrust.

Age.—The faults of the Bisbee quadrangle may be grouped as follows: (1) Those of post-Pennsylvanian but pre-Cretaceous age, (2) those of post-Cretaceous but pre-Quaternary age, and (3) those which are post-Pennsylvanian and pre-Quaternary, but can not be assigned with certainty to either of the two preceding groups.

To the first group belong the intrusion faults and the fissures so directly connected with these as to preclude the idea of difference in age. Such are the Dividend fault, the Quarry fault, the Bisbee West fault, and most of the faults on the southwest slope of Escabrosa Ridge. The nearly horizontal overthrust west of the Bisbee West mine probably belongs here, although there is reason to believe that it was formed a little earlier than the nearly vertical faults in its vicinity. The Black Gap fault certainly belongs in this group, as it dislocates the Pennsylvanian Naco limestone, but not the unconformably overlying Cretaceous Glance conglomerate.

To the second group are assignable the faults cutting the beds of the Bisbee group. Such are the nearly vertical faults northeast of Bisbee, several small displacements in Mule Gulch, southeast of town, the Gold Hill overthrust, with its associated complex minor faulting as manifested southeast of Gold Hill, and the Glance overthrust. Accompanying this post-Cretaceous faulting there was very likely some revival of movement along the Dividend and other faults whose initial displacements dates from pre-Cretaceous time.

To the third group belong a few faults in the Paleozoic terrane southwest of Bisbee, which are not so clearly related to the granite-porphyry intrusions as to establish conclusively their pre-Cretaceous age. The most prominent example of these is the Abrigo fault. Although the age of these faults can not be directly ascertained, there is nevertheless strong probability that they are of the same age, at least so far as their initial displacements are concerned, as the faults of the first group. Their general similarity, as regards trend, dip, and character of dislocation, to faults known to belong to this group, and their lack of relation with the known post-Cretaceous faults, affords a reasonable basis for considering that the faults placed in the first and third groups are all post-Pennsylvanian and pre-Cretaceous in age, and that but two general periods of faulting were concerned in the structure of the Bisbee quadrangle.

With this preliminary outline of the nature and expression of the principal dynamic process concerned in the structure of the quadrangle, we may pass at once to the consideration of the whole geological fabric, introducing into this general discussion such further details in connection with the faults and such reference to folds and igneous intrusions as may be required.

GENERAL STRUCTURAL ANALYSIS.

Divisions of the quadrangle based upon structure.—Clearness of treatment requires us for the present to strip from a somewhat complex structure those various details with which nature loves to embellish her handiwork, and to compress essentials into the artificial simplicity of a diagram. In Pl. II the quadrangle has been roughly divided into several structural blocks or tracts. On the northeast and southwest are the broadly spread Quaternary deposits of Sulphur Spring Valley and Espinal Plain, effectually concealing the underlying rocks in these quarters. Between Bisbee and Sulphur Spring Valley and stretching from the top to the bottom of the diagram is the main *Cretaceous tract*, occupied by the rocks of the Bisbee group—broad at the north, but constricted in the south by the Gold Hill and Glance overthrusts. Here blocks consisting in their lower part of Paleozoic strata, but bearing Cretaceous beds on their backs, have been thrust from nearly opposite directions through and over the Cretaceous beds toward each other.

Extending from the northwest corner of the diagram past Bisbee is outlined an area of Pinal schist representing the largest exposure in the quadrangle of the ancient pre-Cambrian foundation of the region. It is shown as cut by the granite stock of Juniper Flat and by the smaller granite-porphyry stock of Sacramento Hill. The latter is indicated as being of later origin than the Dividend fault. South of the pre-Cambrian schist area is a triangular area of Paleozoic beds characterized by a gentle southwesterly dip. The relation of these beds to the schists north of them is that of unconformable deposition. The schists, the intrusive masses, and the triangular area of Paleozoic beds are all included in a single structural unit, which has been distinguished in the diagram (Pl. II) as the *Bisbee block*.

On the southwest the Bisbee block is separated diagrammatically by a simple line, representative of the complex zone of faults and dikes along Escabrosa Ridge, from an area of Paleozoic rocks possessing a general southwesterly dip. This has been called the *Escabrosa block* and with reference to the Bisbee block is downfaulted.

Southwest of the Escabrosa block, and separated from it by the Abrigo fault, is the *Naco block* of gently folded Pennsylvanian limestone. With reference to the block northeast of it, this mass represents a further important downthrow to the southwest.

The remaining area of Paleozoic rocks distinguished in the diagram is that designated the *Copper Queen block*, lying south of the Dividend fault and extending eastward to the Gold Hill fault. Structurally this is a fragment of a syncline. Its relation to the Bisbee block is that of a downfaulted mass. Its relation to the Escabrosa block is that of an upheaved mass. Its relation to the Gold Hill block is that of the underlying mass over which the latter has been partly shoved.

Comparison of the diagram with the geological map (Pl. I) at this stage of the discussion will not only aid in comprehension of the latter, but will give some idea of the intricate mass of structural detail which must now be adjusted to the bare framework of a diagrammatic conception.

Bisbee block.—The Bisbee block is bounded on the southwest and southeast by faults. On the northeast it is overlapped by the Cretaceous beds comprising the Bisbee group and on the northwest extends beyond the limits of the quadrangle. It consists fundamentally of crumpled crystalline schists (Pinal schist) partly overlain by Paleozoic formations and cut by granitic intrusives. Structurally, it is the highest of the several simple blocks into which the quadrangle has been divided, all the others having been relatively downfaulted. It is thus the block which in the present stage of regional erosion best exhibits the crystalline pre-Paleozoic foundation upon which the stratified rocks of the quadrangle have been laid.

Of the pre-Paleozoic structure, which must once have belonged to the rocks now known as the Pinal schist, nothing is directly discoverable. The bedded sediments from which the schists were likely derived by metamorphism were probably much folded and perhaps considerably faulted; but metamorphic recrystallization has obliterated the direct record of these processes. The present lamination of the Pinal schist is on the whole nearly vertical and the dominant strike is a little north of east; but the dip and strike of this cleavage are very variable and the rock is too monotonously uniform to reveal, in so limited an area of exposure, any clue to the character of the pre-Paleozoic deformation.

The granite mass of Juniper Flat and the smaller granite-porphyry body of Sacramento Hill, both of which are important structural elements of the Bisbee block, have the typically irregular forms of intrusive stocks. The comparatively simple southwest boundary of the Juniper Flat stock, with its approximate parallelism with the dominant dikes and faults of Escabrosa Ridge, indicate that the intrusion took place along a northwest-southeast fault or fault zone. The evident relation of the Sacramento Hill mass with the Dividend fault shows that here, too, intrusion was facilitated by faulting. Something more than simple faulting, however, is necessary to explain the irregular invasion of the schists and Paleozoic rocks by the granitic magma. There is no evidence that the latter fused and assimilated the invaded rocks in the vicinity of the contact. It must, therefore, be concluded that the magma made place for itself either by forcing the encircling rocks aside or upward, or by the process of block engulfment to which Daly[a] has recently given much needed clearness of conception and the suggestive name of "overhead stoping." So far as available evidence goes, either or both of these processes may have been operative in the case of the Bisbee intrusions.

In that portion of Escabrosa Ridge surmounted by Mounts Martin and Ballard, and corresponding to the triangular area indicated in the diagram (Pl. II) between the Quarry fault and the Escabrosa zone of faults, there is preserved a section of the Paleozoic rocks which is complete very nearly to the top of the Escabrosa limestone and rests unconformably upon the crystalline basement of the Pinal schist. These beds dip generally to the southwest at about 25°, but to the southwest of Mounts Martin and Ballard, where they are cut off by the faults of the Escabrosa zone, they become horizontal or dip slightly to the northeast. They thus constitute a fragment of the northeast half of a gentle syncline with northwest-southeast axis and with a southeasterly pitch. Outlying remnants of Bolsa quartzite, formerly parts of this syncline, occur perched along the crest of Escabrosa Ridge for some distance beyond the western boundary of the quadrangle, showing that the present crest of the ridge northwest of Mount Ballard corresponds approximately to the bottom of this structural trough and to the old Paleozoic surface of erosion. This same ancient surface can be identified on the northeast side of Mule Gulch by a few outlying remnants of the Bolsa quartzite—one on the hilltop just north of Bisbee and four at lower altitudes east of the Sacramento Hill porphyry mass. These remnants were formerly connected, probably through an intervening anticline, with the Mount Martin syncline, and their present positions indicate that the Dividend fault terminates on the west at its juncture with the Quarry fault. In other words, that part of the Copper Queen block between the Dividend and Quarry faults may be likened to the first wedge-shaped slice cut from a circular cake. This conclusion is supported by the absence of any evidence to show that either of these important faults continues into the Pinal schist beyond their meeting point.

The distribution of these outlying remnants of Bolsa quartzite is further significant as showing that the Cretaceous beds north and east of Bisbee were laid down upon an erosion surface that was locally very nearly coincident with the pre-Cambrian peneplain. (See also p. 62.)

When the fragmentary Mount Martin syncline is further examined it is seen to be dissected by numerous faults. The most important of these is one of northeasterly trend which crosses Escabrosa Ridge about halfway between Mount Martin and Mount Ballard. This is a normal fault which drops the beds on its northeast side about 250 feet.

[a] Daly, R. A., The mechanics of igneous intrusion: Am. Jour. Sci., 4th ser., vol. 15, 1903, pp. 269–298.

Escabrosa block.—This complex structural division is bounded on the northeast by the Escabrosa zone of faults and dikes, and on the southwest by the Abrigo fault. On the northwest it extends beyond the bounds of the quadrangle and on the southeast it passes beneath the Quaternary of Espinal Plain. In its broadest structural aspect it may be imagined a wide step upon which one mounts from the Naco block, and thence ascends to the Bisbee block. The rock most extensively exposed upon the surface of this block is the Abrigo limestone. The general dip of these beds is southwesterly, but they are usually gently folded, the axes of the folds striking northwest and southeast. In the vicinity of faults and dikes the Abrigo beds often show local departures from the prevalent strike and dip, and near the Escabrosa fault-and-dike zone the beds pass as a rule through rapidly increasing steep southwesterly dips into a nearly vertical attitude.

The other formations exposed in this block are the Pinal schist along the northeastern margin, the Bolsa quartzite, and the Martin, Escabrosa, and Naco limestones, all constituting a mosaic of minor fault blocks, diversified by dikes and sills of granite-porphyry.

The Escabrosa zone of faults and dikes is far from being the simple line of dislocation indicated in the diagram (Pl. II). As described on page 91, it is a complex belt of branching and reticulating dikes and faults. The net result of the faulting along this zone has been to drop the Escabrosa block with reference to the Bisbee block. The total throw can not be exactly determined. It is over 2,000 but probably less than 2,500 feet. Northwest of Abrigo Canyon the dislocation has been effected mainly by intrusion faults of the reversed type. Southeast of Abrigo Canyon, however, the greater part of the displacement occurs along the Bisbee West fault, which is normal in type. The faults of the Escabrosa zone are occasionally opposed in throw. For example, the Mount Martin syncline is cut off, half a mile southwest of the summit of the peak, by an intrusion fault which has dropped the beds to the northeast of it, thus counteracting in part the prevalent southwest downthrow of the zone as a whole.

Just north of Abrigo Canyon the Escabrosa block is transversely divided by a nearly northeast-southwest fault, with downthrow to the southeast. The throw of the fault is probably nowhere more than 500 feet, but it is sufficient to bring the Escabrosa limestone in contact with Abrigo beds. Inclosed between this fault, the Bisbee West fault, the Abrigo fault, and some minor faults to the southeast, is a block a little over 1½ miles in area, in which are exposed the Abrigo, Martin, and Escabrosa limestones. The Martin limestone overlies the Abrigo formation in its usual conformable position. But the Escabrosa limestone, as may be seen from the geological map (Pl. I), rests unconformably upon both the Martin and Abrigo limestones. Such a relation may obtain either from erosional unconformity or from faulting. If from the former, then it implies post-Devonian deformation and erosion of such intensity as may fairly be considered incompatible with the apparent conformity that elsewhere in the quadrangle prevails between the Devonian and lower Carboniferous beds. The hypothesis of a fault is further supported by the noticeable and unusual brecciation of the superincumbent Escabrosa beds in the immediate vicinity of Abrigo Canyon, and the development of much secondary chert along what appear to have been nearly horizontal planes of movement in the limestones above the supposed main fault. Although the contact between the Escabrosa limestone and the underlying Martin and Abrigo beds is usually concealed by a talus of limestone and cherty breccia, its immediate vicinity is usually marked by indubitable evidence of disturbance and frequently by an abundance of silicified limestone breccia. The only point where the contact is clearly exposed is in the western angle of the little fault block, close to the Abrigo fault in that part of its course coincident with Abrigo Canyon. Here the shattered Escabrosa limestone may be seen resting discordantly above the Martin limestone and separated from the latter by a foot or more of breccia, consisting of limestone fragments in a triturated reddish matrix. It is concluded from the foregoing evidence that the Escabrosa limestone in the vicinity of Abrigo Canyon has been thrust by a nearly horizontal fault over the Martin and Abrigo formations. This movement evidently (see Pl. I) took place before the nearly vertical faults, now inclosing the block in which it is recorded, were formed. The continuation of this overthrust beyond the fault block, in which the observed phenomena connected with it are now isolated, has been removed by erosion or carried down by later faulting below the present surface. The direction and original extent of the overthrust are accordingly unknown.

Naco block.—This unit, lying on the southwest or downthrown side of the Abrigo fault, is structurally the most simple of the divisions into which the quadrangle has been diagrammatically divided. Its exposed portion consists of Naco limestone cut by two small masses of rhyolite. The beds have the form of a gently arched anticline pitching at an angle of 10° or 15° to the north, but becoming nearly horizontal near the Abrigo fault. Upon this general anticline are superposed slight minor corrugations with various axial trends. The Abrigo fault, which bounds the block on the north, is a simple dislocation with a southerly dip of about 75°. The throw is normal and amounts to something over 2,000 feet. The fault is well exposed in Abrigo Canyon (Pl. XVII, *B*), where it is associated with a breccia of crushed limestone.

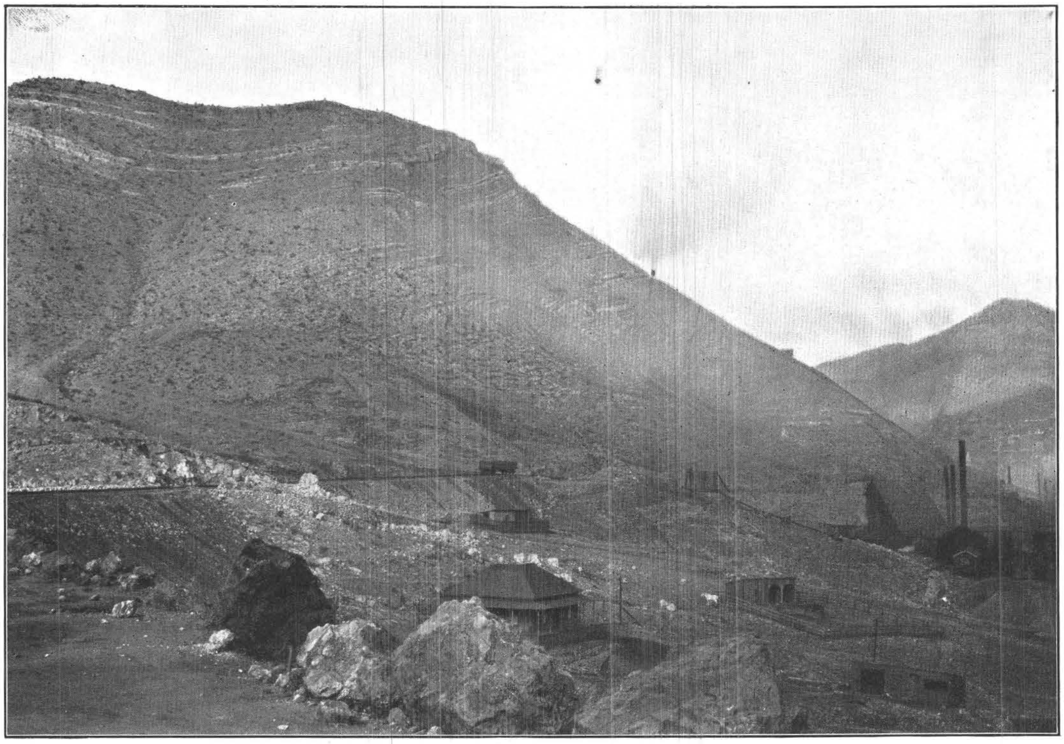
Copper Queen block.—Economically, this is by far the most important structural division of the quadrangle, as within it occur all of the productive copper deposits known in the Mule Mountains. On the northeast it is bounded by the Dividend fault, the granite-porphyry stock of Sacramento Hill, and, surficially, by the overlapping Cretaceous beds of the Bisbee group. On the northwest it is cut off by the Quarry fault. On the southwest it is limited by the Bisbee West fault of the Escabrosa zone and is partly overlapped by Quaternary deposits. On the southeast it disappears beneath the Gold Hill overthrust.

In its broader structural aspect the Copper Queen block is a fragment of a canoe-shaped syncline with a nearly northwest-southeast axis, pitching to the southeast. The northwestern limb of this syncline, cut off by the Dividend fault and relatively upheaved, has been removed by pre-Cretaceous erosion. In the down-dropped Copper Queen block is preserved the northeastern end of the southwestern half of the original synclinal canoe.

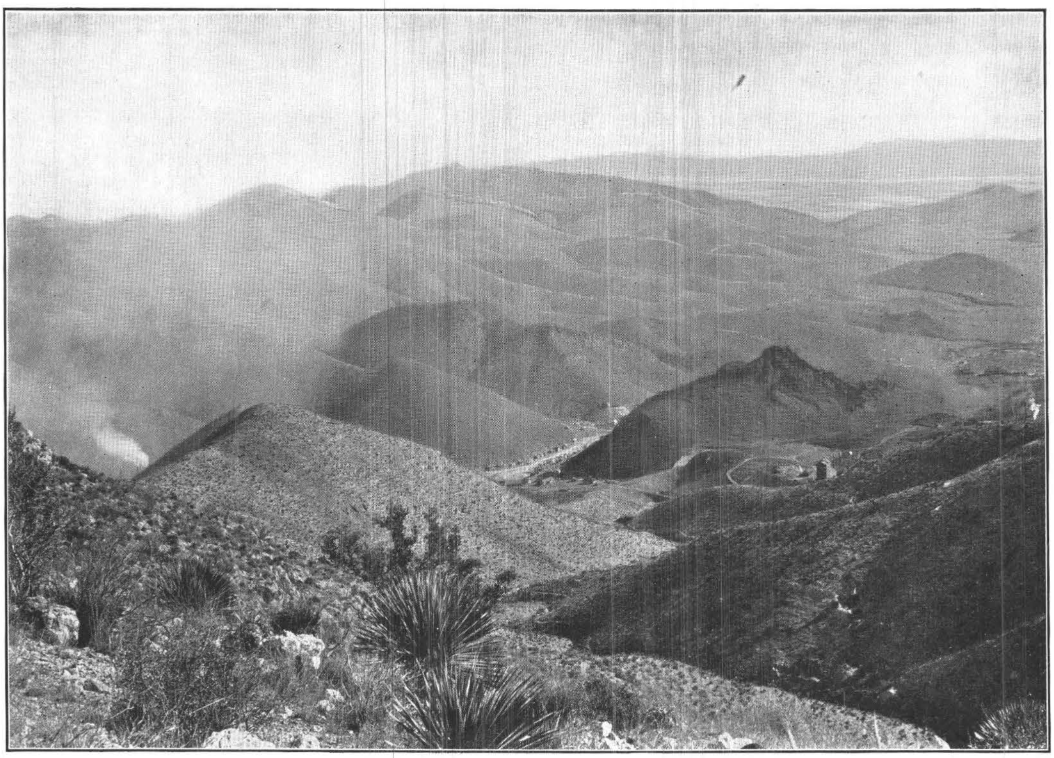
In this structure are represented all of the pre-Cretaceous rocks of the quadrangle. At the bottom is the Pinal schist bent downward into a basin by the forces which produced the syncline. Lining this basin is the Bolsa quartzite, and occupying it, in successive layers, are the Abrigo, Martin, Escabrosa, and Naco limestones, the latter filling up the central part of the depression to the present surface of erosion. Finally, the Sacramento Hill stock is an eruptive mass that has broken up through the schists and overlying Paleozoic beds on the line of the Dividend fault, which is nearly coincident with the synclinal axis.

In spite of the complexity introduced by faulting, the syncline is distinctly recognizable in the accompanying geological maps (Pls. I and III). Extending southeastward from Bisbee, along the south side of Mule Gulch, is the area of Naco limestone forming the thick axial core. Inclosing this on the west and south are successive faulted bands which, beginning at the Dividend fault west of Bisbee and sweeping in a strong curve around the pitching end of the syncline toward Gold Hill, represent the outcrops of the Escabrosa, Martin, Abrigo, and Bolsa formations, conforming in general strike and dip to the synclinal structure. Lastly, in the southwest corner of the Copper Queen block, about a mile and a half northwest of Don Luis, the fundamental Pinal schist is exposed in a few small fault blocks.

When the Copper Queen block is more closely scrutinized it appears that the syncline constituting its dominant feature may be distinguished from a minor structural division of the main block occupying the triangular area including and lying west of Escacado Canyon and inclosed between the Quarry and Bisbee West faults. This area is characterized by many vertical or normal faults, some of which have throws of over 1,000 feet. It corresponds to a downthrown block with refer-



A. QUEEN HILL FROM THE SOUTHEAST; HOLBROOK SHAFT ON THE RIGHT.



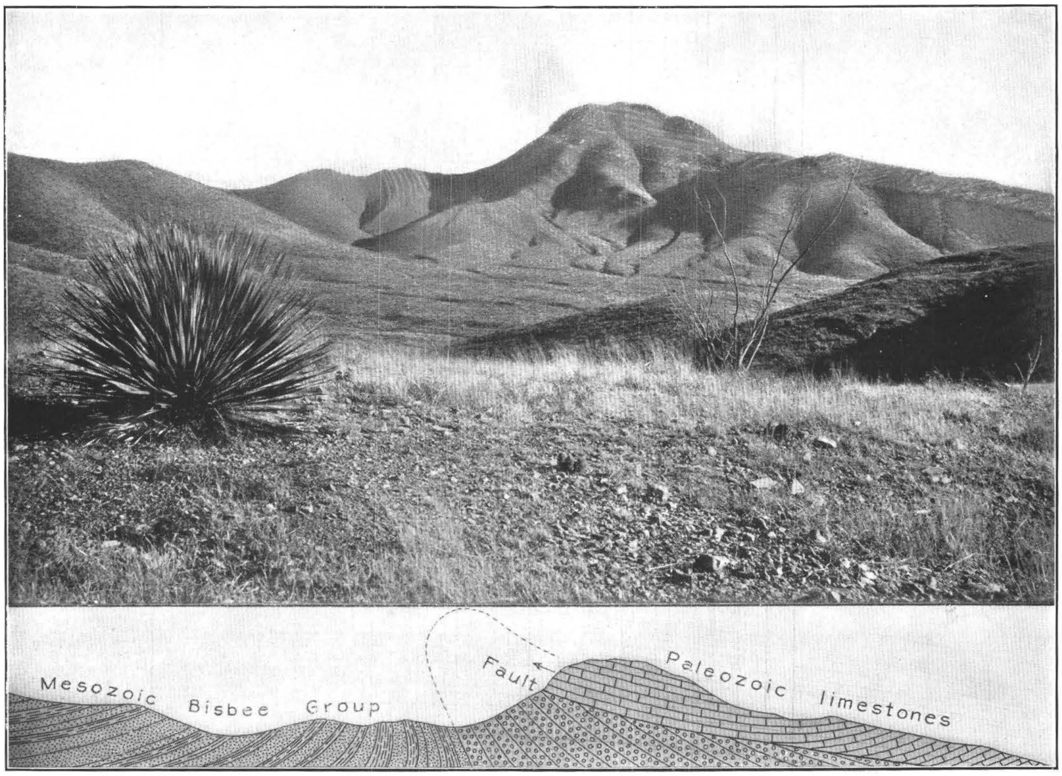
B. GENERAL VIEW EASTWARD FROM THE HEAD OF UNCLE SAM GULCH OVER SACRAMENTO HILL TO THE MOUTH OF MULE GULCH.

On the left are Queen Hill and the flues of the Copper Queen smelter. In the right middle-ground is the Spray shaft and just beyond it Sacramento Hill Still farther to the right is the Irish Mag shaft. In the distance are the hills carved from the beds of the Bisbee group.

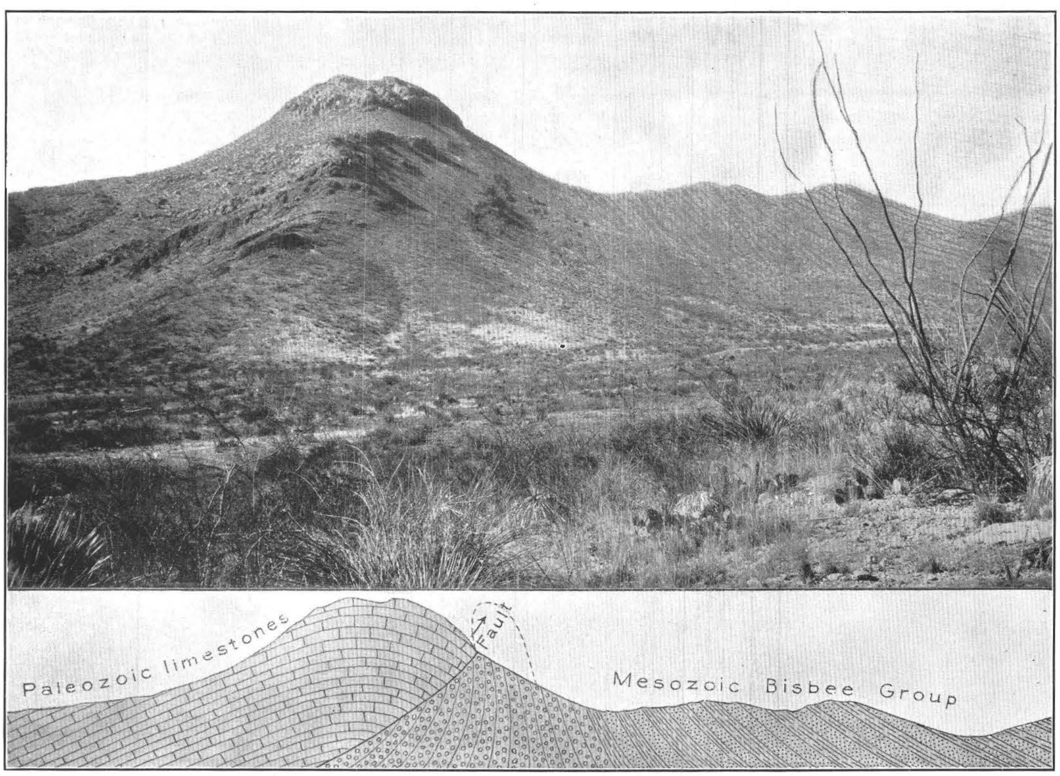
ence to the Bisbee block and to the synclinal part of the Copper Queen block. Owing, however, to its internal faulted structure the amount of this relative downthrow is variable. It is slight in the southern part of the triangular area, where Cambrian and pre-Cambrian rocks prevail, but is very much greater in the northern part where Pennsylvanian limestone composes most of the surface. This minor structural division may be considered as a marginal portion of the Copper Queen block, from which it became detached and fault shattered in the general dislocation of the quadrangle at the close of the Carboniferous; or it may be regarded as one or more structural units of equivalent rank although inferior in size to the larger structural divisions recognized in the accompanying diagram (Pl. II).

Where faults are so numerous as in the Bisbee quadrangle, descriptive reference to each feature is out of the question. Although, owing to their important relation to economic problems, the dislocations of the Copper Queen syncline will be described somewhat fully, yet for many of the details of structure the geological maps and sections (Pl. I and III) must be left to speak for themselves. The explanatory notes should be read with special reference to the geological map of the vicinity of Bisbee (Pl. III).

The greater part of Queen Hill, including the summit and southeastern slope, is composed of beds of Naco limestone. Instead of dipping to the southeast, as they should were they strictly conformable to the general synclinal structure, these particular beds constitute a little local syncline with northwest-southeast axis, as may be seen upon viewing Queen Hill from the north or from the vicinity of Sacramento Hill (Pl. XXI, *A*). This structure, however, is very local, and passes by change of dip, in the vicinity of Uncle Sam Gulch, into that of the main syncline. North and west of Queen Hill are several faults that complicate the general structure of the Copper Queen syncline. The lower part of Hendricks Gulch, including the old open cut of the Copper Queen mine, is in Escabrosa limestone. Instead, however, of passing conformably beneath the Naco limestone of Queen Hill, the Escabrosa is separated from the latter by the Czar fault. This dislocation has dropped the Naco limestone for a distance of over 500 feet so that it abuts against the Escabrosa limestone which stratigraphically belongs below it. The head of Hendricks Gulch is in a block of Naco limestone which has been faulted down into the Escabrosa. One of the faults bounding this block continues north-northeast to the Dividend fault near Castle Rock and effects a conspicuous displacement of the Escabrosa and Martin limestones. Between this north-northwest fracture and the Quarry fault are other important dislocations (Pl. III) which drop Martin and Escabrosa beds of the Copper Queen syncline against the stratigraphically lower Abrigo lime-



A. GOLD HILL FROM THE NORTHWEST, SHOWING OVERTHRUST FAULT.



B. GOLD HILL FROM THE SOUTH, SHOWING OVERTHRUST FAULT.

East of the foregoing fault the beds composing the Copper Queen syncline, with the exception of a moderate displacement at Black Gap, retain their normal synclinal structure up to the point where this structure disappears beneath the Gold Hill overthrust. These beds do not exhibit the changes in strike and dip characteristic of the curved, pitching northwest bow of the synclinal canoe, but constitute part of the straight side.

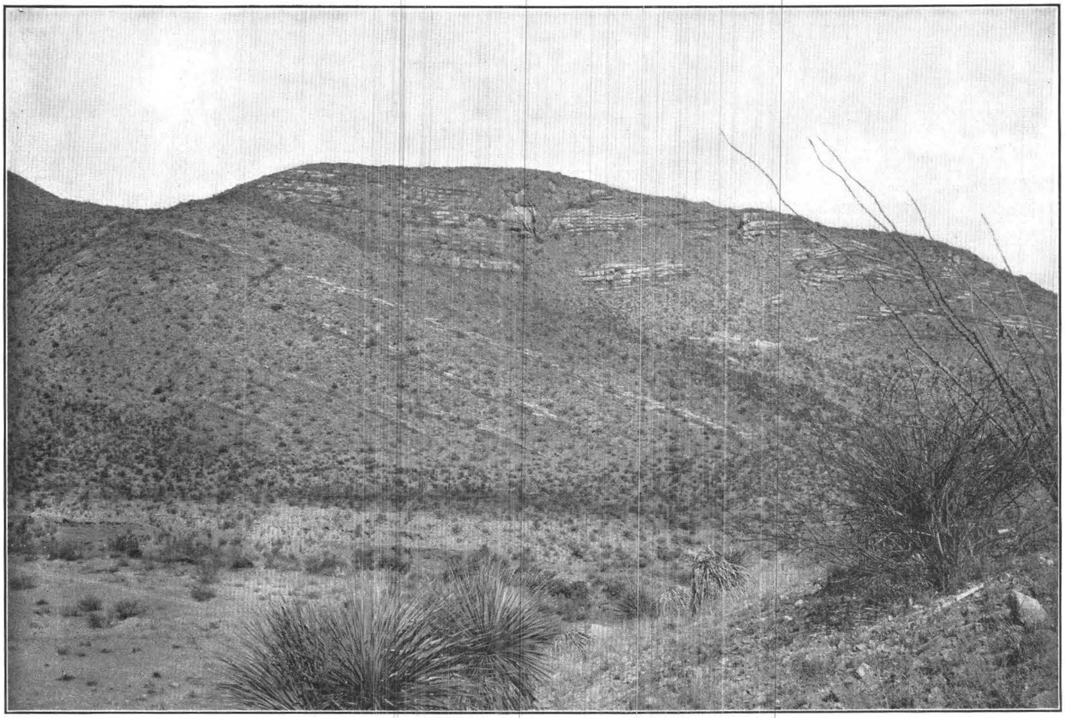
Gold Hill block.—This structural unit is bounded on the north and east by the Gold Hill overthrust fault. On the west it passes beneath Quaternary deposits and on the south extends into Mexico. Superficially it is composed for the most part of Cretaceous beds arched into an anticline with northwest-southeast axis. These beds lie upon a Paleozoic, and perhaps in places upon a pre-Paleozoic, foundation, which is exposed along the northeastern edge of the block. The block rests, at least in part, upon Cretaceous beds. It owes its position to faulting. The entire block has been thrust from the southwest up a gently inclined undulating fault fracture for a distance that can not be accurately determined, but is thought to be at least 2 miles.

Before the mechanics of the fault are discussed the evidence for its existence will be briefly presented. The contact between the Paleozoic rocks north and east of them is so related to the topography as to indicate that the older rocks overlie the younger rocks. A view of Gold Hill from the northwest (Pl. XXII, *A*) strongly reenforces this suggestion. A view of the hill from the southeast (Pl. XXII, *B*) is scarcely less suggestive, and the same relation is apparent to one looking northwest from Glance station. Close examination confirms the unanimous suggestion of distant views and of the areal distribution of the rocks with reference to the topography. Wherever the contact between the Paleozoic and Cretaceous rocks is exposed the former are found to overlie the latter and to be separated from them by a zone of fracturing and brecciation. On the northwest side of Gold Hill a tunnel has been run from Gold Gulch into the hill. The tunnel is entirely in Glance conglomerate, and its face is apparently nearly vertically under the outcrop of the fault on the hillside above. The fault itself has not been reached, but the conglomerate near the face of the tunnel is greatly sheared and crushed. The approximate line of the fault can be readily followed along the north slope of Gold Hill, where it has a rather steep dip to the south and is accompanied by much crushing and disturbance of the underlying conglomerate and overlying Escabrosa and Naco limestones. In the saddle northeast of the hill the Glance conglomerate has been squeezed between the upthrust limestone and the mass of Cretaceous beds northeast of it into a closely compressed local anticline. On the southeast side of the hill the thrust fault is exposed in some prospects and exhibits a local southwesterly dip of 50°. The Cretaceous beds upon which the overthrust Paleozoic rocks rest are much disturbed in the immediate vicinity of the fault. They are crushed and sheared and in some places metamorphosed to a much-crumpled, greenish sericitic schist, very similar in appearance to some of the vastly older Pinal schist.

We may pass for the moment the very complicated corner just southeast of Gold Hill and continue to follow the course of the main overthrust. This swings through a saddle half a mile southwest of Black Knob and thence down past Glance station. While it is not always clearly exposed, the tracing of its approximate course presents no difficulty, owing to the signal discordance in lithology and structure of the rocks it separates and the visible signs of disturbance that accompany it. South of Glance the fault comes to the surface along the bottom of the open valley that extends southward past the Glance mine and is not very well exposed. The dip is to the southwest, as usual, but its amount is unknown. It is probably about 40°. It is noteworthy that throughout its course the Gold Hill fault actually outcrops with a somewhat steeper dip than might be expected from the general character of the overthrust. It is probable that this dip becomes less beneath the mass of the block and that its steepness near the present exposures of the fault is local and due to causes that will be later pointed out.

A return may now be made to the faults already referred to southeast of Gold Hill. These features are not well exposed as a whole, and the complicated structure to which they give rise may be variously interpreted. The explanation most in harmony with the facts obtained in the course of a minute investigation of this particular area is briefly as follows: The offsetting of the Gold Hill overthrust and the cutting out of the Glance conglomerate southeast of Gold Hill are due to a nearly east-west normal fault with southerly dip. This fault is younger than the overthrust. About a mile southeast of Gold Hill is a little mass of Mural limestone inclosed by faults. It occurs with small fault blocks of the Martin and Morita formations in the axis of the Cretaceous syncline where normally we should expect to find only Glance conglomerate. It apparently extends beneath the Martin limestone and is a part of the Gold Hill overthrust block. We are driven to conclude that it was derived from the overridden and buried southwest limb of the Cretaceous anticline and was formerly part of the beds in that limb corresponding to those now exposed in the northeast limb in the vicinity of Black Knob. If the anticline was originally fairly symmetrical, this little block of Mural limestone must have been shoved by the Gold Hill overthrust for a distance of at least 2 miles from the southwest. It thus affords an approximate measure of the minimum amount of overthrust.

The mechanical conditions under which the Gold Hill overthrust was initiated can not be satisfactorily determined. As the Paleozoic strata are involved, the forces concerned were by no means superficial and it is unsafe to conclude that



A. THE GLANCE OVERTHRUST FAULT FROM THE SOUTH.

The line of the fault is accentuated by a growth of bushes. The nearly horizontal beds above the fault plane are Naco limestone. The easterly dipping beds below the fault plane are Mural limestone.

B. BISBEE FROM THE SOUTHEAST, LOOKING UP MULE GULCH.

The town lies in the canyon under the fumes of the smelter. The dark knob in the middle of the picture is Sacramento Hill. To the left of it may be seen the Spray and Irish Mag shafts.

the locus and character of the faulting were determined by any preexisting structure in the Cretaceous beds. The most that can be said is that the overthrust was effected by strong compression acting along northeast-southwest lines. There is reason to believe that the hanging wall of the fault has been thrust over the foot wall for a distance of at least 2 miles, but nothing can be learned of the antecedent structural conditions that determined the fracture.

As movement along the fault continued, the Paleozoic rocks of the hanging wall were thrust forward and upward until they pressed against the Cretaceous beds northeast of Gold Hill, and squeezed the latter into a closely compressed anticline in the immediate vicinity of the fault. The effect of the thrust appears also to have been recorded, at a distance from the fault, in the change of strike and upturning of the Mural limestone near the Easter Sunday mine. It is probable that the overthrust Paleozoic beds never extended much farther to the northeast than the present outcrop of the fissure. The steep dip of the fault where actually exposed and the nature of the local folding and squeezing of the Cretaceous beds in its vicinity, are phenomena to be expected along the plowing front of a rigid overthrust mass rather than in those portions of the foot wall which have been greatly overridden.

Glance block.—This is a well-defined overthrust mass that emerges from beneath the Quaternary deposits of Sulphur Spring Valley and rests upon the Mural limestone northeast of Glance station. The block consists of Naco limestone in nearly horizontal beds, unconformably overlain by Glance conglomerate. It has been thrust from the east over the Mural limestone by a fault that is parallel to the bedding of the latter. The outcrop of this fault-plane is marked by a slight topographic bench (Pl. XXIII, *A*) and the presence of a distinct fault breccia. The dip of the fault is about 25° to the east.

Owing to the covering of Quaternary deposits, the geological structure that gave rise to this dislocation and the horizontal extent of the overthrust can not be determined. It was evidently effected by forces operating along nearly east-west lines. It is likely that the Naco limestone of this block was originally thrust forward until it met the Naco beds of the Gold Hill block advancing from the southwest. The meeting of these resistant masses probably formed a competent arch over the Morita beds of Black Knob and put a stop to the nearly opposite movements of the two overthrust blocks.

Cretaceous tract.—This, the largest of the several areal units into which the quadrangle has been diagrammatically divided, is not, like the others, a definite structural block.

On the north, it is an area within which the pre-Cretaceous structure is hidden by the overlying beds of the Bisbee group, with their gentle folds and moderate normal faults. Its western boundary is here the sinuous eroded edge of the Glance conglomerate which rests with low northeasterly dip upon granite, schist, and limestone, and conceals the northeastern extensions of the Bisbee and Copper Queen blocks. Its eastern boundary is the similarly overlapping but less indented edge of the Quaternary deposits.

On the south the Cretaceous tract appears as a narrow strip surficially constricted by the opposed Gold Hill and Glance overthrusts, and overlapped on the east by the Quaternary deposits of Sulphur Spring Valley.

The outline of the tract is thus conditioned by erosion, by Quaternary overlap, and by low-angle overthrusts. Its internal structure has already been briefly described on pages 56 to 57.

GEOLOGICAL HISTORY.

The geological history of the Bisbee quadrangle is divisible into three grand eons—(1) that of pre-Cambrian sedimentation, deformation and metamorphism; (2) that of pre-Cambrian erosion, and (3) that embracing the Paleozoic, Mesozoic, and later eras.

The dimmed and time-worn record of the oldest eon is found in the Pinal schist. It has been shown that this formation probably consisted originally of sediments. It follows that these were derived from still more ancient rocks and were deposited in a pre-Cambrian sea. Long before Cambrian time these sediments were altered to crumpled crystalline schists and were therefore presumably deeply buried beneath other rocks, and intensely folded and compressed. As a result of such folding, they were probably elevated as an extensive mountain mass.

During the second eon, which may not have been sharply marked off from the preceding one, this mountainous land was eroded.

It perhaps underwent many vicissitudes during this interval, involving oscillations in level and accumulations of fresh sediments which were only to be again stripped away by erosion. All that is recorded, however, is a vast interval of erosion during which mountains were brought low, and rocks bearing the the stamp of deep-seated metamorphic processes were exposed at the surface of a nearly level plain of erosion.

With the opening of Cambrian time this plain sank beneath the sea. The waves, as the shore-line enroached upon the land, rounded the fragments, chiefly of vein quartz, that lay upon the subsiding land surface, added to them such coarse material as they produced by direct attack upon the schists, and spread the detritus evenly over the sea bottom as the basal conglomerate of the Bolsa quartzite. As the shore advanced inland the quartzite was deposited as sand above the conglomerate in the deeper water of the outer littoral zone to a thickness of 430 feet.

Then a change took place. Either there was an increased subsidence which carried this part of the sea bottom beyond the reach of littoral currents having sufficient power to transport sands, or the nearest land mass still remaining above water no longer supplied arenaceous sediments. The Bolsa formation was succeeded by the siliceous calcareous muds of the Abrigo formation, 770 feet in thickness. Here for the first time in this region marine life makes its appearance and in the impure cherty Abrigo limestones are inclosed pteropods, abundant fragments of trilobites, and small linguloid brachiopods. An incursion of white quartz-sand, now consolidated as the upper bed of the Abrigo formation, marked the close of Cambrian sedimentation. Probably at no time during this period was the local sea bottom depressed to a very great depth, and it appears to have been only occasionly cut off entirely from the finer terrigenous silts.

The Silurian period, so far as known, has left no record in the Bisbee quadrangle, the fossiliferous beds of the middle Cambrian Abrigo limestone being succeeded with no visible stratigraphic interruption by the Martin limstone carrying abundant characteristic Devonian fossils. In spite of the apparent conformity, however, the absence of the Silurian can be satisfactorily accounted for only by supposing that an interval of erosion separates the Cambrian and Devonian formations; that is, there is an actual although locally imperceptible unconformity. Any other explanation meets with insuperable obstacles. The existence of such an unconformity is indicated by the similar conditions described by Walcott[a] in the Grand Canyon of the Colorado, about 350 miles northwest of Bisbee, where Silurian beds are absent and the Devonian is separated by an erosional unconformity from the underlying Cambrian Tonto group. It must be noted, however, on the other hand, that Lindgren[b] has described the Silurian of the Clifton district, about 100 miles a little east of north from the Mule Mountains, as overlain conformably by the Devonian. But the presence of Silurian beds at Clifton, even if conformably beneath the Devonian, is evidence for, rather than against, pre-Devonian erosion at Bisbee, where such beds are lacking. It is one of many facts tending to show that the earlier Palezoic sedimentation of Arizona was accompanied by great diversity of local conditions.

Whatever may have been the conditions during the Silurian, in the Devonian period the quadrangle was covered by an open sea of moderate depth, in which flourished abundant marine organisms that contributed their calcareous parts to

[a] Walcott, C. D., Pre-Carboniferous strata in the Grand Canyon of the Colorado, Arizona: Am. Jour. Sci., 3d ser., vol. 26, 1883, pp. 438-439.

[b] Manuscript of a forthcoming report on the Clifton-Morenci district.

form the Martin limestone. That there was still a land mass rising above the Devonian sea at no great distance from the tract of deposition now under consideration is shown by the occasional occurrence of shales within the Martin formation.

Walcott[a] has shown that in the Grand Canyon region there was an interval of erosion between the Devonian and the Carboniferous periods. The evidence available in the Bisbee quadrangle is not decisive on this point. The most that can be said is that there is apparent conformity between the Martin and Escabrosa limestones. The latter formation, consisting chiefly of pure granular limestone made up very largely of the fragments of crinoids, records probably the deepest water that ever covered the Bisbee region. So far as known no land-derived sediments found their way into this part of the lower Carboniferous sea.

The most careful examination of many excellent natural sections has failed to discover any evidence of unconformity between the Escabrosa and Naco limestones. It is concluded that the deposition of limestone continued without any interruption from the Mississippian into the Pennsylvanian epoch. The depth of the water probably gradually decreased as a consequence of the steady accumulation of thousands of feet of calcareous material. It is probable, too, that there was a general elevation of the sea bottom or of a not very distant landmass, for fine terrigenous sediments are occasionally found intercalated between the Naco limestones as they are in the Martin formation.

With the close of the Pennsylvanian epoch the long era of Paleozoic sedimentation, during which deposits had piled up to a thickness of over 5,000 feet, or, approximately, a mile, came to an end. Orogenic forces became dominant, and the region of the Bisbee quadrangle was elevated above sea level. To this elevation faulting, folding, and igneous intrusions all contributed. The beds appear to have been first rather gently folded by forces acting in northeast-southwest directions. There was some overthrust faulting, as shown by the sliding of the Escabrosa over the Martin and Abrigo limestones in the vicinity of Abrigo Canyon. This was closely followed by the nearly vertical normal faults and the reversed intrusion faults, which constitute the salient features of the pre-Cretaceous structure. The intrusion of the Juniper Flat and Sacramento Hill stocks accompanied or immediately followed this general faulting, which may have occurred in the Permian epoch of the Carboniferous period.

During Triassic and Jurassic time the mountainous country elevated by the post-Pennsylvanian deformation was subjected to erosion. If any sediments were deposited within the quadrangle during these periods they were removed prior to the opening of the Cretaceous and have left no trace of their former presence. Erosion had stripped most of the Paleozoic beds from the elevated fault block

[a] Walcott, C. D., Pre-Carboniferous strata in the Grand Canyon of the Colorado, Arizona: Am. Jour. Sci., 3d ser., vol. 26, 1883, p. 438.

northeast of the Dividend fault and reduced the quadrangle as a whole to a moderately hilly topography, when the Cretaceous period was introduced by a rapid general subsidence, during which the Glance conglomerate was deposited as described on page 62.

With the entire disappearance of the quadrangle beneath the sea the deposition of the Glance conglomerate came to an end and was followed by the accumulation upon a gradually sinking sea bottom of 1,800 feet of sands and muds composing the Morita formation. This is a shallow-water deposit and records conditions intermediate between those under which the littoral Glance conglomerate was formed and those represented by the Mural limestone. The actual source of the Morita sediments is unknown. It is evident that the Pinal schist contributed detritus to the basal beds, but as it is probable that all of the schist within the limits of the quadrangle was covered by the Glance conglomerate before any considerable part of the Morita beds was laid down the land mass that furnished the sands and muds must have been outside of the area under investigation. The main shore line probably lay to the west of the Mule Mountains.

After the greater part of the Morita sands and silts had accumulated in a sea apparently but poorly provided with animal life there was a change in the character of the sediments. They became more calcareous and gradually passed into the impure limestone, often crowded with marine shells that make up the lower member of the Mural limestone. These fossiliferous calcareous muds were in turn succeeded by the fairly pure limestone beds of the upper member of the Mural formation, indicative of a moderately deep sea containing abundant animal life. The 650 feet of Mural limestone, however, mark an episode in a general accumulation of sands and silts as shown by the return in the Cintura formation to conditions of deposition similar to those which prevailed during the laying down of the Morita formation.

The early Cretaceous (Comanche epoch) is represented by nearly 5,000 feet of sediments. How much more material was deposited during later Cretaceous and Tertiary time is unknown. Since the deposition of the Cintura formation the rocks of the quadrangle have been deformed by folding and faulting and were subjected to erosion. The exact sequence of these events is not revealed. The latest faults, for example, are certainly older than much of the erosion, but the quadrangle may also have been actively eroded long before its final dislocation.

The first event subsequent to Comanche sedimentation recorded in the structure of the quadrangle was a general tilting of the quadrangle to the northeast at an angle of 15° or 20°. This movement was probably connected with regional elevation that converted the sea bottom of early Cretaceous time into dry land. The northeasterly tilting, which appears to have affected the whole of the Mule Mountain mass, may have resulted from a gentle anticlinal arching of the Cretaceous beds and their underlying Paleozoic and pre-Paleozoic basement. If so, the Mule Mountains are part of the northeastern limb of a broad anticline whose southwestern limb must have extended over the region now occupied by the San Pedro Valley, and has been downfaulted or cut away by erosion. Another possible explanation is that the Mule Mountains constitute a tilted fault block whose weathered escarpment overlooks the downthrown tract of San Pedro Valley. The verification of either of these principal hypotheses involves, however, more than the study of a single quadrangle. From the fact that the Cretaceous beds of the Bisbee quadrangle exhibit minor northwest-southeast folds, the hypothesis that the post-Cretaceous northeasterly tilting is a result of a broad anticlinal structure is for the present, regarded as having the greater probability.

As a result of this differential elevation, the beds of the Bisbee group stood highest in the southwestern part of the quadrangle. With the progress of erosion these upraised beds were first carried away and more and more of the pre-Cretaceous basement exposed, until at the present day the Cretaceous beds have been stripped from the greater part of the southwestern half of the quadrangular area. This denudation, however, has not gone on without interruption. At some stage during its progress occurred post-Cretaceous faulting of two distinct kinds—normal faults of moderate throw, exemplified by the Mexican Canyon fault, and extensive overthrusts produced by forces operating along nearly east and west lines and resulting in the structure of the Gold Hill and Glance blocks.

During late Cretaceous and Tertiary time the Bisbee quadrangle was probably a land area undergoing erosion. No formations referable to these periods are known within the quadrangle. It is possible that some of the unconsolidated material penetrated by deep wells in Sulphur Spring Valley may be Tertiary, but there is as yet no evidence justifying the separation of these deposits from the overlying Quaternary accumulations.

The record of Quaternary time is one of uninterrupted erosion. During this period the present topography was carved. Under the more humid conditions that probably prevailed during the Pleistocene epoch much of the material stripped from the Mule Mountains was carried down to the sea. But with the increasing desiccation of later Pleistocene and recent time the bulk of the detritus has accumulated in the neighboring Sulphur Spring and San Pedro valleys.

ORE DEPOSITS.

GENERAL CHARACTER OF MINERALIZATION.

The Bisbee quadrangle owes its economic importance exclusively to the occurrence of ores of copper. The unimportant deposit of lead carbonate in Hendricks Gulch, which was the first discovery in the district, is still being worked in a small way, and the Easter Sunday mine has supplied a siliceous gold ore used in the Copper Queen smelter for converter lining. But these, so far as known, are the only instances in the quadrangle of ores commercially exploited for other metals than copper. In comparison with the copper deposits, the known occurrences of other ores are economically insignificant.

For a district that has produced nearly 400,000,000 pounds of copper the Bisbee quadrangle, in spite of the general bareness of its rocky slopes, exhibits little patent evidence of its mineral wealth. The porphyry mass of Sacramento Hill, and the schists that partly inclose it southeast of Bisbee, show considerable alteration and contain abundant disseminated pyrite, which by oxidation imparts a rusty stain to the rocks. But so far as known no deposits of value occur wholly within these discolored rocks. Some dark rusty masses, composed principally of limonite, outcrop along the Dividend fault in Bisbee. Similar ferruginous ledges occur in Hendricks Gulch, on Queen Hill, and in the limestones south of Bisbee. Experience has shown that such limonitic croppings, although rarely containing appreciable quantities of copper-bearing minerals, are nevertheless frequently, although not invariably, associated with an underlying ore body. They mark loci of fracturing and mineralization in the limestone. They evidently result from the oxidation of pyrite, the less soluble iron oxide and some silica remaining near the surface, while such copper as was originally present has been carried down by percolating solutions and redeposited at lower levels. These bodies of limonite, when not too siliceous, are the best surface indications of ore that the district affords. Many of the most important ore bodies, on the other hand, would have remained undiscovered were surficial phenomena alone relied upon to suggest exploration.

Although the rocks of the quadrangle are seamed with faults and dikes, none of the workable ore deposits occur as lodes or fissure veins. With a few exceptions they are irregular replacements of limestone. Originally pyritic, containing probably subordinate amounts of chalcopyrite, they owe their present value to secondary concentrations effected by processes of sulphide enrichment and oxidation.

DISTRIBUTION OF THE ORES.

The principal bodies of copper ore thus far exploited in the quadrangle are contained within an irregular area of approximately a quarter of a square mile in extent. This area begins on the north in the heart of the town of Bisbee and extends south for three quarters of a mile. It lies west and northwest of Sacramento Hill and for the most part between the Czar and Calumet and Arizona (Irish Mag) shafts. (Pl. XXIV, *A*.) Its general outline is indicated by the underground workings projected upon the geological map of the vicinity of Bisbee (Pl. III).

Outside of this limited area no large bodies of copper ore have yet been discovered, although more or less ore is known to occur in the Lowell, Uncle Sam, Whitetail, Wade Hampton, and other mines and prospects. The extent to which future development in these outlying properties is likely to increase the known area of important production will be discussed in another place.

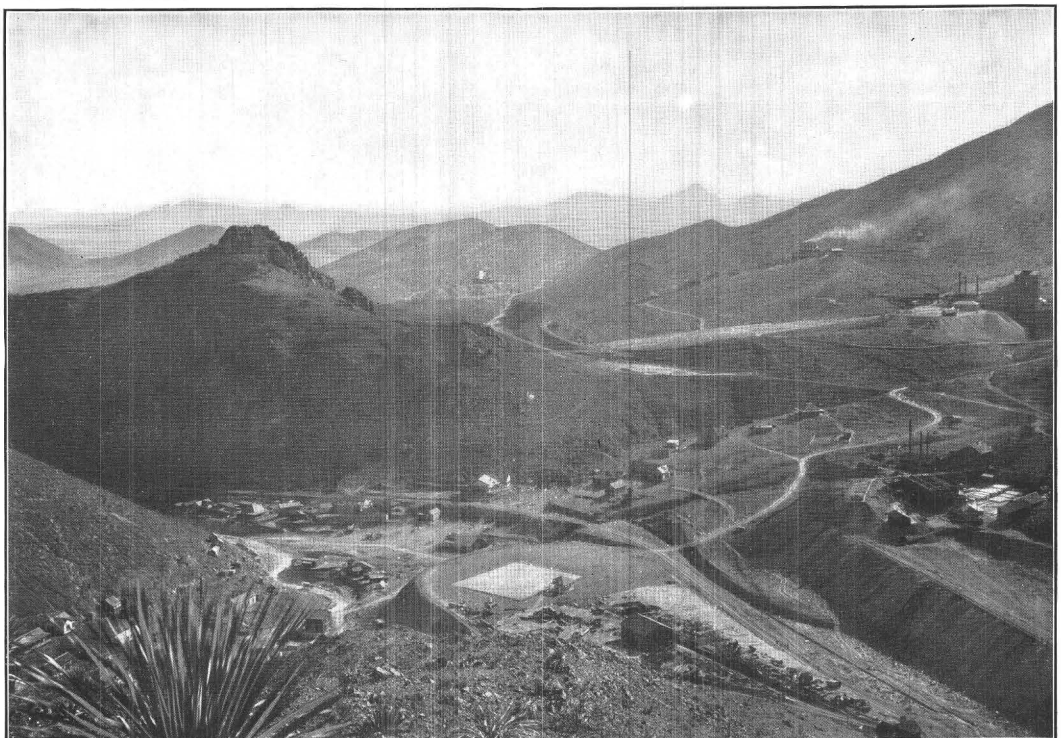
UNDERGROUND DEVELOPMENT.

Preliminary statement.—The Bisbee quadrangle contains two large productive mines—the Copper Queen and the Calumet and Arizona. In addition to these are a few undeveloped mines that have produced comparatively small quantities of good ore, and a number of prospects ranging from shallow pits to shafts several hundred feet deep connected with extensive systems of drifts.

Copper Queen mine.—This comprises a maze of workings connecting with the surface through four working shafts and several other less-used openings. The area more or less thoroughly intersected by drifts and crosscuts covers nearly half a square mile, while the extreme vertical range of underground exploration is about 950 feet. A general plan of the workings is shown in Pl. XXV. They are practically all in Carboniferous (Naco and Escabrosa) limestone.

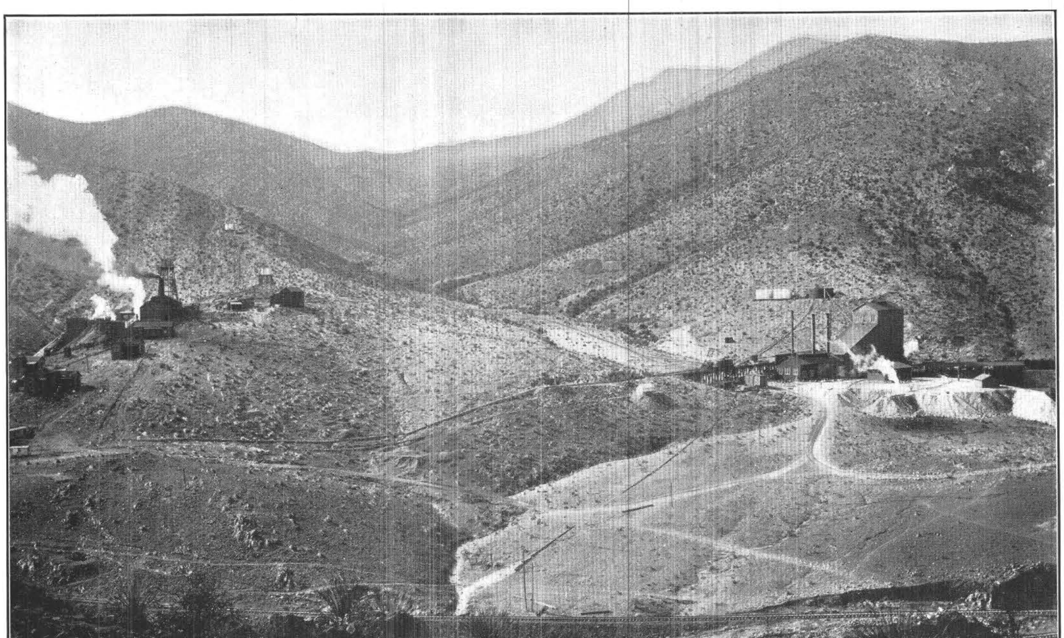
The ore at the only point where it was exposed at the surface was first worked by an open cut, which still yawns upon the hillside just above the Copper Queen store, and is conspicuous from the windows of the hotel in Bisbee. With the need for deeper development the Queen incline was sunk just east of the open cut. From this incline, which reached a vertical depth of 280 feet, four levels were run, known as A level, B level, 300-Queen level, and 400-Queen level. With the exception of the lowest level, a very small part of these old workings is now accessible.

As work proceeded and successive ore bodies were discovered to the southeast, vertical shafts were put down and levels run approximately 100 feet apart. The first of these shafts is the Czar, 440 feet deep, situated on the southwest edge of the town of Bisbee. The Czar levels are four in number, the second level, corresponding to the old 400-Queen level, being the most extensive. As may be seen from Pl. XXV, large bodies of ore have been stoped southwest of the Czar shaft. All of the important ore bodies so far discovered west of a meridian drawn through the Czar shaft have been above the third level.



A. SACRAMENTO HILL FROM THE NORTH, SHOWING THE VARIOUS MINES IN LIMESTONE AROUND THE INTRUSIVE MASS OF PORPHYRY.

In the foreground is the old Copper Queen slag dump, beneath which and the low ground just southwest of it occurred some of the largest ore bodies. On the right is the Holbrook shaft, and just above it in the picture, the Spray shaft. To the left of the Spray is the Calumet and Arizona mine, and some distance to the left of that, the Lowell mine. The mountains visible in the distance are in Mexico, the conical peak on the right being Mount Magellan, and the group on the left the Morita Hills.



B. IRISH MAG AND SPRAY SHAFTS, FROM SACRAMENTO HILL.

The Spray is on the right.

The Holbrook shaft, 540 feet deep, is 1,100 feet south-southeast of the Czar shaft and gives direct access to five levels. The first Holbrook level is 27 feet lower than the first Czar level, connection being made through raises. The second, third, and fourth Holbrook levels are identical with the corresponding Czar levels, with which they are directly connected. The fifth Holbrook level is 100 feet below the deepest workings from the Czar shaft. Large bodies of ore have been stoped from the country southeast of the Holbrook shaft. With one exception (see Pl. XXV) these have all occurred above the fourth level.

Nearly due south of the Holbrook, and 1,400 feet distant, is the Spray shaft, 954 feet deep, equipped with a powerful modern hoist. The second, third, fourth, and fifth Spray levels are practically the same as the corresponding Holbrook levels with which they are directly connected. The sixth, seventh, and eighth levels, however, are deeper than any workings from the Holbrook and Czar shafts. The ore bodies so far developed in the Spray workings lie northeast of the shaft (see Pl. XXV) and occur chiefly between the third and fifth levels. As the Spray is comparatively a new shaft, little work has yet been done below the fifth level, which certainly does not define the lower limit of the great ore bodies.

The Gardner is a small shaft situated 1,440 feet east-southeast from the Spray shaft, and at the time of visit, when sinking was in progress, was about 700 feet deep. Alternate levels only, the second, fourth, and sixth, have been run from the Gardner shaft. These connect directly with the corresponding Spray levels. The Gardner is essentially a prospecting shaft for the underground exploration of the country lying east of the Spray and adjacent to the porphyry mass of Sacramento Hill.

The Hayes is a small disused shaft, between the Holbrook and Spray. The bulk of the ore, from 650 to 700 tons per day, is raised through the Spray, Holbrook, and Czar shafts, and at the time of visit, was smelted close to the latter in Bisbee. This arrangement, however, will be abandoned when the new reduction works at Douglas are finished. Spurs of standard gage run from the main railway line to the Holbrook and Spray shafts and the ore from these shafts is brought to the smelter in trains of ore cars.

The relative position of the various shafts and the general relation of the Copper Queen workings to their topographic and geological environment may be seen from the geological map of the vicinity of Bisbee (Pl. III).

Calumet and Arizona mine.—This mine, the underground development of which is chiefly within the bounds of the Irish Mag claim, is operated through the Irish Mag shaft (Pl. XXIV, *B*), situated 900 feet south-southeast of the Spray shaft and about three-quarters of a mile in the same direction from Bisbee. The general relation of the Calumet and Arizona property to that of the Copper Queen Company is shown in the accompanying claim map of a portion of the Warren mining district. (Pl. XXVI.)[a]

The Irish Mag shaft, begun November, 1900, was about 1,200 feet deep at the time of visit. It was connected with four levels, run at depths of 750, 850, 950, and 1,050 feet below the surface, and a station was then being cut for the 1,150 level.

For 750 feet the shaft was carried down, without drifting, through barren limestone. At this level (Pl. XXVII) some exploratory drifts were run and connection made with the air shaft near the northeast end of the Irish Mag claim. Very little ore was encountered, however, until the 850-foot level was reached. This level is about 30 feet lower than the sixth level of the Spray, with which there is connection through a raise in the northern corner of the Irish Mag claim. On the 850-, 950-, and 1,050-foot levels large bodies of ore were discovered and partially blocked out before active stoping was begun in November, 1902. The general distribution of this ore is roughly indicated on the accompanying plan of the underground workings. (Pl. XXVII.) As the stoping had only just begun at the time of visit, it is impossible to show even rude outlines of the ore bodies.

The ore from the Calumet and Arizona mine is all hoisted through the well-equipped Mag shaft and carried in steel cars to the company's smelter near Douglas. By the end of 1902 this plant was turning out about 30 tons of copper per day, with a single furnace running on ore with an average tenor of about 10 per cent.

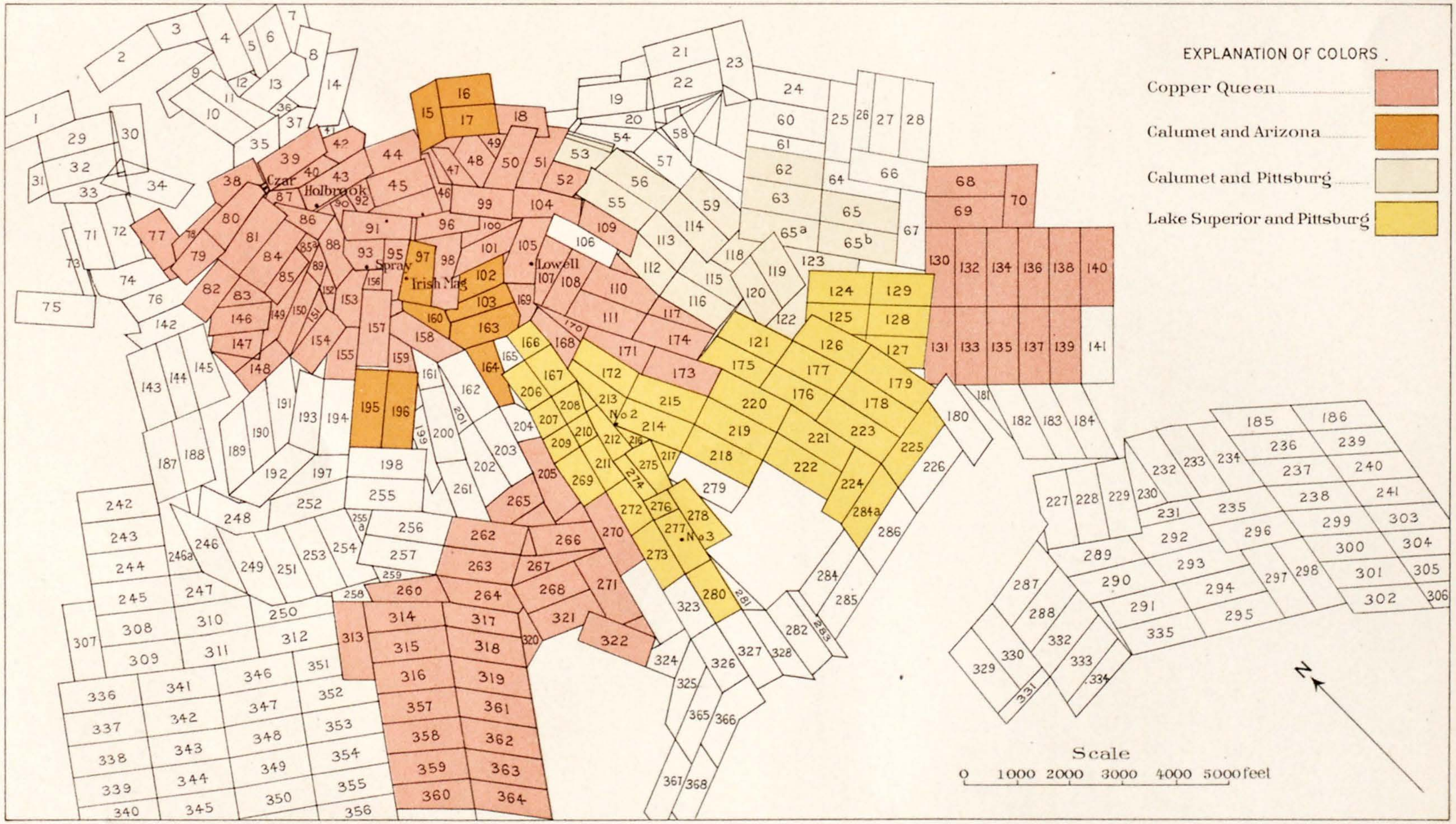
Lowell mine.—This property, purchased for half a million dollars by the Copper Queen Company in June, 1901, is situated a little over a mile south-southeast of Bisbee. It is worked through a vertical shaft about 1,120 feet in depth. A general plan of the underground workings is shown in Pl. XXVIII. There are nine main levels consisting chiefly of drifts running about N. 16° E. and S. 16° W. from the shaft, and numerous crosscuts. The longest of the north drifts, about 650 feet in length, is on the 1,000-foot level, and extends to a point under the bottom of the ravine just north of the mine, or about a third of the distance to the porphyry mass of Sacramento Hill. The workings are probably entirely within Naco limestone, which is cut by some small dikes of granite-porphyry. The drifts in general follow the strike of the easterly dipping beds, which are disturbed by slips along the bedding planes and by strike faults.

No important ore bodies have been encountered in the Lowell above the 900-foot level. Ore occurs, however, on the 1,000-foot and 1,100-foot levels, but has not yet been developed by stoping.

At the time of visit the mine was making about 175,000 gallons of water a day, mostly from the 1,100-foot level, and active operations were delayed pending the arrival of pumps. When these are installed the Lowell mine will play an important

[a] By mutual agreement the ground belonging to each company is defined by vertical planes passing through the claim boundaries. By this fair and sensible arrangement disputes have been wisely obviated.

PLATE XXVI.

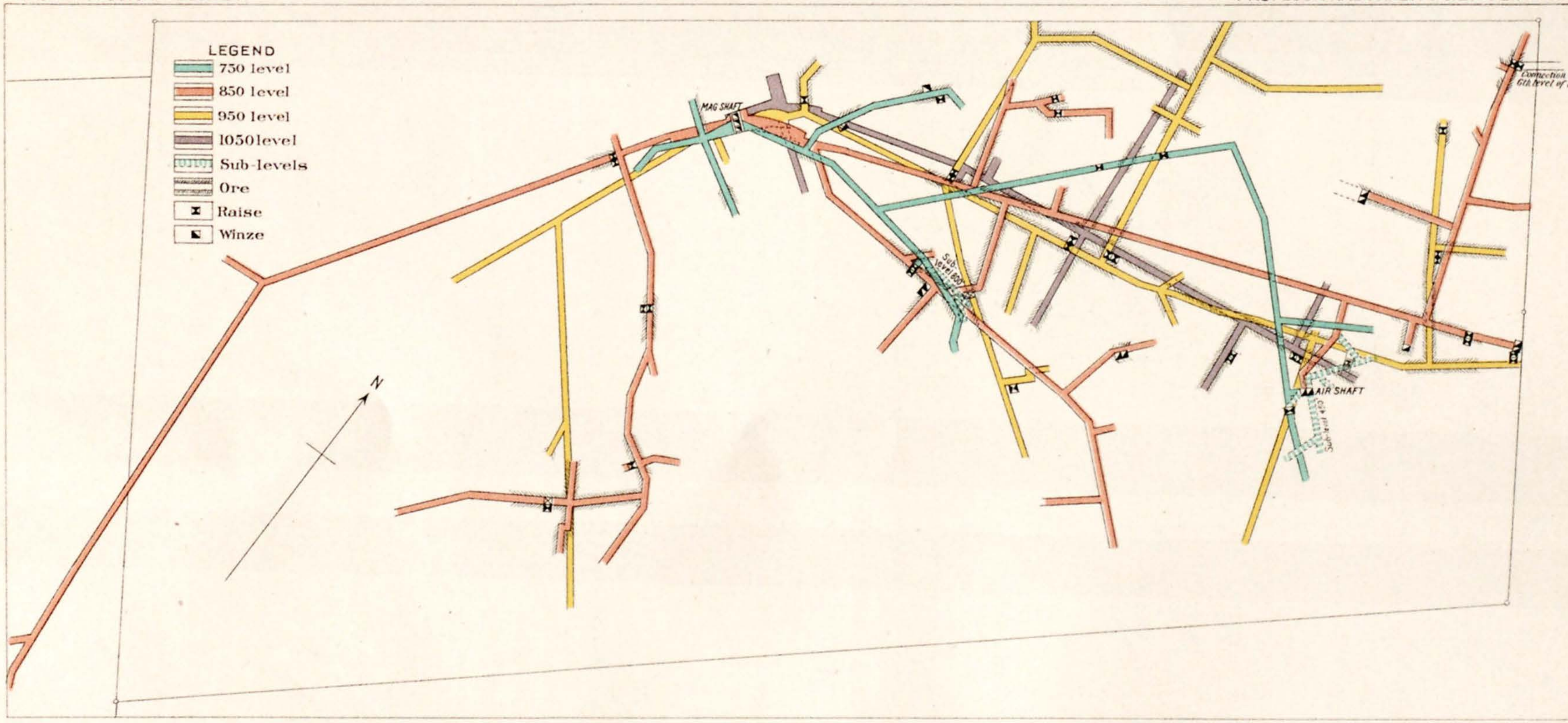


CLAIM MAP OF PART OF THE WARREN MINING DISTRICT, COCHISE COUNTY, ARIZONA

SHOWING THE HOLDINGS OF THE PRINCIPAL COMPANIES

FROM A MAP COMPILED BY THE CALUMET AND ARIZONA MINING COMPANY

173. ——— ———.
174. Danville.
175. Christmas '96.
176. Alaska.
177. Bucky O'Neil.
178. Arizona.
179. Modoc.
180. Mascot.
181. ——— ———.
182. Jake.
183. Railway.
184. Station.
185. Don Francisco.
186. Don Carlos.
187. Contact.
188. Soudan.
189. Southwest.
190. Copper Rock.
191. Iron Prince.
192. Morning Star.
193. Leo.
194. Roy.
195. Wagner.
196. Hope.
197. Tamarack.
198. Hattie Manchester
199. Crown Point.
200. Belle Flower.
201. Ballarat.
202. Summit.
203. Alhambra.
204. Sunnyside.
205. Tuscarora.
206. ——— ———.
207. Granville.
208. Election.
209. ——— ———.
210. Jessie Glencairn.
211. Iron Cap.
212. Magnet.
213. Triangle.
214. Atlas.
215. John and James.
216. John P. Jr.
217. William A.
218. Alabama.
219. Alma.
220. Alice.
221. Agnes.
222. Hamilton.
223. Waterloo.
224. Last Chance.
225. Margaret.
226. Sister.
227. Morning Star.
228. Libbie.
229. Irene.
230. Triangle.
231. Alamo.
232. North Star.
233. Lawrence.
234. California.
235. Greely.
236. St. Ansgar.
237. Osage.
238. Mitchell.
239. Haynes.
240. Lubiens.
241. Denton.
242. Kite.
243. Buck.
244. Grandview No. 2.
245. Grandview No. 1.
246. Trotter.
246*a*. Dewey.
247. Bisbee.
248. Chicago.
249. Louisiana.
250. B. C. Dunlap No. 1.
251. Kentucky.
252. Georgia.
253. Memphis.
254. Cairo.
255. Mohawk.
255*a*. Bornite.
256. Crescent.
257. Broken Promise.
258. Oden.
259. Hillsborough.
260. Extension.
261. Smuggler.
262. Sweepstakes.
263. Whitetail Deer.
264. Reaves.
265. No. 4.
266. Night Hawk.
267. Allen.
268. Superior.
269. Crown King.
270. Boreas.
271. Space.
272. Raven.
273. Monarch.
274. South Bisbee.
275. Bay State.
276. Della Mack.
277. Uncle Sam.
278. South Pole.
279. Magenta.
280. Transatlantic.
281. Lillie.
282. Alcatraz.
283. Major.
284. Wales.
285. Rustler.
286. Germany.
287. Excelsior.
288. Homestead.
289. Leslie.
290. Azurite.
291. Nome City.
292. Bisbee.
293. Wolverine.
294. Lake Superior Boy.
295. Bonanza.
296. Grant.
297. Tombstone.
298. Dawson City.
299. Carpenter.
300. Mona.
301. Jones.
302. Putnam.
303. Appleby.
304. Stacyville.
305. Hilda.
306. Margarita.
307. Bonita.
308. Alfreda.
309. Cliff.
310. B. C. Dunlap No. 2.
311. Lovers' Leap No. 2.
312. Lovers' Leap No. 1.
313. Greene C.
314. Bush.
315. Thurdell.
316. Lucky Loss.
317. Colorado.
318. Nebraska.
319. Upeter.
320. Scallawag.
321. Monitor.
322. Wade Hampton.
323. ——— ———.
324. Skukum.
325. Fredericksburg.
326. Irish.
327. Sepoy.
328. Contractor.
329. Yankee.
330. Cactus.
331. ——— ———.
332. Myrtle.
333. Skaguay.
334. Arthur.
335. Escanaba.
336. West Bisbee No. 12.
337. West Bisbee No. 8.
338. West Bisbee No. 4.
339. West Bisbee No. 3.
340. West Bisbee No. 7.
341. Summit No. 3.
342. Saddle No. 2.
343. West Bisbee No. 2.
344. West Bisbee No. 6.
345. West Bisbee No. 10.
346. Summit No. 2.
347. Saddle No. 1.
348. West Bisbee No. 1.
349. West Bisbee No. 13.
350. West Bisbee No. 16.
351. Summit No. 1.
352. Orphan Boy No. 2.
353. Orphan Boy.
354. West Bisbee No. 14.
355. West Bisbee No. 15.
356. Augusta.
357. Sunny Slope.
358. Contact.
359. Loyalty.
360. Thordenshall.
361. Family.
362. Iron Mountain.
363. Happy Home.
364. Covert.
365. Alexander.
366. Don Luis.
367. Emma.
368. Elisa.



PLAN OF THE UNDERGROUND WORKINGS OF CALUMET AND ARIZONA MINE
FROM THE COMPANY'S MAPS, CORRECTED TO NOVEMBER 30, 1902

Scale
100 50 0 50 100 150 200 feet


PLAN OF THE
UNDERGROUND WORKINGS
OF THE
LOWELL MINE
Scale of feet
100 50 0 50 100
LOWELL SHAFT
N
MAGNETIC NORTH
LOWELL SHAFT
5341.92'
203.88'
200 level
103.12'
Intermediate
Level unknown
300
103.06'
400
103.53'
500
102.76'
600
200.24'
800
202.50'
1000
1100
Shafts and winzes
Upraises and chutes

beds strike nearly northwest and southeast and dip northeast at angles ranging from 35 to 45 degrees.

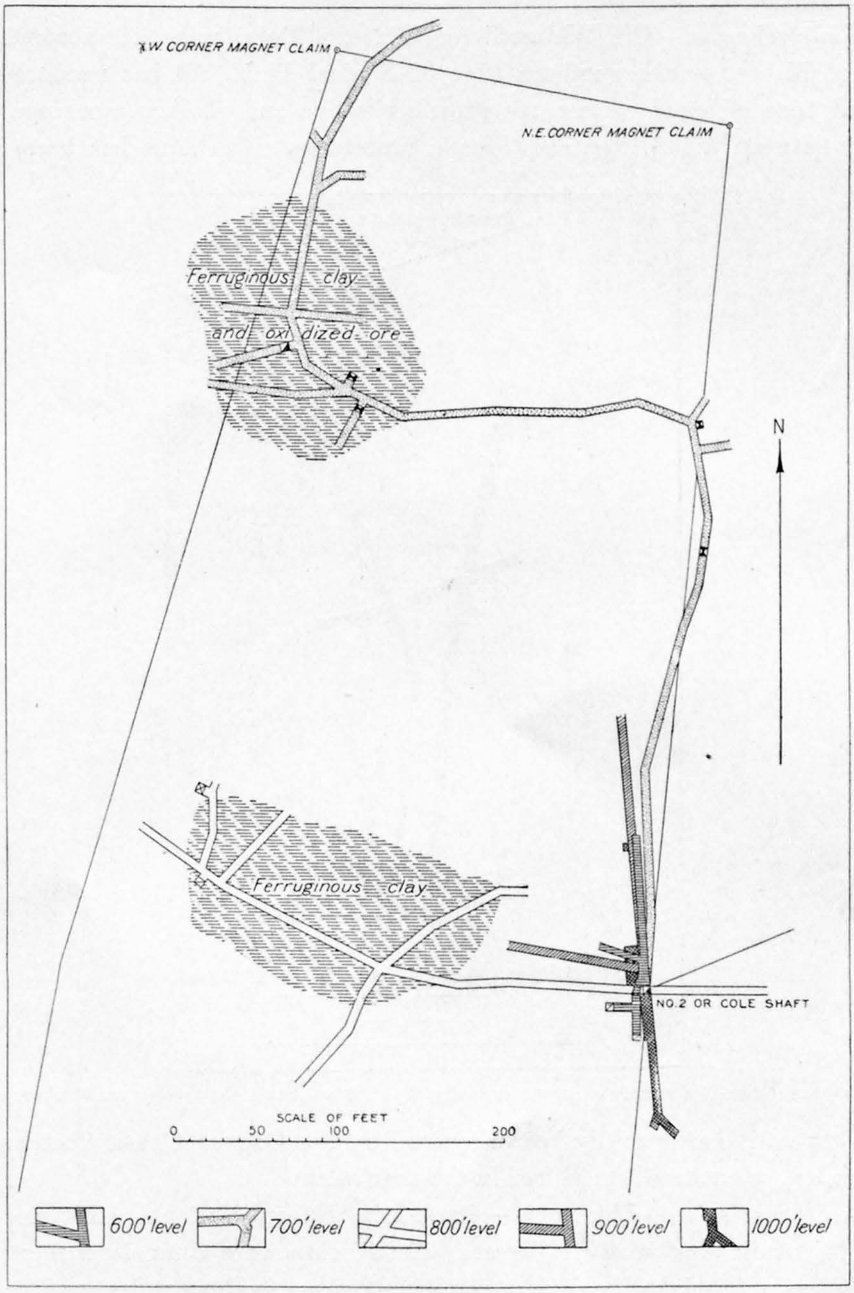


FIG. 2.—Plan of the underground workings connected with shaft No. 2 of the Lake Superior and Pittsburg mine.

As may be seen from Pl. III there are several faults in the vicinity of the No. 3 shaft, some of which are well mineralized and carry chalcocite and malachite near the surface. Underground developments, however, do not as yet throw much light upon the character of this mineralization in depth, since they are chiefly confined to fairly solid Abrigo limestone.

Whitetail mine.—The Whitetail (or Whitetail Deer) mine lies about 1¾ miles south of Bisbee, on the northern edge of Espinal Plain. It has produced a few hundred tons of good copper ore from primitive and shallow workings on the contact between the Abrigo and Martin limestones. The mine has been idle for

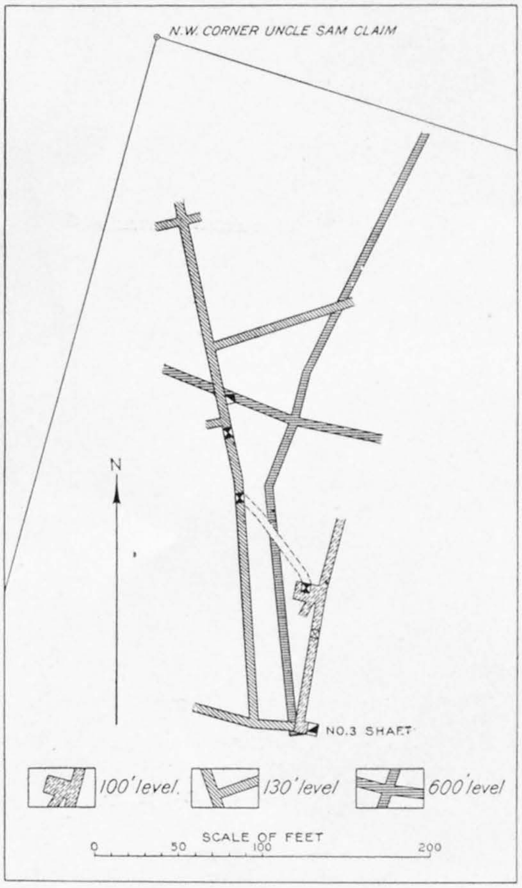


FIG. 3.—Plan of the underground workings connected with shaft No. 3 of the Lake Superior and Pittsburg mine.

years, but as it has recently been acquired by the Copper Queen Company it is likely to be systematically explored in the near future.

Uncle Sam mine.—This mine—situated in the gulch of the same name—lies five-eighths mile southwest of Bisbee. The developments comprise a tunnel and a shaft, but as no work has been done for several years both were inaccessible at the time of visit. The dump of the tunnel shows evidence of considerable mineralization, and the mine is said to have produced a little good copper ore.

Bisbee West mine.—This is a prospect situated a little over 2 miles southwest of Bisbee. A vertical shaft about 700 feet deep has been sunk close to the junction of the Bisbee fault with a short northeast fault (see Pl. III). The shaft was partly filled with water at the time of visit, and none of the levels could be examined. The workings apparently do not explore the great fault just southwest of the shaft, but extend northeastward along the transverse fault and along a small dike of granite-porphyry parallel to the Bisbee West fault (Pl. III). At the time of visit a new shaft was being sunk east of the one just described. This shaft is in Abrigo limestone, on the line of continuation of the porphyry dike. If, as is the reported intention, this shaft will be sunk to a depth of 2,000 feet in search of ore, it will pass through the Abrigo limestone, through the Bolsa quartzite, and penetrate a long way into the Pinal schist.

Easter Sunday mine.—This mine is situated 5 miles a little south of east from Bisbee on the south side of Mule Gulch. It has been worked on a small scale and in a very primitive manner. The developments comprise a tunnel a few hundred feet in length run into a steep northern hill slope, and a series of irregular stopes and raises extending up to the surface.

The mine is unique in this district, inasmuch as it produces a free-gold ore. The gold occurs rather irregularly in a fractured quartzitic bed of the Morita formation. The best ore is said to run as high as $30 per ton. But as such ore contains considerable calcite, and as the Copper Queen Company, which has been utilizing the ore as a siliceous lining for its converters, requires that the silica shall not fall below 84 per cent, the ore actually hauled to the smelter is purposely allowed to contain more or less quartzitic waste.

Glance mine.—This is a prospect situated about 8 miles southeast of Bisbee, near Glance station, on the El Paso and Southwestern Railroad. It consists of a vertical shaft 505 feet in depth all in Glance conglomerate. At the date of writing the shaft had just penetrated this conglomerate and reached the underlying limestone, but encountered at the contact so strong a flow of water that sinking had to be temporarily abandoned. A drift has been run for 120 feet to the southwest, just above the water level, cutting through a dike of monzonite-porphyry about 13 feet thick. According to a letter from Mr. S. W. Clawson, portions of the dike carry as much as 3 per cent of copper. This is probably the same dike that is exposed on the surface at the hoist and in the little saddle just south of the shaft.

The property of the Glance Mining Company includes a considerable area of ground lying principally to the south and west of the main shaft. The surface rock is everywhere the Glance conglomerate, which shows considerable diffused mineralization, and has been prospected by several small pits and shafts.

Modern mine.—This prospect is situated just outside of the northern boundary of the quadrangle on the northeast side of the Tombstone Canyon, and is in Pinal schist. The developments comprise a vertical shaft 200 feet in depth and two short drifts. Two narrow veins are encountered, one in the schist and the other between the schist and a dike of granite-porphyry. They are nearly vertical and their general strike is from 10° to 30° east of north. The maximum width of the veins is 18 inches and they contain cupriferous pyrite with a little galena and sphalerite, in a gangue of quartz. The presence of native copper and cuprite was reported by those in charge of the work, and the ore was said to carry as much as an ounce of gold, but there was no opportunity of confirming these statements. The schists in the vicinity of the shaft show considerable fissuring and are traversed by narrow anastomosing dikes of granite-porphyry and by veins of quartz.

MINERALOGY OF THE ORES.

ORE MINERALS.

NATIVE METALS.

Copper.—In the native state, this metal was not an uncommon constituent of the lower portions of the great oxidized ore bodies worked a few years ago in the Copper Queen mine. According to Dr. James Douglas,[a] it was abundant just above the third level at the bottom of the great ore body southwest of the Czar shaft, occurring in masses, some of which weighed several hundred pounds. Native copper is now, however, rather rare in this mine. In the course of the present investigation the metal was observed as small particles in stope 38, just above the third level and about 750 feet northeast of the Holbrook shaft. The ore body at this point is a rich mass of chalcocite and pyrite enveloped in a soft white clay that is evidently derived from altered limestone, and is in part taken down as ore. The native copper occurs as small hackley particles in this clay, associated with occasional specks of cuprite and little streaks of chalcocite. Native copper occurs also in partly oxidized ore, containing residual bunches of chalcocite, in a rich stope (No. 4) between the fifth and sixth levels, about 400 feet east of the Spray shaft. In the Lowell mine it was observed on the 1,000-foot level in oxidized ore near pyrite, and on the 1,100-foot level, just north of the shaft, embedded in a ferruginous clay near a body of chalcocite ore which immediately overlies a mass of pyrite.

At the present time native copper is found most abundantly in the Calumet and Arizona mine, particularly on the 950-foot and 1,050-foot levels. It is usually closely associated with cuprite, and occurs as a rule in proximity to sulphide ores. On the 950-foot level, about 400 feet southeast of the shaft, the bulk of the ore of a large rich stope consists of crystalline cuprite bound together into a tough mass by an irregular web of native copper. With the cuprite and copper are associated some limonite and other earthy oxides and a little fibrous malachite, chiefly in vugs.

[a] Douglas, J., The Copper Queen mine, Arizona: Trans. Am. Inst. Min. Eng., vol. 29, 1900, p. 518.

On the 1,050-foot level native copper is abundant as tough spongy aggregates of small crystals, sometimes encrusting chalcocite and sometimes enveloped in ferruginous clay or earthy oxide ores. It also occurs as thin layers along fissures in clayey, oxidized ground as small loose crystals, up to 2 or 3 millimeters in diameter, showing the usual modified cubes and octahedra embedded in a soft earthy mixture of cuprite, limonite, and kaolin.

Gold.—This metal occurs free in the Easter Sunday mine, rather irregularly distributed through some beds of light-colored quartzitic sandstone belonging to the Morita formation. The bulk of the ore occurs in a bed about 4 feet thick dipping about 55° to the north-northeast, but the mineralization is not entirely confined to this bed. The sandstone has been irregularly fractured, probably during the post-Cretaceous folding, and the resulting small fissures have been filled with veinlets of quartz and calcite. No gold was seen at the time of visit, but it is said to be occasionally visible, usually in little calcite vugs stained with oxide of iron. It appears to have been introduced into the beds subsequent to the fracturing.

Small quantities of placer gold have been obtained from the upper part of Gold Gulch. This gold has been derived from the Glance conglomerate, and concentrated in the sand and gravel of the present arroyo. It is not present in sufficient quantity to be of economic importance.

SULPHIDES.

Pyrite.—Although not, strictly speaking, an ore, pyrite is here included with the ore minerals on account of its intimate chemical, physical, and genetic relationship with them. It is the most abundant and ubiquitous sulphide in the district, and the one of which all the ore bodies, however varied may be their present constitution, originally in greater part consisted.

In the form of small crystalline grains, disseminated through masses of altered rock, pyrite is abundant in the intrusive porphyry mass of Sacramento Hill and in the adjacent schists which partly inclose that mass on the east. Associated with the great bodies of copper ore disposed about the porphyry mass in the limestones south of Bisbee, pyrite occurs in large quantity. In the upper levels of the mines, where oxidation has been active, it is sometimes found in isolated masses inclosed in envelopes of chalcocite and oxidized ore. In the lower levels it forms extensive bodies, which pass somewhat gradually into altered limestone, in which the pyrite occurs disseminated in small grains, usually of rather irregular outline, and in little bunches and stringers. Of these pyritic bodies only those portions that contain chalcopyrite or chalcocite have proved workable.

With the object of gaining insight into the problem of the genesis of the ore bodies, the pyrite disseminated through the limestone has been studied with some care. Microscopical examination of thin sections shows that its occurrence is nearly always associated with the development of silicates in the limestone, particularly tremolite, diopside, garnet, and vesuvianite. In some cases the calcite has been entirely replaced by silicates and pyrite, with usually more or less quartz. In other cases the silicates are lacking, and the limestone has been altered to a mass of quartz and pyrite. The pyrite is contemporaneous with and intergrown with these minerals, and to this fact is perhaps largely due the general absence, in all but the smallest individuals, of that sharpness of crystallographic outline common in pyrite that has been introduced into rocks by processes subsequent to the development of their general texture and mineralogical composition; as, for example, the cubical crystals of pyrite disseminated through the slaty rocks in the vicinity of many of the Mother Lode veins in California. The essential contemporaneity of the pyrite and the amphibole, pyroxene and other metamorphic minerals, is a very important fact, and will be again referred to in discussing the genesis of the ores.

Chalcopyrite.—So far as observed in the Bisbee quadrangle, this mineral occurs only in massive form, never in distinct crystals. It is apparently confined to the limestones. Unlike the pyrite, it is rarely met with in a disseminated condition, but when present at all is likely to be accompanied by pyrite and to constitute fairly solid masses of ore. An excellent example of such an occurrence is found in the body of chalcopyrite ore on the seventh level of the Spray mine. Mr. Douglas,[a] in his interesting account of the Copper Queen mine, refers to this mineral as disseminated with pyrite in fine grains through the rock. But of mineralized limestone collected in 1902, only two specimens—one from the third level, about 700 feet southeast of the Holbrook shaft, and one from the face of a new northeast crosscut on the sixth level, which at the time of visit was about 150 feet northeast of the Gardner shaft—show this mineral in disseminated form associated with pyrite, chlorite, and a little sphalerite. It undoubtedly occurs elsewhere in a similar state, but it is certainly not abundant throughout the mass of the pyritized limestone. As an ore-forming mineral, too, it is much less common in the present workings than chalcocite and the various oxidized ores. In addition to the occurrences just mentioned chalcopyrite was noted on the sixth level between the Spray and Gardner shafts. Here a small body of sulphide ore had been taken out alongside the main drift. A little left adhering to the walls showed minute bunches and veinlets of chalcopyrite in a mass consisting chiefly of pyrite and chlorite. It is also reported in the old Dividend stope on the fourth level of the Holbrook mine.

A little chalcopyrite occurs with chalcocite and pyrite on the 1,100-foot level of the Lowell mine and is reported to have been found in bunches within a mass of pyritic ore cut by the shaft at this level. In the Calumet and Arizona mine a

[a] Douglas, J., The Copper Queen mine, Arizona: Trans. Am. Inst. Min. Eng., vol. 29, 1900, p. 532.

little chalcopyrite with pyrite was noted on the 1,050-foot level, and the mineral is said to have been met with in the shaft about 50 feet below this level.

Sphalerite.—Sphalerite, or zinc blende, is of rare occurrence in the Bisbee quadrangle. In the course of the present investigation it was noted at two places only. One of these is near the Cogswell stope on the third level of the Holbrook mine, where it occurs in little specks with pyrite and chalcopyrite in silicified limestone. The other is in the sixth level of the Gardner mine, where, in a new crosscut northeast of the shaft, small particles of sphalerite are associated with pyrite in altered limestone. Sphalerite also occurs in small quantities with pyrite and galena at the Modern mine, just north of the quadrangle.

Chalcocite.—This mineral, familiarly known as copper glance, or "glance," is the most important sulphide occurring in the Bisbee quadrangle, since nearly all of the bodies of workable sulphide ore owe their value to its presence. So far as observed, it occurs only in massive form, distinct crystals being nowhere seen. It is sometimes firm and compact in texture, but is often rather soft and occasionally has almost a sooty character.

In the Copper Queen group of mines chalcocite is found at various depths, but never far from oxidized ore. Its most characteristic place of occurrence is in the irregular zones of rich sulphide ore that usually intervene between masses of lean pyrite and oxidized ores containing cuprite, native copper, and carbonates.

In the Copper Queen mine chalcocite was observed on the second level in the Cogswell (or "Neptune") stope, about 700 feet southeast of the Holbrook shaft. The ore of this stope is a mixture of loosely cohering granular pyrite and chalcocite, the latter occurring in part as dark envelopes about the grains of pyrite. The ore body is surrounded by a soft white clay which is speckled with pyrite and traversed by little veinlets of chalcocite.

On the third level chalcocite was seen in stope 38, about 800 feet northeast of the Holbrook shaft. Here again the ore is a crumbling mixture of pyrite and chalcocite. The country rock, originally limestone, has been altered to a white clay-like material streaked with chalcocite and speckled with native copper.

Similar chalcocite and pyrite ore was noted on the fourth level in the Old Dividend stope, northeast of the Holbrook shaft. Just above the same level, about 500 feet south of the Spray shaft, a stope has been opened on a mass of solid compact chalcocite, intimately mixed with a little bornite. The chalcocite immediately overlies ferruginous oxidized material. Close to the copper glance, and cut in the drift near the stope, is a body of pyrite, the individual granules of which are in part covered by a black coating of chalcocite. Development had not gone far enough at the time of visit to discover what connection, if any, exists between this body of pyrite and the chalcocite ore body, or to show what overlies the latter. All of the ore is inclosed in altered mineralized limestone into which the pyritic mass passes by insensible gradations.

Some chalcocite occurs on the fifth level of the Copper Queen mine, but it was not seen below this, in the deeper levels connected with the Spray shaft.

By no means all of the occurrences of chalcocite in the Copper Queen mine have been here recorded, but those mentioned are enough to indicate the general mode of its occurrence and distribution and to illustrate its characteristic association with masses of pyrite on the one hand and with oxidized ores on the other.

In the Calumet and Arizona mine chalcocite is found associated with cuprite, limonite, malachite and brochantite (a basic sulphate of copper) in an ore body about 400 feet south of the shaft, on the 850-foot level.

On the 950-foot level the ore in what is known as "the big sulphide stope," about 650 feet east-northeast of the shaft, consists chiefly of pyrite with which is intimately associated dull cryptocrystalline chalcocite in the form of a thin coating on some of the pyrite grains. At one point in the stope the ore consists of pyrite and chalcocite in a hard quartzose gangue. The microscope shows that the sulphides are embedded in a matrix of granular quartz. The chalcocite is seen to occur as and envelope about many of the pyrite grains and to fill microscopic fissures in the latter. This ore body shows incipient oxidation at a height of about 15 feet above the level.

Chalcocite in similar close association with pyrite is found also on the 1,050-foot level, particularly in a body of mixed sulphide and oxide ore about 300 feet east of the shaft, where the chalcocite occurs as irregular envelopes around residual masses of lean pyrite. Chalcocite, in the condition of a soft black powder, was noted also in the main drift on this level, 500 feet east of the shaft.

As a rule, on the 1,050-foot level, wherever the pyritic masses are soft and traversed by fissures, they constitute workable ore. The miners know that when their picks leave dark metallic marks the ore is good. Close examination of such ore always reveals the presence of chalcocite, and it is the shining streak of this mineral that gives the miner his rough but effective test.

In the Lowell mine, chalcocite occurs on the 1,000-foot level in a soft, black earthy form with partly oxidized pyrite, and on the 1,100-foot level in a similar association. It is also found on the latter level in a more compact form, associated with pyrite, native copper, and malachite, and resting upon a body of lean pyrite cut by the shaft.

Outside of the larger mines, chalcocite is found irregularly but widely distributed through the large area of Glance conglomerate stretching from Gold Hill southward to the international boundary. The mineral occurs in minute reticulating veinlets, often microscopic in size, and in little rounded bunches, rarely over half an inch in diameter, usually inclosed within a thin envelope of malachite. The chalcocite is usually accompanied by the development of a secondary quartz in veinlets and small vugs. Both chalcocite and quartz have in part filled minute fissures in the conglomerate, but have also in part replaced some of the finer interstitial, calcareous matrix by which the pebbles are held together.

The mass of conglomerate forming the hill just west of the Glance mine exhibits well the scattered mineralization just described. The occurrence of this chalcocite in the Glance conglomerate has led to extensive prospecting which has not, however, revealed workable ore bodies.

About 1,000 feet northwest of the No. 3 shaft of the Lake Superior and Pittsburg Company (Pl. III) chalcocite, altering to malachite, occurs in a little vein in Martin limestone. This is the only observed instance in the quadrangle of the occurrence of the mineral in a fissure vein.

CARBONATES, SILICATES, SULPHATES, AND OXIDES.

Malachite.—The familiar green basic carbonate of copper is found in greater or less quantity wherever copper ores are undergoing oxidation. In the older workings of the Copper Queen mine this mineral was abundant, occurring in large and beautiful masses with azurite and calcite in limestone caverns. The walls of these caves were covered with velvety moss-green malachite, and sparkled with the blue crystals of azurite, while from the roofs hung translucent stalactitic draperies of calcite, delicately banded and tinted with the salts of copper. But the caves have been stripped of their treasures and either filled with waste or allowed to collapse. They are things of the past, and museum specimens, of which perhaps the finest collection is that in the American Museum of Natural History in New York, can but feebly suggest their former splendor.

The malachite occurred in the form of mammillary incrustations, which, while often of considerable thickness, were of fibrous texture, and not adapted to the ornamental purposes to which the well-known Russian malachite has long been applied. Mr. Douglas says:

"The malachite is never found in such large and compact masses as to make it commercially valuable for decorative purposes; besides, occurring generally in thin botryoidal masses, it is usually streaked with manganese, which detracts from its purity. Its most striking mode of occurrence is in geodes, which are lined with velvety crystals of the same mineral. These hollow spheres, the walls of which are composed of concentric layers, are rare, but when found, are usually in nests imbedded in soft, wet, ferruginous, or manganiferous clays, such as constitute the gangue, or 'ledge-matter' of nearly all the ore; and they occur at no great distance from a limestone wall or partition." [a]

[a] Douglas, J., The Copper Queen mine: Trans. Am. Inst. Min. Eng., vol. 29, 1900, pp. 517–518.

In the present workings of the Copper Queen mine malachite is not very abundant. It occurs usually in little nests and bunches in soft limonitic ore containing earthy cuprite. The presence of little green specks of malachite in such ores is generally indicative of a high tenor in copper.

The Calumet and Arizona mine exhibits similar occurrences, but the mineral is here found also in vugs within masses of crystalline cuprite and native copper.

In both the Copper Queen and Calumet and Arizona mines malachite is frequently associated with small amounts of brochantite, a mineral easily mistaken for the green carbonate, and with chrysocolla. No where at the present time does it constitute more than a very small proportion of the ore.

Azurite.—The blue basic carbonate of copper, while formerly fairly abundant and occurring in large crystalline slabs in the oxidized ores in the Copper Queen mine, is now seldom met with except in occasional little bunches in the earthy ferruginous ores of the thoroughly oxidized zones.

Cerussite.—The carbonate of lead occurs in impure sandy form, the so-called "sand carbonate," in Hendricks Gulch, where it forms very irregular bunches in the limestone in the vicinity of a fault fissure. It was not observed in connection with the copper ores in the larger mines.

Chrysocolla.—The hydrous silicate of copper, like malachite, azurite, and brochantite, is a minor constituent of the Bisbee copper ores, and seems never to have been very abundant. It was noted in the Calumet and Arizona mine forming thin concentric shells about kernels consisting of crystalline cuprite, native copper, and brochantite, and enveloped in turn by malachite and calcite. Intimately associated with the chrysocolla is a lustrous, brittle, pitch-black substance which Koenig[a] has recently described as a new mineral species and named melanochalcite.

Melanochalcite.—This is described by Koenig[b] as forming a thin envelope about kernels of cuprite and inclosed in turn by chrysocolla. It is black, with a pitchy luster, and apparently amorphous. According to Koenig's chemical analyses, it is a silico-carbonate of copper with the formula $Cu_2(Si, C)O_4 . Cu(HO)_2$.

Material indentical with that described by Koenig was obtained from the same locality, namely, the 850-foot level of the Calumet and Arizona mine. It occurs as thin shells about nuclei consisting of crystalline cuprite, native copper, and brochantite. Under the miscroscope the melanochalcite is opaque in an ordinary thin section. It is inclosed by a concentric envelope of olive-green material, which is fairly transparent. The olive-green substance is traversed by reticulated microscopic cracks, shows concentric banding, and with high powers a rather indistinct radially fibrous structure. In color and structure it suggests chrysocolla, but unlike common chrysocolla it is apparently isotropic. This material

[a] Koenig, G. A., On the new species melanochalcite and keweenawite: Am. Jour. Sci., 4th ser., vol. 14, 1902, pp. 404–409.
[b] Ibid.

is in turn enveloped in chrysocolla showing the usual optical behavior of that mineral, and the chrysocolla is succeeded by an outer shell of malachite. Sometimes the chrysocolla is absent and the malachite directly envelops the olive-green substance. Whether the latter is actually chrysocolla, owing its apparent isotropy to the arrangement of its minute fibers, or whether, like melanochalcite, it is perhaps to be regarded as a distinct mineral, are questions which the material at hand does not suffice to answer. It is not improbable that there may be several obscure hydrous silicates or silico-carbonates of copper, which on account of intimate association and lack of distinct crystal form are commonly included with chrysocolla.

Aurichalcite.—This mineral, a basic carbonate of zinc and copper, has been reported from the Copper Queen mine,[a] but none was seen in 1902.

Brochantite.—This green, orthorhombic, basic sulphate of copper is not abundant in the Bisbee quadrangle, but has been noted in small amounts, often associated with malachite, for which it might be readily mistaken upon superficial examination.

As a rule it is recognizable in the Bisbee ores only by the microscopical examination of thin sections. Its most characteristic occurrence is in the form of little nests and irregular veinlets in the cuprite of the Copper Queen and the Calumet and Arizona mines. These nests and veinlets are aggregates showing a pale bluish-green tint by transmitted light, and composed of irregular granules with a decided tendency toward prismatic form. They exhibit a distinct cleavage, presumably that parallel to the brachypinacoid. The extinction is parallel to the cleavage, which also defines the direction of least elasticity. As the acute bisectrix of brochantite is perpendicular to the brachypinacoidal cleavage and the mineral is optically negative, the observed optical behavior is in accord with the character of that mineral. The double refraction is noticeably high, green of the first order predominating in sections of ordinary thickness.

The double refraction of malachite, with which brochantite might be confused without optical or chemical investigation, is higher, but the interference colors are much less brilliant. In fact the introduction of the analyzing nicol often seems merely to dim the green tint of the mineral as seen by ordinary transmitted light. The interference tints of malachite are also accompanied by an indistinct shimmering appearance similar to that characteristic of calcite and other highly birefringent mineral carbonates.

Brochantite is not sufficiently abundant to form an important constituent of the Bisbee ores, and its occurrence in the district has not been previously recorded. Its identification in the present instance might have presented greater difficulty

[a] Dana, System of Mineralogy, 6th ed., 1895, p. 298.

had not Mr. Lindgren kindly called my attention to its abundant occurrence in the Clifton-Morenci district and permitted me to examine some of his specimens.

Cuprite.—The red oxide of copper is an abundant and important constituent of the Bisbee ore bodies. It occurs sometimes in an impure earthy condition mixed with limonite and ferruginous clays, sometimes in crystalline masses associated with native copper. The latter occurrence is particularly characteristic of the deeper oxidized zones in the vicinity of chalcocite and other sulphides.

In the present workings of the Copper Queen mine the bulk of the cuprite occurs in the earthy condition mixed with limonite, pure crystalline masses of any size being comparatively rare. In stope 27, in the southwestern part of the mine, just above the second level, distinctly crystalline cuprite was noted, associated with limonite, malachite, brochantite, melanochalcite, and a little quartz. At the time of visit this was the only place in the mine in which any quantity of the mineral was seen in other than the prevalent impure earthy matter.

In the Calumet and Arizona mine, however, new stopes had been opened in ore bodies containing cuprite in large crystalline masses, usually associated with native copper, and in beautiful druses of ruby-red isometric crystals, usually in the form of simple cubes, or of cubes modified by the octahedron and dodecahedron. It is particularly abundant in the fine stope on the 950-foot level about 650 feet northeast of the shaft, where it occurs in glittering bunches in the more earthy ore, penetrated by dendritic masses of bright metallic copper and spotted with little vugs of acicular malachite. It has been found also on the 850-foot level in irregular bunches surrounded by malanochalcite, chrysocolla, malachite, and calcite.

Tenorite.—The crystalline form of the black oxide of copper was not observed in the course of the present investigation. The earthy variety, however, commonly known as melaconite, occurs in some of the soft clayey ores, usually mixed with the black oxide of manganese in the form of a light sooty powder. Ore of this character containing about 5 per cent of copper was observed on the 1,000-foot level of the Lowell mine. In the Calumet and Arizona mine, about 30 feet above the 850-foot level there is a natural cavern in the limestone, whose damp walls are covered with a black moss-like botryoidal growth. This material is apparently still being deposited, for the fragile stems of the dendritic efflorescence break off by their own weight when they reach a length of over half an inch, and the floor of the cavern is deeply covered with a fluffy carpet of this black material. Inspection of the walls shows that they are composed of alternating irregularly overlapping layers of the black efflorescence with druses of calcite. Chemical tests of the black material, made by Dr. W. F. Hillebrand, show that it is a mixture of the oxides of copper and manganese, probably melaconite and bog manganese, or wad. According to

Foreman J. G. Merrill, some of this mixture contains as much as 15 per cent of copper.

Koenig[a] in 1891 described some small black crystals from the Copper Queen mine, and concluded that they were essentially a mixture of cupric and cuprous oxides, and were tetragonal in crystal form. He considered that they represented a distinct mineral species, for which he proposed the name *paramelaconite*. It appears, however, that more chemical and crystallographic work is necessary before paramelaconite can take final rank as a species distinct from tenorite, the crystallographic symmetry of which is still in doubt.

Footeite.—This mineral, a deep blue chlorhydrate of copper occurring in minute monoclinic prisms implanted with paramelaconite on limonite, was first described and named by Koenig,[b] from a specimen said to have come from the Copper Queen mine. Footeite is evidently a rare occurrence in the Bisbee mines and was not seen in 1902.

GANGUE MINERALS.

Of the various minerals associated with the ores, calcite, in its rôle of principal constituent of the limestone in which the important ore bodies occur, is the most abundant. It is seldom, however, that the mineral forms so large a part of the altered limestone in the immediate vicinity of the ore as it does of the unchanged rock in which mineralization has not been active. As will presently be shown, it has been largely replaced in the process of mineralization by pyrite, amphibole, pyroxene, garnet, chlorite, quartz, vesuvianite, and other minerals.

In the form of stalactites, often beautifully colored with salts of copper, and in showy crystalline masses, calcite was abundant in the bodies of oxidized ore worked in early days in the Copper Queen mine, and is still encountered to some extent within the oxidized zones. It is rarely, however, a conspicuous gangue mineral in the ores now exploited.

The unoxidized pyritic ores, particularly those too poor for working, are intimately associated with several minerals, chiefly silicates of calcium, magnesium, and aluminum in varying proportions, which so far as observed occur only in crystals of microscopic size. Their identification accordingly depends upon the microscopical investigation of thin sections. Of these minerals probably the most common is the calcium-magnesium amphibole, tremolite, usually occurring in aggregates of minute radiating prisms, which under the microscope show the characteristic cross sections, cleavage, and optical properties of this mineral. Nearly or quite as abundant, and usually accompanying the tremolite, is a colorless pyroxene in microscopic grains, usually less than a tenth of a millimeter in diameter,

[a] Koenig, G. A., On paramelaconite and the associated minerals: Proc. Philadelphia Acad. Nat. Sci., 1891, pp. 284–289.
[b] Ibid., pp. 289–291.

rarely showing sharp crystal outlines, but exhibiting a distinct tendency to the development of stout prismatic form. This mineral has the optical properties of diopside. Although neither tremolite nor diopside, so far as observed, occurs in the Bisbee quadrangle in crystals large enough to be seen with the naked eye, their presence in the altered mineralized limestone can generally be recognized by a faint greenish tint in the rock, joined with a certain compactness of texture that is unlike that found in any of the unaltered limestones. Most of the limestone encountered in the Spray workings from the fourth level down, and in the Calumet and Arizona mine from the 850-foot level down, exhibits this development of tremolite and diopside, and all gradations may be studied, from limestones consisting almost exclusively of calcium carbonate to those in which all of the carbonic anhydride has been replaced by silica.

A colorless garnet, probably the calcium-aluminum garnet, grossularite, occurs in some of the altered limestone, associated with tremolite and diopside. As seen under the microscope in thin section, it occurs in imperfect crystals of rounded outline, often poikilitically inclosing other constituents of the rock. It is seldom perfectly isotropic, usually exhibiting an indistinct and irregular birefringence—a not uncommon phenomenon for grossularite.[a] This mineral, associated with tremolite, diopside, and calcite, was particularly noted in the altered limestone from the new station on the 1,150-foot level of the Calumet and Arizona mine (the deepest point reached in the underground exploration of the district) and on the fifth level of the Holbrook, northeast of the shaft. It is probably fairly abundant throughout the compact, greenish, pyritized limestones in the deeper levels of the Copper Queen, Calumet and Arizona, and Lowell mines.

In several thin sections of the altered limestones from the Copper Queen and Calumet mines, there was noticed, in addition to the minerals already enumerated, small colorless prisms, having an index of refraction about equal to garnet but with a birefringence somewhat lower than quartz. A few cross sections found are square or octagonal, and remain dark between crossed nicols. The mineral extinguishes parallel with the prism, and the prismatic axis corresponds with the direction of greatest elasticity. The mineral is probably vesuvianite, a basic calcium-aluminum silicate of somewhat uncertain formula.

The metasilicate of calcium, wollastonite, was looked for in the altered limestones but was not detected in any of the thin sections, although the silicates described are those with which it is often associated.

Quartz varies greatly in abundance in different portions of the ore-bearing ground. A few small veinlets of quartz, carrying pyrite, were observed in the

[a] See Dana, System of Mineralogy, 6th ed., 1895, p. 438; and Rosenbusch, Mikroskopische Physiographie, 3d ed., 1892, vol. 1, p. 301.

altered limestone on the 950-foot level of the Calumet and Arizona mine, but vein quartz is exceptional in connection with the cupriferous ore bodies. The mineral, where it occurs at all, usually has the form of fine-grained aggregates that have replaced the calcium carbonate of the limestone or the feldspars of the granite-porphyry. Small amounts of quartz may usually be found as a microscopic constituent associated with tremolite, diopside, garnet, and pyrite in the altered limestones of the locally prevalent type. Near the porphyry mass of Sacramento Hill quartz is more abundant than elsewhere. Much of the rock in the vicinity of the Gardner shaft, for example, originally limestone, now consists essentially of a finely crystalline granular aggregate of quartz with varying amounts of pyrite and chlorite. The bottom of the shaft, at the time of visit, was in such material. Quartz of the same fine-grained granular character associated with pyrite, sericite, and kaolin, also makes up much of the altered and mineralized granite-porphyry of Sacramento Hill.

On the 800-foot level of the Lowell mine, the greater part of the west drift is in a mass of loosely coherent pulverulent silica, much of which, when dry, runs like sand. This material is associated with some yellow clay, a little decomposed porphyry, and occasional bunches of oxidized ore. Embedded in the sandy material are occasional very irregular harder masses composed of finely granular quartz. These are cavernous and drusy on their peripheries and lie in the loose siliceous powder much like flints in chalk. The microscope shows that the pulverulent silica is composed of grains which are neither rounded by attrition nor yet bounded by crystal planes. They are rough in outline, showing either that they have undergone corrosion, or formed part of a fine-grained aggregate from which some more soluble constituent has been removed. It is probable that this saccharoid quartz represents a zone of fissuring and brecciation in the limestone, along which some silicification took place. The calcium carbonate of the shattered, partly silicified limestone was then dissolved away, leaving the quartz in its present incoherent condition.

Most of the soft, earthy oxidized ores mined in the Copper Queen and Calumet and Arizona mines are accompanied by, and more or less intimately mingled with, limonite and clays of various colors. The limonite sometimes occurs in stalactitic or botryoidal form, but in the present workings is more often earthy and mixed with ore or clay.

The clay is sometimes white, sometimes pink or greenish-gray, but more often it is yellow or reddish from the presence of limonite. A snow-white waxy variety, beautifully diversified by little veinlets of light-green malachite, was collected on the second level of the Copper Queen mine, about 250 feet south of the Holbrook shaft, and subjected to chemical examination as representative of the purest form in which these clay-like secondary products occur. According to Dr. W. F. Hillebrand, the material contains no carbon dioxide and no magnesia. It suffers a loss of 22.8 per cent on ignition, and the residue consists chiefly of silica and alumina. It is thus probably nearly pure kaolinite, although too minutely crystalline to reveal any distinct structure under the microscope. This white kaolinite, which occurs in bunches and streaks in earthy limonite and ore, is usually associated with bright-red and pale-green varieties, the former owing its color to oxide of iron and the latter to some salt of copper.

These clays, in varying purity, together with soft earthy limonite, constitute the most abundant and characteristic gangue materials of the thoroughly oxidized ores.

PARAGENESIS OF THE ORE AND GANGUE MINERALS.

By paragenesis is meant the association of the various ore and gangue minerals, with special reference to the order and mode of their formation. It is not, however, implied in the definition that the minerals were formed in any rigid unalterable sequence, or that the development of any one mineral was a synchronous process in different ore bodies, or was peculiar to any particular division of geological time.

Among the metallic sulphides of the Bisbee copper deposits pyrite was undoubtedly one of the first to form. Whether small quantities of chalcopyrite and minute amounts of sphalerite were deposited at the same time as the primary pyrite is a moot question. Although some of the chalcopyrite is certainly later than the bulk of the pyrite, yet the contemporaneous formation with the latter of more or less disseminated chalcopyrite is by no means disproved or improbable. The association of most of the pyrite with amphibole, pyroxene, garnet, and vesuvianite is such as to demonstrate their essentially contemporaneous development in the limestone. To the same general epoch of mineralization belongs also the formation of most of the quartz and chlorite associated with the ores. In the development of the ore and gangue minerals there is thus distinguishable an early stage characterized by the practically simultaneous appearance of pyrite, tremolite, diopside, grossularite, vesuvianite, chlorite, quartz, and perhaps also of chalcopyrite and sphalerite. Both these last-named minerals are known to occur as primary ore constituents in other deposits in which the foregoing silicates are prominently developed, as, for example, at Cananea, about 40 miles southwest of Bisbee, and they are among those mentioned by Lindgren [a] as characteristic of true contact ore deposits.

That at least some of the chalcopyrite is of more recent origin than pyrite is shown by study of the chalcopyrite ore on the seventh level of the Spray mine. Microscopical examination of thin sections, from specimens taken from the periphery of the ore body, near the inclosing, altered and pyritized limestone, shows that the

[a] Lindgren, W., Character and genesis of certain contact deposits: Trans. Am. Inst. Min. Eng., vol. 31, 1902, p. 227.

massive chalcopyrite frequently envelops ragged kernels of pyrite, and in at least two instances little microscopic veinlets of chalcopyrite were observed traversing these pyritic nuclei. It is necessary to conclude that this particular mass of chalcopyrite was formed after the pyrite and probably in part by alteration or replacement of the latter.

On the sixth level, between the Spray and Gardner shaft, a small bunch of sulphide ore has been extracted from the side of the main drift. Remnants of this ore adhering to the walls show it to have consisted largely of pyrite in a chloritic gangue. Within this are little specks of chalcopyrite and perhaps some chalcocite in films on the pyrite. But most significant in connection with the present discussion is the occurrence of chalcopyrite in little veinlets and lenses along shear planes in the mass of the ore. These shear planes were formed after the pyrite, since crystals of the latter mineral have been slickensided by the movement. The chalcopyrite in this case, also, is therefore younger than the pyrite with which it is associated.

In the new northeast crosscut from the Gardner shaft, on the sixth level, some chalcopyrite occurs in altered limestone heavily impregnated with pyrite. The chalcopyrite, unlike the pyrite, is not disseminated generally through the rock, but occurs erratically distributed along zones of relatively easy fracture. Such a fracture surface may show an apparent abundance of chalcopyrite with a suggestion of identical crystallographic orientation over several square inches of area. If, however, the specimen be broken across at right angles to the surface showing most chalcopyrite, the latter is found to be a mere skin backed by pyrite and gangue. This relation strongly suggests, although it does not prove, that the chalcopyrite was formed later than the disseminated pyrite.

Such sphalerite as was observed in the Bisbee quadrangle was always closely associated with chalcopyrite, and was probably formed at the same time as the latter mineral.

Chalcocite is undoubtedly the most recently formed of the sulphide minerals occurring in the Bisbee ore bodies. The evidence that in this district the important occurrences of chalcocite have resulted from the action upon other sulphides, chiefly pyrite, of solutions moving generally downward from the zone of oxidation, is conclusive. It will be enough in this place to consider the evidence from specimens and microscopical investigation, leaving the broader relations of occurrence for the section devoted to discussion of ore genesis.

Such pyritic ore as contains enough copper to be workable occurs in crumbling masses of noticeably dark color as compared with the worthless pyrite. Close examination of such ore reveals the presence of chalcocite as envelopes about the grains of pyrite and as a sooty interstitial powder, which chemical tests show to be essentially cuprous sulphide. Such is much of the ore now worked in the Copper Queen mine southeast of the Holbrook shaft. This material is usually too incoherent for microscopical examination in thin section. Some of the harder and more compact forms of the mineral may, however, be so studied. A specimen of "glance ore" from the 950-foot level of the Calumet and Arizona mine when first examined seemed to consist chiefly of pyrite in a quartzose gangue. Closer examination, however, revealed the presence of chalcocite, which observation was confirmed by blowpipe tests. A thin section of this ore, looked at under the microscope with incident light, shows that many of the pyrite grains are surrounded by a thin, dark coating of chalcocite. They are traversed moreover by a multitude of intersecting microscopic cracks which are filled with chalcocite. Little flecks of chalcopyrite also occur inclosed within the pyrite, but these were plainly formed before the cracking of the latter and are older than the chalcocite. The sulphides are inclosed in a hard gangue consisting of a fine-grained crystalline aggregate of quartz. It is of interest to note that either the solutions which transformed the pyrite peripherally into chalcocite were able to penetrate this apparently impervious gangue, or else the latter was formed after the chalcocite. The former is the more probable, solutions containing cupric sulphate very likely finding access to the pyrite through microscopic fissures, and depositing chalcocite by a reaction which, according to Dr. H. N. Stokes,[a] may be written in somewhat simplified form as follows:

$$5\,FeS_2 + 14\,CuSO_4 + 12\,H_2O = 7\,Cu_2S + 5\,FeSO_4 + 9\,H_2SO_4 + 3\,H_2SO_4,$$

the last H_2SO_4 being formed by oxidation of the sulphur of the pyrite.

Of the minerals of the oxidized zone, cuprite and native copper are apparently among the first to form from the sulphides, since they occur usually near the bottom of the oxidized ore in proximity to the sulphides. The direct alteration of chalcocite into native copper is exhibited by specimens from the 1,050-foot level of the Calumet and Arizona mine. These show very irregular kernels of compact chalcocite incrusted with a spongy aggregate of small sparkling crystals of native copper, associated with a little earthy cuprite. The copper is not strictly confined to the exterior of the chalcocite kernels, but penetrates the latter for varying distances, up to about half an inch, in the form of little vugs and indefinite stringers.

As a rule, cuprite has formed just after the native copper with which it is immediately associated, but the sequence is by no means always clearly shown. On the 1,050-foot level of the Calumet and Arizona mine native copper occurs in branching crystalline masses beautifully incrusted with crystals of cuprite. The cuprite is in such cases obviously the younger mineral. On the 950-foot level, on

[a] Oral communication.

the other hand, the two minerals are found so intimately associated that it is difficult to determine which was the first to form. The copper constitutes a metallic mesh or sponge which is filled with crystalline cuprite. Although some of the copper may have formed slightly in advance of some of the cuprite, both minerals were probably crystallizing at the same time.

In the zone of oxidation, where many complex chemical reactions are constantly taking place, where the active solutions are continually varying in strength, and where the relative masses of the reacting elements or compounds are inconstant, it is not to be supposed that all of the material undergoes the same transformations in its alteration from sulphide to oxidized ore. Reactions are probably frequently reversed and repeated. Native copper may form from chalcocite, be oxidized to cuprite, and this again reduced to native copper by the action of dilute sulphate solutions. The most that can be hoped for in a study of paragenesis is to establish a general sequence of mineral formation in a given set of deposits without losing sight of the fact that to that sequence are many exceptions.

Brochantite has been found only in close association with cuprite, and appears to have been formed shortly after that mineral. Melanochalcite and chrysocolla are also characteristic of the deeper portion of the oxidized zone. The sequence of formation, as shown in specimens from the Calumet and Arizona mine, was native copper, cuprite, brochantite, melanochalcite, chrysocolla, malachite, and calcite.

In general the formation of limonite appears to have accompanied or closely followed that of cuprite and to have continued for sometime after, so that it is also intimately associated with the occurrence of malachite and azurite.

The azurite, on the whole, belongs to a later stage of the general oxidation than the malachite. But there is much overlapping in the occurrence of these two carbonates.

Tenorite is usually associated with wad or "bog manganese" in the upper part of the zone of oxidation.

FORM AND GEOLOGICAL ENVIRONMENT OF THE ORE BODIES.

GENERAL SHAPE AND DIMENSIONS.

The Bisbee copper ores as exploited in the Copper Queen, Calumet and Arizona, and Lowell mines occur for the most part very irregularly as large masses in the Escabrosa and Naco limestones. The horizontal dimensions of these ore bodies are usually much greater than the vertical. They are rudely tabular or lenticular in form, and lie generally parallel to the bedding planes of the inclosing limestones. Definite walls are exceptional. As a rule, the oxidized ore passes gradually and irregularly on its peripheries into so-called "ledge matter," consisting chiefly of soft limonitic clays, which in turn grade into more or less altered limestone. The unoxidized sulphide ores may exhibit a peripheral transition either to oxidized ores or to metamorphosed limestone impregnated with pyrite.

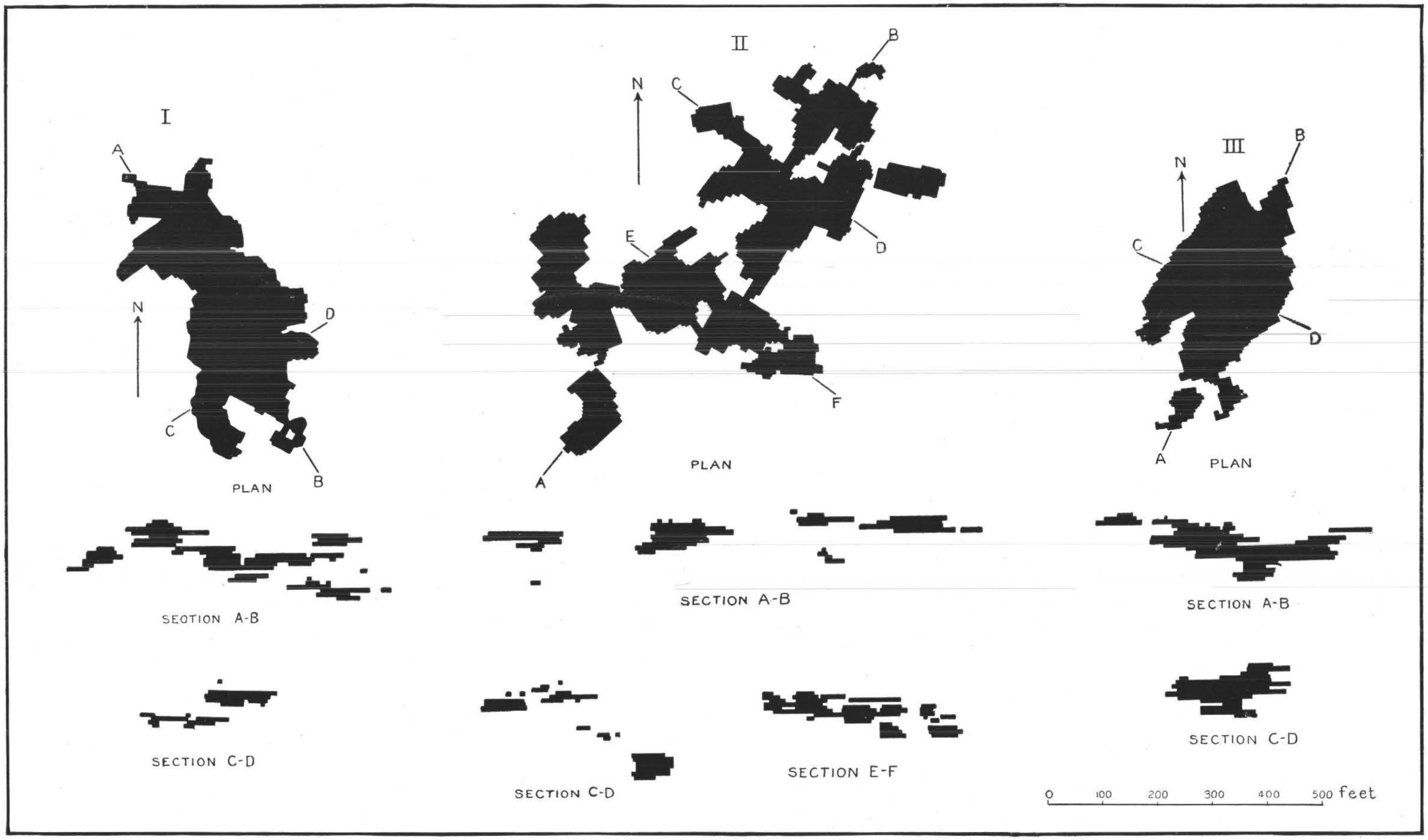
Under these circumstances the actual shape of an ore body is variable, being dependent upon the price of copper and the economic conditions of working. It is possible, however, to gain a fairly definite idea of the size and form of typical ore bodies by considering some of the older stopes, which while not exhausted have yet run through the ore at so many points as to establish its general contour.

In Pl. XXIX are shown plans and sections of three such typical stopes in the Copper Queen mine, while in fig. 4 (p. 137) and in fig. 5 (p. 138) are represented additional sections throwing light upon the general outlines of the ore bodies. On any single horizontal plane the dimensions of the ore masses rarely exceed 150 by 200 feet, but series of connected stopes indicate that in general plan these figures may be considerably exceeded. Thus the stopes northeast of the Holbrook shaft indicate the existence of a practically continuous body of ore and "ledge matter" about 800 feet in length and 600 feet in width. On the other hand, the actual maximum thickness of the ore bodies hitherto extensively worked rarely exceeds 125 feet.

RELATION OF ORE BODIES TO THE BEDDING OF THE LIMESTONES.

The statement that these very irregular tabular or lenticular masses of ore lie parallel with the bedding planes of the inclosing limestones is the simplest expression of a general relation and requires some qualification when the ore bodies are studied in detail. It is then found that the original structure of the limestone in the vicinity of the ore is very much obscured by metamorphism, if it is not entirely obliterated by the extensive formation of ferruginous clays resulting from the oxidation and decomposition of the ores and country rock. Furthermore the ore sometimes cuts across the bedding of the limestones for considerable distances, as will be later shown.

Owing to the extensive alteration of the limestones in the vicinity of the ore bodies, observations on dip and strike of the beds can be made in but a small part of the extensive underground workings of the Copper Queen mine. Such observations as were recorded indicate a general southeasterly dip of less than 20°. But there is much diversity, and the beds were evidently subjected to considerable local disturbance prior to the deposition of the ore. At the old Queen incline, which follows the bedding, the dip is about 40° and is toward the south. This steep and unusual local dip apparently accounts for the exceptional attitude of the original Queen ore body, a roughly cylindrical mass 60 feet in diameter and 400 feet in length, which, according to the section published by Mr. Douglas



PLANS AND SECTIONS OF STOPES IN THE COPPER QUEEN MINE, SHOWING APPROXIMATE FORMS OF TYPICAL ORE BODIES.

(fig. 4), had its axis more nearly vertical than horizontal.[a] As this body presented some points of difference from those now open to study, the description of it by Mr. Douglas may fitly be quoted. He writes:[b]

"The outcrop of copper which was first attacked, and which was, in fact, the only extensive surface indication, was on the northern exposure of a limestone hill. In this place stripping revealed a solid body of oxidized copper, iron, and manganese ore over 60 by 60 feet in area, and so rich in copper that the furnace, fed from the surface ores above, yielded for a few months 23 per cent of metal. * * * This large outcrop was inclosed in an almost circular unaltered limestone frame. Associated with the ore was an abundance of calcite,

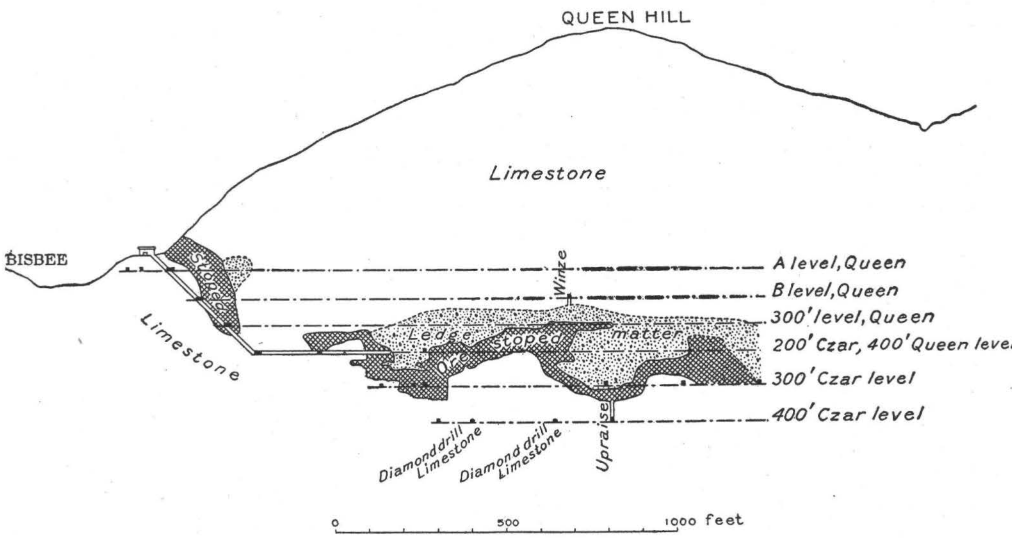


FIG. 4.—Section of the Copper Queen mine through the open cut and the southwest stope. After Douglas.

but the percentage of silica was so small that quartz had to be added to the furnace charge. This body, retaining its general dimensions and well-defined limestone walls, dipped at an angle of about 30° southeasterly into the hill. Between the 100- and 200-foot levels the ore changed into a clay, with well-marked bedding, too lean in copper carbonate to be profitably worked, but below this zone of clay the copper, as carbonates and oxides, increased to 12 per cent, and was associated in a measure with limonite, embedded in ferruginous clay. This ore body extended to a depth of 400 feet on the incline from the surface, and there terminated abruptly in hard limestone."

This single ore body yielded about 80,000 tons of ore and 20,000,000 pounds of copper.[c]

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[a] In his description, however, quotation of which follows, Mr. Douglas states that the dip was only 30° into the hill.
[b] Douglas, J., The Copper Queen mine, Arizona: Trans. Am. Inst. Min. Eng., vol. 29, 1900, p. 513.
[c] Ibid., p. 514.

Between the Queen incline and the Holbrook shaft (Pl. XXV) and southwest of the Czar shaft, the usual gentle southeasterly dip seems on the whole to prevail, although opportunities for satisfactory observation are rare. The very important ore bodies occurring in this part of the Copper Queen mine have been found on the whole to be nearly horizontal (Pl. XXVIII). As a rule very few traces of original bedding are discoverable in the much altered, mineralized, and decomposed material occurring within 500 feet of the probable position of the Dividend fault (Pl. XXIV).

In the Spray workings the general dip of the limestones appears to be toward the southeast at an angle of about 15°. The ore bodies correspond roughly to this

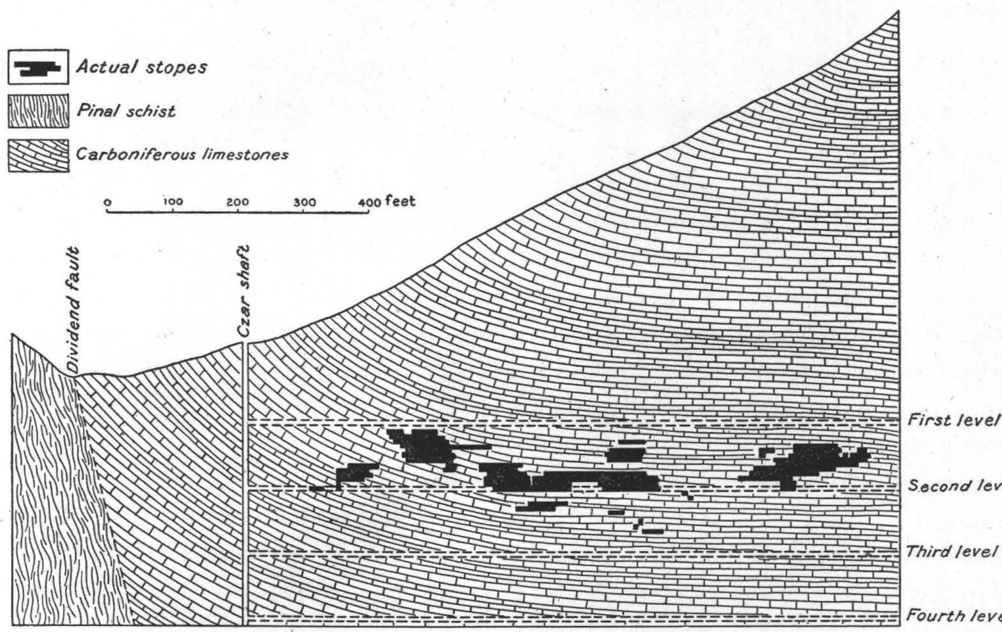

FIG. 5.—Diagrammatic northeast-southwest section through the Czar shaft of the Copper Queen mine, showing the general structural relation of the ore bodies.

The black shows actual stopes. The structure of the limestones is generalized and no attempt is made to distinguish mineralized limestone or the altered clayey material known as "ledge matter" from the normal unaltered beds.

gentle inclination. This fact was particularly noticeable in the case of a relatively small body of chalcopyrite ore being stoped on the seventh level at the time of visit. On the eighth level, also, it was noticed that bands of pyrite show a marked tendency to follow what seem to be bedding planes in the mineralized limestone.

In the Calumet and Arizona mine the limestones maintain their general southeasterly dip, but are more steeply inclined than in the adjoining Copper Queen workings, the average dip being about 35°. Stoping had not gone far enough in this mine at the time of visit to demonstrate the approximate shape of the large ore bodies. There is little doubt, however, but that they are of the same general character as those worked from the Spray shaft, although more noticeably inclined in conformity to the increased dip of the inclosing beds. There is observable in the deeper levels of this mine the same pronounced influence of the bedding planes in directing pyritic impregnation as was noted in the Spray.

The development of the Lowell mine is as yet insufficient to throw much light on the shape and extent of the ore bodies. They are evidently of irregular form, but lie with their two greater dimensions parallel to the bedding planes of the limestone, which here have an easterly dip of from 35° to 45°. These ore bodies are undoubtedly of the same general type as those found in the Copper Queen and Calumet and Arizona mines.

RELATION OF THE PRINCIPAL ORE BODIES TO THE ESCABROSA LIMESTONE.

Although the ore bodies as a rule have their greater dimensions in the planes of bedding, they are not confined to any particular bed or to any definite stratigraphic horizon. The original Queen ore body occurred in the lower part of the Escabrosa limestone. The ore in the Baxter tunnel near the Holbrook shaft occurs in part in the lower part of the Naco limestone. In the latter formation also, probably occurs a portion of the ore in the Calumet and Arizona mine, and almost certainly that so far discovered in the Lowell mine. The problem of determining the stratigraphic horizon at which most of the great ore bodies of the Copper Queen and Calumet and Arizona mines occur is a difficult one. Not readibly distinguishable over the quadrangle at large, the Naco and Escabrosa limestones can not be separately identified in the mines, where metamorphism has altered the original texture and composition, obscured much of the structure, obliterated all of the fossils, and transformed both limestones to similar aggregates of silicates and pyrite. When upon such metamorphism there is further imposed widespread alteration into limonitic clays and oxidized ore, the possibility of distinction between the two original limestones vanishes. Structural relations (see structure sections, Pl. III) render it very probable that the great ore-bearing member of the Paleozoic series is the lower Carboniferous or Escabrosa limestone with a thickness of about 700 feet. More exact and assured conclusions might be drawn from general structural relations as interpreted in the structure sections (Pl. III), were there less local disturbance in the beds, were the presence and effect of faults in the limestones more readily determinable, and did the underground workings afford some direct check on the deeper structure as projected from studies on the surface. The probability, however, is strong that the Escabrosa limestone, while not the only ore-bearing formation, is the one that contains most of the great known ore bodies in the Copper Queen and the Calumet and Arizona mines.

Facts lending some additional support to this hypothesis are (1) the known occurrence of the original Queen ore body in the Escabrosa limestone; (2) the greater depth at which other ore bodies were subsequently discovered southeast of the Queen incline, suggesting that they were formed in the same limestone as the Queen ore body but occur at a lower level because that limestone had been dropped prior to the general mineralization by the Czar fault (see Pl. III); and (3) the progressively increasing depth at which large ore bodies are encountered in developments pushed toward the southeast. The correspondence between the increasing depth of the larger ore bodies and the augmenting thickness, from northwest to southeast, of the overlying wedge of relatively barren Naco limestone, while it can not be shown to be exact, is at least roughly demonstrable and can scarcely be a chance coincidence. It contains a strong suggestion that the maximum deposition of ore in the general zone thus far exploited was directly connected with the Escabrosa formation.

In his paper on the Copper Queen mine, Dr. James Douglas has distinguished "two series of limestone beds, both of Carboniferous age: The upper bedding recognized as the white; and the lower as the blue—though this distinction of color is not always well marked."[a] The lithological distinction made by Mr. Douglas could not be recognized in the course of the present investigation, and does not appear to correspond with the division of the Carboniferous limestones into the Escabrosa and Naco formations adopted in this report. In the Copper Queen mine a somewhat vague distinction is commonly made between the so-called upper and lower "limes." It was found, however, that the "lower lime" meant the compact metamorphosed limestone occurring underneath any of the known ore bodies. It could not be ascertained that the term had any precise stratigraphic or lithological significance, or that the rock so designated was essentially different from certain unoxidized portions of the "upper lime."

RELATIONS OF THE ORE BODIES TO STRUCTURES OTHER THAN BEDDING.

Bedding planes are not the only elements of geological structure that have influenced the deposition of ore. In the deeper workings of the principal mines, particularly of the Calumet and Arizona, there is a well-marked and significant tendency of the original pyritic impregnations to concentrate along minor zones of fissuring and shearing in the generally mineralized limestone. This tendency, clearly shown on a small scale, usually below and at a little distance from the main ore bodies, is not merely a minor phenomenon, but illustrates in miniature what has taken place on a much larger scale in connection with the great ore masses. In the case of the latter, however, the important part played by fissures in ore deposition is to a considerable extent obliterated by later changes wrought in ore and country rock by general oxidation and secondary concentrations.

[a] Douglas, J., The Copper Queen mine, Arizona: Trans. Am. Inst. Min. Eng., vol. 29, 1900, pp. 516-517.

Inspection of the generalized map of the underground workings of the Copper Queen mine (Pl. XXV) shows that the horizontal distribution of the ore bodies is related to certain structures that are nearly vertical. These are the Czar and Dividend faults and the main limestone-porphyry contact. The ore bodies on the whole constitute a broad belt, about 900 feet in width, which, beginning (so far as present explorations show) at a point about 2,000 feet southwest of the Czar shaft, continues northeasterly, chiefly along the southeast side of the Czar fault to the Czar shaft, thence southeasterly along the southwest side of the Dividend fault to the contact with the Sacramento Hill porphyry near the hospital (Pls. III and XXIV). Here the ore belt swings to the south, skirting the porphyry mass toward the Spray and the Calumet and Arizona shafts. Whether it continues to skirt the porphyry eastward, past the Gardner and Lowell shafts toward the ice factory and Mule Gulch, is yet to be proved by underground work.

The Czar fault is a well-established but remarkably inconspicuous normal dislocation, with an estimated downthrow of about 500 feet to the southeast. The surface phenomena connected with it are described on page 89. The identification of the fault in the underground workings is unsatisfactory. The drift from the Czar shaft to the Queen incline on the second level ought to cut across the fault. It does in fact cross two distinct fissures, one about 300 feet from the Czar shaft, striking north 35° east, and dipping northwest at an angle of 70°, and another about 110 feet east of the bottom of the Queen incline. The latter is nearly vertical and has a local strike of about south 10° west. This is possibly the Czar fault, although the strike as observed in the short exposure in the drift is too southerly for the general trend of that dislocation. The long crooked drift running southwest from the Queen incline on the second level probably crosses and recrosses the Czar fault. It was found impossible to identify the fissure, however, owing to the prevalent decomposition of the disturbed and altered limestone to the soft, ferruginous, clayey material known as "ledge-matter." In general, the fault seems to separate extensive areas of this "ledge-matter," containing large ore bodies and extending eastward toward the Holbrook shaft, from harder less mineralized limestones on the northwest, in which no important ore bodies have yet been found on this level. It is probable, although by no means certain, that the "ledge-matter" on the southeast of the supposed fault line is altered and decomposed Escabrosa limestone, and that the harder limestones on the northwest is Martin, or perhaps in part, Abrigo limestone. The stope worked for converter clay in this part of the mine is probably in altered Martin or Abrigo limestone on the northwest side of the Czar fault. If the foregoing interpretation of the structure is correct, it affords a reasonable explanation of the failure to find ore bodies on this level on the northwest side of the supposed fault line. For it is evident that the bottom of the particular limestone, probably the Escabrosa, that carries the ore on other parts of the level, must be sought for above this level on the northwest side of the fault. (See section DD, Pl. III.)

It was probably in consequence of the Czar fault that so much difficulty was encountered in finding new ore bodies after the exhaustion of the original Queen stope. That great cylindrical ore mass was on the northwest side of the Czar fault, while the bodies afterwards discovered at lower levels have been in the downthrown southeast block.

The detailed relations of the ore bodies of the Copper Queen mine to the Dividend fault (Pl. XXV) are very obscure. Large bodies of ore have been mined and are still being worked in the vicinity of this great fissure, but the ground is soft and openings in it very difficult to maintain. Such crosscuts as have been run northeastward beyond the ore bodies are no longer accessible, and it is not known whether any of them penetrate the schist, which at the surface forms the country rock northeast of the fissure. The ore bodies in this part of the mine were apparently formed for the most part in limestone, but the mineralization and subsequent alteration has been so intense that very little of the original country rock can now be identified. Masses of earthy oxidized ore and bodies of crumbling pyrite, more or less enriched with chalcocite, occur very irregularly amid abundant soft clayey and limonitic material. The general parallelism of the ore bodies with the bedding planes of the limestone, elsewhere in these mines a noticeable feature, is much less distinctly shown in those workings near the Dividend fault.

In that very productive part of the Copper Queen workings lying northeast of the Holbrook shaft and in the corner formed by the Dividend fault and the contact of the limestones with the porphyry of Sacramento Hill minor intrusions of porphyry, probably apophyses or offshoots from the main intrusive stock, have evidently influenced the deposition of the ore to an extent recognized by the miners, who expect, usually, to find ore bodies in contact with them. They appear to have the form of irregular dikes, or occasionally sills. They are sometimes impregnated with a little pyrite and often decomposed to a white or yellow clay, which usually reveals its origin by the presence of grains of quartz representing former phenocrysts in the porphyry.

The relation of the ore to the porphyry is illustrated in the old Dividend stope on the fourth level, about 650 feet northeast of the Holbrook shaft. The drifts running eastward toward the stope pass through metamorphosed limestone, impregnated with pyrite, into an irregular dike of porphyry. The ore occurs as pyrite and chalcocite, with a little chalcopyrite in soft, oxidized ground along the eastern side of this dike. According to Supt. S. W. Clawson, this ore is continuous with a large, nearly horizontal ore body near the second level, which was found to turn abruptly down along the eastern side of the porphyry dike. It was not practicable to verify this reported relation at the time of visit, nor to learn what became of the dike at the point where the ore passed over it and turned down along its eastern side. While much of the ore in the vicinity of the Dividend stope was deposited originally in limestone, the alteration has been such that the original character of the gangue material can not always be determined. It is possible that some of the ore now worked may have been deposited in porphyry, although, as a rule, this rock, when occurring as dikes and sills in the pyritized limestones, is seldom itself conspicuously mineralized.

Directly under the Hayes air shaft, on the fourth level, there is exposed a considerable mass of porphyry, which apparently forms an irregular sill in the limestones. Immediately under the porphyry, which is undecomposed and not perceptibly mineralized, separated from it by a sharp contact, is a small, nearly horizontal mass of pyritic ore, which, as is shown by a winze, rests upon mineralized limestone.

These and other examples indicate that the presence of porphyry dikes and sills in the limestones, while by no means a necessary condition to the formation of ore bodies, is yet favorable to their occurrence. The function of these minor porphyry intrusions with reference to ore deposition appears to have been similar to that of fissures in influencing the movements of the mineral-bearing solutions in their circulation through the limestones.

That there is a genetic connection between the porphyry mass of Sacramento Hill and the deposition of the ores is certain. The actual relation of the ore bodies to the porphyry-limestone contact is, however, nearly as obscure as in the case of the Dividend fault. On the surface (Pl. III) the contact is concealed by surficial material in the gulch that comes down from the Spray shaft past the hospital. Even on the western slope of Sacramento Hill, where the rocks are well exposed, the alteration of porphyry and limestone is such that the actual contact between the two is rather indefinite. Underground crosscuts have not been driven far enough to throw much light upon the details of the relation between porphyry and ore. They have usually been stopped whenever anything supposed to be porphyry appeared at the face.

On the second level of the Copper Queen workings a crosscut has been run toward the porphyry from a point about 700 feet northwest from the Gardner shaft (Pl. XXV). This passes from soft ferruginous "ledge matter" into hard metamorphosed limestone heavily impregnated with pyrite. At the face this mineralized limestone is in contact with altered sericitized porphyry containing abundant disseminated pyrite. The contact here is a fault plane, dipping toward the northeast, and exhibiting evidence of recent movement. The extent of this movement can not be determined from the available exposure. It may merely indicate slight displacement along the intrusive contact.

On the third level is another crosscut a short distance north of the one just described. This also encounters porphyry, which is altered to a soft siliceous material almost as porous and friable as pumice. As the crosscut was only partly accessible, it could not be seen whether its face is also in porphyry.

East of the Hayes shaft a crosscut extends eastward about 200 feet beyond an ore body indicated in Pl. XXV. It is all in rock that has been altered to an aggregate of quartz, pyrite, and kaolin and is regarded as probably metamorphosed limestone, since it grades in other directions into material that was certainly limestone originally. Nothing recognizable as porphyry occurs in this crosscut, although it would seem (Pl. XXV) as if this rock should have been encountered.

From the generally inaccessible crosscuts toward the porphyry, northeast of the Holbrook shaft, no definite information could be obtained as to the precise relation of the ore to the porphyry contact. According to Mr. Clawson the crosscut extending farthest east on the fourth level, in this part of the mine, reaches the porphyry and encounters a body of good sulphide ore near the contact.

On the sixth level a crosscut is being run toward Sacramento Hill from the Gardner shaft. At the time of visit this was in metamorphosed limestone carrying abundant disseminated pyrite and a little chalcopyrite and sphalerite. According to Dr. L. D. Ricketts, mining engineer for the Copper Queen Company, the crosscut, at the date of writing, has passed through this material and has entered rock that appears from specimens sent by Mr. Ricketts to have been originally porphyry, but is now an aggregate of quartz, sericite, and pyrite. The change took place about 335 feet northeast of the shaft (Pl. XXV).

The general conclusion drawn from such meager data as are obtainable in regard to the contact between the Sacramento Hill porphyry and the limestones may be given in a few words. The contact is very imperfectly explored. It is apparently irregular, with conspicuous departures from a simple curved surface. It is the locus of pronounced metamorphism and mineralization which extends both into the limestones and into the porphyry. Pyrite occurs in great abundance in the immediate vicinity of the contact—characteristically in disseminated form, but occasionally in considerable masses. The workable bodies of ore, owing their value to processes of enrichment subsequent to the primary pyritic mineralization, occur within the mass of the limestones, usually at some little distance from the actual contact to whose curved course their distribution in the main conforms.

It is highly probable, if not reasonably certain, that other fissures than the Czar and Dividend faults have helped to determine the form and position of individual ore bodies. Such fissures, however, can not be satisfactorily studied in mines where ore value and extensive oxidation are so closely related and where workings in the soft clayey ground soon close upon disuse. In the Lowell mine there is abundant evidence that ore deposition was facilitated by irregular fissuring of general north-south trend. Most of the disturbance appears to have consisted in differential movements along planes of bedding (bedding faults) with occasional irregular fractures of no great vertical persistency cutting across the beds.

GROUND WATER AND DEPTH OF OXIDATION.

The general ground-water level is rather difficult of definition in the Bisbee district. As in other arid regions, it lies deep, and oxidation has been unable to convert all of the sulphides above it into what are commonly termed oxidized ores. As country rock and ore do not constitute homogeneous material, there is thus a very irregular downward transition from the oxidized ores to the sulphide masses involving a zone several hundred feet in depth within which ores of both classes occur. It may be pointed out in passing that these conditions harmonize with other geological facts, indicating a more humid climate during the Pleistocene epoch and consequently a former higher ground-water level.

Large masses of sulphide ore have been found on the second level of the Copper Queen mine, less than 200 feet below the surface, in the vicinity of the Dividend fault. In the Calumet and Arizona mine, on the other hand, partial oxidation has extended to a depth of over 1,050 feet, as shown by the abundance of cuprite and native copper, with some limonite and malachite. In the Lowell mine oxidation has penetrated irregularly to a depth of 1,100 feet. At this depth the mine, formerly nearly dry, developed a flow of water amounting to about 175,000 gallons per day.

Within the transition zone between completely oxidized and unaltered sulphide ores, which has a maximum depth or thickness of about 900 feet, the oxidizing processes are controlled to a large extent by recent irregular fissuring and by the relative permeability of the various sulphide masses to generally descending solutions. Fissures cutting through masses of lean pyrite are almost invariably accompanied by streaks of rich ore, often containing chalcocite, together with cuprite and native copper. Where there are several such fissures near one another important ore bodies result. The general association of profitable ore with fissured, broken, permeable ground is well recognized in practical operations and turned to good account in underground exploration.

Care has been taken to refer to the movement of the oxidizing solutions as *generally* downward. There is abundant evidence that for comparatively short distances these solutions moved laterally and even upward. The occurrence of considerable masses of lean pyrite completely enveloped in rich ore, consisting of chalcocite and the usual minerals of the oxidized zone, is fairly common. Mr. Douglas, writing of the Copper Queen mine in 1899, says:

"The sulphurets in these limestones occur in layers of various thickness and solidity. When solid and thin they are generally partially oxidized, and are rich. Two very large compact masses have been encountered and in part explored. The largest apexes on the 200-foot level and has been traced to the 400-foot level, and a string of stopes nearly 500 feet in length has been opened upon it, but the profitable ore bears only a small proportion to the whole mass. Roughly speaking, the mass is enveloped in a shell of oxysulphide, and streaks of similar black copper ore of good grade intersect it; but the core consists of compact bisulphide of iron, very lean in copper."[a]

The essential facts of occurrence as presented in the foregoing description were fully confirmed by the observations made during the present investigation. The more recent workings of the Calumet and Arizona and Lowell mines afford ample opportunity for verifying the frequent occurrence of residual kernels of lean pyrite enveloped by good ore, and this in turn sometimes inclosed in oxidized ferruginous clays or "ledge matter." Such a mass of pyrite was noted on the 1,000-foot level of the Lowell mine, lying generally parallel with the bedding of the limestones, and in contact with partially oxidized ore both above and below. Some native copper was seen in the oxidized ore close to the pyrite. Similar residual masses of worthless pyrite surrounded by good ore, usually containing chalcocite, were seen on the 1,050-foot level of the Calumet and Arizona mine, particularly in a stope about 300 feet east of the shaft.

It thus appears that the oxidizing solutions, guided by fissures, bedding planes, and relatively porous masses of rock or ore, move generally downward, but locally also along lateral planes and upward. Permeable or fissured masses of pyrite have been more or less thoroughly altered, while compact or unfissured masses have retained to a large extent their original character, and contain but little copper.

GENESIS OF THE ORES.

GENERAL PROCESSES INVOLVED.

The account of the Bisbee ore bodies given in the preceding pages shows beyond need of further demonstration that two general processes have operated to form the ores now exploited. These are (1) metasomatic alteration, including pyritic mineralization, and (2) oxidation and its attendant phenomena of transportation and enrichment. Concerning the precise boundary between these two general activities some difference of opinion is possible, but as regards the essential share of each in

[a] Douglas, J., The Copper Queen mine, Arizona: Trans. Am. Inst. Min. Eng., vol. 29, 1900, p. 531.

the genesis of the ores there can be no question. There are few known ore bodies in the Bisbee quadrangle which do not demonstrably owe their value to the cooperation of both processes. This was also the conclusion reached by Emmons[a] from the descriptions of Douglas and from a brief visit to the Copper Queen mine. The existence of workable masses of ore that have resulted wholly from the primary metasomatic mineralization, while not denied, is still as far from proof as when Mr. Douglas published his excellent account of the Copper Queen mine three years ago.

PRIMARY METASOMATIC ALTERATION AND MINERALIZATION.[b]

As shown in those underground workings which are below the intermediate zone penetrated by oxidizing reagents, the sulphide minerals ascribable to the earlier period of metasomatic alteration are common pyrite, and perhaps also a little chalcopyrite and sphalerite. The occurrence of some cerussite in the limestones suggests that galena may also occur, although this mineral has not been seen. Associated with these sulphides are amphibole (tremolite), pyroxene (diopside), garnet (grossularite), vesuvianite, quartz, and chlorite in the limestones; quartz, sericite, chlorite, perhaps kaolin, and a little epidote in the granite-porphyry; and quartz and sericite in the Pinal schist. Tests made in the chemical laboratory of the Survey upon representative specimens of the mineralized limestone, containing abundant disseminated pyrite, but no visible chalcopyrite, afforded in one case a trace and in the other 0.12 per cent of copper.[c] The pyrite is therefore cupriferous, the copper probably occurring as an admixture of the chalcopyrite molecule.

A chemical analysis of a typical specimen of mineralized limestone from the fifth level of the Holbrook mine, about 200 feet south of the shaft, is given on the following page under I.

[a] Emmons, S. F., The secondary enrichment of ore deposits: Trans. Am. Inst. Min. Eng., vol. 30, 1901, p. 192.

[b] In a preliminary sketch of the Bisbee copper deposits (Bull. U. S. Geol. Survey No. 213, 1903, pp. 149–157), published before any microscopical study had been made of the ores and country rock, it was stated that little or no contact metamorphism had been effected in the limestone. Closer study has shown that the metamorphism is much greater than mere field examination indicated.

[c] It is to be noted that these are percentages of the rock as a whole. The actual percentages of copper in the pyrite itself, free from the abundant gangue present in the specimens examined, would be much higher.

Analyses of altered and unaltered limestones.

[W. F. Hillebrand, analyst.]

	I.	II.	III.	IV.
SiO_2	28.55	0.06	2.52	8.52
TiO_2	.16	.12 (TiO₂, Al₂O₃, Fe₂O₃, FeO)	.24 (TiO₂, Al₂O₃, Fe₂O₃, FeO)	.64 (TiO₂, Al₂O₃, Fe₂O₃, FeO)
Al_2O_3	.98			
Fe_2O_3	None.			
FeO	.84			
FeS_2	5.63			
MnO	.40			
MgO	13.62	.13	.76	.55
CaO	26.20	55.80	53.68	50.07
K_2O	.06			
Na_2O	.14			
H_2O below 110° C	1.05			
H_2O above 110° C	3.08			
CO_2	19.00			
P_2O_5	.54			
SO_3	None.			
Cu	(a)			
	100.25			

a Trace; not over 0.05 per cent.

I. Metamorphosed and mineralized limestone from the fifth level of the Holbrook mine.
II. Partial analysis of typical unaltered Escabrosa limestone.
III. Partial analysis of typical unaltered Naco limestone.
IV. Partial analysis of typical unaltered Martin limestone.

The rock analyzed contains a moderate amount of pyrite disseminated in small irregular grains and minute crystals through a fine-grained pale greenish-gray groundmass. It effervesces with dilute acid, particularly along small irregular shear surfaces that traverse the rock in various directions and are rather characteristic of the mineralized limestone as seen in the deeper workings of the Bisbee mines. The microscope shows that the specimen consists chiefly of calcite, tremolite, pyrite, and grossularite. Assuming, as seems to be the case, that the carbonate present is chiefly calcite, the altered rock consists of about 43 per cent of calcite, about 47.5 per cent of silicates, chiefly of magnesia and lime, 5.5 per cent of pyrite, and 4 per cent of water.

In view of the fact that this rock probably belongs to the Escabrosa formation, which in unaltered condition is a pure nonmagnesian limestone, the foregoing analysis indicates that the metamorphism involved not only the introduction of iron and sulphur in the form of pyrite, but of notable quantities of silica and magnesia. In the table of analyses the essential composition of a typical specimen of the metamorphosed Escabrosa limestone, collected from the top of Escabrosa Ridge, is indicated under II, while under III and IV are placed partial analyses of the Martin and Naco limestones. Comparison with these shows that even if the reference of the mineralized limestone to the Escabrosa formation be erroneous the evidence of pronounced chemical change remains unweakened.

The large amount of alumina occurring with the oxidized ores in the form of kaolinite and clay led to the expectation that the unoxidized metamorphic limestone would be decidedly aluminous. But the mineral composition as determined by the microscope lends little support to this suggestion, and the chemical analysis of the specimen from the fifth level of the Holbrook mine, apparently representative of large masses of the mineralized limestone, shows that very little alumina is present. That found is probably for the most part combined with silica and calcium to form the small quantity of colorless garnet observed in thin sections. According to Mr. Douglas, "a series of analyses taken from a drift in the eastern section of the [Copper Queen] mine, as an ore body is approached, indicates the gradual change from unaltered limestone to clays, involving a decrease in lime from 24 per cent to 0.33 per cent, and an increase in alumina from 2.20 per cent to 16.9 per cent."[a]

The "unaltered limestone" of Mr. Douglas, however, is evidently already metamorphosed, as shown by its containing only 24 per cent of lime. (Compare analysis on page 148.) The increase in alumina, therefore, appears to be connected with the general process of oxidation rather than with the earlier metamorphism now under discussion.

The metamorphic minerals mentioned are not distributed uniformly through the limestone, but are arranged in zones about the porphyry mass of Sacramento Hill. Nearest the porphyry the former limestone is now a fine-grained aggregate consisting chiefly of quartz and calcite. Such is the rock of the Gardner shaft. The width of this siliceous zone has not been accurately determined, but may be roughly estimated at about 200 feet. It is probably very irregular and is not sharply defined at its outer border. Although heavily impregnated with pyrite, it has not proved such favorable ground for the occurrence of ore bodies as the next zone to be described.

Encircling the siliceous zone are the pale-green altered limestones in which pyrite, tremolite, diopside, grossularite, and probably vesuvianite, are the characteristic minerals. In this zone quartz is comparatively rare. Calcite, however, is abundant, and may make up half or more of the altered limestone. At its inner

[a] Douglas, J., The Copper Queen mine, Arizona: Trans. Am. Inst. Min. Eng., vol. 29, 1900, pp. 519–520.

edge this zone grades somewhat indefinitely into the siliceous zone. About its circumference it passes by obscure gradation into the unmetamorphosed limestones of the region. The rock of this zone of metamorphic silicates is softer than that of the inner siliceous zone. It is frequently traversed by little irregular surfaces of shearing, so that the rock tends to break along many curved surfaces into small fragments. The width of this zone can not be stated with precision, on account of the indefinite character of its boundaries, but it may be very roughly estimated at about 1,000 feet. The zone is not, however, limited in plan to a simple concentric band about the porphyry, but extends for a considerable distance to the northwest toward the Czar shaft. Whether the development of metamorphic silicates was also characteristic of the ore-bearing limestones along the southeast side of the Czar fault is a question which the present investigation leaves in doubt. The workings above the fourth level in this part of the Copper Queen mine are largely in oxidized ground. The fourth level, however, is in compact gray limestone apparently containing no metamorphic silicates. But as no specimen was taken of the limestone in this particular part of the workings, the absence of such silicate minerals has not been confirmed by microscopical examination.

In general, the zone in which the metamorphic silicates are developed is that in which most of the ore bodies are found. In the western part of the Copper Queen mine, however, extensive ore bodies occur in limestone that is perhaps outside of this zone. In other words, the deposition of metallic sulphides appears to have had a wider range and to have extended farther from the porphyry into the fissured limestones than did the formation of the metamorphic silicates.

As metasomatic alteration has affected the entire Sacramento Hill stock, it is impossible to secure any of the porphyry in its original condition for comparison with the altered rock. The intrusive mass is impregnated with pyrite throughout. This mineral is very abundant in the vicinity of the contact with the limestone, but, as the dump of the Copper King mine shows, may be nearly or quite as abundant in the areal center of the stock. In addition to the introduction of pyrite, the alteration involves a general recrystallization which has in some cases obliterated the original porphyritic texture, in others left it still faintly recognizable. The microscope shows that the quartz phenocrysts have recrystallized as quartz aggregates, and that the feldspars and groundmass have become areas of sericite, quartz, and pyrite, with occasionally a little epidote, chlorite, zircon, and rutile. Kaolin also occurs in microscopic aggregates with the sericite, and may be in part a product of the metasomatic alteration. Upon exposure to the weather the pyrite in the metamorphosed porphyry oxydizes, and the sericite, probably through the action of the sulphuric acid so formed, becomes converted into kaolin. The porphyry as exposed on the surface is thus a siliceous mass containing nests of kaolin, which sometimes weather out, leaving empty cavities. It is surficially stained and streaked with oxide of iron, but is generally nearly white on freshly fractured surfaces.

The alteration of the Pinal schist in the vicinity of the Sacramento Hill stock has resulted in a rock which the closest examination does not always serve to distinguish with certainty from the altered porphyry. Like the latter, it is composed chiefly of pyrite, quartz, and sericite. The schistose structure, however, is usually distinguishable and the rock does not exhibit the characteristic spotted appearance which is often all that remains of the original porphyritic texture of the intrusive rock. The alteration gradually fades out away from the porphyry and at a distance of about a quarter of a mile the schists exhibit their normal character.

How were the pyritic ores formed? and whence was their material derived? Not only are these questions of absorbing scientific interest, but in a region where ore bodies lie deeply buried, and where some knowledge of the relation of the ores to geological structure may prevent the costly failures of blind prospecting, they assume direct practical importance. Unfortunately they can not be fully answered. But even partial answers may be of service, if reasonable inductions from observed facts be kept distinct from more or less speculative hypotheses.

The miner who lays stress upon his practical knowledge often condemns what he terms theory, including under that name ideas as different as truth and falsehood. He is led by theory as he drifts on a narrow seam toward the expected ore body, but he knows it not. He calls by that name, and in his unguarded hours all too willingly follows, a gay will-o'-the-wisp whose wanton flight ignores the path of fact. No human eye has watched the slow deposition of ores in the rocks. Reason alone can in part reconstruct the process from the carefully collected fragments of fact. It is the legitimate province of the scientific imagination to piece together these fragments into a consistent if imperfect structure. Many of them are troublesome in the fitting, and it would be easier far to throw them aside and build with fresh material. But the unfinished edifice whose missing parts serve to suggest and direct further search for truth is of value, while the apparently completed structure may be entirely the "baseless fabric of a vision."

The spatial relation of the ores to the porphyry mass of Sacramento Hill is such as to justify the conclusion that there is some genetic connection between them and the intrusive stock. The fact that the pyrite was formed at substantially the same time as amphibole, pyroxene, garnet, and vesuvianite—minerals characteristic of contact zones in limestones—is not only additional evidence of such a general connection, but indicates to some extent its specific character.

Not all of the masses in the quadrangle resulting from the intrusion and solidification of granitic magma are associated with important mineralization. The granitic stock of Juniper Flat is connected with no conspicuous mineralization of the inclosing schists, and is not itself mineralized. It is thus suggested that extensive mineralization may be dependent upon the juxtaposition of porphyry and a particular rock—limestone. But there are many porphyry dikes in the quadrangle that cut limestones without producing mineralization. These, however, are relatively small masses, and this fact leads to the further tentative suggestion that extensive mineralization competent for the production of workable ore bodies requires the fortunate conjunction of an intrusive mass of considerable size with limestones. These conditions are fulfilled in the vicinity of Sacramento Hill and nowhere else in the quadrangle. Here, too, occur the only important bodies of copper ore thus far discovered in the quadrangle. It might, therefore, possibly be concluded on this rather slender evidence that the conditions named were all that were necesary to produce the ores. But the case is not quite so simple.

Small bodies of copper ore occur at several points in the quadrangle in situations that show no discoverable simple connection with granite-porphyry. Fissuring in the limestones is frequently, although not invariably, accompanied by mineralization even when no porphyry is near. At the Whitetail mine, for example, ore has been extracted from the vicinity of a bedding fault between the Abrigo and Martin limestones. At the Wade Hampton claim, northwest of Don Luis, near United States Land Monument No. 3, ore has been taken from a hanging wall of Abrigo limestone faulted against Bolsa quartzite. Hence it is concluded that fissures in the limestone are factors in the mineralization apart from any direct connection with intrusive masses.

The general relation of the great ore bodies of the Copper Queen mine to the Dividend and Czar faults has already been pointed out. There can be no doubt but that the presence of these, and probably also of other less prominent fissures, constitutes an additional important factor in determining the initial mineralization from which subsequent processes were to produce the workable bodies of ore that now lie about the southwest side of Sacramento Hill.

The conclusion that the original mineralization in the vicinity of Sacramento Hill was the result of extensive metasomatic metamorphism in some way due to the coincident occurrence of limestones, a considerable intrusive mass of porphyry, and prominent fissures extending to great depth, is firmly based upon observed facts. In the further search for the source of the ores, and for light upon the actual processes by which they were introduced into the rocks where they are now found, we enter upon somewhat speculative ground.

The objection to regarding the metamorphism and mineralization as an ordinary case of contact action about an intrusive stock is twofold. The stock itself has been thoroughly altered and mineralized and could not have originally supplied from its own mass the large quantities of magnesia and sulphide of iron and other constituents introduced into the adjacent limestones. The greater part at least of the mineralization must have taken place after the porphyry had solidified. It is probable, although perhaps not in this case susceptible of definite proof, that the mineralization and metamorphism were effected by heated aqueous solutions.

It is pertinent at this point to recall the general geological structure of the rocks in which the ores occur. The limestones have already been described as forming part of a syncline. They dip toward the Dividend fault and toward the porphyry mass of Sacramento Hill. The inclination of the beds is such that any waters sinking into the limestones within a radius of 7,000 or 8,000 feet from the summit of Sacramento Hill and within an arc of nearly 90°, measured southwesterly from the Dividend fault, would, if they moved along the concave surfaces of the various beds, find their way downward to the Dividend fault and to the contact with the porphyry stock. Water moving along the lower beds, say at the base of the Abrigo limestone, would reach the Dividend fault and the porphyry at a depth of over 1,000 feet below the deepest ore bodies now known. It would then tend either to rise, by hydrostatic pressure along the Dividend fault and the contact with the porphyry, or it would tend to sink deeper into the earth along these structures. Whether it would follow either or both of these courses would depend upon the adjustment of a number of factors, such as hydrostatic head, volume of flow, relative size of channels, and difference in temperature. If the porphyry mass still retained a part of its original heat of intrusion, the waters would have some of this heat imparted to them and tend to rise. If in addition, solutions, presumably heated, were rising from depths below the bottom of the Paleozoic syncline through the Dividend fault and along the contact of the porphyry and limestone, then there would be a mingling of solutions and localized chemical activity in the vicinity of the fault and the porphyry.

It is accordingly advanced as a tentative hypothesis that the deposition of the cupriferous pyrite and the metamorphism of the limestone, schist, and porphyry was affected by the mingling of solutions from different sources in the vicinity of the Dividend fault and of the Sacramento Hill porphyry. The principal function of the porphyry is believed to have consisted in supplying heat to such solutions as rose from great depth and in thus determining the locus of the chemical activity that resulted in the deposition of the ore.

The source of the ore materials is not known. They may have risen through the Dividend fault from depths far below the bottom of the syncline of Paleozoic rocks. They may have been collected by solutions moving through one or more of the Paleozoic limestones on their way down to the locus of deposition. Lastly, they may have been derived from both sources.

The hypothesis that the ore constitutents rose from unknown depths—from sources within or below the fundamental Pinal schist—has for its support the known occurrence in the veins of the Modern and other prospects of small quantities of ore in the schists and the general evidence from other mining regions for the ascension of similar ores from great depths through fissures.

The hypothesis that the ore constituents were originally deposited on the sea bottom with one or more of the Paleozoic limestone formations, and were concentrated by underground waters from a condition of minute dissemination into large masses, has for its support the conclusions of Van Hise and Bain in regard to the lead and zinc deposits of the Ozark region,[a] and the known presence of iron, copper, and zinc in determinable quantities in certain invertebrate marine organisms.[b]

In the Bisbee quadrangle, as in the Ozark region, ore deposition has taken place chiefly in relatively pure Carboniferous limestone underlain by less pure limestones containing interbedded shales and known to be in part magnesian. In both regions there is reason to believe that underground waters, after moving for considerable distances through the lower limestones, have been conducted up through fissures to the overlying beds composed of nearly pure calcium carbonate. In both regions the ore has been deposited where the structure leads to the supposition that there was a mingling of solutions, differing in temperature and diverse in mineral content. In both regions the depositing solutions carried magnesia. In the Ozark deposits this magnesia effected a dolomitization of the Carboniferous limestone. At Bisbee, under the influence of heat supplied by the intrusive stock and an adequate supply of silica, the magnesia entered into combination with the silica to form metamorphic silicates. The relative proportions of the different sulphides are widely different in the two regions, but all of the sulphides possibly ascribable to the original mineralization in the Bisbee quadrangle occur also in the Ozark ores. There is, in short, no known fact that invalidates the hypothesis that the Bisbee ores derive their source from the limestones themselves. There is perhaps a slight preponderance of local evidence for the view that at least a part of the ore constituents were so derived. The direct evidence on this question, however, is so meager, and its slight weight so easily shifted from one side to the other by whatever bias may have been given to the observer's trend of thought by familiarity with other fields of ore deposition, that an expression of choice between the two general hypotheses can have little real value. Both are, in the nature of the case, speculative.

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[a] Preliminary report on the lead and zinc deposits of the Ozark region, by H. F. Bain, with an introduction by C. R. Van Hise, and chapters on the physiography and geology by George I. Adams: Twenty-second Ann. Rept. U. S. Geol. Survey, pt. 2, 1902, pp. 59-60, 203-215.

[b] Bradley, H. C., The occurrence of zinc in certain invertebrates: Science, vol. 19, 1904, pp. 196-197.

OXIDATION AND SECONDARY CONCENTRATION.

Few if any of the ore bodies now known and worked in the Bisbee quadrangle were formed directly by the original mineralization discussed in the preceding section. That process resulted, so far as underground workings show, mainly in the formation of bodies of cupriferous pyrite passing peripherally into metamorphosed and pyritized limestone. These bodies contained originally too little copper to be classed as ore, as that term is defined by present economic conditions of working. Further concentration was necessary, and the profitable ores of to-day have been derived from these pyritic masses by secondary processes involving general oxidation, with all its attendant chemical phenomena, transfer of material, and the local enrichment of certain portions of the sulphide masses.

This general conclusion with reference to the Bisbee ore bodies is not novel, but was reached a few years ago by Mr. Douglas. He says:

"With regard to the ledge-matter and the oxidized ore my own opinion is that they are the products of replacement and local concentration; that where there is ledge-matter to-day there was originally more or less compact iron pyrites carrying a small percentage of copper, and that during the process of alteration not only did ferruginous solutions of alumina replace the pyrite, but the copper, by a process of segregation akin to crystallization, was concentrated and collected into areas of limited size, thus constituting the comparatively small bodies of oxidized ores which are disseminated irregularly through the very large masses of ledge-matter."[a]

Again he writes, after describing the so-called ledge-matter:

"This envelope gives place to a black sulphuretted ore of very diverse composition.[b] At places it runs very high in copper, as indicated by the erubescite streaks under the pick. At other places, though the same in appearance, it consists merely of an oxysulphide of iron. On the whole, however, this second shell contains the most profitable of the sulphuretted ores. It is not of uniform thickness any more than of uniform composition, but thick enough to permit large stopes to be opened upon it. The kernel of the mass is very much leaner in copper than the shell and consists of compact iron pyrites averaging about 45 per cent sulphur."[c]

The oxidation of pyritic ore bodies constitutes a chemical and physical problem of great complexity, and offers a broad field for extensive investigation. The process has frequently been outlined in the literature of ore deposits,[d] but the entire subject is still greatly in need of masterly treatment from the chemical and experimental side. The oxidation of the single mineral pyrite, under the simpler of the

[a] Douglas, J., The Copper Queen mine, Arizona: Trans. Am. Inst. Min. Eng., vol. 29, 1900, p. 534.

[b] Now known to be cuprous sulphide or chalcocite in part.—F. L. R.

[c] Douglas, J., loc. cit., p. 533.

[d] See Emmons, S. F., The chemistry of gossan: Eng. and Min. Jour., vol. 54, 1892, pp. 582–583. Penrose, R. A. F., The superficial alteration of ore deposits: Jour. Geol., vol. 2, 1894, pp. 288–317. Weed, W. H., Enrichment of mineral veins by later metallic sulphides: Bull. Geol. Soc. America, vol. 11, 1900, pp. 179–206.

many conditions possible in nature, has not yet been carefully investigated. It is evident that such studies are a necessary preliminary to the definite statement of a process which commonly involves the oxidation, not of one but of several sulphides, is associated with extensive alterations in the gangue minerals, and is effected through a multitude of chemical reactions, reversible in part, and taking place under varying conditions of temperature, concentration, and volume of the natural solutions concerned.

No attempt will be made in the present paper to do more than briefly and tentatively outline what seems to be the general nature of the process, and discuss a few phases of the general problem that are particularly suggested by the occurrence of the Bisbee ores.

A mass of pyrite exposed to oxidation by atmospheric agencies is probably gradually changed to ferrous sulphate and this in turn to the ferric salt. If the sulphur in the pyrite is completely oxidized, some free sulphuric acid is also formed.[a] Such copper as may be originally present in the pyrite, probably in the form of the chalcopyrite molecule, may be supposed to undergo a similar alteration to cuprous and cupric sulphates. These comparatively simple conditions, while they may have obtained at some early period in the geological history of most ore bodies, are not those under which the ore masses actually studied have been and are now being altered. The pyrite as a rule is not exposed at the surface, but is overlain or enveloped by the products of earlier chemical activity which, while of an oxidizing character in the main, has probably involved reduction as a minor phenomenon. These products the oxidizing solutions must penetrate before they can directly attack the fresh pyrite. Furthermore, in an arid region, such as Bisbee, where oxidation, instead of extending uniformly down to a ground-water level at a moderate distance below the surface, has penetrated very irregularly to depths of 1,000 feet or more, leaving residual masses of unoxidized sulphides at higher levels, the solutions moving downward to react upon any given pyritic mass may have been modified not only by passage through the generally oxidized zone and through secondary sulphides, but through original sulphides as well.

The ferric and cupric sulphates formed by direct oxidation of the cupriferous pyrite are, as Van Hise, Emmons, Weed, and others have clearly shown, themselves active agents in furthering the general change.

The ferric sulphate may attack fresh pyrite, oxidizing the latter, and giving rise to sulphuric acid and free sulphur. This sulphur, while difficult of direct oxidation, may, like other similarly inert substances, be oxidized in the presence of other compounds undergoing oxidation, and so form free sulphuric acid. It is

[a] Brauns, Chemische Mineralogie, Leipzig, 1896, p. 368.

probable that ferric sulphate may also oxidize the copper contained in any chalcopyrite present in the original pyrite into cupric sulphate, which can in turn elsewhere react with sulphides.

Ferrous sulphate, owing to its capacity for further oxidation, may, if formed, act as a reducing agent in certain portions of the ore deposit and precipitate cuprous oxide (cuprite) or native copper from solutions of copper salts.[a] It is perhaps in this way that some of the cuprite and native copper in the Bisbee mines has been formed. The usual occurrence of these two minerals near the sulphides in the deeper portions of the zone of oxidation is further suggestive of this explanation. Cuprite, however, may form directly from chalcocite by the oxidation and removal of all of the sulphur and part of the copper as cupric sulphate.[b] Native copper also, as shown experimentally by Dr. H. N. Stokes,[c] may result from certain easily reversible reactions between cupric sulphate on the one hand and cuprous sulphide (chalcocite), iron disulphide (pyrite), ferrous sulphate, or ferrous silicates on the other. The essential feature of these reactions is the reduction of cupric sulphate to the unstable cuprous sulphate, which decomposes, on cooling, to copper and cupric sulphate. These reactions require neutral or slightly acid solutions, such as probably obtained in most parts of the oxidizing ore bodies.

The cupric sulphate resulting from the oxidation of cupriferous pyrite also reacts upon fresh pyrite, and is reduced to cuprous sulphide (chalcocite) in accordance with the simplified reaction

$$5FeS_2+14CuSO_4+12H_2O=7Cu_2S+5FeSO_4+9H_2SO_4+3H_2SO_4.$$ [d]

The conversion of cupriferous pyrite to chalcocite by solutions of cupric sulphate has recently been experimentally confirmed by H. V. Winchell,[e] who obtained a coating of chalcocite upon grains of pyrite similar to that characteristic of some of the Butte ores, and described in this report as a common feature of the Bisbee ore bodies also. As Winchell points out, hematite does not form where the reacting solutions are acid, and is absent at Butte. The formation of chalcocite at Bisbee appears likewise to have been effected by acid solutions and without the development of ferric oxide as a by-product.

In the presence of solutions containing carbon dioxide or bicarbonates of the alkaline earths, or by direct reaction with the calcium carbonate of the gangue, the sulphates of iron and copper may be converted into carbonates, those of copper being fairly stable, while the ferrous carbonate readily undergoes a further oxidation and hydration into limonite. In this way the close association of limonite with the

[a] Brauns, Chemische Mineralogie, Leipzig, 1896, p. 369.
[b] Bischof, Lehrbuch der chemischen und physikalischen Geologie, 2d ed., Bonn, 1866, vol. 3, p. 689.
[c] Unpublished manuscript.
[d] Stokes, unpublished manuscript. The 3 molecules of H_2SO_4 come from oxidation of the sulphur in the pyrite.
[e] Winchell, H. V., The synthesis of chalcocite and its genesis at Butte: Eng. and Min. Jour., vol. 75, 1903, p. 782.

carbonates of copper in certain portions of the oxidized zone is in part explained.[a] The ferric sulphate may also pass into basic sulphate and then into limonite,[b] while the cupric sulphate may be transformed to the basic sulphate brochantite. Becquerel[c] succeeded in producing small crystals of this mineral by keeping a fragment of porous limestone for several months in contact with a saturated solution of cupric sulphate. By the addition of sodium bicarbonate to the solution the brochantite was transformed to malachite ("cuivre carbonaté bibasique"). Brochantite is probably of common occurrence as a transitional step in the formation of malachite from the sulphate, although it does not occur in great quantity in the Bisbee mines.

The sulphuric acid which forms under certain conditions of oxidation may play a varied part in the further alteration of the ore. It may in zones of such deep and irregular oxidation as those at Bisbee come in contact with cuprite and form cupric sulphate and native copper.[d] Or it may form various metallic sulphates, or gypsum.

The abundance of kaolin or clay in connection with the oxidized limonitic ores has been dwelt upon by Mr. Douglas[e] who concludes that the alumina sometimes forming as much as 17 per cent of the "ledge matter" has been derived from the neighboring porphyry. While kaolin has undoubtedly been produced in the porphyry through the action of sulphuric acid formed from the oxidation of pyrite, upon feldspar and sericite, yet it does not appear that all, or even most of the kaolin in the oxidized ores and "ledge matter," can be traced to this source. Like limonite it is one of the common products of the oxidation of the mineralized limestones, and is clearly a local concentration of material, which, before the oxidation of the pyrite, was more widely distributed through the rocks. If the limestones in connection with which the ores occur were noticeably shaly and argillaceous the abundance of kaolin might easily be accounted for by the action of sulphuric acid upon such beds, the acid coming, of course, from the oxidizing pyrite. The alumina would go into solution as a sulphate, and might then be transported and redeposited as kaolinite in the presence of solutions containing silica. The analysis of mineralized limestone given on page 148 shows less than 1 per cent of alumina, and the Escabrosa limestone on the whole contains very little argillaceous impurity. In spite of these facts, however, the occurrence of the clays is such as to strongly suggest that the alumina contained in them was originally a constituent of the limestones. Its concentration in the porous limonitic "ledge matter" has probably been effected by mechanical as well as by chemical agencies.

[a] Bischof, G., Lehrbuch der chemischen und physikalischen Geologie, 2d ed., Bonn, 1866, vol. 3, p. 690.

[b] Penrose, The superficial alteration of ore deposits: Jour. Geol., vol. 2, 1894, p. 293. Also Brauns, Chemische Mineralogie, Leipzig, 1896, p. 368.

[c] Comptes rendus des séances de l'Académie des Sciences, Paris, vol. 34, 1852, pp. 577–578.

[d] Bischof, loc. cit., p. 692.

[e] Douglas, J., The Copper Queen mine, Arizona: Trans. Am. Inst. Min. Eng., vol. 29, 1900.

The conclusion that large quantities of gypsum must have been produced by the reaction of the metallic sulphate solutions with the partly calcareous gangue of the original pyritic ore seems inevitable. But no gypsum has been seen in any of the Bisbee mines. Owing to its solubility and to its chemical stability which prevents it from entering into less soluble combinations, it has probably been removed by percolating waters as fast as formed. A large amount of sulphur has been eliminated from the ore bodies by their partial oxidation, and this removal seems to be most reasonably accounted for by the supposition that it has been carried away in the form of gypsum. Mr. Douglas[a] calls attention to the fact that in regions yet more arid than Bisbee gypsum accompanies the oxidized ores in limestone and cites the Boleo mines in Lower California. Under certain conditions, however, gypsum, resulting from the attack of sulphate solutions from oxidizing pyrite upon limestone, may not be entirely removed even in comparatively humid climates. This is shown by the occurrence of gypsum having this origin in the Logan mine at Rico, Colo.[b]

The most marked physical effect of the oxidation of the ore bodies has been a great increase in the porosity of the masses acted upon. This, by enabling solutions to percolate easily through the partly oxidized zone, has greatly facilitated the migration and concentration of the desulphurized ores and their segregation in workable masses from the bulk of the limonitic and clayey "ledge matter."

The oxidized material is not only more porous but much softer and more plastic than the original mineralized limestone, and hence greatly weakens by its presence the rocky structure in which it occurs. The overlying limestones, no longer adequately supported, fissure and settle down upon the soft plastic ore and gangue. The access of solutions is thus still more facilitated, and the processes of oxidation and solution proceed so much the faster. That part of the surface which is underlain by oxidizing ore bodies is thus rendered less resistant to erosion, other things being equal, than the surrounding country. This accounts for the frequent concurrence, pointed out by Mr. Douglas,[c] of ore bodies with relatively low ground. It by no means follows, however, that because most of the known large ore bodies near Bisbee have occurred beneath topographic depressions, all low ground in the vicinity is underlain by ore, or that no ore occurs except under such hollows.

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[a] Douglas, J., The Copper Queen mine, Arizona: Trans. Am. Inst. Min. Eng., vol. 29, 1900.

[b] Ransome, F. L., The ore deposits of the Rico Mountains, Colorado: Twenty-second Ann. Rept. U. S. Geol. Survey, pt. 2, 1902, pp. 391-392.

[c] Douglas, loc. cit., p. 537.

AGE OF THE ORES.

All of the ore of the Bisbee quadrangle is post-Pennsylvanian, since it is later than the granite-porphyry which cuts the Naco limestone. If, as there is reason to suppose, the heat of the intruded mass of porphyry forming Sacramento Hill was a factor in the original mineralization, then the latter was probably initiated soon after the close of the Pennsylvanian epoch, perhaps in Permian or Triassic time. It may have continued with diminishing intensity into the Tertiary. That there has also been some post-Comanche (i. e., late Cretaceous or Tertiary) mineralization is shown by the occurrence of small mineralized veins in the Glance conglomerate near Juniper Flat and south of Gold Hill, by the introduction of chalcocite into the same conglomerate in the vicinity of the Glance mine, and by the occurrence of a gold ore in the Morita formation at the Easter Sunday mine.

The secondary processes connected with oxidation, which have transformed the low-grade pyritic masses near Bisbee into rich ore bodies, may have begun in Tertiary, or even Cretaceous, time and are still in progress.

VALUE OF THE ORES.

The percentage of copper in the ore as mined is to a very large extent subject to direct control by those who direct mining operations. With ample facilities for extensive and economical operation, the grade of ore that can not be handled sinks lower and lower. Thus, while a large mine may contain ore as rich as it did when first opened, the average tenor of the ore now worked is usually very much lower.

This almost self-evident fact is well illustrated by the Copper Queen mine. The ore first worked, early in the eighties, averaged 23 per cent of copper. As the mine developed, as methods of treatment improved, and as transportation became less costly, the tenor of the ore was gradually reduced until the average at present is about 7 per cent, with a range from 4 to 20 per cent. The minimum grade, however, is only mined when occurring with better ore, or when particularly desirable for fluxing purposes.

The average tenor of the ore from the Calumet and Arizona mine in 1902 was about 10 per cent of copper, according to Mr. I. L. Merrill. But the stopes were then recently opened and contained some remarkably good, oxidized ore. As development progresses it will probably be found economical to reduce the average grade of the ore.

The gold ore of the Easter Sunday mine is reported to run about $30 per ton when sorted. But as the small quantity of ore thus far produced has been accepted by the Copper Queen smelter upon the condition that the silica shall not fall below 84 per cent, the actual tenor that the ore would show if mined and treated directly as a gold ore is unknown.

FUTURE OF THE DISTRICT.

Although more or less mineralization occurs at many points in the Mule Mountains, there is little to indicate that any deposits of copper ore will ever be found in the Bisbee quadrangle approaching in importance those already known and those probably awaiting discovery in the faulted limestone syncline about Sacramento Hill. For over twenty years the Copper Queen mine has produced an average of more than 16,000,000 pounds of copper annually. Recently the Calumet and Arizona Company has begun energetic operations in ground almost surrounded by the property of the Copper Queen. Not only is there sufficient ore known in these mines to keep them in operation for many years to come, but there is no clear evidence that the bottom of the ore-bearing ground has been reached in any of these extensive workings. Moreover, the statement may be ventured that the specter of the "lower lime" has hitherto had an undue influence in restricting prospecting to nearly horizontal planes. There is certainly a reasonable hope of finding ore bodies in the Martin and Abrigo limestones beneath the masses that have been so profitably worked in the overlying Carboniferous beds. The occurrence of small bunches of ore in the Abrigo limestone at the Whitetail and Wade Hampton claims shows that ore deposition may take place in these lower beds. It may be that, owing to their greater depth, such ore bodies, if discovered, will be found to consist of low-grade cupriferous pyrite, unenriched by the generally descending solutions that have contributed so largely to the value of the known masses. This, however, is a point that prospecting alone can determine. It would seem that near the Dividend fault the conditions are favorable for the continuance of enriching processes to depths greater than those now reached in this part of the underground workings.

But more than this, it may be pointed out that less than half of the semicircular mineralized zone about the porphyry mass of Sacramento Hill has been explored at all. Ore was first discovered at the surface on Queen Hill at the northwest end of the zone. From this discovery developments have been pushed by underground exploration to the south, often with little or no surface indication of ore. There still remains, however, an extensive area of unknown but promising ground, lying just south of Sacramento Hill and extending eastward toward the southeastern continuation of the Dividend fault—an area which is here concealed by the Glance conglomerate. This is the eastern half of the semicircular mineralized girdle about the intrusive mass of porphyry. While structurally the beds south of Sacramento Hill form a less favorable nook for the deposition and concentration of ores than that inclosed between the Czar and Dividend faults and the northern contact of the porphyry, yet their attitude with reference to the intrusive stock, and to the continuation of the Dividend fault down Mule Gulch, is distinctly favorably to mineralization. The developments in the Spray and Calumet and Arizona mines have shown that profitable ore bodies are by no means confined to the structural pocket in the vicinity of the Czar and Holbrook shafts. There is no known reason why they should not yet be found skirting the southern and southwestern contact of the porphyry, which, as recent explorations with diamond drills show, extends from the ice factory in a southeast direction for a distance of at least 2,000 feet under the Glance conglomerate.

It is true that the easterly dip of the beds southwest of the porphyry stock carries the Escabrosa limestone to a much greater depth near Mule Gulch than it reaches in any of the present workings. It is probable that this depth, a short distance east of the Gardner shaft, may be so great as to preclude the occurrence within the Escabrosa limestone of any but original, unenriched pyritic ore, which may or may not be workable. But judging from surface indications there has been considerable mineralization of the Naco limestone south of Sacramento Hill, and there is nothing improbable in the occurrence of high-grade ores in this limestone at stratigraphically higher horizons than those in which ore bodies have hitherto been found. The exploration of this ground calls for no greater outlay or boldness than is already displayed in other parts of the district with less reasonable hope of reward.

The outlook for finding profitable ore bodies within the main porphyry stock of Sacramento Hill is not regarded as particularly promising. As the dump of the Copper King shaft shows, this rock may be very heavily impregnated with pyrite. But the mineralization seems to tend more to abundant dissemination than to the formation of solid sulphide masses. Even if the latter occur, it is doubtful whether they would be found sufficiently cupriferous to constitute ore. Moreover, the chemical and physical character of the porphyry renders it very much less favorable than the limestones to the deep oxidization and secondary concentration that has played so important a part in the genesis of the known ore bodies. Very little exploration of the porphyry has been made, however, and work in this direction can not be condemned as altogether vain.

Scattered over the quadrangle are several outlying prospects—some following up surface indications of mineralization, others honestly testing, at considerable outlay of capital, various geological hypotheses. No attempt will here be made to measure out to these enterprises the probable success or failure likely to be their respective portions. It is hoped that the general conclusions reached in this respect as to the geological relations of the ore bodies may prove to be of value in affording the mining engineer a general basis of fact from which he may intelligently plan individual operations.

In conclusion, it may be said that Bisbee is less likely to suffer from a lack of ore than from too rapid exhaustion of those high-grade oxidized ores which are necessary for the economical smelting, by present processes, of the low-grade sulphides.

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PUBLICATIONS OF UNITED STATES GEOLOGICAL SURVEY.

[Professional Paper No. 21.]

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