Ore Deposits of the Kokomo-Tenmile District, Colorado

By M. H. BERGENDAHL *and* A. H. KOSCHMANN

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By M. H. BERGENDAHL and A. H. KOSCHMANN

ABSTRACT

The Kokomo-Tenmile district is an irregularly shaped area of about 45 square miles, located in parts of Summit, Eagle, and Lake Counties, in the mountainous part of central Colorado. Excluding the molybdenum mine at Climax, which is not described in this report, the district is now deserted, but it has produced silver, lead, zinc, copper, and gold ores valued at least at $25,942,000. Lead and silver were the chief commodities before 1900, but thereafter, zinc was the most valuable metal produced from the district. Through 1965, Climax has produced more than 1 billion pounds of molybdenum and substantial amounts of tungsten.

The rocks exposed in the Kokomo-Tenmile district range in age from Precambrian to Quaternary. The Precambrian rocks consist of a sequence of tightly folded metasedimentary rocks at least 22,000 feet thick and intrusive bodies of biotite-muscovite quartz monzonite, gneissic granite, pegmatite, aplite, and alaskite. The metasedimentary rocks are of the sillimanite-almandine subfacies of regional metamorphism and comprise four mappable units—granulite, banded gneiss, migmatite, and pink migmatite.

The Paleozoic rocks are predominantly sedimentary units that were deposited in deltaic and shallow marine environments. The Peerless Formation of Cambrian age, the Harding Quartzite of Ordovician age, the Chaffee Formation of Devonian age, and the Leadville Dolomite of Mississippian age are reported as an undifferentiated sequence, because of their erratic local occurrences as fragmentary, disconformable, and faulted patches.

The Minturn Formation of Pennsylvanian age and the Maroon Formation of Pennsylvanian and Permian age have a combined thickness of about 7,000 feet in the district. These formations unconformably overlie the Precambrian basement and the scattered areas of lower Paleozioc sedimentary rocks. The pre-Pennsylvanian erosion surface probably had a relief of as much as 5,000 feet. A few lenses of rhyolite-tuff, breccia, and other volcanic rocks occur locally in the Minturn and Maroon sequence and indicate volcanism during late Paleozoic time.

The Tertiary rocks are all of igneous origin and comprise several varieties of sills, dikes, and stocklike masses dominantly of quartz monzonitic composition and a large mass of rhyolite that underlies the southwestern part of the district. Units of Quaternary age are unconsolidated deposits of glaciofluvial origin, a landslide mass, and talus accumulations along the steep-walled cirques and gulches.

The rocks of the district show the effects of severe and repeated deformation highlighted by several periods of plastic deformation during Precambrian regional metamorphism; broad warping accompanied by locally intense folding and faulting during Paleozoic time; and uplift, folding, large-scale intrusions, and widespread faulting during post-Paleozoic, probably early Tertiary time. The conspicuous high-angle Mosquito fault, which trends N. 5°–25° E., has been traced into the southwestern part of the district; its vertical displacement is roughly 8,000 feet. Some faults in the western part of the district trend N. 45°–75° E.; a few have northwest trends.

The tightly folded Precambrian rocks are overlain by sedimentary rocks that were less severely warped into a northwest-trending monocline upon which was superimposed the northwest-plunging Kokomo syncline.

Ore deposits are of three types: massive sulfide replacement deposits, veins, and high-temperature deposits. The replacement deposits were the most important economically and occur in the Robinson, White Quail, and Jacque Mountain Limestone Members of the Minturn Formation. The typical replacement deposits consist of large masses of sufides, ranging in length from 100 to more than 2,000 feet, in thickness from a few inches to 30 feet, that are distributed along both sides of faults and fissures where they intersect the limestone beds. The principal sulfide minerals are pyrite, pyrrhotite, marcasite, sphalerite, galena, and chalcopyrite; the gangue minerals are fine-grained quartz and phases in the calcite-rhodochrosite-siderite and dolomite-ankerite-kutnahorite series. Banding in some of the ore is possibly inherited from original layering in the replaced limestone. Near faults the ore-bearing limestones are brecciated, and the fragments are cemented with fine-grained sulfides; some vugs are lined with coarsely crystalline sulfides. Oxidized replacement ore, mined in the early days, contained cerussite, anglesite, manganese and iron oxides, smithsonite, and small amounts of azurite, malachite, chrysocolla, gold, and silver. The vein deposits are of little economic importance and are widely distributed as fissure fillings in both sedimentary and metamorphic rocks. The veins are of two types: carbonate veins and pyrite-sphalerite-galena veins. The high-temperature deposits are characterized by magnetite, garnet, and molybdenite and occur as veins, disseminations, and replacement bodies.

The ore deposits are distributed in a pattern that coincides in a general way with zones of garnet and epidote alteration. The high-temperature deposits are associated with the garnet and epidote zones, and the sulfide replacements and veins are peripheral to these zones.

Polished sections of ore specimens indicate that the deposits were formed during three stages, which were separated by periods of fracturing. Pyrrhotite, coarse-grained pyrite, magnetite, and molybdenite were formed in the early stage; sphalerite was deposited during the intermediate one; and galena, chalcopyrite, fine-grained pyrite, and gangue minerals characterize the latest stage.

The rough zoning and the close association of the deposits with intrusives indicate that the deposits were formed from hydrothermal solutions that emanated from an igneous source. For such solutions to have moved upward through fractures, they must have been submitted to pressures greater than 600

bars and to temperatures in excess of 100°C—the respective approximate pressure-temperature values caused by the sedimentary load and the geothermal gradient at the beginning of ore emplacement. The hot rising solutions first deposited magnetite, molybdenite, and hematite along fractures. Later, and farther from the igneous source and at concomitant lower temperatures and pressures, the pyrite, pyrrhotite, sphalerite, and galena precipitated from these solutions along fractures and also replaced limestone beds.

It is doubtful that any further prospecting on the surface will reveal additional significant ore deposits in the district; however, exploration of the Robinson and White Quail Limestone Members at depth may disclose new deposits downdip from those already mined or may delineate extensions of known ore bodies that terminate against faults.

INTRODUCTION

LOCATION AND ACCESSIBILITY

The Kokomo-Tenmile district is located in the heart of the rugged and mountainous country of central Colorado and comprises a somewhat irregular and elongate area of about 45 square miles enclosed within long 106°07′ and 106°14′ W. and lat 39°21′ and 39°31′ N., in parts of Summit, Eagle, and Lake Counties (fig. 1).

Physiographically, the area is just west of the Front Range, as defined by Lovering and Goddard (1950, p. 9), and most of it is just east of the Gore Range. The western part of the district, which includes Jacque Peak and Tucker and Copper Mountains, is part of the Gore Range. The Tenmile Range, part of which forms the east boundary of the map area, is the northward extension of the Mosquito Range; the division between the two ranges is generally considered to be the Continental Divide in the vicinity of Climax, which is near the great cirques that contain the headwaters of the South Platte, Arkansas, and Blue Rivers.

Within the boundaries of the map area are the mining camps of Kokomo and Climax. Breckenridge is about 4½ miles east of the map area, Dillon is about 9½ miles northeast of the area, and Leadville is 12 miles south. Denver is about 90 miles by highway to the east.

Despite the high altitudes and the remoteness from large population centers, the Kokomo-Tenmile area is well traversed by paved highways. U.S. Highway 6, one of the main routes across the Rocky Mountains, crosses the northern part of the area. Colorado Highway 91 crosses the western part from north to south, joining U.S. Highway 6 at Wheeler Junction and linking Kokomo and Climax with Leadville and the Arkansas Valley to the south. About 4 miles to the east of the map area, Colorado Highway 9 traverses part of the north-trending valley of the Blue River, connecting Brecken-

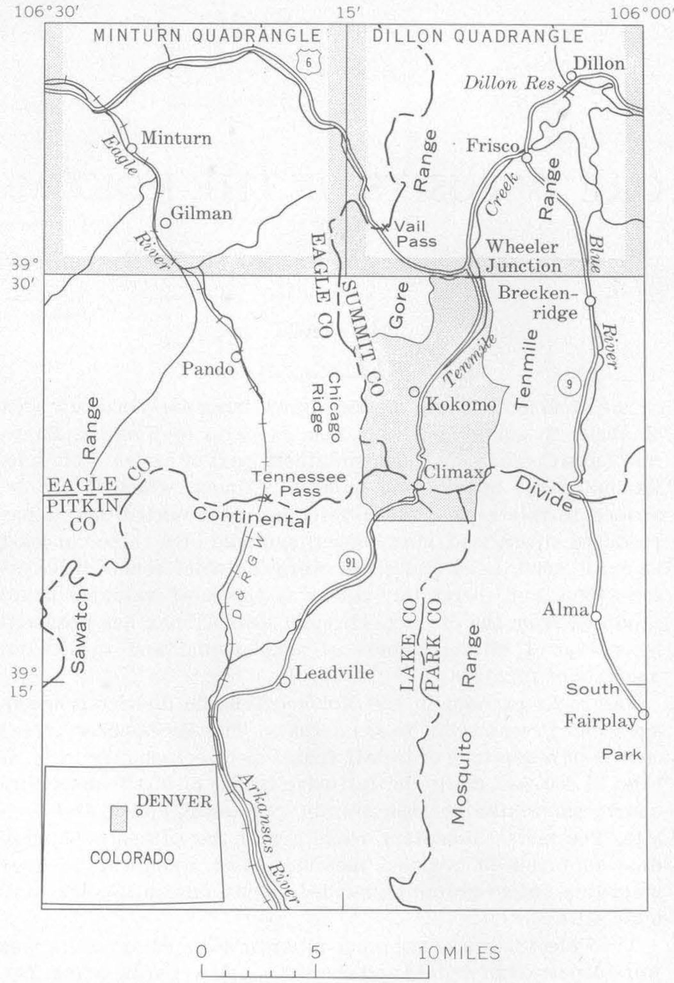

FIGURE 1.—Index map showing location of Kokomo-Tenmile district (patterned).

ridge with Dillon to the north and the towns of Alma and Fairplay to the south.

In the vicinity of Kokomo, roads lead up Searle and Kokomo Gulches, and jeep trails extend up Mayflower and Clinton Gulches on the east side of Tenmile Creek. Except for the Copper Mountain-Tucker Mountain area in the western part of the district, any part of the area is accessible by a 2- to 3-hour foot traverse.

A branch of the Colorado and Southern narrow-gage railroad formerly extended from Leadville to Climax, thence to Kokomo and down the valley of Tenmile Creek to Frisco, where it turned east, entering the valley of the Blue River at Dickey and joining the track that ran from Dillon up the Blue River valley to Breckenridge and on to Denver by way of South Park. In 1965 only the Colorado and Southern Railway was providing limited standard-gage freight service between Leadville and the Climax molybdenum mine; all other trackage has been abandoned.

CULTURE

It might seem paradoxical that two mining towns only 5 miles apart could contrast so markedly as do Climax and Kokomo. Climax, which is situated on the world's largest molybdenum deposit, is a bustling and thriving mine. Kokomo (fig. 2), however, is a weather-beaten shell, virtually deserted.

Most of the Kokomo-Tenmile area is included within the Arapaho National Forest, and a limited amount of lumbering is permitted at times. During the summer months, sheep are brought in to feed on the lush alpine meadows above timberline, and occasionally a few cattle graze in the open areas at lower elevations. Mining has ceased in the area, except for the activity at Climax and sporadic small-scale lead and zinc production at Breckenridge.

RELIEF, PHYSICAL FEATURES, AND DRAINAGE

Altitudes in the district range from a low of about 9,695 feet at Wheeler Junction to a maximum of 13,957 feet on Pacific Peak, which is on the sawtoothed narrow spine that forms the crest of the Tenmile Range along the east boundary of the map area.

The Kokomo area is glaciated, but not uniformly so. The gulches near Kokomo that head in the Sheep Mountain–Jacque Peak–Tucker Mountain–Copper Mountain area did not contain glaciers, and this high country resembles an erosion surface of moderate relief, which contrasts sharply with the topography of the steep-walled cirques of Mayflower, Clinton, and Pacific Gulches and Humbug Creek in the Tenmile Range to the east. The main glacier of the Kokomo area was fed from these cirques and pushed down Tenmile Valley, overflowing into parts of Searle and Kokomo Gulches. The glaciation is evidenced by faceted spurs of Jacque Peak and Tucker and Copper Mountains that extend into Tenmile Valley and debris of Precambrian rocks in Searle Gulch, where no Precambrian rocks are exposed.

The area is drained mainly by the northward-flowing Tenmile Creek, which is on the Pacific side of the Continental Divide, and by the tributaries of the Arkansas and Eagle Rivers, the Arkansas being on the Atlantic side and the Eagle on the Pacific side of the Continental Divide. The Arkansas River heads in the large cirque southeast of Fremont Pass and flows west, turning abruptly south outside the map area. The Eagle River tributaries drain the west slope of the saddle between Chalk and Sheep Mountains in the southwestern part of the district. Tenmile Creek is fed by perennial snow-

FIGURE 2.—Town of Kokomo from the southeast. Jacque Peak in the background consists of red beds of the Maroon Formation, intercalated with sills of Elk Mountain Porphyry. Date of photograph, 1963.

fields in the gulches and cirques of the Tenmile Range and by the creeks of Kokomo, Searle, Tucker, and Copper Gulches entering it from the west.

CLIMATE

The Kokomo-Tenmile area is characterized by severe winters and pleasant, cool summers. Most of the precipitation, except for summer showers, falls in the form of snow. At Breckenridge, for example, the 20-year annual snowfall average to 1952 was 184.8 inches and at Dillon it was 117.6 inches (U.S. Dept. Commerce, Weather Bureau, 1953, p. 43). The average annual precipitation at these stations for the same period was 23.93 inches and 18.78 inches, respectively (U.S. Dept. Commerce, Weather Bureau, 1953, p. 5). During the summer most of the snow melts from the Tenmile Range by July, but at altitudes near 13,000 feet and above, small patches of snow persist in the deeper, north- and east-facing gullies and cirques, and a few snow cornices along the crest of the range outlast the warm weather. Severe thunderstorms occur almost daily during July and August, but these cease with the crisp September weather. Cloudless skies are predominant in September and much of October. Brief periods of stormy weather in these months may mantle the area with the first snow of the season and are precursors of the more violent storms to follow.

The average annual temperature for the 20-year period to the end of 1952 was 33.0°F at Dillon. The maximum for this same period was 85°F, and the minimum was −46°F (U.S. Dept. Commerce, Weather Bureau, 1953, p. 47, 50). Summer temperatures in the area are pleasant; sultry, hot days are unknown. Subzero readings are not uncommon in the winter, but periods representing these are of short duration.

FIELDWORK AND ACKNOWLEDGMENTS

The U.S. Geological Survey investigation of the Kokomo-Tenmile area leading to this report was first undertaken in 1936 by F. G. Wells and Joseph Lindner. The project was recessed from 1937 until 1942, when A. H. Koschmann resumed the geologic studies to provide information that might be useful to mine operators who were reopening many of the mines in response to the urgent need for base metals during World War II. Fieldwork was continued through 1950, during which time the area under investigation was expanded to include the entire Tenmile Range. For various periods during this interval Koschmann was joined by J. W. Odell, H. T. Schassberger, W. R. Griffitts, and D. F. Kent. Work was interrupted from 1951 to 1956 because of the assignment of Koschmann to other duties. Beginning in 1957 and continuing through 1960, Koschmann and Bergendahl, assisted by J. A. Randall in 1957 and by R. J. Lutton in 1958, finished the field investigations, but work was again disrupted by the assignment of these men to other duties. After Koschmann's death in 1962, Bergendahl was given the assignment of completing the final phase of the project.

Throughout the long history of the project, many local mining people, most of whose names are not known to the surviving author, contributed a wealth of information and numerous sketches, maps, and well data. To these individuals go my grateful thanks. Others who extended wholehearted cooperation are Walter Byron of Frisco, Colo., H. T. Schassberger, manager of Western Operations, AMAX Exploration Inc., and Stewart R. Wallace, formerly chief geologist, Climax Molybdenum Co.

Fieldwork by the authors was conducted in cooperation with the Colorado Metal Mining Fund Board, predecessor of the Colorado Mining Industrial Development Board.

PRODUCTION

The Kokomo-Tenmile district, excluding Climax, does not qualify as one of Colorado's major mining areas; nevertheless, the camp experienced the cyclic periods of prosperity and depression that characterized mining trends in many of the great mining districts of the West. A relatively small producer of silver in its early days, the district became more important for its production of zinc and lead, especially during World War II and the period immediately following it.

Annual production data are given in table 1 for the years 1905–65. (The molybdenum output of Climax is not included.) The district was inactive from 1957 to 1965. Before 1905, systematic records of production were not kept, and the only means of obtaining any reasonable total was from annual production figures of Summit County and scattered data on production of individual mines. According to Henderson (1926, p. 245), the total value of mineral output in Summit County for the years 1859 to 1904 inclusive is computed to be $26,749,740. This amount, of course, represents production from the Breckenridge and Montezuma districts and scattered mines throughout the county in addition to that from the Kokomo-Tenmile district. Emmons (1898, p. 4) noted that the original Robinson ore shoot yielded ore valued at $6,000,000, and incomplete data on production of other mines in the district before 1900 indicate an additional $1,300,000 worth of ore. Considering these totals and the scale of activity in the district, especially in the 1880's, it seems safe to assume a production valued at a minimum of $10,000,000 (mostly in silver and lead) from the time of the first discoveries through 1904. Adding to this the total for 1905–65 (table 1), the total value of ores produced in the district is at least $25,942,491.

In the 1880's, silver, and, to a lesser extent, lead and gold were the chief commodities. Zinc came into prominence about 1900, although it seems probable that a large part of the zinc yield of Summit County listed by Henderson (1926, p. 245) for the period 1885–1904 came from the Kokomo-Tenmile district. From 1905 to 1957, zinc was the most valuable product, followed in order by lead, silver, gold, and copper.

After the initial bonanza period in the 1880's and early 1890's, production declined and remained at a low level until about 1900, when the installation of the Wilfley table at Kokomo was reflected in a sharp increase in zinc output that continued through the early 1900's. The post-World War I drop in the price of zinc is reflected in a lack of production of this metal from 1919 through 1922. Depressed metal prices kept activity at a low level through the late 1920's and 1930's, and operations were limited to only a few properties.

The demands for minerals created by World War II resulted in a marked increase in output of lead and zinc in 1942. This renewed mining inaugurated the most prosperous interval in the history of the district, with a total production valued at $13,822,389 from 1942 through 1950. Unfavorable metal prices coupled with insufficient reserves to sustain large-scale operations caused the district to lapse into virtual inactivity in 1951, and the succeeding years witnessed first a further decline and then a complete dormancy from 1957 through 1965.

TABLE 1.—*Production of the Kokomo-Tenmile district, 1905–65*

[N.r., not reported; ...., no production. Data from U.S. Bur. Mines (1925–31, 1932–65); U.S. Geol. Survey (1904–24)]

Year	Tons of ore sold or shipped	Gold (troy ounces)	Silver (fine ounces)	Copper (pounds)	Lead (pounds)	Zinc (pounds)	Total value
1905	N.r.	2,958	110,437	----	1,035,929	1,267,458	$251,313
1906	N.r.	822	34,554	----	408,000	600,115	110,007
1907	N.r.	1,571	70,645	20,270	450,925	807,187	[1] 154,681
1908	N.r.	N.r.	N.r.	N.r.	N.r.	N.r.	79,020
1909	N.r.	N.r.	N.r.	N.r.	N.r.	N.r.	21,028
1910	N.r.	N.r.	N.r.	N.r.	N.r.	N.r.	[1] 180,000
1911	N.r.	N.r.	N.r.	N.r.	N.r.	N.r.	168,800
1912	8,398	446	60,679	2,052	754,176	414,419	109,414
1913	3,409	666	25,926	3,667	664,221	265,632	73,999
1914	663	104	4,866	625	85,729	105,673	13,661
1915	1,666	402	13,412	3,057	183,872	8,968	25,388
1916	11,553	850	40,935	5,809	376,913	66,672	80,880
1917	14,915	1,868	111,676	17,487	513,977	298,696	210,084
1918	12,190	770	75,562	11,453	315,873	98,396	125,688
1919	4,948	311	43,825	1,194	178,453	----	65,201
1920	9,533	752	58,200	----	21,337	----	80,680
1921	N.r.	778	55,686	12,798	211,311	----	82,924
1922	N.r.	1,192	88,882	92,465	81,821	----	130,498
1923	2,758	265	15,881	14,109	39,957	29,800	25,391
1924	----	----	----	----	----	----	----
1925	----	----	----	----	----	----	----
1926	N.r.	N.r.	N.r.	N.r.	N.r.	N.r.	N.r.
1927	N.r.	N.r.	N.r.	N.r.	N.r.	N.r.	N.r.
1928	----	----	----	----	----	----	----
1929	137	N.r.	N.r.	N.r.	N.r.	N.r.	N.r.
1930	19	N.r.	N.r.	N.r.	N.r.	N.r.	N.r.
1931	4	N.r.	N.r.	N.r.	N.r.	N.r.	N.r.
1932	5	30	8	----	----	----	613
1933	159	92	307	----	8,000	----	2,298
1934	494	201	1,603	----	46,600	----	9,784
1935	343	273	1,221	----	4,000	----	10,601
1936	719	220	927	----	1,600	----	8,491
1937	902	461	2,578	1,300	25,000	91,200	25,703
1938	138	167	458	----	23,800	----	7,229
1939	1,239	64	2,756	----	79,300	----	7,838
1940	440	124	1,838	----	18,500	----	6,572
1941	915	46	3,773	200	99,700	141,000	20,575
1942	8,693	200	30,091	8,300	985,600	1,286,800	215,109
1943	16,264	402	28,163	7,700	451,000	1,941,500	278,605
1944	22,387	1,544	47,385	2,000	482,300	2,966,000	464,714
1945	34,203	1,175	67,223	200	1,360,500	4,283,800	698,595
1946	41,852	1,233	88,995	7,000	1,619,200	4,980,000	900,250
1947	51,980	1,655	106,481	46,300	2,333,300	9,173,000	1,609,941
1948	110,244	2,427	271,944	100,000	8,353,000	20,676,000	4,597,863
1949	115,869	2,129	254,294	119,000	7,342,000	19,432,000	3,897,711
1950	35,197	473	68,289	23,800	1,819,300	5,849,900	1,159,601
1951	346	45	811	----	12,000	32,000	10,209
1952	262	15	671	----	16,000	24,000	7,692
1953	(2)	----	----	----	----	----	----
1954	4	----	34	----	800	----	141
1955	368	68	205	400	4,500	3,800	3,852
1956	518	61	1,257	300	15,400	29,400	9,847
1957–65	----	----	----	----	----	----	----
Total	513,734	26,860	1,792,278	501,486	30,423,894	74,873,416	15,942,491

[1] Estimate.

[2] Combined with production from Montezuma district.

HISTORY

During the gold rush to the Pikes Peak region in 1859, some of the prospectors made their way up to the headwaters of the Arkansas River, crossed the divide now known as Fremont Pass, and entered the upper valley of Tenmile Creek, where in 1860 they found deposits of placer gold in McNulty Gulch. The values were spotty, but it was not unusual for an area 20 feet square to yield from $10,000 to $20,000 in gold, which included nuggets weighing as much as 50 pennyweight. Nuggets of metallic silver weighing from 1 ounce to 1 pound were also found in these early placer workings (Hollister, 1867, p. 330).

Shortly after the initial placer discoveries, vein deposits of argentiferous galena were found in the Precambrian rocks high in the cirques of the Tenmile Range; however, high costs of transportation hindered development of these deposits. One of the earliest

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recorded attempts to mine the veins in this area was that of the company of Whitney & Whiting, who, according to Hollister (1867, p. 330–331), drove a tunnel into Fletcher Mountain with the intention of intercepting the Capitol vein 1,200 feet from the entrance and 1,000 feet below the outcrop of the vein. The final results of this venture are unrecorded. Several years later Raymond (1870, p. 341), in his report for the year 1869, also noted activity by "a Boston company" engaged in driving a tunnel under Fletcher Mountain. In 1870 the Bullion & Incas Mining Co. completed a tunnel 800 feet long near the head of Clinton Gulch (Raymond, 1872, p. 331). This tunnel cut several veins, but the production, if any, is not known.

Throughout most of the first two decades of the history of the district the records show only sporadic small-scale activity. This slow development was due in no small part to the remoteness of the area; it was not until the spring of 1879 that the first road, a toll road from Georgetown by way of the Argentine Pass, was opened into the district, and it was on August 9 of that year that the stage from Georgetown made its first run to Kokomo (Eng. Mining Jour., 1879, p. 95).

Placer deposits were discovered along the tributaries of the Blue River on the east side of the Tenmile Range in 1860, and placer mining rapidly increased. The town of Breckenridge came into prominence as the center for placer mining by 1870. This type of mining was extended to the east flanks of the Tenmile Range in 1873, when J. E. Izzard prospected some distance north of Breckenridge, on the west side of the Blue River and secured water rights from Miners Creek, North, Middle, and South Barton Gulches, and several unnamed gulches that drain the east slope of the Tenmile Range (Raymond, 1877, p. 318).

The upper part of the Tenmile Valley, which includes the Kokomo district, did not become active until the discovery of bonanza silver ore in the sedimentary rocks at Robinson and Kokomo in 1878, shortly after the discovery of argentiferous lead ores in the sedimentary rocks in the Leadville area (Henderson, 1926, p. 11).

In 1879 activity increased, and from two to three thousand people flocked to the district. According to reports (Eng. Mining Jour., 1879, p. 132), the early operations proved "so satisfactory as to warrant an amount of prospecting equal to that done at Leadville." The Engineering and Mining Journal (Mar. 1879, p. 206) reported that "On Sheep Mountain there are said to be 50 mines which show mineral in veins from 3 to 34 feet in thickness. The ore so far shipped has averaged 280 ounces of silver." By August 1879 many mines, showing assay values of ore ranging from 50 to 130 ounces of silver, were being developed on Elk Mountain also (Eng. Mining Jour., 1879, p. 95), and many bodies of oxidized ore were discovered and rapidly developed on Chalk Mountain, Chicago Ridge, and Jacque Peak. In 1880, according to Henderson (1926, p. 11), the production of lead and silver was valued at $200,000. The Robinson Consolidated Mining Co. paid its first dividend in June 1880.

By the spring of 1881 many properties that were to become the large producers had been located. Production of the district increased to an estimated $2,000,000 in 1881 (Henderson, 1926, p. 237), and by 1882 the Tenmile district was regarded as the principal mining district of Summit County. The largest and most productive mine in the district at that time was the Robinson mine.

The settlements of Kokomo, Recen, Robinson, Carbonateville (at the mouth of McNulty Gulch), and Wheelers (Wheeler Station) were formed during this period of rapid expansion. The original town of Kokomo burned in 1882, and the population moved to nearby Recen, which was then renamed "Kokomo." Railroads soon linked this area with Leadville and Breckenridge and served to lower the cost of hauling ore to Leadville smelters. In 1881 the Denver and Rio Grande Railroad completed a line from Leadville to Robinson; and in 1883 the Denver and South Park and Pacific Railroad, which later became part of the Colorado and Southern, was completed to Leadville by way of Como, Breckenridge, and the Tenmile Valley (Henderson, 1926, p. 11).

Mills and smelters were constructed in the district as early as 1880. The Pittsburg smelter at Kokomo and the smelter of the Robinson Consolidated Mining Co. at Robinson were the first to begin operations, followed in 1881 by the White Quail and Greer lead smelters at Kokomo and by the Summit at Robinson. Much ore also was shipped to Argo and to the Leadville smelters.

The blanket of rich oxidized and secondarily enriched ore in the district was rapidly mined out, bringing the bonanza period of the camp to an early close. Before the end of 1881 the Robinson mine could not fulfill its contracts with the smelters, and other mines in the district likewise soon exhausted their bonanza ore. Mining activity ebbed, and the data for the ensuing 20 years are meager and fragmentary.

Steady decline in the prices of lead and silver at this time also was an important factor in bringing about the rapid decline in the mining activity of the district. The price of lead had begun to fall in 1890, and it reached a low of 2.65 cents in August 1896 (Kirchhoff, 1897, p. 254). Likewise, the price of silver dropped from more than 1 dollar per ounce in 1890 to about 67 cents in 1897.

Because of such low metal prices it is probable that production in the Kokomo district was at a low level from 1893 to 1897. Although it is impossible to give any details, it is known that mining activity was confined chiefly to shoots sufficiently high in lead, silver, and iron and low enough in zinc to yield ore that could be smelted directly.

Development of the district was hampered by the high zinc content of the primary sulfide ores that were encountered beneath the blanket of oxidized ore. From the earliest days of mining in the Kokomo area, roasting plants and smelters had been built which were designed to treat the complex oxidized ore. For treatment of the primary complex ores, milling procedures had to be developed to obtain concentrates that could be profitably smelted. Zinc was deleterious, and early and persistent attempts were made to devise special milling techniques that would free the ores of sphalerite, because the smelters penalized concentrates for zinc content.

The most successful of these attempts was that by Arthur R. Wilfley, who with some associates took leases on some properties on Elk Mountain (Emmons, 1898) in 1886, and drove the Wilfley and Delphose tunnels, where they developed large bodies of primary sulfide ore. Wilfley developed a concentrating table by means of which the zinc could be separated from lead in crushed ore. This invention, made in 1895 and now known as the Wilfley table, was first put into use at the Wilfley mill in Kokomo in 1896. It immediately became widely used in ore dressing before the advent of the flotation process. Details of the construction and operation of the Wilfley table are given by Richards (1909, p. 326–350) and by Liddell (1945, p. 139–141).

Successful use of the Wilfley table and increase in prices of silver, lead, and zinc kept the district active from 1903 to 1907. The large producers during this period were the Selma, Michigan group, Uthoff tunnel, and Delaware properties. In the Frisco area, the Excelsior was the major producer, and development work was done by the King Solomon Tunnel & Development Co. A special roaster to treat low-grade pyritic ores was installed in the Wilfley mill in 1906. Ore was roasted and then passed through a Dings magnetic separator. The following year, the Wilfley, Kimberly, and Summit interests were combined into the Kimberly-Wilfley Mining Co.

Owing to decreasing metal prices, production from the district again fell off sharply in 1908. Mining activity fluctuated for several years but continued at a low level until 1917, except during 1910–11, when production from the International, a new mine at Robinson, caused brief flurries.

Production from the Climax mine began in 1915 (Butler and Vanderwilt, 1933, p. 201), and output continued at a generally increasing scale through 1965, independent of most of the economic factors that have affected the other mines.

During 1917–18, the district responded to the short-lived price increases generated by World War I, and production temporarily increased. Twelve mines were open, the most productive being the Wilfley, Felicia Grace, Michigan-Uthoff, Silver Queen, King Solomon, and Excelsior.

Throughout the 1920's, sporadic small-scale activity produced small shipments of ore from the Wilfley, Michigan-Uthoff, King Solomon, and Golden Queen. The Eureka placer, a new mine in NcNulty Gulch, produced considerable gold during 1921–22. On September 1, 1923, mining in the district practically ceased when the Michigan-Snowbank-Uthoff tunnel group, which had been the largest producer in the area since 1920, was closed. In 1925 the American Metal Co. acquired a 10-year exploration lease on 3½ square miles between Kokomo and Robinson on Elk and Sheep Mountains. After cleaning out the Wilfley, Kimberly, and Uthoff tunnels in preparation for development work, the company decided that insufficient ore was in sight; therefore, it abandoned the entire project and relinquished its claims.

The inactivity that was typical of the 1920's continued throughout the 1930's. Placer operations in McNulty Gulch produced small quantities of gold during this period, and the Boston, Golden Crest, Payrock, Delaware, Wilfley, Byron, Free America, Excelsior, and Frisco Lode were operated for brief intervals, but from 1927 to 1942 little more than assessment work was done in the area.

The unprecedented demand for metals created by World War II and its aftermath again aroused interest in these zinc-lead deposits. With flotation equipment installed in the Wilfley mill in 1941, the Wilfley Leasing Co. reopened the Wilfley tunnel and commenced mining in 1942. This venture was aided by the Reconstruction Finance Corporation loan of $71,000. The Lucky Strike mine on Sheep Mountain was opened and began to produce in 1942. The Kokomo-Tenmile district responded with marked yearly increases in production from 1942 to 1948, when the ore mined was valued at $4,597,863, the highest output since the early 1880's. Largely responsible for this 7-year increase was the entry of the American Smelting & Refining Co. into the Kokomo area. In 1944 this company acquired the Lucky Strike group, formerly operated by A. R. Rhine and L. J. Gould, and developed this property by means of the 1,000-foot-long Victory tunnel. Later acquistions included the Wilson and McKinley groups. Other operators were active in the district during these years, and the Wilfley mine, the Colonel Sellers, the Kimberly, and the Snowbank made significant contributions to the output of the district. Beginning in 1944 and continuing with but a few brief interruptions until 1949, the U.S. Bureau of Mines carried on an exploration program in the district (Hamilton and McLellan, 1955).

By April 1950, production from the district had virtually ceased. The American Smelting & Refining Co. closed down its operations completely and moved out all its machinery, tools, and equipment. The Wilfley mine also was closed, but the Colonel Sellers, Kimberly, and Boston mines were worked on a small scale. Small-scale operations were carried on in the Wilfley-Kimberly and Colonel Sellers mines in 1952 and 1953 and the Queen of the West in 1954; minor amounts of ore were produced from undisclosed properties in 1955 and 1956. The district has been idle from 1957 through 1965.

PREVIOUS STUDIES

W. H. Emmons (1898) published the first comprehensive report on the Kokomo-Tenmile district. His work, which was done while many mines were active, outlined the chief elements of structure and stratigraphy and the relation of the ore deposits to porphyry intrusives. Koschmann and Wells (1946) wrote a preliminary report on the Kokomo district in which Emmons' earlier stratigraphy was revised and considerably more data were presented on the geologic structure and the classification of the ore deposits. The petrography and petrology of the Precambrian rocks of the area were later discussed by Koschmann (1960), and a general outline of the structure and stratigraphy of the metasedimentary rocks was given at the same time by Koschmann and Bergendahl (1960). Most recently, Bergendahl (1963) has described the geology and ore deposits of the northern part of the Tenmile Range, an area of about 50 square miles which joins the area of this report on the east and northeast.

The Climax molybdenite deposit, which is situated within the investigated area, will not be discussed in this report. Excellent papers have been written on the geology of this deposit by Butler and Vanderwilt (1933) and by Wallace and others (1968).

GENERAL GEOLOGY

The Kokomo-Tenmile district contains a wide variety of rocks ranging in age from Precambrian to Quaternary. The northern and eastern parts of the district, including the central part of the Tenmile Range, are underlain by Precambrian metasedimentary and igneous rocks (pl. 1). Overlying the Precambrian in the central, southern, and western parts of the district are sedimentary rocks of Paleozoic age. The stream valleys and cirques are underlain by unconsolidated glaciofluvial deposits. The oldest rocks were regionally metamorphosed during Precambrian time, were folded, faulted, and uplifted periodically throughout Paleozoic and Mesozoic time, and were uplifted, fractured, intruded, and mineralized during early Tertiary time. Tectonic instability throughout the Paleozoic resulted in numerous unconformities in the sedimentary section. As a result, the stratified rocks are represented by only fractions of their normal stratigraphic thicknesses. The stratigraphy of the sedimentary rocks in this area is important because it records sedimentation close to a strandline that fluctuated widely owing to extreme tectonic unrest. Detailed descriptions of the partial measured sections are not presented, since it is doubtful that they would be of any value for purposes of correlation.

PRECAMBRIAN ROCKS

The Precambrian rocks of the Kokomo-Tenmile district are part of a belt of metamorphic and igneous rocks that make up the central parts of the Gore, Tenmile, and Mosquito Ranges in central Colorado (Burbank and others, 1935). Predominantly of sedimentary origin, the rocks have been metamorphosed to the sillimanite-almandine subfacies of the almandine-amphibolite facies of regional metamorphism, as described by Fyfe, Turner, and Verhoogen (1958, p. 230–232). The metasedimentary series is estimated to be at least 22,000 feet thick and consists of four stratigraphic units: granulite, banded gneiss, migmatite, and pink migmatite. These rocks were subjected to at least two periods of plastic deformation and were folded into northwest-trending isoclinal anticlines and synclines.

The metamorphic complex was intruded by numerous small stocks, plugs, and dikes of Precambrian granitic rocks and pegmatite.

GRANULITE

Granulite[1] is exposed in the core of the northwest-trending anticline that is cut by Clinton, Mayflower, and Pacific Gulches, Humbug Creek, and locally to the north, near Tenmile Creek. This rock is faintly to strongly foliated and forms the lowermost unit of the metasedimentary sequence in the area.

Typical granulite is nearly white in color and consists primarily of quartz, microcline, and oligoclase-andesine (An_{23-36}) and minor biotite and muscovite

[1] The term "granulite" as used here follows the usage of Harker (1939, p. 246–248) to designate a high-grade foliated metamorphic rock consisting mostly of quartz and feldspar. The term denotes a lithologic type and should not be confused with the granulite facies of metamorphism.

segregated into short lenses that locally impart a lineation to the rock. Small amounts of garnet, chlorite, clinopyroxene, and epidote are present locally. Accessory minerals include apatite, sphene, magnetite, rutile, and zircon. The percentages of the major constitutents are variable, causing the granulite to range from a feldspathic quartzite to a rock composed dominantly of feldspar with quartz as an accessory mineral.

BANDED GNEISS

The banded gneiss is a relatively thin unit that overlies the granulite. It is well exposed in Humbug Creek, Pacific and Mayflower Gulches, and part of Clinton Gulch, and consists of alternate white and black layers ranging from a sixteenth of an inch to several feet in thickness (fig. 3). These layers are remarkably continuous, some layers less than 3 inches thick extending continuously for 150 feet along the outcrop. The contacts between layers are sharp and even, but contacts of the entire unit with the underlying granulite and the overlying migmatite are gradational from 2 feet through several tens of feet (fig. 4). The dark layers are commonly contorted and broken and show excellent boudinage structure, the dark layers having yielded to stress by rupture, the light layers by flowage (fig. 5).

The white layers of the banded gneiss are medium grained and are composed of either quartz, microcline, and plagioclase or quartz and plagioclase. Both contain minor biotite, and the plagioclase is oligoclase-andesine (An_{27-38}). The dark layers are medium- to coarse-grained amphibolite, composed of hornblende and andesine (An_{32-45}) and minor amounts of quartz, biotite, clinopyroxene, chlorite, and epidote. Biotite is more abundant in the dark layers near the top of the unit.

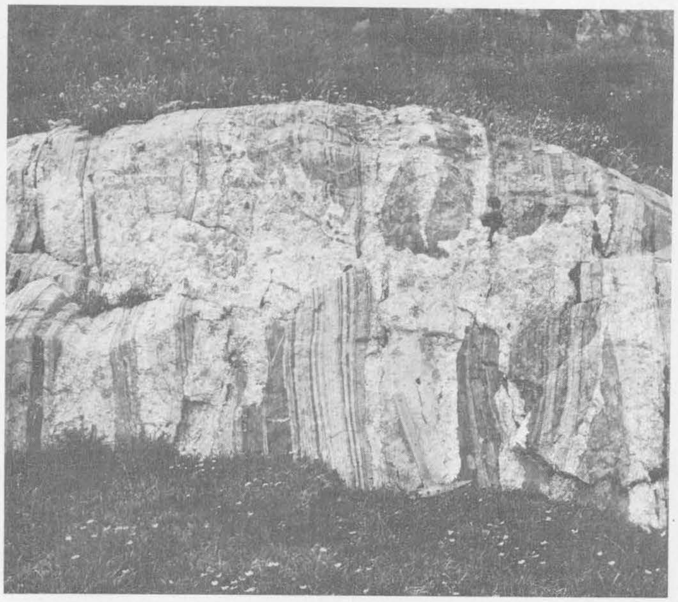

FIGURE 3.—Banded gneiss cut by pegmatite, Humbug Creek. Dark layers are hornblende, andesine, and minor quartz; light layers are quartz, microcline, and oligoclase-andesine.

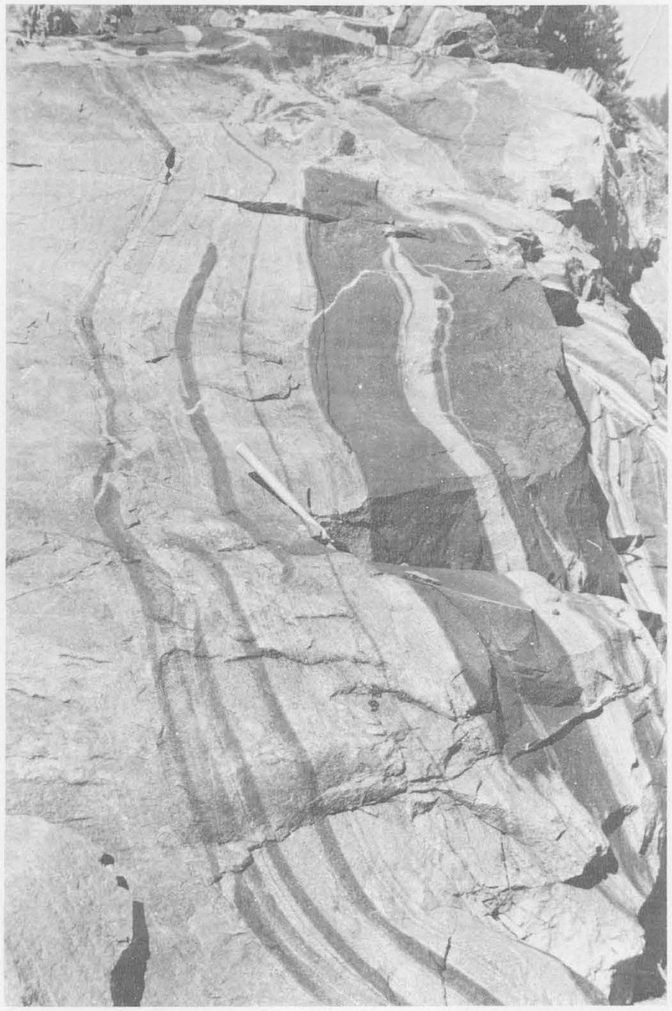

FIGURE 4.—Contact of granulite (left) and banded gneiss (right), Tenmile Range. Contact is gradational through 2-foot interval in vicinity of hammer.

MIGMATITE

The term "migmatite" is here used for a unit that consists of a mixture of rock components separated by boundaries that are irregular or gradational. No genetic implications are intended by use of the term.

The migmatite overlies the banded gneiss and is the most widespread unit in the Precambrian terrane. It forms most of the walls and floors of Clinton Gulch and the upper parts of Mayflower and Pacific Gulches and Humbug Creek. It underlies a large area on the southeast slope of Copper Mountain and several irregular areas in the southeast corner of the map area.

FIGURE 5.—Boudinage structure in banded gneiss, Tenmile Range. Felsic material between ends of boudins is very coarse grained.

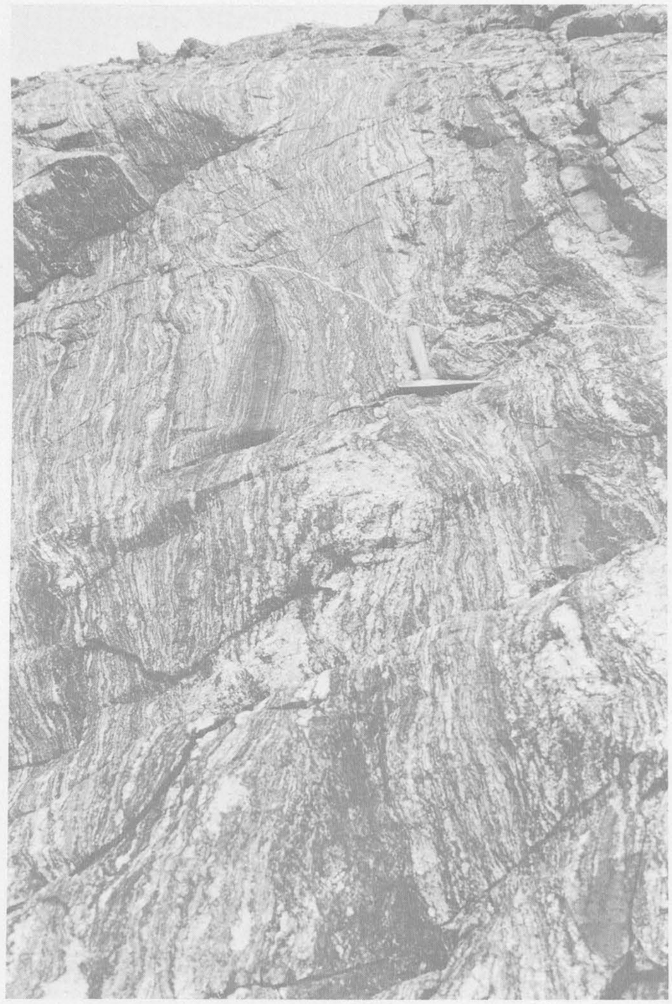

FIGURE 6.—Migmatite, showing typical wavy foliation, Pacific Gulch. Dark layers are biotite and oligoclase-andesine; light layers are mainly quartz, microcline, and oligoclase-andesine.

The migmatite is a medium- to coarse-grained foliated rock composed of laminae of biotite, hornblende, plagioclase, and quartz alternating with discontinuous layers, pods, and lenses of quartz or quartz, plagioclase, and microcline. Many of the felsic layers are pegmatitic. The characteristic features of the migmatite are an abundance of biotite and a wavy foliation that is produced by wispy layers of biotite and clots and septa of quartz and feldspars (fig. 6). Lineations are well developed as axes of drag folds and as crinkles, mineral alinements, and slickensides. Ptygmatic folds are common (fig. 7). The plagioclase in the migmatite is oligoclase-andesine (An_{26-45}). Some of the migmatite contains megascopically noticeable amounts of sillimanite, but it commonly comprises less than 5 percent of the volume of the rock. Large euhedral garnets (almandite) are locally conspicuous.

PINK MIGMATITE

A medium- to coarse-grained decidedly pink gneiss crops out on the east slope of Copper Mountain. The stratigraphic relations of this unit with the other metasedimentary rocks are not clear. In places north of the Kokomo-Tenmile district the pink gneiss appears to be in normal contact with granulite (Bergendahl, 1963, p. D9), but on Copper Mountain it either interfingers with, or overlies, the migmatite. The contact was not seen in outcrop, but within a few hundred feet, along the east flank of Copper Mountain, the migmatite grades into pink migmatite.

Most of the pink migmatite is composed of wavy discontinuous layers of biotite intercalated with layers of medium- to coarse-grained quartz and pink plagioclase. Individual layers are less than 2 inches thick. Except for its pink color, this rock strongly resembles the

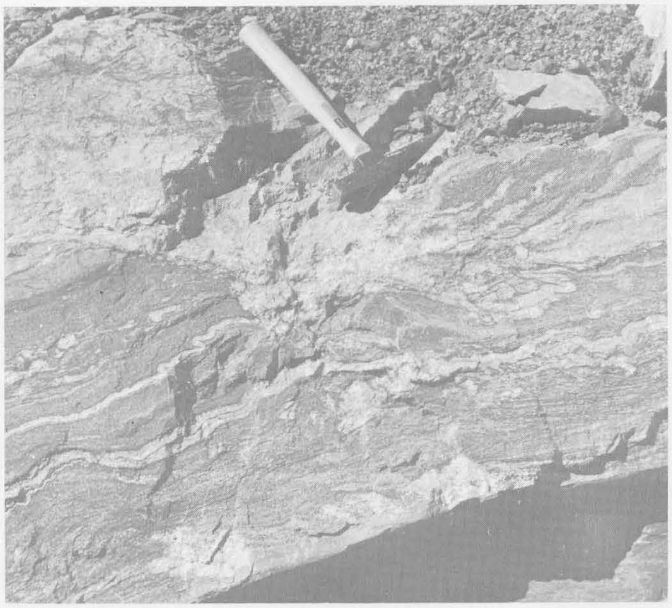

FIGURE 7.—Migmatite, showing contorted layering and ptygmatic folds, Pacific Gulch.

migmatite. A less abundant variety of pink gneiss is indistinctly foliated, rather homogeneous, pink, speckled with black, and has the same mineral composition as the layered variety.

The major minerals of the pink migmatite are quartz, oligoclase, and biotite. Microcline and, locally, sillimanite are minor constituents, and sphene and zircon are accessory minerals. The pink color of the rock is due to submicroscopic inclusions or dust in the plagioclase. This dust is probably hematite, but no analytical determinations were made.

BIOTITE-MUSCOVITE QUARTZ MONZONITE

An area of roughly 2½ square miles in the Tenmile Range a short distance east of Climax is composed of a stock of biotite-muscovite quartz monzonite, and locally to the north in Clinton and Mayflower Gulches and along Humbug and Tenmile Creeks small plugs of this rock intrude the older Precambrian rocks. The biotite-muscovite quartz monzonite was called Silver Plume Granite by Koschmann (1960, p. 1364–1365) and was referred to as "granite similar to Silver Plume Granite" by Bergendahl (1963, p. D12, D13). Indeed, it is similar to the type Silver Plume Granite (Ball, 1906) in both texture and mineral composition; however, as both Bergendahl (1963, p. D12) and Koschmann (1960, p. 1364) noted, the rock is not a true granite but is a quartz monzonite, containing quartz, microcline, and plagioclase in roughly equal amounts.

The biotite-muscovite quartz monzonite is light pink on weathered surface and gray, speckled with black, on fresh surface. The microcline occurs as euhedral laths, most of which are about 1 centimeter long, and are conspicuous in a granitoid matrix of anhedral to subhedral quartz and oligoclase. Locally, these minerals are arranged in subparallel alinement, which probably reflects flow in the magma, inasmuch as this planar structure is discordant with the foliation of the enclosing migmatite. Muscovite and biotite are present in variable amounts, each mineral rarely exceeding 8 percent of the volume of the rock. Apatite is an accessory mineral.

GNEISSIC GRANITE

Three small irregular bodies of a gneissic granitic rock are exposed in, and just south of, Spaulding Gulch. The largest of these bodies is roughly circular in plan and has a diameter of about 750 feet. This rock intrudes the migmatite, but it is probably of Precambrian age because its strong gneissic character seems conformable with the trend of foliation in the migmatite.

The gneissic granite is medium grained and light gray speckled with black. The major minerals are quartz, potassium feldspar, and plagioclase. Biotite is the dominant mafic mineral and, together with quartz, has a preferred orientation that gives the rock its gneissic character.

Because this rock crops out in only a few small bodies that are isolated from any other igneous rocks of Precambrian age, its origin is not clear. It does not seem to be genetically related to any intrusive mass in the district, although, megascopically, it is similar in a general way to the granite of Cross Creek, a large body of which underlies parts of the Minturn and Dillon quadrangles 7–8 miles to the northwest.

PEGMATITES AND OTHER DIKELIKE ROCKS

The Precambrian rocks are interlaced with myriads of dikes, sills, and podlike bodies of pegmatite, aplite, and alaskite. Only a few of the larger pegmatites are shown on the geologic map; most of the intrusives are less than 10 feet thick and could not be shown at the map scale. The pegmatites and associated rocks cut across and intrude one another; thus, they are of several ages. At least one group of pegmatites seems to be related to the biotite-muscovite quartz monzonite; other relationships were not determined because of limited access imposed by vertical cirque walls, falling rock, unstable talus, and other hazardous features of the terrain. A Precambrian age for these rocks is assumed on the basis that none have been observed that cut Paleozoic or Mesozoic rocks.

The mineralogy of the pegmatites is simple and uniform, consisting of quartz, microcline, andesine, and minor amounts of muscovite and biotite. The large crystals of rare minerals that characterize many zoned pegmatites are absent, except for two crystals of beryl, 4–6 inches long, that were found in a pegmatite in the upper part of Pacific Gulch. Clusters of magnetite grains as much as several inches in diameter occur locally in some pegmatites.

The alaskite bodies are composed mainly of microcline, oligoclase, quartz, and muscovite. The aplites consist of sugary-textured quartz, orthoclase, and oligoclase and minor muscovite.

PALEOZOIC ROCKS

The rocks of Paleozoic age are predominantly deltaic and shallow marine units that were deposited adjacent to an area of crustal instability. Tweto (1949) and Koschmann and Wells (1946) have described these rocks in detail; consequently, their descriptions are generalized in this report and are presented in tabular form in table 2. Because of the local and fragmentary nature of occurrence, sedimentary rocks of pre-Pennsylvanian age, except for the Sawatch Quartzite, are shown as undifferentiated on the geologic map. These rocks are found as patches along the east edge of Chalk Mountain, in Mayflower Gulch, and across the divide between Mayflower Gulch and Humbug Creek. Parts of the following formations are included in the undifferentiated sequence: Peerless Formation of Cambrian age, Harding Quartzite of Ordovician age, Chaffee Formation of Devonian age, and Leadville Dolomite of Mississippian age.

Sedimentary rocks of Pennsylvanian and Permian age, consisting of the Minturn and Maroon Formations, are well exposed throughout the western two-thirds of the district. In the northern part of the district, on Copper Mountain, these rocks unconformably overlie the Precambrian gneiss. In the eastern part of the district they are faulted against the Precambrian rocks. The Belden Shale, which is the lowermost unit of the Pennsylvanian sequence (Tweto, 1949, p. 192–193), was not seen in the district; but it might be present at depth in the southern part of the map area.

MINTURN FORMATION

The Minturn Formation, which normally overlies the Belden, composes most of the lower part of the exposed sedimentary section. It is about 6,000 feet thick in the Pando area, west of the Kokomo-Tenmile district (Tweto, 1949, p. 194), but it thins eastward owing to overlap of the younger beds. On Copper Mountain, the Robinson Limestone Member, which is 4,200 feet above the base of the Minturn, lies directly on the Precambrian migmatite. A drastic thinning also occurs from the south edge of the district northward to Copper Mountain. The Jack 8 limestone, a persistent marker bed in the lower 1,800 feet of the Minturn (Tweto, 1949, p. 196), is exposed on the slopes above Chalk Creek, just outside the southwest corner of the map area.

Tweto (1949, p. 186–228) revised a previously unsatisfactory stratigraphic nomenclature for the Pennsylvanian and Permian Systems in west-central Colorado and described in detail the lithology of the Minturn Formation. Koschmann and Wells (1946, p. 59–69) described the Minturn as the lower and middle units of the Pennsylvanian and Permian (?) rocks. In general, the formation consists of lenticular beds of arkosic grit, sandstone, shale, siltstone, quartzite, and conglomerate. Most of the formation is gray, except for the lower 100–500 feet and the upper 900 feet, which are various shades of red. A few relatively persistent beds of limestone and dolomite occur at widely spaced stratigraphic intervals. These have been useful as marker beds and have been given member status.

Marine fossils from the Hornsilver Dolomite Member and Robinson and White Quail Limestone Members indicate a Des Moines age, whereas cephalopod and gastropod remains from the Jacque Mountain Limestone Member are less diagnostic species that range from Pennsylvanian into Permian age, but are likely Pennsylvanian (Tweto, 1949, p. 199–206; Koschmann and Wells, 1946, p. 66–69).

Several of the limestones, such as the Robinson, White Quail, and Jacque Mountain, are host rocks for commercially important lead-zinc-silver replacement ore bodies.

MAROON FORMATION

The Maroon Formation conformably overlies the Jacque Mountain Limestone Member of the Minturn and is the highest of the Paleozoic formations in the Gore, Tenmile, and Mosquito Ranges. The Maroon is equivalent to the "upper unit" of the Pennsylvanian and Permian (?) of Koschmann and Wells (1946, p. 69–70). The top of the Maroon is not preserved in the district, and the total original thickness is not known in this region. On Jacque Peak, almost 2,000 feet of Maroon Formation is exposed; this is the thickest section found in the district. The Maroon is also exposed along the ridge between Jacque Peak and Union Mountain. A large area of Maroon crops out in the central part of the district on Carbonate Hill. As its name implies, the Maroon is dominantly red; it consists of siltstone, sand-

TABLE 2.—*Paleozoic sedimentary rocks in the Kokomo-Tenmile district*

Age	Formation (Tweto, 1949)	Member (Tweto, 1949)	Major divisions of Koschmann and Wells (1946)	Thickness (feet)	Lithologic characteristics
Permian and Pennsylvanian	Maroon Formation		Upper unit	2,000±	Mostly brick-red thin-bedded sandstone, siltstone, and mudstone; locally conglomeratic; a few thin limestone beds; unfossiliferous.
Pennsylvanian	Minturn Formation		Middle and lower units	5,000–6,000	Predominantly arkosic micaceous grit, sandstone, mudstone, and conglomerate separated by thin beds of limestone and dolomite. The 7 named carbonates are listed below in sequence with the youngest at the top. Mostly red and maroon above Robinson Limestone Member; gray and red below Robinson.
		Jacque Mountain Limestone		15–25	Limestone, gray- to bluish-gray; oolitic in places; characterized by large cephalopods, oolitic texture. Marks top of Minturn Formation.
		White Quail Limestone		175	2, locally 3, beds, each 5–30 ft thick, of gray to black limestone separated by 25–150 ft of sandstone, shale, and grit. Limestone is oolitic and contains abundant gastropods, casts of cephalopods, pelecypods, brachiopods. About 5,000 ft above base of formation.
		Elk Ridge Limestone		250±	2 thin limestone beds separated by 200–225 ft of red sandstone and conglomerate. Upper limestone is 5–7 ft thick and is dark bluish gray. Lower limestone is 10–15 ft thick and is pale gray to bluish gray. Member is 4,800 ft above base of formation.
		Robinson Limestone		200–250	Generally 3 beds of limestone separated by red and gray sandstone. Limestone beds are dark gray to black 15–35 ft thick, and contain fusulinids. About 4,200 ft above base of formation.
		Resolution Dolomite		30–125	1–3 beds of gray dolomite separated by gray grit and shale. Roughly 3,700 ft above base of formation.
		Hornsilver Dolomite		18–28	Massive and thin-bedded gray dolomite. About 2,900 ft above base of formation.
		Wearyman Dolomite		15–75	Massive gray to buff reef-forming dolomite. About 2,600 ft above base of formation.
	Belden Shale			Unknown	Gray and black shale interbedded with thin-bedded dark-gray limestone. Present only in subsurface.
Mississippian	Leadville Dolomite	Dolomite		67–95	Massive gray to black cherty dolomite.
		Gilman Sandstone		16–22	Dolomitic sandstone, cherty; dolomite breccia.
Devonian	Chaffee Formation	Dyer Dolomite		73–80	Dark-gray to black thin-bedded dolomite.
		Parting Quartzite		45–57	Tan, pink, and white quartzite and conglomerate.
Ordovician	Harding Quartzite			0–27	Tan, white, and green quartzite and sandstone.
Cambrian	Peerless Formation			35–99	Buff, purple, green, and pink sandy dolomite and dolomitic sandstone.
	Sawatch Quartzite			140–185	Thin-bedded to massive white quartzite.

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stone, and mudstone, interbedded with minor shale layers and, locally, with nonpersistent thin limestone beds. North of Jacque Peak, the formation is chiefly conglomerate and coarse-grained micaceous arkose. No fossils were found in the Maroon, but the formation is assigned to the Pennsylvanian and Permian in this area on the basis of Tweto's (1949, p. 229) revision of the stratigraphic nomenclature.

VOLCANIC ROCKS

A few lenses of rhyolite tuff and breccia and altered feldspathic rocks and dikes and a small mass of white rhyolite tuff are found in the sedimentary rocks on the southeast slope of Tucker Mountain. These rocks have been described in some detail by Koschmann and Wells (1946, p. 70–73), who postulate Pennsylvanian and possibly also Permian volcanism in the Tucker Mountain area on the basis both of the local distribution of these rocks and also of altered bentonite in Pennsylvanian rocks northwest of the Kokomo-Tenmile district (Brill, 1942, p. 1388).

TERTIARY ROCKS

Rocks of Tertiary age in the district consist of sills, dikes, and stocklike bodies of igneous rock. Most of these are of quartz monzonite composition and porphyritic texture; but the large mass that underlies Chalk Mountain, in the southwestern part of the district, is rhyolite porphyry. Chemical analyses of some of these rocks are given in table 3. Except for small variations in the content of SiO_2, Fe_2O_3, and MgO, the chemical compositions are practically identical.

Sills and sill-like bodies that locally crosscut the sedimentary strata are the most common forms of these rocks. These bodies range in thickness from less than 20 feet to somewhat more than 300 feet; a few are continuous along the strike for more than 1 mile. Some of the sills can be followed into discordant irregularly shaped masses.

The quartz monzonite body that crops out in the lower part of Humbug Creek and, locally, along the northwest side of Tenmile Creek is part of a stock that extends easterly across the Tenmile Range.

The rocks of Tertiary age in this area were described in some detail by Emmons (1898, p. 2, 3) and by Koschmann and Wells (1946, p. 73–83); for this reason only brief summaries of the individual units are given here.

ELK MOUNTAIN PORPHYRY

The Elk Mountain Prophyry is the oldest and most abundant of the intrusive rocks in the district. Its relative age is determined by its structural relations with the other intrusive rocks. The large mass of Elk Mountain Porphyry that crops out along the southwest slope of Searle Gulch is cut by a dike of Quail Porphyry. Near the mouth of Searle Gulch, just north of the Free America mine, a sill of Elk Mountain is cut by dikes of Quail and Lincoln Porphyries; on Tucker Mountain several irregular bodies of Elk Mountain are intruded by Lincoln Porphyry dikes.

TABLE 3.—*Chemical analyses (weight percent) of Tertiary intrusive rocks, Kokomo-Tenmile district*

	1	2	3	4	5	6
SiO_2	69. 41	68. 49	67. 18	66. 20	65. 67	68. 88
Al_2O_3	15. 25	15. 36	15. 24	15. 82	15. 91	15. 33
Fe_2O_3	1. 43	1. 47	1. 86	2. 18	2. 20	. 72
FeO	1. 54	1. 58	1. 54	1. 92	1. 89	1. 72
MgO	. 84	. 86	1. 26	1. 43	1. 60	1. 03
CaO	2. 63	3. 74	2. 36	3. 34	3. 66	2. 49
Na_2O	3. 62	3. 71	3. 95	4. 19	3. 98	3. 71
K_2O	3. 89	3. 66	3. 48	3. 33	3. 18	3. 69
H_2O+	. 29	. 70	1. 22	. 41	. 11	. 48
H_2O-	. 06	. 08	. 64	. 03	. 14	. 20
TiO_2	. 35	. 35	. 39	. 48	. 51	. 39
P_2O_5	. 21	. 21	. 13	. 27	. 28	. 21
MnO	. 09	. 07	. 09	. 06	. 04	. 02
CO_2	. 01	. 42	. 41	. 01	. 01	. 01
SO_3	. 01	. 02	. 01	. 01	. 00	. 08
Cl	. 00	. 00	. 00	. 04	. 02	. 02
F	. 05	. 05	. 05	. 05	. 05	. 05
S	. 00	. 00	. 00	. 00	. 00	. 53
BaO	. 15	. 15	. 14	. 10	. 14	. 15
	99. 83	99. 92	99. 95	99. 78	99. 39	99. 71
Less oxygen	. 02	. 02	. 02	. 03	. 02	. 15
Total	99. 81	99. 90	99. 93	99. 75	99. 37	99. 56

1. Quartz monzonite from Peak 9, Tenmile Range (Serial No. E 2283).
2. Lincoln Porphyry from upper part of Mayflower Gulch, Tenmile Range (Serial No. E 2284).
3. Quail Porphyry from sill in Minturn Formation in Kokomo Gulch, opposite Connors tunnel (Serial No. E 2288).
4. Porphyritic quartz monzonite from northeast slope of Tucker Mountain, just above Copper Creek (Serial No. E 2289).
5. Elk Mountain Porphyry from southwest slope of Tucker Mountain, above Boston Cooney mine (Serial No. E 2290).
6. Elk Mountain Porphyry from southwest slope of Tucker Mountain (Serial No. E 2291).

The typical Elk Mountain Porphyry is quartz monzonite and consists of a fine-grained gray groundmass of quartz and orthoclase, with abundant phenocrysts of quartz and albite-oligoclase as much as 8 mm (millimeters) in maximum dimension. The quartz phenocrysts are rounded and embayed. Biotite and hornblende occur in variable, but minor, amounts and are commonly altered to chlorite (Koschmann and Wells, 1946, p. 77, 78).

PORPHYRITIC QUARTZ MONZONITE

A small stocklike mass of porphyritic quartz monzonite is exposed on Tucker Mountain. This rock seems to grade into a facies similar to the Elk Mountain Porphyry. Its mineral composition is identical with that of the Elk Mountain, but its groundmass is coarser grained (Koschmann and Wells, 1946, p. 78).

QUAIL PORPHYRY

The Quail Porphyry occurs in only a few localities in the district. A large sill is exposed on the south slope of Elk Ridge; several small dikes and sills crop out farther north on Elk Ridge, on the east side of Tucker Mountain, on the southwest slope of Jacque Peak, and along the highway just south of Chalk Mountain.

The diagnostic features of the Quail Porphyry are its quartz monzonite composition, its content of well-formed phenocrysts of hornblende, as much as 2 mm in maximum dimension, and its dark-greenish-gray color. Phenocrysts of sericitized and epidotized plagioclase, about 2 mm in diameter, are also common. The groundmass is composed of fine-grained quartz, orthoclase, and plagioclase.

QUARTZ MONZONITE

The western apophyses of a large stock of quartz Monzonite are exposed along the east wall of Humbug Creek and, locally, along the highway to the west and north, where they intrude the Minturn Formation. The quartz monzonite is clearly older than the Lincoln Porphyry, but its relations with the other intrusive rocks are not known.

The rock is mottled light gray and black and is medium grained and holocrystalline; locally, it contains abundant phenocrysts of euhedral oligoclase-andesine and microcline. Major minerals are quartz, microcline, and oligoclase-andesine. Biotite, hornblende, and magnetite are minor constituents, and apatite and sphene are accessory minerals (Bergendahl, 1963, p. D15, D16).

LINCOLN PORPHYRY

The Lincoln Porphyry, with its large euhedral phenocrysts of orthoclase as much as 2 inches in maximum dimension, is the most distinctive appearing of the intrusive rocks and commonly occurs throughout the district as dikes and sills. The Lincoln is the youngest of the quartz monzonitic intrusive rocks, as determined by its crosscutting relations with all the other igneous rocks, including the quartz monzonite stock (Bergendahl, 1963, p. D15).

The Lincoln Porphyry contains, in addition to conspicuous white to pink orthoclase, abundant small phenocrysts of quartz, biotite, and plagioclase. The quartz grains are rounded and resemble those in the Elk Mountain Porphyry; the plagioclase forms white subhedrons, and the biotite occurs in small hexagonal flakes partly altered to chlorite (Koschmann and Wells, 1946, p. 80, 81). The groundmass is composed of fine-grained quartz, orthoclase, and plagioclase.

CHALK MOUNTAIN RHYOLITE

Chalk Mountain, the prominent ridge that forms the Continental Divide in the southwestern part of the district, is underlain by a large tabular mass of white rhyolite, called nevadite by Emmons (1898, p. 3). Although the field evidence does not conclusively prove the mode of emplacement of the white rhyolite, Koschmann and Wells (1946, p. 82) concluded that the rhyolite was a surface flow on a rough terrain rather than an intrusive as Emmons (1886, p. 195–196) believed.

The rhyolite contains abundant phenocrysts of sanidine and smoky quartz, many of which are 2–5 mm in maximum dimension. Phenocrysts of albite and biotite occur sparingly. The groundmass of the Chalk Mountain Rhyolite is a white microgranular aggregate of quartz and feldspar (Koschmann and Wells, 1946, p. 82, 83).

QUATERNARY DEPOSITS

Large areas of the district are blanketed with unconsolidated deposits of sand and gravel of glaciofluvial origin. These deposits doubtless represent several advances and retreats of glaciers during Pleistocene and Holocene time and reworking of the detrital material by streams; they probably could be subdivided into several map units, but for the purposes of this report, considering them as one unit was deemed adequate.

Other unconsolidated deposits consist of accumulations of talus of Holocene age, which occur along the lower slopes and the steep-walled gulches and cirques throughout the district, and a large landslide mass on the west side of Copper Mountain.

STRUCTURE

The rocks of the Kokomo-Tenmile district show the effects of an eventful tectonic history highlighted by several periods of plastic deformation and faulting in Precambrian time, regional warping accompanied by faulting and folding during Paleozoic time, and uplift, folding, faulting and large-scale intrusion in post-Paleozoic, probably early Tertiary time. The sedimentary rocks are deformed into broad open folds that overlie the complexly contorted Precambrian terrain.

The faults of the district are nearly all high-angle normal and reverse faults that may be grouped into several systems. In the southeastern part of the district the Mosquito and several subsidiary faults trend N. 5°–25° E. In the western part most faults trend N. 45°–75° E.; several have easterly trends. Northwest-trending faults are few in number and are found mostly in the northern and western parts of the district.

Regional metamorphism during Precambrian time produced tight folds which, in the northern part of the area, plunge moderately northwest and, in the southeastern part of the area, plunge southeast. Locally, these folds are complicated by superimposed sets whose axes plunge to the southwest or northeast. Folded structures in the sedimentary rocks are much less intensely folded than those in the Precambrian. They are broad and open and reflect periodic uplift along the Sawatch axis to the west and along the Mosquito-Tenmile axis to the east.

FAULTS

MOSQUITO FAULT

The Mosquito fault brings Precambrian rocks against Paleozoic sedimentary rocks in the southeastern part of the area. Behre (1953, p. 66) noted that this fault is traceable for at least 33 miles along the west flanks of the Mosquito and Tenmile Ranges and considered it to be one of the major faults in the Rocky Mountains of Colorado. The fault enters the south edge of the map area and follows a north-northeast course to Mayflower Gulch, where evidence of it was seen at the Boston mine. Where the Mosquito fault cuts across the spurs of the Tenmile Range, the lower rounded slopes of sedimentary rocks give way abruptly to a high, rugged, and steep Precambrian terrane (fig. 8). The fault could not be detected along the projection of its strike in the northeast wall of Mayflower Gulch. Indeed, the sedimentary rocks exposed on the ridge between Mayflower Gulch and Humbug Creek seem to be in normal unfaulted contact with the Precambrian rocks. Emmons (1898) mapped the fault as extending northward to the east flank of Copper Mountain. The authors could find no good evidence for continuing the Mosquito fault beyond Mayflower Gulch and prefer to consider the north-northeast fault exposed on the east slope of Copper Mountain to be a separate fault.

The fault plane dips steeply to the west in some places and steeply to the east in others. In the vicinity of Climax the Mosquito fault is a normal fault, with a 71°–80° westward dip (Koschmann and Wells, 1946, p. 90). Emmons (1898, p. 3) also reported a steep westward dip of the fault in mines in Mayflower Gulch. Roughly 13 miles south of Climax, outside the map area, on the south slope of Empire Hill in the Mosquito Range, Behre (1953, p. 66) reported a 75°–80° east dip of the fault.

The amount of displacement along the Mosquito fault is difficult to ascertain because the total thickness of the sedimentary section along it varies by as much as 4,000 feet. In addition, the amount of actual movement may have been different from place to place. South of the Kokomo-Tenmile district, Behre (1953, p. 66) noted a variation of downdip displacement of from 600 to 5,100 feet. The net vertical displacement in the Kokomo-Tenmile area is probably nearly 8,000 feet.

In the southeastern part of the district several dikes of Lincoln and Elk Mountain Porphyries apparently fill fractures that were parallel and subparallel to the Mosquito fault.

NORTHEAST-TRENDING FAULTS

In the western part of the district the Minturn and Maroon Formations are cut by a swarm of N. 45°–75° E. high-angle faults. These are the continuation of a zone of similar faults mapped and described by Tweto (1949, 1956) in the Pando and Tennessee Pass areas west and southwest of the Kokomo district.

These faults comprise a belt of closely spaced faulted blocks about 3 miles wide. Individual faults do not exceed 1 1/2 miles in length; the majority are less than half a mile long. Vertical components of movement are, in general, less than 100 feet, but strike-slip components along some are considerable. As much as 800–1,000 feet of strike slip is indicated along the fault in Kokomo Gulch.

If projected to the northeast, the zone of northeast-trending faults would intersect the northern extension of the Mosquito fault in the vicinity of the east flank of Copper Mountain; however, outcrops in this area do not show any evidence of intersecting structures. On the contrary, the intensity of faulting seems to diminish.

The northeast-trending faults are directly related to the distribution of ore deposits in the district, in that the faults served as channelways for the ore-bearing solutions in gaining access to those carbonate beds that were chemically favorable for replacement.

NORTHWEST-TRENDING FAULTS

The most prominent of the northwest-tending faults is exposed in Mayflower Gulch, where it trends about N. 45° W. and offsets some of the banded gneiss of the Precambrian metasedimentary sequence by as much as 875 feet laterally and 525 feet vertically. Apparently the Mosquito fault has been cut by this fault, for the fault cannot be found to the north. The fault is a conspicuous iron-oxide stained zone of crushed and silicified rock 90–300 feet wide.

Another fairly prominent zone of faults, en echelon with the one in Mayflower Gulch, crosses the ridge between Pacific Gulch and Humbug Creek and heads beneath the moraine in Humbug Creek. This fault, which is also in Precambrian rocks, has placed migmatite against granulite, but no estimate of the amount of movement can be made. A small mass of unsheared

Silver Plume Granite cuts across the fault, thereby demonstrating that all movement has been in pre-Silver Plume time. A wide zone of silicified and iron-oxide stained breccia characterizes this fault also.

A few other northwest-trending faults are exposed in the vicinity of Tucker Mountain and Union Mountain and near the south-central boundary of the map area. These faults offset the Minturn and Maroon Formations by less than 100 feet vertically.

OTHER FAULTS

Many more faults are revealed in mine workings that can be seen on surface outcrops, where weathering has obliterated much of the detail. These faults are mostly small, with displacements of only a few feet; nevertheless, they give important information on the recurrent nature of movement and the degree of fracturing that has occurred. Emmons (1898, p. 5) described closely spaced faults in the Queen of the West mine, some of which were the localizing structures for veins. Bedding faults developed later and offset the veins and high-angle faults. Other faults not detectable on the surface are northwest-trending strike-slip faults. A series of these with displacements of from 2 to 15 feet was observed by Emmons (1898, p. 5) in the White Quail workings.

A possible major fault, the Tenmile fault, is hidden by surficial deposits in the valley of Tenmile Creek, but it was described by Emmons (1898, p. 5) and by Koschmann and Wells (1946, p. 95, 96). The fault was detected in workings of the New York and Daughenbaugh shafts and apparently is roughly parallel with the course of Tenmile Creek. Koschmann and Wells (1946, p. 95) reported that strata in the southeast block are moved vertically downward 335 feet relative to those on the northwest side and that a zone of breccia 220 feet wide marks the fault zone.

PERIODS OF DEFORMATION

Movement along faults was periodic, and abundant evidence shows that some faults were inactive after Precambrian time, whereas others were rejuvenated recurrently throughout the Laramide orogeny and perhaps even more recently.

The faults in Precambrian rocks are marked by wide zones of crushed and granulated rock, as contrasted with their more planar character in the sedimentary rocks. These shear zones contain gouge and breccia and are interlaced with ramifying quartz veinlets and impregnated with fine-grained pyrite that has weathered to iron oxides, giving the zones a conspicuous yellowish-brown stain. In some places the crushed rock has been silicified for tens of feet across, and the ferromagnesian minerals have been converted to chlorite. Slickensides in these zones have inconsistent attitudes, which suggests differential and repeated movement of blocks, rather than uniform movement along a plane. Under the microscope the minerals show the effects of strain. Quartz grains are crushed and show shadowy extinction, plagioclase laths are bent, and chlorite grains are oriented with their long dimensions in the direction of least stress. Epidote veinlets commonly fill small cracks and fissures, and many of them are offset. Quartz veinlets of several generations cut across the older fabric.

Pegmatites, derived from local fusion and segregation during Precambrian regional metamorphism or from late differentiates of the magma that formed the mass of Silver Plume Granite near Climax, occupy some fault zones in Precambrian rocks and are not dislocated by later movement. Other faults contain veins of presumed Tertiary age which show several stages of mineral filling and brecciation.

Indications of numerous episodes of fault movement are also seen in the sedimentary rocks. The N. 45°–75° E. system of faults came into existence sometime after consolidation of the Pennsylvanian and Permian rocks and before the introduction of Tertiary ore-bearing solutions (p. 40). On the basis of evidence, such as the parallel relations of some Lincoln Porphyry and Quail Porphyry dikes with northeast-trending faults, the truncation and displacement of other dikes and sills of Elk Mountain, Quail, and Lincoln Porphyries by other northeast-trending faults, and observations in mines that ore bodies were offset against faults, Koschmann and Wells (1946, p. 93) proposed three main stages of movement on these faults: (1) one before or during intrusion of the porphyry sills; (2) one after intrusion of some sills and during ore deposition; and (3) one after ore deposition. The second stage apparently consisted of repeated movement over a long time, for the early formed minerals in many veins are fractured and brecciated, and the later ones are not.

FOLDS

The general deformation of virtually all the rocks in central Colorado indicates that this area has been a region of crustal instability throughout much of geologic time. The Precambrian rocks bear the imprint of several stages of regional metamorphism during which the rocks were plastically deformed. The sedimentary rocks are less severely contorted and reflect more recent tectonic activity, which is chiefly related to the Sawatch uplift to the west and the Mosquito-Tenmile belt of folding in the eastern part of the area.

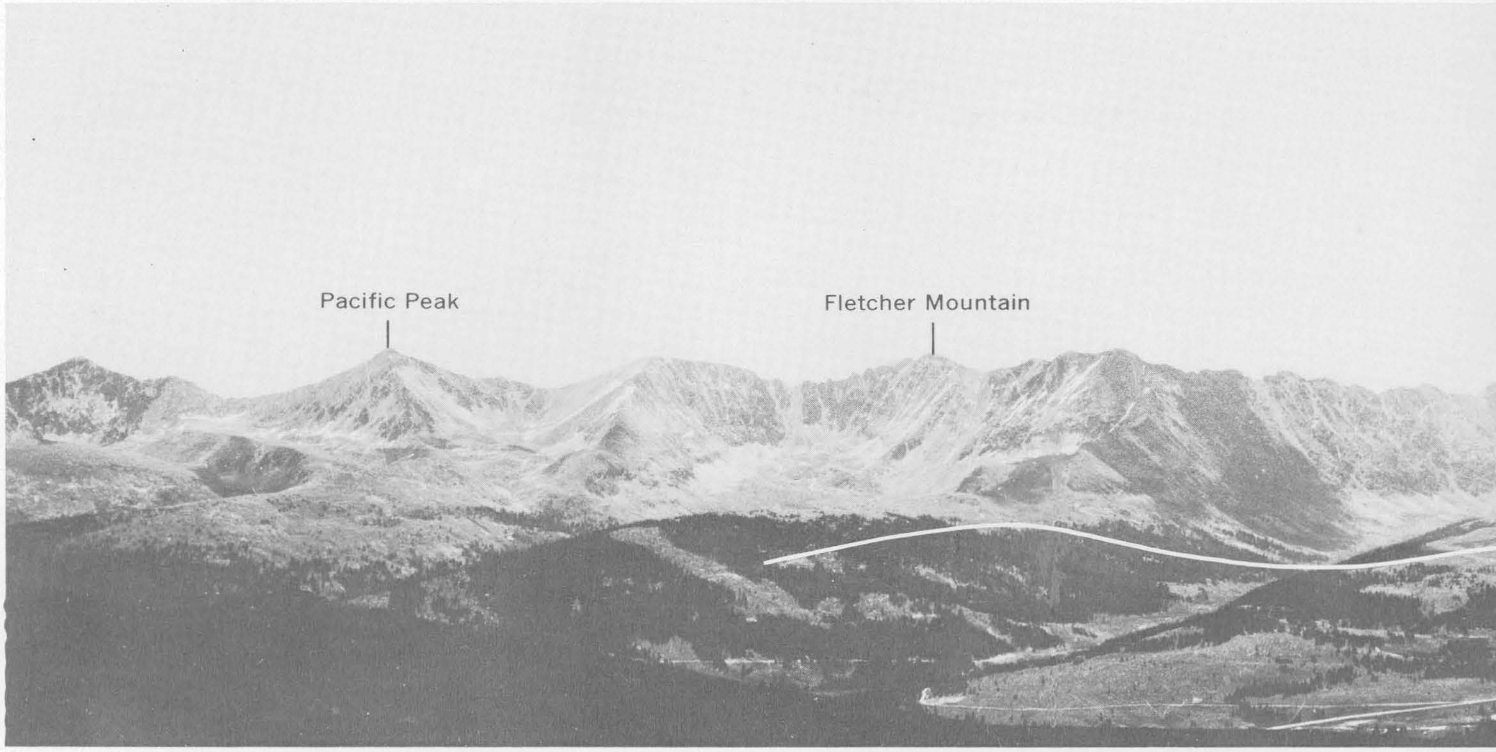
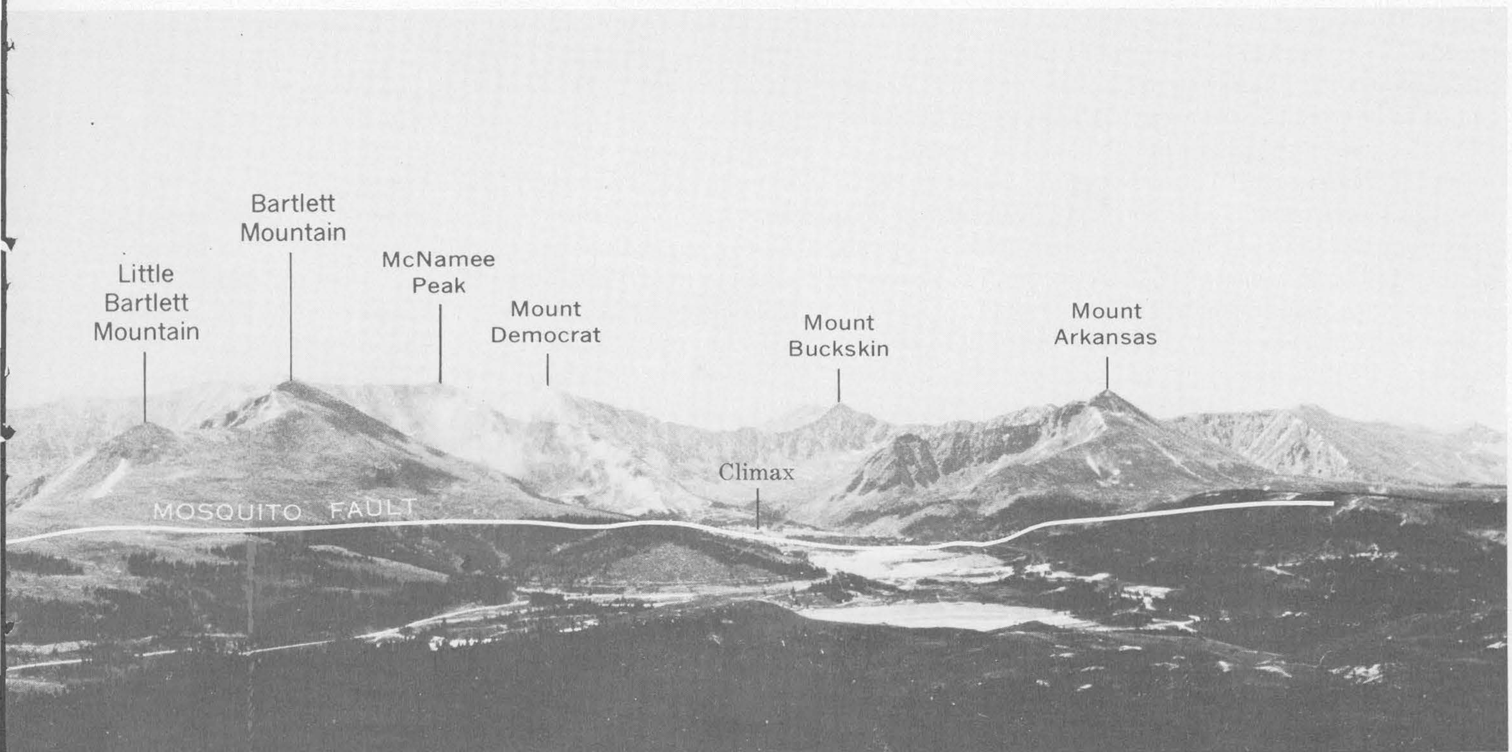


FIGURE 8.—View from the west of southern part of Tenmile Range, showing approximate trace of Mosquito fault and t
Jagged ridges and cirque walls cons



rupt change of topography across the fault. Rounded slopes in foreground are of Minturn and Maroon Formations.
f Precambrian crystalline rocks.

FOLDS IN PRECAMBRIAN ROCKS

Textures and structures of the Precambrian rocks indicate deformation by plastic flowage, probably under conditions of high temperatures and pressures and deep burial. The rocks show strong foliation; this foliation is marked by a preferred mineral orientation, which is concordant with compositional layering and is thus assumed to be parallel with original bedding in the rocks. Lineations are also generally developed in the plane of foliation either parallel to the axes of major folds (*b* lineation) or perpendicular to them (*a* lineation). The most common is the *b* lineation, which locally consists of drag-fold axes, mineral alinements, small-scale warps and wrinkles, and slickensides.

The Precambrian rocks have been folded into at least one large doubly plunging anticline, the axis of which plunges northwest north of Mayflower Gulch and southeast in Pacific and Clinton Gulches. The limbs of the fold dip from about 40° to vertical. Superimposed on the limbs of this large fold are many smaller ones; some of these are parallel to the main fold axis, others are related to other Precambrian tectonic events. The large anticline is outlined by outcrops of granulite, banded gneiss, and migmatite in Humbug Creek and Pacific, Mayflower, and Clinton Gulches. Granulite forms the core of the anticline. The core is bordered by banded gneiss, which swings around the southeast-plunging nose of the anticline. Migmatite overlies the banded gneiss. Granulite is not found northwest of Pacific Gulch, except for a few small outcrops along Tenmile Creek. The abundant northwest-plunging *b* lineations in the migmatite on Copper Mountain indicate that the axis of the main fold plunges to the northwest and that the granulite is at a considerable distance beneath the surface.

No large folds related to any other period of deformation were found, although it is possible that they may be present but unrecognizable in a thick homogeneous unit such as the migmatite. Small folds, on the other hand, are abundant and their attitudes were determined by measurements of *b* lineations. At places in the Copper Mountain area, numerous southwest- and a few northeast-plunging folds were noted in addition to those of northwest trend. In Pacific Gulch a belt of steep northeast-plunging lineations is conspicuous, and in Clinton Gulch two southeast-plunging trends of folding were found. No consistent and clear-cut age relations among the different fold directions could be determined because only rarely could more than one set of lineations be found superimposed on another, and none of these examples displayed conclusive evidence that one set preceded the other.

FOLDS IN PALEOZOIC ROCKS

In the western part of the district, the northeast-dipping beds in the Minturn and Maroon Formations are part of the monocline that forms the east flank of the Sawatch Range. The continuity of the monocline is disrupted in places by great sill-like intrusions of Elk Mountain Porphyry that have pushed apart the sedimentary rocks, causing changes in dip and strike; the normal outcrop pattern of the Minturn and the Maroon is broken by irregularly shaped plugs and dikes of this same material. In the central and eastern parts of the district the sedimentary strata are warped into a broad asymmetrical northwest-plunging syncline, called the Kokomo syncline by Koschmann and Wells (1946, p. 89, 90), the trough and northeast limb of which are partly truncated by the Mosquito fault. Dips on the northeast limb of the syncline are, in general, steeper than those on the southwest limb. The northeast limb is rather poorly defined, owing to irregularities caused by the intrusions of the quartz monzonite stock and several large masses of Elk Mountain Porphyry. The northeast limb of the syncline is also poorly defined in the northern part of the district because of the abrupt thinning of the sedimentary section, which has brought the Precambrian-Pennsylvanian unconformity to the surface, introducing anomalous dips and strikes.

To the northwest the strike and dip of the Kokomo syncline merges into the regional monoclinal strike and dip. The Kokomo syncline does not appear on the geologic map of the Minturn quadrangle (Lovering and Tweto, 1944), and no evidence of it was found in the Dillon quadrangle to the north (Bergendahl, 1969).

UNCONFORMITIES

The sedimentary rocks of the district show extreme variations in thickness from place to place; in addition, many units are sporadically distributed, and few, if any, are present in their total thickness.

Only a few local patches of pre-Pennsylvanian sedimentary rocks are found in the area. On the ridge between Mayflower Gulch and Humbug Creek and extending into Mayflower Gulch to the vicinity of the Boston mine, is a strip of poorly exposed sedimentary rocks, roughly 150 feet thick, that comprises parts of the Leadville Dolomite and the Chaffee Formation, and possibly parts of the Harding Quartzite and the Peerless Formation. A small area of lower Paleozoic sedimentary rocks, including Sawatch Quartzite, also appears near the top of Chalk Mountain between rhyolite on the west and steeply eastward-dipping beds of the Minturn Formation on the east. A thin layer of Sawatch Quartzite occurs on the southeast slope of Copper Mountain between Precambrian gneiss and the Minturn Formation. Little Bartlett Mountain, in the southeastern part of the district, is capped by a small remnant of Sawatch Quartzite, with conglomerate at its base, which, in turn, rests on Precambrian Silver Plume Granite.

Apparently, the main sedimentary basin during pre-Pennsylvanian time was west and southwest of the Kokomo-Tenmile area, and the local areas of sedimentary rocks of earlier Paleozoic age represent deposition during intervals of maximum incursion of the sea. Possibly, these rocks originally covered the entire region and were eroded before Pennsylvanian sedimentation, leaving only remnants in the lower areas. Considering the incomplete thicknesses of the formations in these patches, it seems more reasonable to assume that the rocks did not originally cover the area completely and that the sea level fluctuated widely, resulting in sporadic and interrupted sedimentation.

The maximum thickness of the Minturn Formation in this area is not known, but it ranges from 1,000 feet or less in the northern part to probably 5,000 feet in the southern part. Thinning occurs at both the top and bottom. On Copper Mountain the Robinson Limestone Member, which is about 4,200 feet above the base of the Minturn, overlies a bed of bouldery conglomerate 7–10 feet thick, which, in turn, lies on Precambrian gneiss. In the southern part of the district at least 2,000 feet of Minturn beds below the Robinson is exposed, and the total depth to the Precambrian surface below the Robinson may be as much as 5,000 feet. Apparently, the upper part of the Minturn was eroded from the northern part of the district before deposition of the Maroon Formation. The Jacque Mountain Limestone Member, which forms the top of the Minturn Formation, cannot be traced into the northeast limb of the Kokomo syncline in the Tucker Gulch–Copper Creek area. The Maroon Formation, however, extends uninterrupted along the ridge from Jacque Peak to Union Mountain, except where it is cut by bodies of porphyry.

Koschmann and Wells (1946, p. 86, 87) postulated warping during deposition of the Minturn Formation. They noted inconsistencies in strikes and dips that led them to divide the formation locally into three homoclinal units, each characterized by different attitudes of the beds.

The Maroon Formation overlaps all older sedimentary units in this area and rests directly on Precambrian rocks at several places along the west flank of the Gore Range in the southwestern part of the Dillon quadrangle just north of the Kokomo-Tenmile area.

Evidence, then, indicates a great amount of crustal instability during Pennsylvanian time, with the strandline apparently in the vicinity of Copper Mountain and the positive area of Precambrian rocks, which shed coarse debris into a steep-sided basin, to the north. Later, the margin of the basin gradually shifted northward, as indicated by the overlap of the Maroon red beds.

ORE DEPOSITS

Ore deposits in the Kokomo-Tenmile district occur as massive sulfide replacement bodies and as veins. The replacement deposits, which consist of large irregular masses of pyrite, sphalerite, and galena, are the most important economically and occur in three limestone members of the Minturn Formation. Lead, zinc, silver, copper, and gold have been the chief metals produced from the district. The deposits are found on the northwest side of Tenmile Creek, on the south end of Elk Ridge, on East Sheep Mountain, and on the south end of Jacque Ridge. A few deposits have been mined along the trace of the Mosquito fault, on Gold Hill, and in Mayflower and Clinton Gulches.

Two types of vein deposits are pyrite-sphalerite-galena veins and barren carbonate veins. Only a few of these have been exploited to any extent. A third type of deposit is that which was developed under high temperature and consists of veins, disseminations, and replacement bodies characterized by magnetite, garnet, and molybdenite.

The deposits display a rough concentric zoning, with the high-temperature deposits in the center, near an area of intrusive and volcanic activity, and the sulfide replacement deposits and veins in a peripheral zone that contains most of the important mines. Mineralization probably occurred as an aftermath of Tertiary igneous activity, inasmuch as the deposits are closely associated with Tertiary porphyry bodies and later fractures.

REPLACEMENT DEPOSITS

The district was inactive and all mines were inaccessible when this report was written; consequently, most of the following data were taken from Koschmann and Wells (1946, p. 92–104), Emmons (1898, p. 4, 5) and from unpublished notes and sketches by Koschmann.

The replacement deposits consist of large masses of sulfide minerals that were formed in limestone beds of the Robinson, White Quail, and Jacque Mountain Limestone Members of the Minturn Formation. Because of their economic importance, these limestones have been carefully mapped throughout the district. Certain small-scale aspects of permeability and chemical composition have made these limestones amenable to attack by mineralizing solutions, whereas intervening limestone members, such as the Elk Ridge, are unmineralized. The factors responsible for the selective mineralization of

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the limestones were not determined. Thin sections revealed no significant textural differences—all the limestones are dense and have very low porosity.

STRUCTURAL RELATIONS

The replacement ore bodies occur on both sides of intersections of limestone strata with nearly vertical normal faults that trend N. 50°–60° E.; thus, their long dimensions plunge down the dip of the limestone beds (fig. 9). The mineralizing solutions apparently originated at some depth, ascended along the fissures, and spread laterally along the contacts of the limestones with the overlying relatively impermeable shale or porphyry.

Later movement occurred along many of the mineralized faults, and numerous new faults, also trending northeast, were formed after mineralization ceased. Emmons (1898, p. 5) reported that the ore bodies in the White Quail mine are offset on the north by a fault and a dike, both of which trend northeastward. He

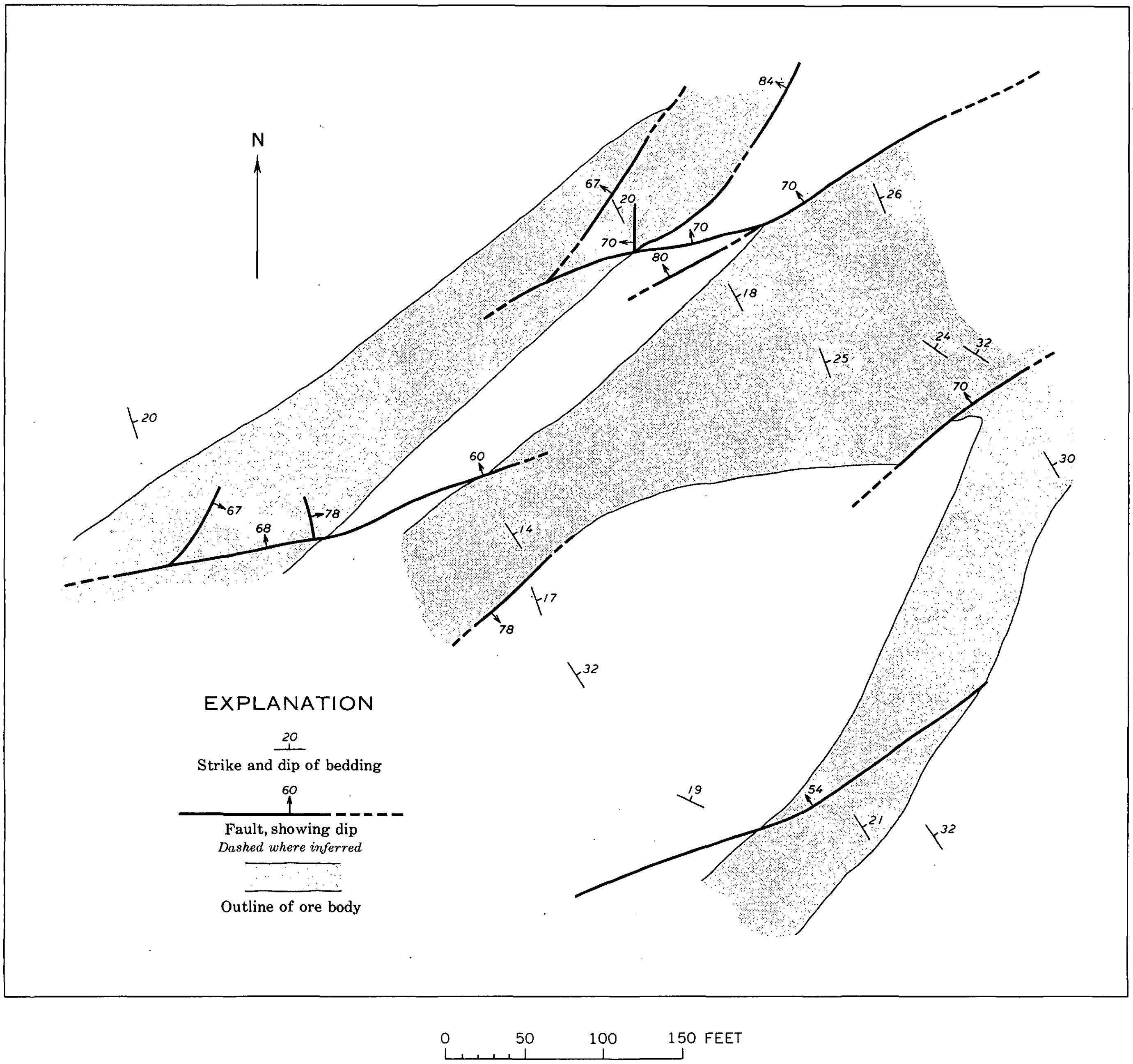

FIGURE 9.—Generalized sketch of ore bodies in middle part, White Quail Limestone Member, showing relation of ore with northeast-trending faults. From Michigan mine, Kokomo-Tenmile district.

also noted that faults trending N. 40° E. cut off ore bodies in the Robinson mine and that a fault trending in general parallel with Tenmile Creek dislocates an ore body that was found in workings extending from the New York shaft. This fault, which is not shown on the geologic map, apparently also was found in workings in the Daughenbaugh shaft, on the west side of Robinson Flat. No evidence, however, could be found of any major fault system in the Tenmile Valley to the northeast.

Other faults associated with the replacement deposits are longitudinal, or strike, faults, reported by Emmons (1898, p. 5) in the workings of the White Quail mine. No faults of this type have been recognized on the surface, although Koschmann and Wells (1946, p. 96) suggested that the extreme width of outcrops of some of the strata in the Minturn Formation on Elk Ridge might be due to duplication of the beds by strike faults. Bedding-plane faults, characterized by seams of clay gouge and dislocation of mineralized vertical fractures, were also observed underground by Koschmann.

Underground mapping in the Lucky Strike-Victory mine revealed a close association of ore with small anticlinal rolls whose axes plunge down the dips of the limestones. The rolls, which are only a few feet in amplitude, may have influenced ore deposition by creating areas of greater permeability, by spreading apart of layers, by causing minute fractures, or by impeding the normal flow of solutions, which would cause slight velocity changes and turbulence where nucleation could occur.

SIZE AND SHAPE OF ORE BODIES

The replacement ore shoots are irregular in size and range in length from 100 feet to more than 2,000 feet and in thickness from a few inches to 30 feet. A typical ore body is shown in figure 10. Replacement progressed outward from both sides of the fissures along the tops of the limestones, and then downward. As a result, the upper surfaces of ore bodies are fairly even and regular and are defined by the top of the limestone, but the bases are undulatory and wavy (fig. 10). The widths of ore shoots are also variable along their plunge.

VARIETIES OF ORE

Most of the ore produced before 1900 came from oxidized ore bodies that were mined principally for lead and silver. These ore bodies, now completely mined out, overlay the massive sulfide ore, and consisted of limonite or goethite, cerussite, anglesite, manganese oxides, and smithsonite, and, locally, of small amounts of azurite, malachite, chrysocolla, native gold, native silver, pyromorphite, and cerargyrite. The oxidized deposits were

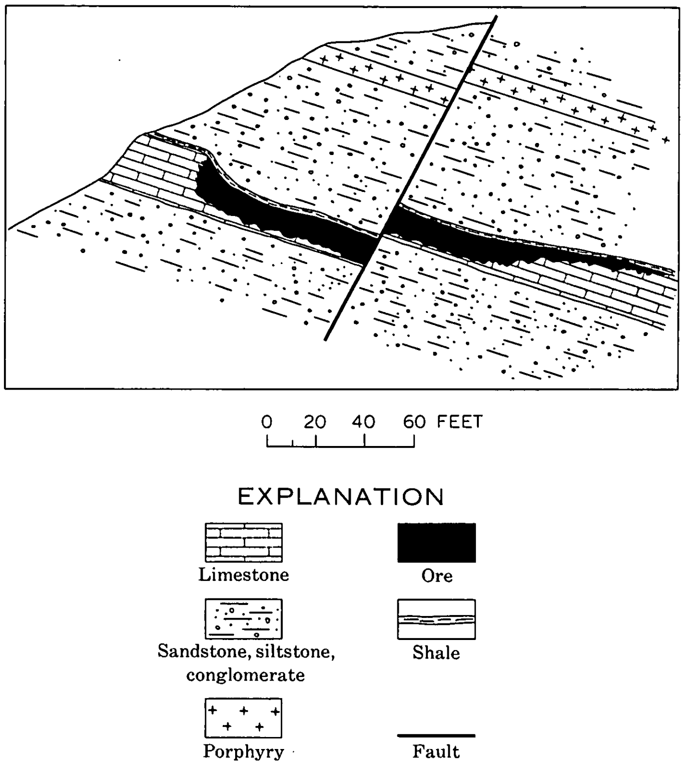

Figure 10.—Diagrammatic section of typical replacement deposit.

irregularly distributed throughout the district and were formed during an erosion cycle that was unrelated to the present topography. Relatively unaltered sulfides are found practically at grass roots in many mines in the Jacque Mountain and White Quail Limestone Members, but deposits in the Robinson Limestone Member are oxidized to various depths, down the dip.

In general, the unoxidized ore consists of large irregularly shaped masses of pyrite, pyrrhotite, marcasite, sphalerite, and galena, surrounded by jasperoid and cut by later carbonate veins and veinlets; however, within any ore body, several textural varieties of ore may be present. Much of the ore throughout the district is banded; individual layers range in thickness from less than ½ to 2 inches (fig. 11). Banding is commonly parallel to bedding in the limestone, but, locally, it is discordant, especially where the layers become obscure. Undulating bands are common in ore from the Lucky Strike-Victory mine. Individual bands or layers typically display a graphic texture in which large tabular crystals of pyrite are intergrown with sphalerite and galena. Banded copper ores with similar concordant relations with the bedding of the host limestone are described by Boutwell (1905, p. 193–194) from the Bingham district of Utah.

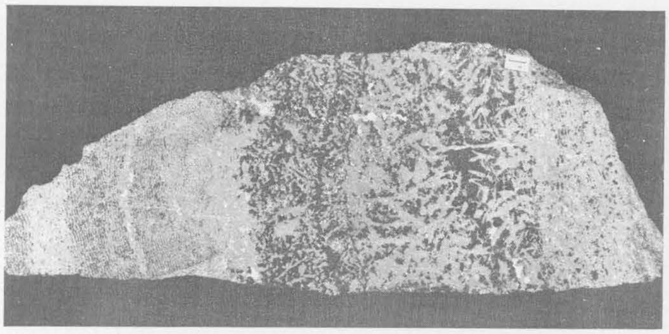

FIGURE 11.—Polished slab of sulfide ore from the Wilfley mine, showing banding and graphic texture. Gray is pyrite; black is sphalerite.

In places the limestone is brecciated; this brecciation is due in some areas to solution and collapse, and in others, to faulting. The breccia fragments are cemented with sulfides, and vugs and cavities are lined with well-formed crystals of pyrite, sphalerite, galena, quartz, and carbonates (fig. 12).

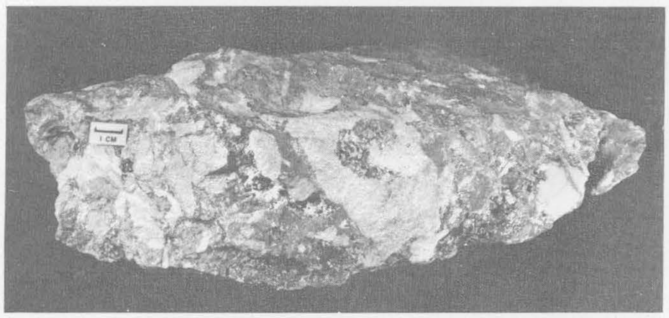

FIGURE 12.—Brecciated limestone cemented and partly replaced by fine-grained sulfides. Vugs are lined with pyrite and sphalerite crystals. Wilfley mine.

Locally, as in the Lucky Strike-Victory mine, large masses and pods of solid galena occur in the mixed sulfide ore (fig. 13).

WALLROCK ALTERATION

Widespread silicification preceded deposition of the sulfides in the replacement deposits, but the transition laterally from mineralized to unmineralized limestone may have been abrupt or gradual. Emmons (1898, p. 5) reported a gradation, through an interval of 500 feet, from solid sulfide, through quartz impregnated with sulfides, to barren jasperoid, then through friable dolomite, which the miners called "short lime," to unaltered limestone. Conversely, in the Lucky Strike–Victory mine, galena was found in contact with fresh limestone. Replacement vertically is generally limited to the limestone containing the ore, except for thin intervals in the sedimentary rocks above the ore bodies. A zone of sericitized sandstone, 1–2 feet thick, that is impregnated

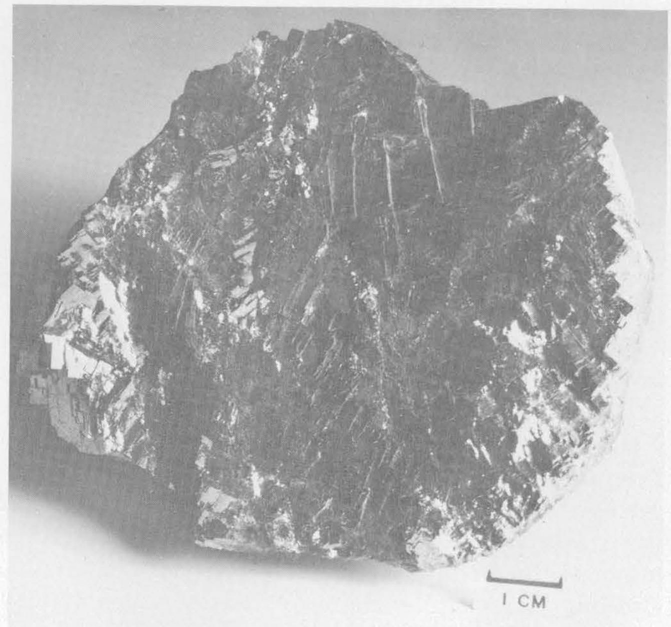

FIGURE 13.—Solid galena from the Lucky Strike-Victory mine.

with marcasite overlies ore bodies in the Robinson Limestone Member. Some deposits in the White Quail Limestone Member are overlain by a thin seam of pyritiferous black shale or jasperoid.

DEPTH OF ORE

The replacement ore shoots are discontinuous bodies and extend from the outcrop for hundreds of feet down the dips of the limestone beds, which are folded into an open, northwest-plunging syncline. The depth of ore, therefore, is dependent on the configuration of the surface, the stratigraphic position of the limestone containing the ore, and the distance of any given point on the plunging structure from the surface. Many ore bodies are faulted, but their vertical displacement caused by faulting is in most places 100 feet or less. The deepest workings in the district were in the Wilson shaft, the bottom of which was 1,200 feet below the level of Tenmile Creek, in the vicinity of Robinson Flat.

The tenor of ore in the Robinson and White Quail Limestone Members was found to decrease with depth; this decrease resulted from the virtual disappearance of the silver- and lead-rich oxidation products from the ores. Depth alone apparently was not a factor in variation of grade of unoxidized sulfide ore shoots.

The total depth to which the replacement ore bodies were mined in the Kokomo-Tenmile district was determined more directly by the relation of mining costs to the market prices of lead, zinc, and silver than to depletion of ore.

GRADE OF ORE

Oxidized replacement deposits, rich in lead and silver and containing small amounts of gold, were mined in the early years of activity in the district. High-grade oxidized ore near the surface in the Robinson mine yielded as much as 400 ounces of silver per ton in 1879 (Eng. Mining Jour., 1881, p. 59, 92). Oxidized ore from the White Quail mine produced 40–100 ounces of silver per ton and 40–60 percent lead in 1879 (Eng. Mining Jour., 1879, p. 456). The grade of ore in the Robinson mine decreased somewhat in later years, averaging 57 ounces of silver per ton for 11 months during 1885–86 (Eng. Mining Jour., 1886, p. 198). Oxidized ore was also mined from the White Quail Limestone Member in the early years. Ore in the Wilfley mine contained 30 ounces of silver and 20 percent lead (Burchard, 1883, p. 556, 557). The oxidized ores were also locally rich in gold. Emmons (1898, p. 5) reported that ore from the White Quail mine assayed from 0.20 to 2 ounces of gold per ton, the average being close to the lower value.

As the oxidized ores became depleted in the late 1890's, attention was turned to the large primary deposits of pyrite, pyrrhotite, sphalerite, and galena, which had hitherto been virtually undeveloped because of the penalty payments levied by the smelters on high zinc content of ore shipments. The success of the Wilfley table, whereby sphalerite could be separated from the milled ore, heralded a new era of production from the massive sulfide deposits. These deposits contain variable amounts of lead and zinc and minor amounts of silver, gold, and copper. Lead values range from trace amounts to 40 percent, and zinc from several tenths of a percent to 27 percent. In general, silver content does not seem to be directly related to either zinc or lead content; it ranges from 0.84 to 78 ounces per ton of ore and the average for all mines is close to 5 ounces. Gold is a minor component and rarely is present in quantities greater than 2 ounces per ton. Copper, also a byproduct, is absent from many ore bodies, but it constituted 0.44 percent of some ore in the White Quail Limestone Member. Copper content was not recorded in early assays, probably because the copper content was below the commercial limit of 1.5 percent.

Some small, but consistent, differences can be ascertained in the metal content in sulfide ore bodies in the various limestone members. Ore from the Robinson Member is slightly richer in lead and silver, whereas ore bodies in the Jacque Mountain Member seem to be the highest in gold content (table 4). Copper is sporadic in its occurrence but is most abundant in the White Quail Member ore shoots; most of the copper production has come from the Michigan and Lucky Strike–Victory mines, but only an infinitesimal amount has been produced from the Wilfley mine, which is also in the White Quail (table 4).

VEIN DEPOSITS

Although the vein deposits of the district are of little economic importance, they are widely distributed in both sedimentary and metamorphic rocks. Two main types have been recognized: carbonate veins and pyrite-sphalerite-galena veins.

Most of the veins are fissure fillings and have formed by deposition from hydrothermal solutions in open spaces. Crustified layering, vugs, and breccia fragments cemented by ore minerals are common features. The nature of the wallrock seems to bear no relation to the distribution of ore shoots or mineral assemblages.

CARBONATE VEINS

Veins consisting mainly of coarse calcite and a little quartz but containing almost no sulfides are common but are of little economic importance. These carbonate veins are associated with both sulfide veins and replacement deposits; in both associations they are late in the

TABLE 4.—*Average grade of ore from some of the major mines, computed from total production from 1902 to 1950*

[Leaders (...) indicate no production]

Mine	Limestone member of Mintum Formation	Zinc (percent)	Lead (percent)	Copper (percent)	Silver (ounces per ton)	Gold (ounces per ton)
Robinson	Robinson	5.53	7.51	Trace	5.25	0.029
Champion	do	...	1.82	...	11.5	.046
Wilson	do	10.0	3.4	0.08	3.4	.06
Little Ivory (Robinson shoot 4)	do	...	2.63	...	69.8	1.03
New York	do	...	1.69	...	15.45	.14
Felicia Grace	do	...	5.11	.004	14.5	.03
Lucky Strike-Victory	White Quail	13.3	3.7	.089	2.9	.027
Wilfley	do	5.2	1.3	.003	2.4	.05
Michigan group	do	.7	.71	.14	4.7	.098
Selma	Jacque Mountain	6.39	6.67	...	10.7	1.5
Wintergreen	do	...	.016	.02	1.7	.29
Free America	do	26.4	3.6	.04	.84	.17

sequence of mineralization, filling open spaces in the central parts or filling fractures that transect the earlier sulfides. Most carbonate veins are narrow and do not persist for any great distance, though a few are of considerable magnitude. Koschmann and Wells (1946, p. 106) reported calcite veins on Tucker Mountain 12–20 feet thick and 750–2,000 feet long.

PYRITE-SPHALERITE-GALENA VEINS

Fissure veins containing pyrite, sphalerite, and galena are widespread throughout the district, but are only locally of any economic importance.

These veins occur in both the sedimentary and metamorphic terranes and fill faults and fractures that trend in almost every direction. In the vicinity of Kokomo and Searle Gulches and the area of Sheep Mountain and Elk Ridge, many of the steeply inclined fissures that guided the solutions that formed the replacement deposits are themselves filled with pyrite, pyrrhotite, sphalerite, and galena, and have been mined along with the massive replacement bodies. Some of these veins are useful guides to replacement ore bodies in the limestone beds above or below the known mineralized interval (Koschmann and Wells, 1946, p. 106).

The vein mineralogy is similar to that of the replacement deposits, except that the minerals that appear late in the paragenetic sequence seem to be more abundant in the veins. Pyrite, sphalerite, and galena are the major sulfides, but, locally, chalcopyrite is common. In ores from the Gold Crest and the Queen of the West mines chalcopyrite occurs as irregular masses in sphalerite and galena. Microscopic reticulated particles of native gold are present between pyrite grains in polished sections of ore from both of the above mines. Ruby silver minerals are also common in small amounts in the vein deposits. Pearcite(?) was found in the Queen of the West mine, and tiny blebs of an unidentified ruby silver mineral showing strong red internal reflection were seen in a polished section from the Littler mine in Clinton Gulch. Fine lamellae of hematite were noted in other polished sections of vein material.

ORE BODIES

The ores of the sulfide veins have yielded small amounts of lead, silver, zinc, and gold, primarily from the Queen of the West mine, on the southeast slope of Jacque Peak. Early production data on this mine could not be found, but from 1902 to 1948 a total of 533 tons of ore yielded 28 ounces of gold, 17,439 ounces of silver, 102 pounds of copper, 8,537 pounds of lead, and 1,059 pounds of zinc. Veins have also been worked on a small scale in the past on Bald Mountain, in Clinton Gulch, and in Mayflower Gulch, from which the Gold Crest mine shipped 516 tons of ore containing 635 ounces of gold, 706 ounces of silver, and 699 pounds of lead during the period 1934 through 1938.

The ore shoots in the Queen of the West mine occur along a series of parallel fissures in the Maroon Formation and Elk Mountain Porphyry. The fissures strike N. 60°–70°E. and are nearly vertical. The richest ore was produced from the oxidized parts of the veins and extended to 200–300 feet below the surface (Emmons, 1898, p. 5).

The Gold Crest mine is on a shear zone in Precambrian migmatite. The shear trends N. 80°–85° E. and is nearly vertical. Ore bodies are narrow pods, less than 2 feet thick, that contain chalcopyrite, pyrite, galena, sphalerite, and native gold. Other veins in the Mayflower Gulch area are on high-angle shears and faults that trend N. 75° E., N. 40°–50° W., and N. 10°–15° W.

Nearly all veins show evidence of considerable movement during mineralization and afterward. Much early pyrite is fractured, and the fractures are healed with sphalerite or gangue minerals. Quartz that is early in the paragenetic sequence is shattered and cut by veinlets of later quartz. Brecciated and pulverized ore was frequently seen along fissures, and in the Queen of the West mine, Emmons (1898, p. 5, 6) reported that movement on nearly flat bedding-plane faults offset some of the ore bodies along the steep fissures.

MAGNETITE-GARNET-MOLYBDENITE DEPOSITS

Mineral deposits in the vicinity of Copper and Tucker Mountains contain an assemblage characteristic of Lindgren's hypothermal or pyrometasomatic classes of ore deposits (Lindgren, 1933, p. 637–745). These deposits were formed at higher temperatures (300°–500° C) and possibly at somewhat higher pressures than the sulfide replacement bodies to the south and southeast. Garnet, epidote, chlorite, sericite, and biotite occur throughout this area as aggregates, large replacement masses, disseminations, and fissure fillings in the sedimentary rocks. Calcite, wollastonite, and hornblende were noted at a few localities (Koschmann and Wells, 1946, p. 98). Commonly, the country rock is converted to quartzite. Where mineralization was most intense, entire beds are converted to garnet or biotite. Epidote is the most widespread of the introduced minerals. It characteristically is found as clusters or disseminations, but, in places, entire shaly or silty laminae have been converted to epidote and chlorite.

Small vein and replacement deposits of molybdenite, pyrite, and sparse chalcopyrite, accompanied by magnetite and specular hematite, are scattered throughout the area of metasomatic alteration. In the upper D and G tunnel, for example, a bed of garnet 2½–5 feet thick and about 300 feet long was impregnated with molybdenite (Koschmann and Wells, 1946, p. 98). Molybdenite and pyrite also occur as disseminations in the outer part of the quartz monzonite stock along the west side of Colorado Highway 91, just south of Tucker Gulch.

An area including the north end of Tucker Mountain, the northeastern part of Jacque Peak, and the southeast flank of Union Mountain has been pervasively saturated with pyritic solutions. Both sedimentary and igneous rocks are thoroughly impregnated with pyrite, the weathering of which has imparted a conspicuous yellowish-brown stain to all the outcrops.

Hematite-quartz fissure veins are abundantly distributed throughout the Precambrian rocks in the eastern part of this report area and also in the Precambrian area to the north (Bergendahl, 1963, p. 19). They are rarely found west of the Mosquito fault. These veins are of very simple mineralogy, containing mostly quartz and minor amounts of hematite. Occasionally, a few grains of pyrite and molybdenite can be seen when viewed with the microscope.

Although several attempts have been made to mine the molybdenite concentrations in these high-temperature deposits, none has been successful because of the small size and erratic grade of the shoots.

ZONING OF ORE DEPOSITS

A direct relation clearly exists between the character of the ore deposits and gangue minerals and the centers of intrusion on Copper and Tucker Mountains. The distribution of epidote and garnet has been plotted on figure 14 and shows a rough concentric zoning of garnet and epidote metasomatism in the sedimentary rocks. This metasomatism is not pervasive, but consists of local seams, knots, and clusters, and, less commonly, of a complete replacement of all, or parts of, certain limestone strata by garnet or epidote. In many areas silicification is a related feature, and certain beds above or below a layer, for example, impregnated with garnet, may be converted to quartzite. Other minerals, such as chlorite, biotite, hornblende, or wollastonite, are associated with both garnet and epidote, but their distribution is local and erratic.

Analyses of garnets from samples collected from various localities throughout the area of metasomatism are given in table 5. The calcic garnets andradite [$Ca_3(Fe^{+3},Ti)_2Si_3O_{12}$] and grossularite ($Ca_3Al_2Si_3O_{12}$), which are the common garnets of contact metasomatic deposits, are the most abundant here as well. Spessartite ($Mn_3Al_2Si_3O_{12}$) was present in amounts of 5 percent or less in two of the samples.

The boundaries of the zones are arbitrarily determined from the density of outcrop, the distribution of the sedimentary rocks, and the frequency of local pockets or occurrences of the introduced minerals. Two inner areas of garnet metasomatism are included in, and are surrounded by, a much larger zone of epidotization. One garnet zone forms an elliptical area between Copper and Union Mountains. The other is a roughly circular area, less than a mile in diameter, on Tucker Mountain. Epidote is more widespread and is found throughout an irregularly shaped area extending from Jacque Peak 3½ miles eastward across Tenmile Creek, and from a point just south of Cresson Gulch, northward about 3 miles to the north slope of Copper Moun-

TABLE 5.—*Varieties of garnet from the Jacque Peak-Tucker Mountain-Copper Mountain area*

[Analyst, E. J. Young. Unit cell size calculated by method of Bradley and Jay (1932); composition determined on basis of diagram by Stockwell (1927, p. 327), as modified by Skinner (1956, p. 428)]

Location	Field No.	Serial No.	X-ray film No.	Unit cell size (in angstroms)	Refractive Index (*n*)	Composition
D and G tunnel	42-K-15	271092	5216	12. 040 ± 0. 006	1. 886 ± 0. 003	100 percent andradite, with <5 percent of other end members.
East slope Tucker Mountain.	44-K-1	271095	5301	12. 004 ± 0. 006	1. 820–1. 855	Andradite, 60–80 percent; grossularite, 20–40 percent.
Iron Mask Gulch, Jacque Peak.	44-K-8b	271096	5289	12. 054 ± 0. 004	1. 888 ± 0. 004	100 percent andradite with <5 percent of other end members.
Copper Mountain	44-K-95	271097	5304	12. 020 ± 0. 005	1. 883 ± 0. 006	2 garnets intergrown with each other. Type 1 is zoned, symmetrically twinned, birefringent, pale pink; is 80 percent andradite and 20 percent grossularite. Type 2 is yellow, isotropic; is 95 percent andradite and 5 percent spessartite.
Tucker Gulch	44-K-113a	271098	5291	11. 932 ± 0. 004	1. 786–1. 810	Grossularite, 55–65 percent; andradite, 35–45 percent; possibly 5 percent spessartite.
Do	44-K-113c	271099	5224	11. 951 ± 0. 005	1. 803–1. 815	Andradite, 50 percent; grossularite, 50 percent.

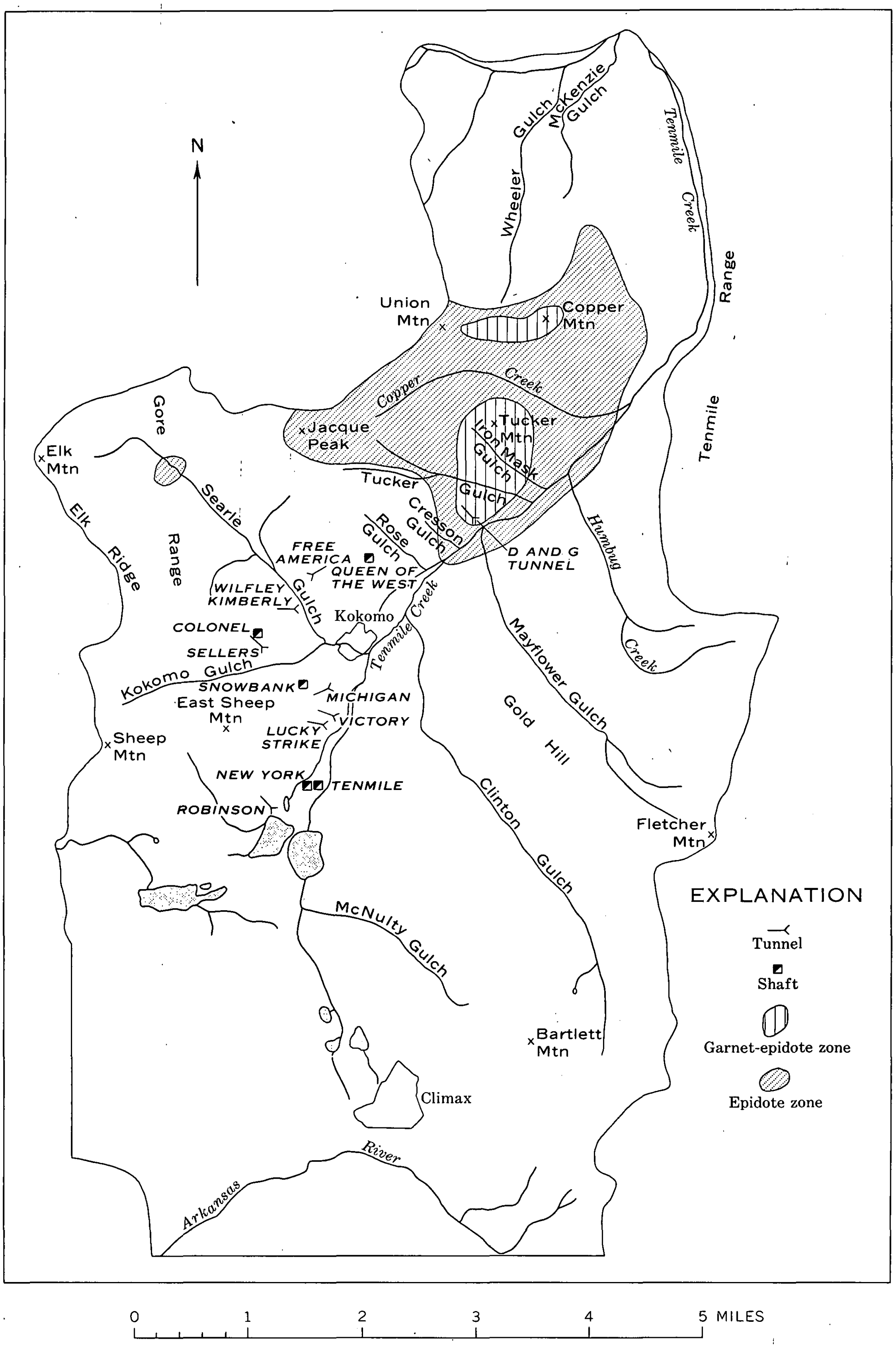

FIGURE 14.—Map of Kokomo-Tenmile district showing areas of garnet and epidote alteration.

tain. A small isolated area of epidote alteration was also found in the upper part of Searle Gulch.

The larger zones of alteration are directly related to sources of heat and mineralizing solutions. The garnet center on Tucker Mountain is adjacent to the small body of porphyritic quartz monzonite of probable Tertiary age and the volcanic rocks of late Paleozoic age. The garnet zone in the Copper Mountain–Union Mountain area is along the south edge of a large sill-like mass of Elk MountainPorphyry of Tertiary age. Furthermore, both zones are on the northwest side of the Tertiary quartz monzonite stock that crosses the Tenmile Range and intrudes the Minturn Formation along Tenmile Creek, just south of Tucker Gulch.

The types of ore deposits are also distributed in a pattern that coincides in a general way with the zones of alteration. The high-temperature molybdenite-garnet-magnetite deposits are found throughout the garnet and epidote zones, and the sulfide veins and replacement deposits are peripheral to them, to the southwest in the Searle Gulch–Elk Ridge–Kokomo Gulch–Sheep Mountain area and to the east and southeast in the Mayflower Gulch, Gold Hill, and Clinton Gulch areas.

A subtle, but systematic, variation in mineralogy of the replacement deposits has also been noted. Pyrrhotite, which may be diagnostic of high-temperature environment of deposition, is most abundant in deposits in the Jacque Mountain Limestone Member. These deposits are just southwest of the epidote zone. Gold seems to be slightly more abundant in the Jacque Mountain Limestone Member deposits. Deposits in the White Quail Limestone Member, ¼–½ mile to the south and southwest of the Jacque Mountain deposits, contain considerably less pyrrhotite. Deposits in the Robinson Limestone Member, which are most remote from the epidote and garnet metasomatism, are virtually barren of pyrrhotite. The other common vein minerals, such as pyrite, galena, sphalerite, and chalcopyrite, occur in all deposits in different quantities, but they do not show any orderly variation which could be related to the zonal pattern.

Whether a depth zoning is present could not be fully determined because of a lack of accessible deep underground workings. The epidote area in the upper part of Searle Gulch is apparently unrelated to any larger or more intense alteration or mineralization at depth. Hole 6 of a drilling program conducted by the U.S. Geological Survey (Koschmann, 1949) during 1948–49 was drilled to test this area. The hole was inclined −45° S. 50° W., normal to the dips of the beds. Total depth was 466 feet. No indication of epidote or garnet alteration was found in the log. The middle part of the White Quail Limestone Member was penetrated at 453 feet and contained only a trace of pyrite and some calcite-filled fractures.

HYPOGENE ORE MINERALS

The primary or hypogene ore minerals are relatively few in number and comprise assemblages that are commonly found in base-metal replacement deposits and veins and contact metasomatic deposits throughout Western United States. The most abundant metallic minerals are pyrite, marcasite, pyrrhotite, sphalerite, galena, chalcopyrite, molybdenite, magnetite, and hematite. Minor amounts of arsenopyrite, tetrahedrite, fluorite, enargite, pearcite(?), and gold are found locally.

The hypogene ore minerals are the original precipitates from the ore solutions and were deposited in a fairly orderly sequence, although their relative abundance varies from one deposit or type of deposit to another.

A complete list of primary and secondary ore minerals is given in table 6. These minerals are grouped according to their classification in Palache, Berman, and Frondel (1944, 1951), but the individual minerals are

TABLE 6.—*Primary and secondary minerals of the ore deposits, Kokomo-Tenmile district*

Primary	
Sulfides:	
Pyrite	FeS_2
Sphalerite	ZnS
Pyrrhotite	$Fe_{1-x}S$
Marcasite	FeS_2
Galena	PbS
Arsenopyrite	$FeAsS$
Molybdenite	MoS_2
Chalcopyrite	$CuFeS_2$
Sulfosalts:	
Pearcite(?)	$(Ag,Cu)_{16}As_2S_{11}$
Tetrahedrite	$(Cu,Fe)_{12}Sb_4S_{13}$
Enargite	Cu_3AsS_4
Native element:	
Gold	Au
Oxides:	
Hematite	Fe_2O_3
Magnetite	$FeFe_2O_3$
Halide:	
Fluorite	CaF_2
Carbonate:	
Rhodochrosite	$MnCO_3$
Secondary	
Sulfide:	
Covellite	CuS
Carbonates:	
Cerussite	$PbCO_3$
Smithsonite	$ZnCO_3$
Malachite	$Cu_2(OH)_2(CO_3)$
Azurite	$Cu_3(OH)_2(CO_3)_2$
Sulfate:	
Anglesite	$PbSO_4$
Oxides:	
Limonite (probably goethite with adsorbed or capillary water)	
Pyrolusite	MnO_2
Psilomelane	$BaMn\ Mn_8O_{16}(OH)_4$
Native element:	
Silver	Ag

listed in order of their relative abundances. The gangue minerals will be considered separately.

PYRITE

Pyrite is by far the most abundant of the primary ore minerals. It is the major constituent of the massive sulfide replacement deposits and is the common sulfide of the veins. It also is disseminated in parts of the quartz monzonite stock and in numerous porphyry sills and dikes, especially in the Copper Mountain–Tucker Mountain area.

The pyrite is commonly coarse grained; many vugs and cavities are lined with cubes and pyritohedrons. Large masses of granular, coarse-grained pyrite with pyrrhotite and small amounts of galena and sphalerite are characteristic of the ores in the Jacque Mountain Limestone Member. Three general textural varieties of pyrite were noted. In areas where pyrrhotite is absent, coarse-grained pyrite is the oldest of the sulfides. Microscopic examinations of polished sections reveal that this early pyrite is fractured and extensively replaced by sphalerite and galena (fig. 15*A*). Some of this early pyrite shows "exploded bomb" replacement texture in which closely spaced pyrite remnants that have ragged outlines are engulfed in coarse-grained galena or sphalerite.

Associated with pyrrhotite is another variety of pyrite, which occurs as small irregularly shaped grains that appear to lie along cleavage directions in the larger pyrrhotite grains (fig. 15*B*). Kullerud and Yoder (1959, p. 566–567) have shown that pyrite cannot form directly from a melt, but that it forms from pyrrhotite + gas at temperatures below the incongruent melting point, which rises about 14°C per 1,000 bars increase in pressure (fig. 16). The presence of pyrrhotite in the final assemblage is determined by bulk composition rather than by temperature. If the bulk composition is more sulfur rich than pyrite, then pyrrhotite will be consumed. If it is less sulfur rich than pyrite, then pyrrhotite and pyrite will be a stable assemblage. These relations are shown on the Fe-S binary (fig. 17), which has been revised from Kullerud (1964, p. 235). Sulfur vapor was present in all the reactions. In hydrothermal systems, additional volatile components, such as H_2O and CO_2, will be present, and these will affect the phase boundaries, as shown in figure 17. The foregoing discussion is intended to describe a principle of possible pyrrhotite-pyrite relations and is not an explanation of the actual field conditions for the hydrothermal system in the Kokomo-Tenmile district.

The third type of pyrite is a fine-grained species that was deposited contemporaneously with the gangue minerals, after galena and chalcopyrite. This late pyrite was observed in polished sections of samples from the Wilfley mine (fig. 15*C*), the Uthoff tunnel, the Robinson mine, and the Colonel Sellers mine.

Gold, which has been a byproduct of the sulfide ores, occurs in pyrite, probably as submicroscopic blebs. Analyses of four samples of pyrite separates (table 7) showed a maximum of 3.4 ppm of gold (roughly 0.1 oz per ton of pyrite). The tellurium content of the samples was negligible.

TABLE 7.—*Gold and tellurium chemical analyses, in parts per million, of samples of pyrite from the Kokomo-Tenmile district*

[Analysts: J. B. McHugh and J. H. Turner]

Serial No.	Field No.	Mine name	Gold	Tellurium
65-70-S	45-K-32	Index	3.4	<0.1
71-S	42-K-6	Lucky Strike	2.0	<.1
72-S	45-K-118b	Wilfley	2.3	<.1
73-S	45-K-119	do	1.4	<.1

SPHALERITE

From the standpoint of tonnage mined, sphalerite was the most important ore mineral produced from the district. Huge masses of sphalerite and pyrite (for example, see fig. 11) form large parts of the replacement ore bodies in such mines as the Wilfley-Kimberly, Lucky Strike–Victory, Robinson, Colonel Sellers, and Michigan. Sphalerite is also a major constituent of the vein deposits. Individual crystals range in diameter from less than 1 mm to 5 cm.

Most of the sphalerite of the Kokomo-Tenmile district is the high-iron variety marmatite and is reddish black. Semiquantitative spectrographic analyses of samples from several mines (table 8) show that the iron content ranges from 0.7 percent to more than 10 percent. Locally in the Jacque Peak area, amber-colored sphalerite lines vugs in veins or occurs as small masses in replacement deposits.

Nearly all the sphalerite examined contains chalcopyrite, visible under the microscope as minute blebs or stringers (figs. 18*A*, 19*A*). In some specimens the small bodies are arranged along the cleavage of the sphalerite. In one specimen from the Wilfley mine (fig. 15*D*), composite blebs of chalcopyrite, galena, and pyrrhotite were found in the sphalerite. The texture of these closely resembled exsolution texture, but their origin cannot be explained simply as a function of falling temperature. B. J. Skinner (written commun., Mar. 29, 1965) suggested that exsolution of pyrrhotite and chalcopyrite occurs mainly in response to increase in sulfur pressure and also that many so-called exsolution textures are in reality depositional features along crystal planes during growth of the sphalerite. A thin section

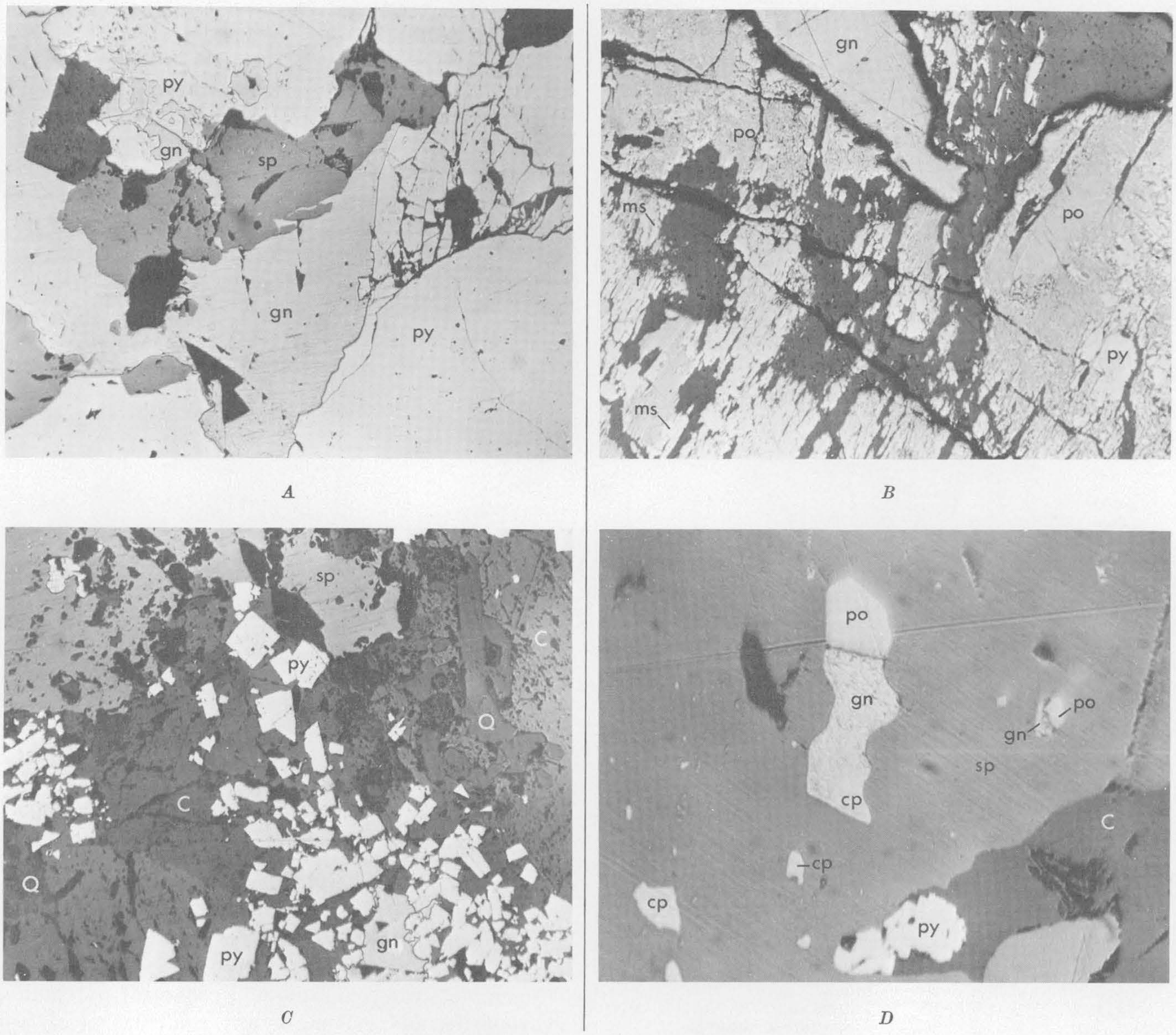

FIGURE 15.—Photomicrographs of polished sections. *A*. Pyrite (py) replaced by sphalerite (sp) and galena (gn). × 60, Lucky Strike mine. *B*. Pyrrhotite (po) partly replaced by pyrite (py) and marcasite (ms). Galena (gn) cuts across earlier pyrrhotite at top. Dark-gray areas are quartz. × 60, Michigan mine. *C*. Late fine-grained pyrite (py) deposited contemporaneously with quartz (*Q*) and carbonate (*C*) that are later than sphalerite (sp) and galena (gn). × 60, Wilfley mine. *D*. Composite bleb of pyrrhotite (po), galena (gn), and chalcopyrite (cp) in sphalerite (sp). Other minerals are pyrite (py) and carbonate gangue (*C*). × 500, Wilfley mine.

was made in an attempt to check the relations between zoning of the sphalerite and distribution of the blebs; but, unfortunately, the sphalerite was almost opaque because of its high iron content, and not enough light could be transmitted through the mineral for meaningful observations.

Sphalerite was deposited during a single stage in the formation of the ore deposits. This stage was preceded by an interval of fracturing of the earlier deposited pyrrhotite and pyrite. The sphalerite was, in turn, fractured, and the fractures were filled with galena and other later minerals.

Although most of the silver of the district is associated with galena, quantitative spectrographic analyses revealed small amounts present also in sphalerite (table 8). Because no discrete silver-bearing inclusions were found in the sphalerite, the silver probably occurs in cationic form in the crystal lattice.

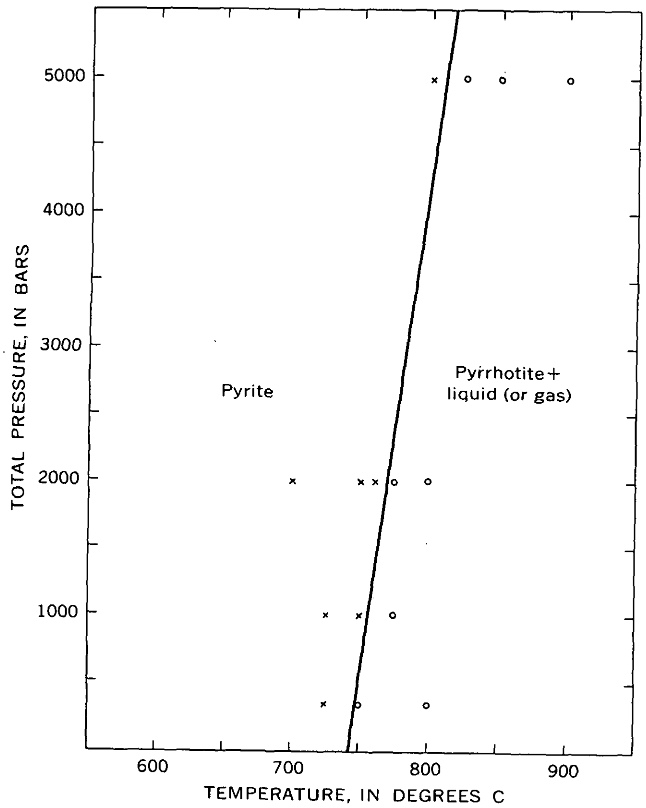

FIGURE 16.—Univariant curve for the reaction $FeS_2 \rightleftarrows Fe_{1-x}S +$ liquid or gas. From Kullerud and Yoder (1959, p. 554).

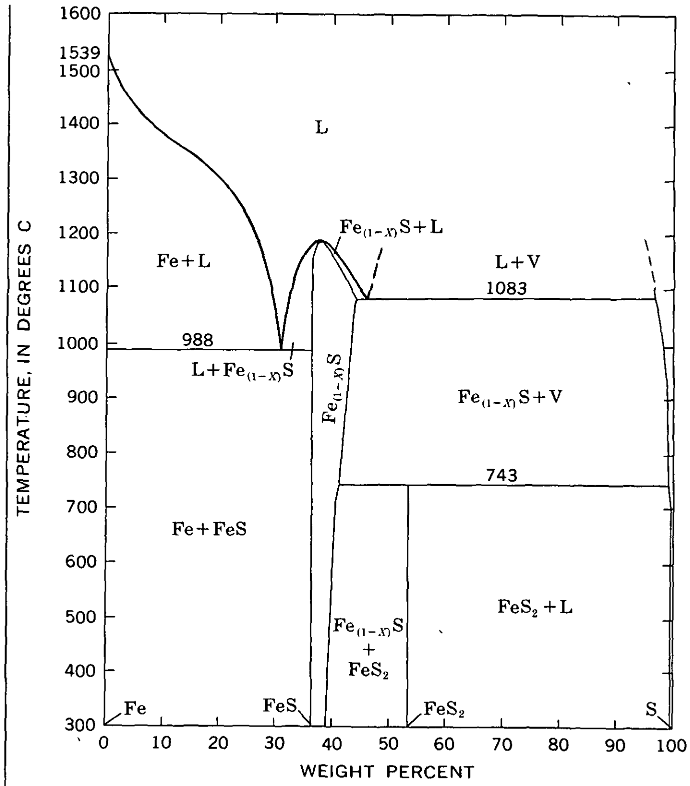

FIGURE 17.—Phases in the Fe-S system. From Kullerud (1964, p. 235). L, liquid; V, vapor.

TABLE 8.—*Quantitative spectrographic analyses of sphalerite for silver, Kokomo-Tenmile district*

[Analyst, A. L. Sutton, Jr.]

Laboratory serial No	Field No.	Mine	Silver[1] (percent)
D116306	KC 4629	Robinson	0.013
6308	42-K-9	Wilfley	.012
6312	45-K-32	Index	.012
6314	45-K-98	Tunnel in Spaulding Gulch.	.011
6315	45-K-118b	Wifley	.027
6319	45-K-119	do	.0057
6320	45-K-135c	Lucky Strike	.024

[1] Analyses have an overall accuracy of ±15 percent, except that they are less accurate near limits of detection, where only 1 digit is reported

PYRRHOTITE

Large bronze-colored masses of granular pyrrhotite mixed with pyrite are abundant in the replacement deposits in the Jacque Mountain Limestone Member, especially in the Selma, Wintergreen, and Free America mines. Locally, pyrrhotite is a major component of ores in the White Quail Limestone Member. It was detected in specimens from the Lucky Strike–Victory, Wilfley, and Michigan mines. Pyrrhotite is generally absent from ore bodies in the Robinson Limestone Member and from the vein deposits in the Clinton and Mayflower Gulch areas.

Under the microscope pyrrhotite seems to be the earliest of the sulfides and to be accompanied generally by pyrite. It also occurs as tiny blebs in sphalerite, which exhibit a texture generally ascribed to exsolution. Some of these blebs are composite and consist of pyrrhotite, chalcopyrite, and galena, or any combination of two of these phases (fig. 15*D*).

Marcasite, in feathery lamellae, and pyrite commonly replace pyrrhotite in cracks and along cleavage (fig. 15*B*). Although far from conclusive, evidence suggests that the alteration of pyrrhotite to marcasite and pyrite was hypogene and occurred before deposition of sphalerite. The sphalerite shown in figure 18*A* has engulfed, and partly digested, an irregular grain of pyrrhotite and marcasite.

MARCASITE

Marcasite is fairly abundant in most of the massive sulfide ores of the district. It is difficult to detect in hand specimens because of its small grain size and its close association with pyrite; however, it is easily rec-

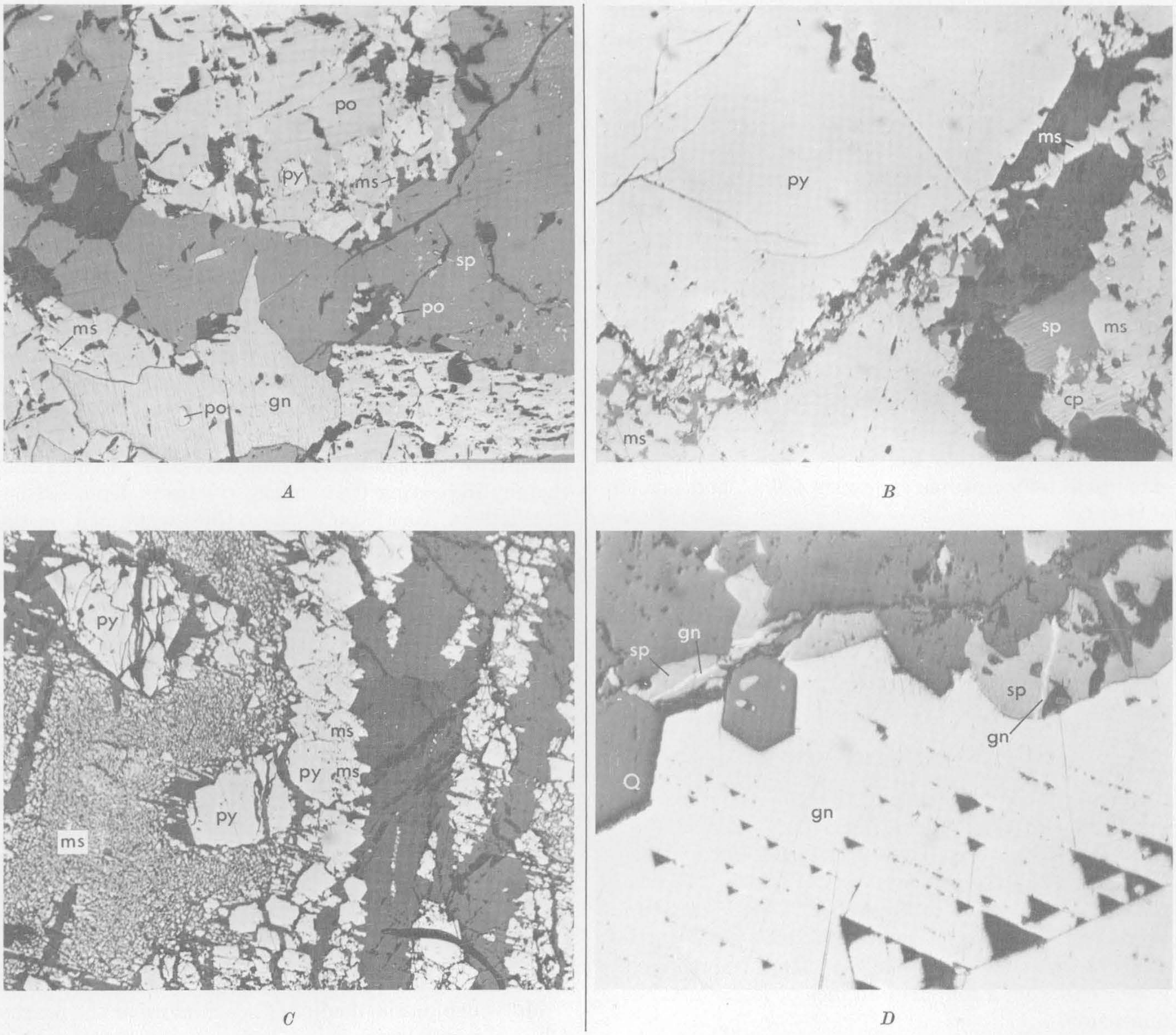

FIGURE 18.—Photomicrographs of polished sections from the Michigan-Snowbank, Triangle, and Lucky Strike mines. *A*. Grains of pyrrhotite (po) partly replaced by pyrite (py) and marcasite (ms), and etched by sphalerite (sp). Galena (gn) cuts sphalerite and pyrrhotite. × 60, Triangle mine. *B*. Large grains of early pyrite (py) coated with marcasite (ms). Sphalerite (sp) and chalcopyrite (cp) fill cavity between pyrite grains. × 175, Lucky Strike mine. *C*. Cellular marcasite (ms) coating fractured pyrite (py) grains. × 60, Michigan-Snowbank mine. *D*. Apophyses of galena (gn) cutting across sphalerite (sp). Quartz (Q) is gangue. × 175, Michigan-Snowbank mine.

ognized under the microscope in polished sections as feathery lamellae that replace pyrrhotite, as tiny euhedral grains coating earlier pyrite (fig. 18*B*), or as vug fillings between pyrite grains. A specimen from the Michigan-Snowbank mine contains fine cellular marcasite that corrodes and embays earlier coarse-grained fractured pyrite (fig. 18*C*). Fractures and cracks that cut the cellular marcasite are lined with later marcasite. Both generations were deposited before sphalerite. A sample from the Wilfley mine is an intergrown aggregate of marcasite and coarse cubic pyrite grains.

Newhouse (1925, p. 59–61) described two types of marcasite from the Free American (Free America) and Michigan mines in the Kokomo district. One type is in the form of concentric shells, 0.5 cm thick, that replace pyrrhotite and, to a lesser extent, pyrite. The second type consists of small globular masses 2–3 mm in diameter scattered through pyrrhotite and grouped around small pyrite crystals. Many veinlets of marcasite form a network connecting the slightly larger spheroids. Where they are well developed, a grill pattern is seen. Newhouse (1925, p. 64–66) considered the marcasite to be of hypogene origin because of its association with carbonate and later pyrite and quartz.

The field of stability of marcasite in terms of temperature and pressure in the Fe-S system is difficult to delineate because of the sluggishness of the pyrite-marcasite inversion. Kullerud and Yoder (1959, p. 539) found that marcasite inverted to pyrite in 2-weeks' time at 400°C. At 350°C no change was noted for a period of 6 months. They were not able to invert pyrite to marcasite to any temperature. They tentatively concluded, therefore, that the field of stability of pyrite extends to temperatures as low as 400°C, and presumably lower.

Mixtures of pyrite and marcasite were obtained in experiments at temperatures as high as 300°C. But, because of the long period of time required to attain the temperature in the thick-walled pressure vessels, marcasite may have grown at lower temperatures and persisted metastably at the temperature of the run (Kullerud and Yoder, 1959, p. 539).

GALENA

One of the most valuable of the economic minerals of the veins and replacement deposits, galena, occurs in close association with pyrite, pyrrhotite, and sphalerite. Large masses of galena, a sample of which is shown in figure 13, were found in the stopes of the Victory mine in the pinched limbs of small anticlines. Some crystals measure 2 inches on a side, but most commonly the galena cubes are a fourth of an inch or less in maximum dimension.

Galena occurs late in the sequence of hypogene minerals. The microscope reveals tiny veinlets and apophyses of galena that cut sphalerite (fig. 18*D*) and large masses of galena that engulf and embay pyrrhotite, sphalerite, and early pyrite (fig. 19*A*). Galena also replaces pyrite along cracks and cleavage surfaces.

Much of the silver produced from the primary ores of the district is associated with galena as very small inclusions with red internal reflections, which are best seen under high magnification. These inclusions probably are some form of ruby silver, but they were too small to be identified. Some galena has curved rows of triangular cleavage pits, but no relation between inclusions and pits could be seen.

CHALCOPYRITE

Chalcopyrite occurs sparingly in nearly all the ores of the district. Most commonly, it is in the form of small grains interstitial to other sulfides or in tiny veinlets. Masses as large as 12 inches in diameter have been noted in some of the replacement ore bodies. Small amounts of chalcopyrite occur in sphalerite, producing a texture strongly resembling the so-called exsolution texture. Myriads of tiny blebs, stringers, and segregation veinlets, many of which are alined along cleavage, are common in the sphalerite of the district (fig. 19*A*).

The paragenetic relations of chalcopyrite and the other sulfides are not always clear. In a polished section from the Michigan mine, F. G. Wells (unpub. data) observed sphalerite that was cut by veinlets of chalcopyrite; the ends of these veinlets near the outside margin of the sphalerite grain were filled with galena, thereby indicating that chalcopyrite was deposited before galena. In all polished sections examined by the authors, chalcopyrite was definitely later than sphalerite, but it exhibited mutual boundaries with galena. The "exsolution" chalcopyrite probably is contemporaneous with sphalerite and may have unmixed from solid solution.

Considerable alteration of chalcopyrite to covellite was noted in several specimens (fig. 19*B*).

ARSENOPYRITE

D. F. Kent (unpub. data) reported isolated small masses of arsenopyrite in massive pyrite-pyrrhotite bodies in the Victory and Colonel Sellers mines. Apparently, the mineral is only of sporadic occurrence, for none was seen in any of the polished sections examined.

MOLYBDENITE

Molybdenite, the dominant ore mineral at the nearby Climax molybdenum mine, occurs in small amounts in the high-temperature veins and replacement deposits of the Kokomo-Tenmile district; however, no economic deposits have been found. In the Tucker Mountain–Copper Mountain area, molybdenite is associated with garnet, magnetite, quartz, pyrite, and chalcopyrite. Parts of the quartz monzonite stock are interlaced by veinlets of pyrite and molybdenite, and in some of the veins of the Tenmile Range, molybdenite occurs sparingly with quartz, pyrite, and specular hematite.

When examined under the microscope, the molybdenite appears as scattered laths, lamellae, and small fibrous masses (fig. 19*C*). Many of the grains are bent. The molybdenite fills fractures in garnet and magnetite and is accompanied by quartz and pyrite.

TETRAHEDRITE

Although D. F. Kent (unpub. data) reported small irregular masses of tetrahedrite from the Gold Crest mine, no positive identification of the mineral was made by the authors. Some tiny grayish blebs seen under high magnification in galena from the Robinson and Wilfley mines could have been tetrahedrite, but these grains were too small to be tested by optical, microchemical, or X-ray techniques.

ENARGITE

Only one occurrence of enargite was seen in this investigation. In a polished section made from a specimen from the Wilfley mine, small inclusions of enargite, roughly 0.01 mm in maximum dimension, were observed in chalcopyrite.

PEARCEITE(?)

Several ore specimens from the Queen of the West mine contain small irregular grains of a greenish-gray anisotropic mineral that was tentatively identified as pearceite. The mineral is present as tiny inclusions in galena and as larger grains, as much as 0.1 mm across, associated with galena, chalcopyrite, and sphalerite (fig. 19*A*). It is clearly later than sphalerite and was probably deposited contemporaneously with galena and chalcopyrite. The mineral displays the characteristic optical properties of pearceite, and etch tests indicate that it is one of the sulfosalts; nevertheless, some uncertainty does exist that it is pearceite. Two hardness determinations on the mineral gave Vickers hardness numbers of 133 and 140, which are somewhat lower than the 153–164 range given for pearceite by Cameron (1961, p. 264). In addition, Schouten (1962, p. 25, 175) comments that polybasite and pearceite cannot be distinguished under the ore microscope.

GOLD

Native gold occurs in recoverable amounts in ores from all three of the principal limestone host rock units of the district (table 4), as well as from the vein deposits. Small amounts of placer gold are found in

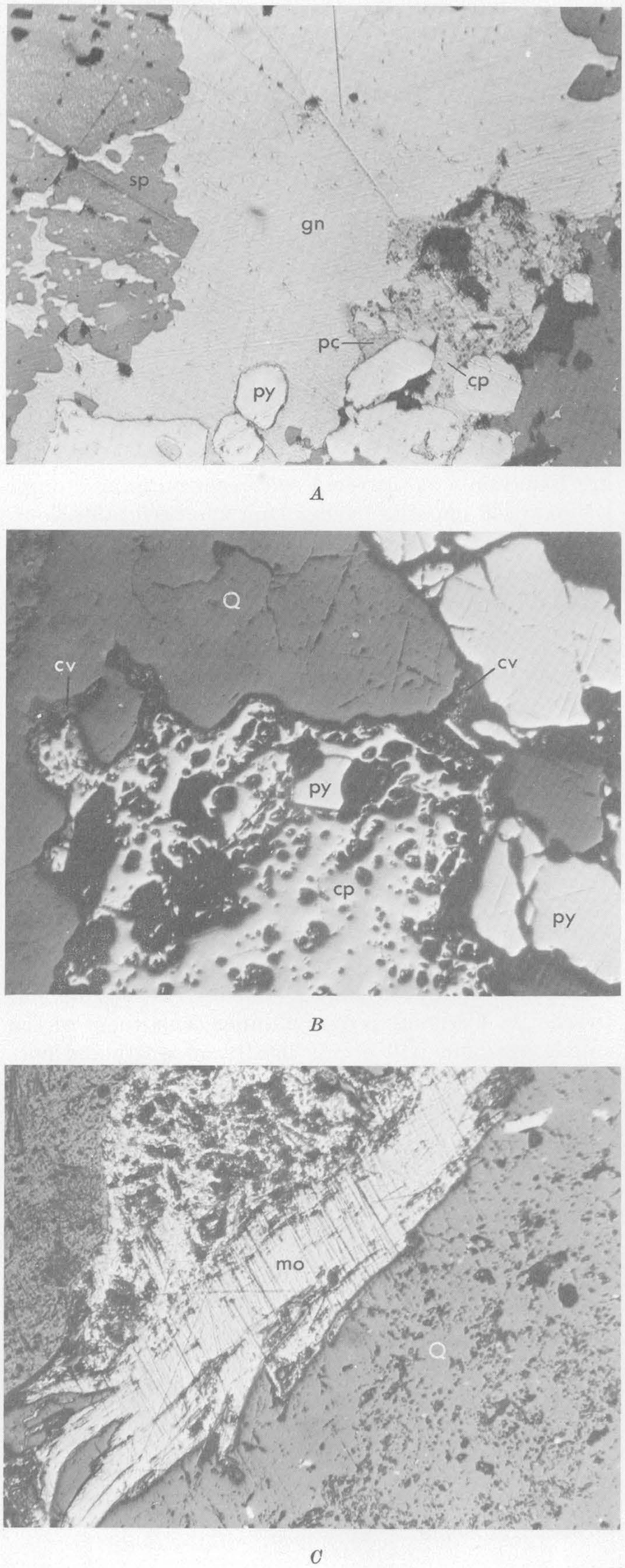

FIGURE 19.—Photomicrographs of polished sections from the Queen of the West and Gold Crest mines and from a prospect in Cresson Gulch. *A*. Galena (gn) engulfing and replacing pyrite (py) and sphalerite (sp). Pearcite(?) (pc) and chalcopyrite (cp) are probably contemporaneous with galena; cloudy area in upper left is due to blebs of exsolved chalcopyrite. × 175, Queen of the West mine. *B*. Chalcopyrite (cp) partly altered to covellite (cv). Other minerals are pyrite (py) and quartz (Q). × 60, Gold Crest mine. *C*. Feathery laths of molybdenite (mo) in quartz (Q) gangue. × 60, unnamed prospect in Cresson Gulch.

stream gravels in many of the gulches and in the main valley of Tenmile Creek.

Gold is not megascopically visible in the Kokomo-Tenmile ores, but a few grains were seen under the microscope in specimens from the Queen of the West and Gold Crest mines. The gold is in the form of small reticulated grains interstitial to pyrite and also as tiny flecks in pyrite (see also p. 30).

MAGNETITE

Small amounts of magnetite are associated with garnet and epidote in the high-temperature deposits. Most commonly, the magnetite is present as grains disseminated through the altered rock, but, locally, solid masses several feet in maximum dimension crop out. Magnetite is also found as clusters of grains as large as several inches in diameter in some of the pegmatites in the Tenmile Range.

Microscopic examination of polished sections showed that magnetite replaces some shattered garnet grains and coats others with fine films, outlining the crystal form. Molybdenite was deposited later, filling fractures and cracks in both garnet and magnetite.

HEMATITE

Earthy red masses and crusts of hematite are found throughout the district. Specularite, the bladed variety of hematite, is associated with magnetite in the high-temperature deposits in the Tucker Mountain–Copper Mountain area. Some veins are composed of quartz, specular hematite, and a little pyrite in the Mayflower Gulch area. The hematite partly replaces pyrite along some grain boundaries and was probably deposited contemporaneously with quartz.

FLUORITE

Fluorite, a sparse mineral in the Kokomo-Tenmile district, was found as small light-green crystals in a few veins near the Payrock mine at the head of Mayflower Gulch.

RHODOCHROSITE

Small aggregates of pink to colorless crystals of rhodochrosite are associated with pyrite, quartz, and dolomite in a few narrow veins on Gold Hill and in Mayflower Gulch.

SUPERGENE MINERALS

The supergene or secondary ore minerals are products of oxidation, during which the original primary sulfides are dissolved in acid sulfate waters generated by oxidizing pyrite. Precipitation of secondary copper and silver sulfides occurs upon neutralization of the acid solutions. Zinc comonly travels farthest in sulfate solutions and is generally deposited as smithsonite in carbonate rocks, or as hemimorphite and other forms where calcite is not abundant. Galena is the least affected by acid sulfate waters and, if altered, is oxidized in place to cerussite and anglesite. Hydrous iron and manganese oxides are ubiquitous in the oxidized zone. Occasionally, metals will remain in solution and will percolate downward to the water table, where, in the absence of oxygen, they will react with pyrite and other sulfide minerals and precipitate as copper sulfides, silver sulfides, sulfarsenides, and sulfantimonides, and as native silver.

The principal supergene minerals of the Kokomo-Tenmile district are covellite, cerussite, smithsonite, malachite, azurite, anglesite, limonite, pyrolusite, psilomelane, and native silver. Most of these minerals are found only as scattered specimens on mine dumps, the oxidized deposits having long ago been mined out.

COVELLITE

Small amounts of covellite are found as coatings and replacement products of chalcopyrite. In all specimens examined, replacement of chalcopyrite was incomplete (fig. 19*B*), and the covellite is restricted to rims and minute fracture fillings.

CERUSSITE

The principal lead mineral of the blanket-type oxidized ores, cerussite, was originally abundant throughout the district as white granular or compact masses and as radiating clusters of crystals in limonite. Generally, it is a replacement product of anglesite. Incompletely oxidized ores on Elk Mountain contain cerussite in cracks and cavities in galena, chalcopyrite, pyrite, and pyrrhotite. Cerussite is only a minor constituent of the sulfide ores, but still occurs locally on weathered outcrops of the Robinson, White Quail, and Jacque Mountain Limestone Members.

SMITHSONITE

Large bodies of silver-bearing smithsonite were mined in the early days from the oxidized parts of the Robinson Limestone Member in the Robinson, Nettie B, and Iron Mask mines and from the White Quail Limestone Member in mines on Elk Mountain. The mineral can still be found on mine dumps and on weathered outcrops of the mineralized limestones.

Smithsonite was most abundant as gray compact masses intermixed with silica and iron and manganese oxides. Less commonly, a fibrous crystalline variety lines fractures and forms coatings on the massive variety or on rock fragments.

MALACHITE AND AZURITE

Malachite and, less commonly, azurite locally are present as crusts, as earthy or botryoidal masses, or as velvety coatings on siliceous or limonitic oxidized material. These minerals were most abundant in copper-rich oxidized ores, but not to the extent of being important ore minerals.

ANGLESITE

Thin layers of granular clear anglesite coat many masses of galena in ore bodies in the White Quail and Robinson Limestone Members. The mineral is also fairly abundant on many mine dumps and, locally, on weathered outcrops of the middle part of the White Quail Limestone Member on Elk Mountain. It is the first alteration product formed during the oxidation of galena and is commonly coated with later cerussite.

LIMONITE

Earthy light-yellow to brown masses of hydrous iron oxides, which are generally considered to be limonite or goethite, are the most abundant and conspicuous constituents of the gossans in all deposits in the district. This material is formed from the oxidation of pyrite, pyrrhotite, sphalerite, and chalcopyrite, and is commonly intermixed with clay minerals, zinc and iron sulfates and carbonates, and manganese oxides. Much of the material is soft and friable, but some is hard, owing to cementation by silica. Limonitic boxworks, pseudomorphous after pyrite, were seen at the Victory mine.

PYROLUSITE AND PSILOMELANE

Steel-gray to black masses composed of pyrolusite and psilomelane are intermixed with limonite and clay minerals and earthy black manganese wad in oxidized parts of deposits throughout the district. At the Free America mine in Searle Gulch, pyrolusite occurs in layers that alternate with psilomelane and limonite.

SILVER

Native silver was reported by Koschmann and Wells (1946, p. 107) as a constituent of ores in the lower part of the oxidized zone. D. F. Kent (unpub. field data) observed tiny black flakes and wires of native silver in vugs and fractures in limonite and smithsonite in oxidized ores from the Robinson, Colonel Sellers, and Queen of the West mines.

Apparently, the silver is a secondary product, which was derived from weathering of silver sulfosalts, transported downward as silver sulfide, and redeposited as native silver and possibly argentite.

DISTRIBUTION OF MINOR ELEMENTS IN SULFIDE MINERALS

Grains of pyrite, sphalerite, and galena from ore specimens were carefully handpicked under the binocular microscope and were then analyzed by semiquantitative spectrographic methods to determine the distributions and amounts of minor elements. These analyses are given in table 9. Percentages of silica, aluminum, magnesium, calcium, and sodium were not included in the table, because these elements probably represent inclusions of gangue material in the samples.

Pyrite contains small amounts of lead, copper, zinc, manganese, silver, chromium, gallium, nickel, and ytterbium. The lead, copper, and zinc are probably due, respectively, to small amounts of admixed galena, chalcopyrite, and sphalerite. The small amounts of manganese and nickel are probably present as hauerite, and vaesite or bravoite, all of which are isostructural with pyrite (Fleischer, 1955, p. 1005–1006). The silver in pyrite is possibly alloyed with gold, the gold being present but below the limit of detectability for the semiquantitative spectrographic method (table 9). The chemical analyses of pyrite (table 7) show small amounts of gold. The trace amounts of chromium, gallium, and ytterbium in the pyrite samples probably substitute for Fe^{+2} cations in the pyrite lattice. The ionic radii of these minor elements are 0.62 A for Ga^{+3}, 0.63 A for Cr^{+3}, and 0.86 A for Yb^{+3} (Ahrens, 1952, p. 168), which are close to the 0.74 A radius of Fe^{+2}, so that diadochic substitution could take place according to Goldschmidt's well-known rule.

Silver and antimony are noticeably abundant in the galena relative to their occurrences in pyrite and sphalerite. These elements are probably present as minute blebs of silver sulfantimonides, barely detectable in polished sections. Copper and iron are doubtless present as small inclusions of tetrahedrite. No inclusions of a bismuth-bearing mineral were found in galena, suggesting that the bismuth is probably in the galena lattice, as are beryllium and manganese. The zinc in the galena is no doubt due to sphalerite contamination.

Sphalerite from the Kokomo district contains so much iron that it can hardly be considered a minor element. Most of the iron occurs in solid solution, but a small amount of it, along with all the copper, can be considered to be a component of the chalcopyrite blebs. In a general way, manganese varies directly with iron. Typical of most sphalerites, the Kokomo sphalerite contains abundant cadmium, although no cadmium minerals have been found. Despite a considerable difference of ionic radii, Zn^{+2} (radius 0.74 A) and Cd^{+2} (radius 0.97 A) readily undergo diadochy at the temperatures of ore formation (Rankama and Sahama, 1950, p. 712).

TABLE 9.—*Semiquantitative spectrographic analyses of some sulfide minerals, Kokomo-Tenmile district*

[Looked for, but not detected: K, P, As, Au, B, Ce, Ge, Hf, Hg, La, Li, Mo, Nb, Pd, Pt, Re, Sc, Sr, Ta, Te, Th, Tl, U, V, W, Y, Zr, Eu. Not listed: Al, Mg, Ca, Na, Si. Results are reported in percent to the nearest number in the series 1, 0.7, 0.5, 0.3, 0.2, 0.15, 0.1, etc., which represent approximate midpoints of group data on a geometric scale. The assigned group for semiquantitative results will include the quantitative value about 30 percent of the time. These sensitivities, however, do not apply to the above analyses, owing to dilution of samples of 1.5:1. Symbols used are: M, major constituent—greater than 10 percent; O, looked for, but not detected (see table of detectabilities); <, with number, less than number shown; usual detectabilities do not apply. Possible contamination of samples, in percent: Fe, as much as 0.05; Mn, as much as 0.0002; Cr, as much as 0.0005; Cu, as much as 0.0002; Sn, as much as 0.03]

Mine	Laboratory Serial No.	Field No.	Fe	Pb	Cu	Zn	Mn	Ti	Ag	Ba	Be	Bi	Cd	Co	Cr	Ga	In	Ni	Sb	Sn	Yb
Pyrite																					
Robinson	D116304	KC4633	M	1.5	0.007	0	0.003	0	0.05	0.0007	0	0	0	0	0	<0.001	0	0	0	0.005	<0.0005
Lucky Strike	D116310	42-K-6	M	.5	.002	0	.01	0	.001	0	0	0	0	0	0	<.0015	0	.003	0	0	<.0003
	D116322	45-K-135c	M	.5	.02	.07	.001	0	.002	0	0	0	0	0	.0003	<.0015	0	0	0	0	0
Index	D116313	45-K-32	M	.3	.1	.7	.001	0	.003	0	0	0	0	0	.0002	<.0015	0	.001	0	0	<.0003
Wilfley	D116316	45-K-118b	M	.5	.07	.5	.003	0	.3	0	0	0	0	0	0	<.0015	0	.001	0	.1	<.0003
	D116317	45-K-119	M	.03	.05	.5	.02	0	.003	0	0	0	0	.001	.0002	<.0015	0	0	0	0	<.0003
Galena																					
Robinson	D116305	KC4633	0.3	M	0.003	0.1	0.003	0	0.3	0	0.02	0	0	0	0	0	0	0	0.07	0.01	0
Victory	D116307	KC4913	.03	M	.0007	.2	.0007	0	.15	0	0	<0.002	0	0	0	0	0	0	.05	.002	0
Lucky Strike	D116309	42-K-6	.05	M	.002	.15	.002	0	.2	0	.0015	.02	0	0	0	0	0	0	.05	.015	0
	D116321	45-K-135c	.1	M	.0015	.7	.0003	0	.15	0	0	.015	0	0	0	0	0	0	,05	.003	0
Index	D116311	45-K-32	.1	M	.0007	.1	.001	0	.1	0	0	0	0	0	0	0	0	0	.07	.07	0
Wilfley	D116318	45-K-119	.2	M	.0005	0	.0007		.1	0	0	0	0	0	0	0	0	0	.05	0	0
Sphalerite																					
Robinson	D116306	KC4629	5	2	0.015	M	0.3	0	0.015	0.0007	0	0	0.3	0	0.0002	0	0	0	0	0.01	0
Wilfley	D116308	42-K-9	M	.7	.1	M	.2	0	.01	.0015	0	0.005	.5	0	.0003	.002	.007	.002	0	0	0
	D116315	45-K-118b	M	.1	.3	M	.5	0	.03	0	0	0	.3	0	0	.015	0	0	0	.05	0
	D116319	45-K-119	M	.5	.1	M	.3	0	.007	0	0	.005	.5	0	.0002	.0015	.01	0	0	.005	0
Index	D116312	45-K-32	3	M	.1	M	.015	.03	.015	.0005	0	0	.15	0	.001	.001	.005	0	0	0	0
Tunnel in Spaulding Gulch	D116314	45-K-98	.7	.5	1	M	.002	0	.01	.0005	0	0	.7	0	.0003	0	.005	0	0	0	0
Lucky Strike	D116320	45-K-135c	7	2	.07	M	.15	0	.02	0	0	.003	.7	0	.0003	.0003	.003	0	0	0	0

Approximate visual detection limits for the elements by semiquantiative spectrographic methods

Element	Percent	Element	Percent	Element	Percent	Element	Percent
Si	0.002	Cd	0.005	La	0.002	Sc	0.0005
Al	.001	Ce	.02	Li [1]	.02	Sn	.001
Fe	.0008	Co	.0005	Lu	.01	Sr	.0002
Mg	.0005	Cr	.0001	Mo	.0005	Sm	.01
Ca	.005	Cs [1]	2	Nb	.001	Ta	.02
Na [1]	.05	Cu	.0001	Nd	.01	Tb	.1
K [1]	.7	Dr	.005	Ni	.0003	Te [1]	.1
Ti	.0002	Er	.005	Os	.01	Th	.02
P	.2	Eu	.05	Pb	.001	Tl	.01
Mn	.0002	Ga	.0002	Pd	.0003	Tm	.01
Ag	.0001	Gd	.005	Pr	.05	U	.05
As [1]	.1	Ge	.001	Pt	.003	V	.001
Au	.002	Hf	.01	Rb [1]	10	W	.01
B	.002	Hg [1]	1	Re	.005	Y	.001
Ba	.0002	Ho	.01	Rh	.005	Yb	.0005
Be	.0001	In	.001	Ru	.01	Zn	.02
Bi	.001	Ir	.01	Sb	.01	Zr	.001

[1] Higher sensitivity can be acquired with a second exposure.

Gallium and indium, which have ionic radii very close to those of zinc, are characteristic trace elements in most sphalerites, and are present in average amounts in the Kokomo sphalerite analyses. Chromium, however, is not commonly found in sphalerite, but was detected in all but one sphalerite sample reported in table 9. The presence of this element can be explained by the Cr^{+3} substituting for Fe^{+2}, apparently a not-too-unusual occurrence despite the charge difference (Rankama and Sahama, 1950, p. 622–623).

Of particular interest in table 9 is the absence of molybdenum from all the samples. Molybdenum is not an uncommon trace constitutent in pyrite, sphalerite, and galena in deposits throughout North America (Fleischer, 1955, p. 981, 994, 1008). In view of the occurrences of small molybdenite deposits in the district and the proximity of the huge molybdenite deposit at Climax, one would normally expect to find trace amounts of molybdenum in ore minerals throughout the district. But, if the molybdenite and massive sulfide deposits are of different ages, the absence of molybdenum is not surprising. A very minor difference in age may be sufficient to account for this.

GANGUE MINERALS

Quartz, carbonates, and small amounts of barite are the principal gangue minerals in most of the deposits of the district.

X-ray powder diffraction studies of five samples of gangue strongly suggest the presence of several phases in both the calcite-rhodochrosite-siderite series and the dolomite-ankerite-kutnahorite series. Characteristic curves for dolomite and siderite were noted, but in some samples the 2θ values for dolomite were slightly above or below the true value, indicating crystal defects due to impurities. In one sample, a strong peak fell midway between those characteristic of siderite and rhodochrosite. A curve strongly resembling that of kutnahorite was revealed from another sample. All these facts are compatible with the crystal chemistry of the carbonates. A complete solid solution series exists between siderite ($FeCO_3$) and rhodochrosite ($MnCO_3$), with manganosiderite as an identifiable intermediate product (Palache and others, 1951, p. 142, 169). In the dolomite series, magnesium, iron, and manganese can apparently substitute freely for one another, resulting in compositional varieties of ankerite, dolomite, and kutnahorite (Deer and others, 1962, p. 279; Frondel and Bauer, 1955, p. 749).

PARAGENESIS OF THE HYPOGENE MINERALS

With the possible exception of the quartz-hematite veins in the Tenmile Range, the ore deposits of the Kokomo-Tenmile district were formed during one period of mineralization that took place in three stages, which were separated by intervals of fracturing. Figure 20 shows the general sequence of deposition of most of the common hypogene minerals. Those of sporadic occurrence, or whose relations are unclear, are not included.

EARLY STAGE

The most abundant minerals deposited during the earliest stage of paragenesis were pyrrhotite and pyrite. Pyrrhotite formed first. Some pyrite was deposited contemporaneously, but considerable evidence shows that pyrite also formed later and replaced the pyrrhotite. Both pyrrhotite and pyrite are extensively fractured, and the fractures are filled with sphalerite, galena, or gangue. The position of marcasite in the paragenetic sequence is not clear; it replaces pyrrhotite and forms coatings on some early pyrite but appears to be coexistent with other early pyrite. It is cut by fractures that are healed by quartz.

The magnetite and molybdenite of the contact-metasomatic deposits were probably deposited early in the sequence, for as Edwards (1954, p. 136) noted, these minerals characteristically form early in the paragenesis of any type of hydrothermal deposit. The relations of magnetite and molybdenite with the other sulfides could not be determined because the mineral assemblages of the contact-metasomatic deposits are separate and distinct and do not contain pyrrhotite or early pyrite; likewise, the deposits that contain abundant pyrite and pyrrhotite do not contain magnetite or molybdenite.

INTERMEDIATE STAGE

Recognizable in nearly every deposit is a separate stage of paragenesis during which only sphalerite was deposited. The sphalerite replaces pyrrhotite and pyrite along cracks, fractures, and grain boundaries, and in places only corroded remnants of the sulfides of the early stage remain. Crystals of sphalerite as much as a fourth of an inch across line cavities in brecciated ore. Some of this sphalerite coats pyrite. Some sphalerite is cut by

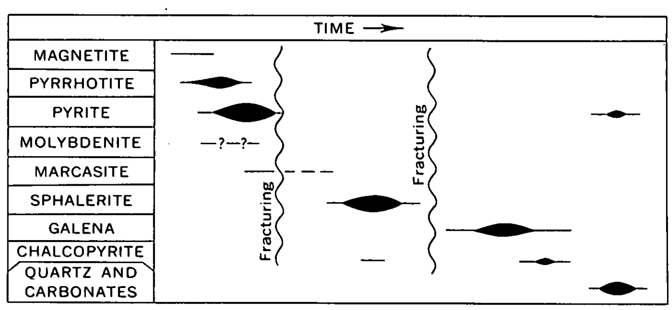

FIGURE 20.—Sequence of deposition of the major minerals of the ore deposits, Kokomo-Tenmile district.

later fractures that are filled with galena, gangue, and, in some places, also with chalcopyrite. Sphalerite is also extensively replaced by galena.

LATE STAGE

The late stage of paragenesis is marked by deposition of massive galena, chalcopyrite, gangue minerals, pyrite, and locally, silver sulfosalts. The galena is the most conspicuous member of this stage, inasmuch as it engulfs and replaces all earlier minerals. Chalcopyrite is found near galena grain boundaries and was probably contemporaneous with, or slightly later than, galena. Pearceite(?) occurs as rounded blebs and irregular grains and was possibly deposited at the same time as chalcopyrite. Quartz and carbonates are later than galena. They fill earlier fractures and preexisting open spaces. In brecciated ore, quartz and calcite crystals coat large crystals of pyrite and sphalerite in vugs and cavities. Considerable pyrite accompanied the gangue minerals. This pyrite is consistently fine grained, euhedral, and unfractured in contrast to the early pyrite which is shattered, coarse grained, ragged, and partly replaced.

TEMPERATURE OF DEPOSITION

Below 743°C the pyrrhotite that formed in equilibrium with pyrite is of variable composition, depending on the temperature of formation. The iron content of sphalerite is also indicative of temperature of formation, provided that the sphalerite formed in equilibrium with pyrrhotite.

Arnold (1962) has investigated the pyrrhotite solvus between 325° and 743°C and noted that the Fe atomic percent of pyrrhotite in equilibrium with pyrite is a function of temperature; the larger the Fe percent, the lower the temperature of formation. Both phases need not have been deposited simultaneously, as long as they could react with each other, the temperature of formation then being representative of the later phase.

A sample of ore from the Lucky Strike mine contains pyrrhotite in coexistence with pyrite and sphalerite. The pyrrhotite contains 46.4 atomic percent of metals (Fe with <0.01 percent Ni and 0.03 percent Cu) and was estimated to have formed at 520°C. Sphalerite from the same specimen contained 15.2 percent by weight FeS and formed at a temperature of 510°C, as indicated by the sphalerite geothermometer (Arnold, 1962, p. 85).

The results from only one specimen are not meant to be indicative of the thermal environment for the entire district. It is very likely that the ores in the Jacque Mountain Limestone Member, which contain abundant pyrrhotite and are closer to the predicted source of hydrothermal solutions, were deposited at substantially higher temperatures than those in the Robinson Limestone Member and that the analyzed Lucky Strike specimen, which is from the White Quail Limestone Member, represents a mean temperature.

GENESIS OF THE ORES

The grouping of the contact-metasomatic deposits around the quartz monzonite stock and the other intrusive bodies in the Copper Mountain–Tucker Mountain–Union Mountain area and the distribution of base-metal sulfide vein and replacement deposits peripheral to the high-temperature zone is compelling evidence that the ore deposits of the Kokomo-Tenmile district were formed from hydrothermal solutions that emanated from this igneous source. Whether a much larger intrusive occurs at depth is not known, but it would be a possible and convenient source of the large quantities of metals composing the ore deposits. Most of the intrusive activity is probably of Tertiary age, although intermittent weak volcanism may have occurred in the area at any time from the late Paleozoic onward, as suggested by the volcanic rocks of Pennsylvanian and Permian age on Tucker Mountain. Lead-alpha ages were determined on zircons from the quartz monzonite stock, but the results were inconclusive because of the presence of both fresh and metamict zircons in the rock. The fresh zircons probably were of the same age as the intrusive, but the ages obtained ranged from 125±25 m.y. to 300 ±30 m.y.[2] and were combinations of the two zircon generations which no doubt were older than the intrusive.

The depth at which the ores were deposited was probably not great. Based on the assumption that Late Cretaceous seas covered the area, the maximum amount of sedimentary cover probably was near 6,000 feet; this thickness would create load pressures of about 600 bars and temperatures of at least 100°C owing to the geothermal gradient. No evidence was found to warrant even a rough estimate of the minimum depth at which the ores were formed, although the mineralogy of the deposits suggests moderate pressures typical of mesothermal deposits.

The numerous northeast-trending faults in the district provided channels along which the solutions could move upward and outward from the source and also provided a mechanism whereby the waste products of replacement could be removed. In the high-temperature zone, nearest the source, the wallrocks were replaced by garnet, epidote, and sericite, and later, by magnetite, hematite, and molybdenite. It is not certain whether deposition occurred simultaneously in the contact-metasomatic and base-metal sulfide deposits, but para-

[2] Analysts: H. J. Rose, Jr., H. W. Worthing, and Nola B. Sheffey, U.S. Geological Survey.

genetic relations of the ore minerals suggest a sequence of deposition beginning in the high-temperature zone.

As the solutions moved outward and upward, they were cooled and diluted with both connate and surface water, and when certain limestone beds were encountered, a series of reactions took place. First, the limestones were dolomitized; later, much of the dolomite was converted to jasperoid; finally, deposition of the massive sulfides took place by replacement of both the dolomite and the jasperoid. In some places, solution of the limestone occurred more rapidly than replacement, and collapse breccias with high permeability were formed. The limestones were also made permeable and brittle by the alteration; slight tectonic movements during mineralization converted the altered limestone to a rubble of angular fragments, thereby providing the solutions with an easy access and providing greatly increased surfaces for reactions to take place between the host rocks and the ore solutions. The graphic texture of much of the replacement ore is no doubt a pattern inherited from the replaced breccia fragments.

The reason for preference of the solutions for certain limestone beds is not clear. It is not purely a matter of permeability, for the bulk of the Minturn Formation is composed of poorly sorted sandstone and siltstone, and is much more permeable than the limestone. The factors that influenced replacement must have been a combination of permeability and a specific chemical composition. The balance between replacement and no replacement also must have been very delicate. As time went on, ore minerals were deposited in open spaces and along fractures, which were reopened periodically by slight movements.

The reasons why zoning exists in ore deposits also are not precisely known; nevertheless, various ideas have been advanced. Differences in solubilities, vapor pressures, correlation of atomic weights with mineral sequences, deposition according to electrode potentials of the elements, differential diffusion of the components, changes in concentration, and solubility in concentrated chloride solutions are all mechanisms that have been invoked by various workers to explain the sequences of mineral deposition and zoning of deposits. One of the more recent concepts considers the relative stabilities of covalent complexes of bivalent metal cations, with such anions as chlorides, sulfides, polysulfides, or thiosulfates, arrived at through calculations involving free energy differences of the cations (Barnes, 1962). Although this approach at present lacks sufficient quantitative authentication, the calculations demonstrate a consistent succession, with manganese, iron, zinc, copper, and lead occurring in order of increasing stability of covalent-bonded ions within any single type of anion complex in the ore solution (Barnes, 1962, p. 34). This is the sequence observed in parageneses and zones in the Kokomo-Tenmile as well as many other districts.

MINE DESCRIPTIONS

The Kokomo-Tenmile district is completely covered by claims, many of which overlap and are of odd sizes and configurations. The main mineralized area is literally pock marked by dumps and mine openings (fig. 21), silent reminders of the tremendous efforts, optimism, and limited successes of the early prospectors.

Periodically during the early part of the field investigations, a few mines were open and these were mapped; but after 1956 all mines were closed and soon became flooded and caved, thereby curtailing underground observations and preventing any systematic program of mine mapping. The three mines that are described in the following sections were the major producers of the district. They were mapped and sampled in considerably more detail by project personnel than the other mines in the district.

WILFLEY-KIMBERLY MINE

HISTORY AND PRODUCTION

The Wilfley-Kimberly mine, as was true for most of the larger properties in the district, evolved from consolidation of several smaller properties on Elk Ridge that had been originally developed by separate workings.

Among the earliest worked claims were the original four claims of the White Quail group which were reportedly located in 1878 and patented in 1881 (Corregan and Lingane, 1883, p. 881–882). The discovery shaft disclosed galena that contained 40–100 ounces of silver per ton at a depth of only 26 feet below the surface. An incline 80 feet long was driven through the ore body in 1879 (Eng. Mining Jour., 1879, p. 456). By 1882 the property had yielded 6,750 tons of ore, and the workings had a total length of 1,700 feet (Burchard, 1883, p. 556–557).

At about this same time, activity was underway on other claims in the vicinity. Burchard (1882, p. 434) reported 25 tons per day production from the Aftermath in 1881, and a total of 3,520 tons of ore from the Milo group for the same year. In his report for 1882, Burchard (1883, p. 556–557) described the Aftermath workings as consisting of an inclined shaft 665 feet deep, with 10 levels. The 10th level connected with the lower level of the Milo mine. The Milo workings were an incline 700 feet long, with levels totaling 2,000 feet, a 900-foot adit, and 1,000 feet of winzes and raises (Corregan and Lingane, 1883, p. 828).

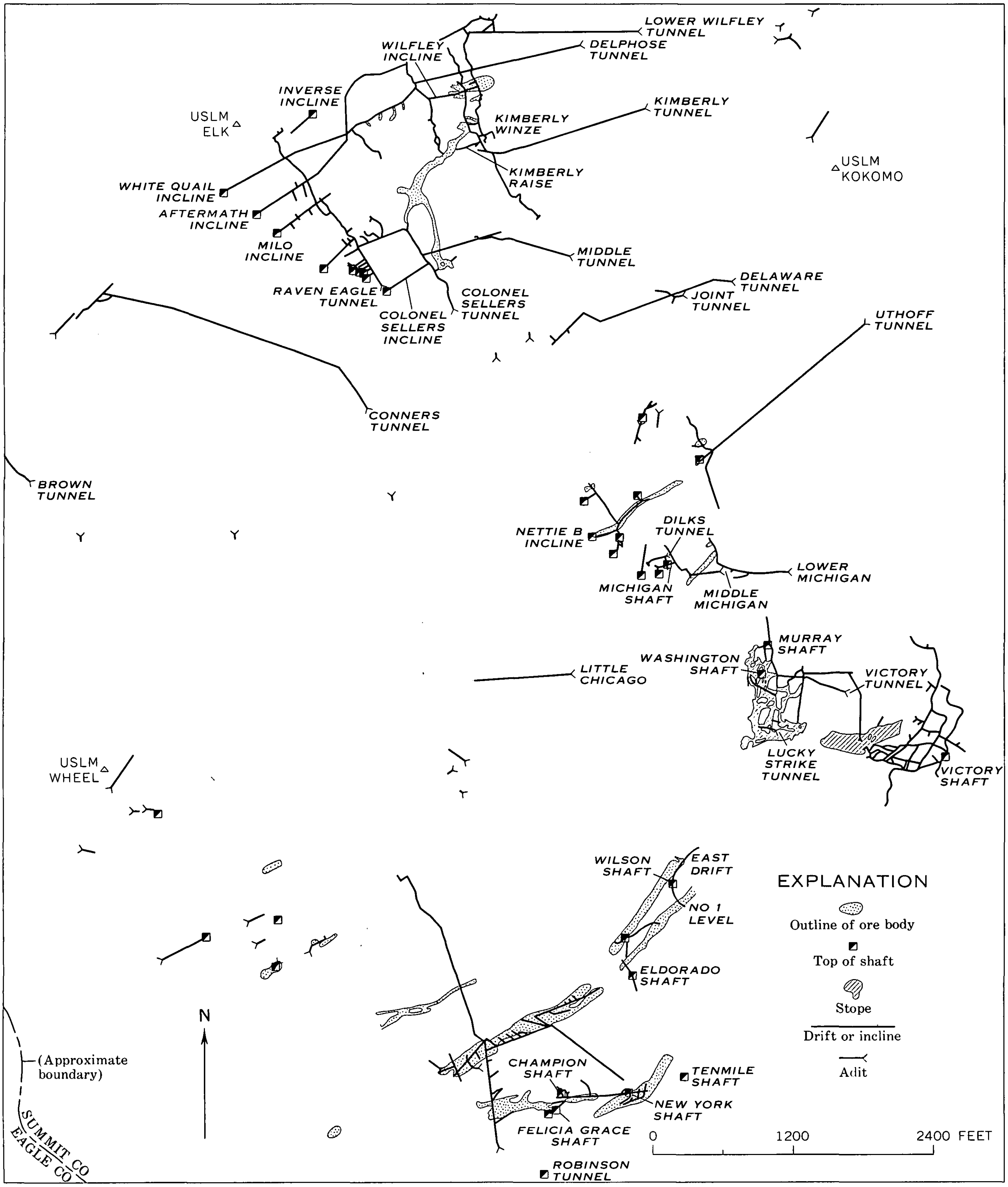

FIGURE 21.—Map showing general outlines of mine workings and ore bodies, Kokomo-Tenmile district, Summit County, Colo.

In 1886, A. R. Wilfley assumed control of the White Quail, Aftermath, and Milo groups and from Searle Gulch drove the Delphose tunnel which intersected the White Quail Limestone Member 1,500 feet from the portal and 750 feet below the top of the White Quail incline. Eventually, the earlier discovered ore bodies were mined out down to the Delphose tunnel.

In 1891 the Wilfley mill burned, and output of the property was curtailed, but in 1893 the Lower Wilfley tunnel was driven from Searle Gulch to mine the downdip extension of the ore body from the Delphose tunnel. In 1902 the Kimberly tunnel was driven from Searle Gulch at an altitude of 10,891 feet.

The properties changed hands frequently during the early 1900's. The Summit Mining & Smelting Co. took control of the Wilfley properties in 1905 and erected a large concentration plant. In 1907 the Wilfley, Kimberly, and Summit interests were consolidated under the name of the Kimberly-Wilfley Mining Co. In 1916 the mines were controlled by the combined Elk Mountain and Summit Mining & Smelting Co. After a few years of inactivity in the early 1920's the Wilfley-Kimberly properties were taken over by the American Metal Co., whereupon the lower workings were reopened, and about 30,000 tons of ore was blocked out. But it was decided that insufficient reserves were in sight, and work was suspended (Henderson, 1929, p. 768). Some production from the Wilfley was reported in 1938, when Walter Byron reopened the mine for a short interval. In 1942 the Wilfley Leasing Co., aided by the Reconstruction Finance Corporation loan of $71,000, began mining the Wilfley property (Henderson, 1943, p. 342), and in 1943 the Kimberly property was reopened by the Kokomo-Kimberly Mines, Inc. (Henderson, and others, 1945, p. 337). Both properties were active on a fairly large scale until 1950. A few small shipments were made in 1951, 1952, and 1953, but thereafter through 1965 the properties have been idle.

Production data on the properties consolidated under the Wilfley-Kimberly group for the period before 1900 could not be found, but from 1902 to 1965 the total recorded production from the mines amounted to 4,485 ounces of gold, 203,358 ounces of silver, 7,759 pounds of copper, 2,313,880 pounds of lead, and 9,183,746 pounds of zinc.

CHARACTERISTICS OF THE ORE BODIES

The rocks on Elk Ridge are on the southwest limb of the Kokomo syncline and have consistent dips to the northeast of from 20° to 35°. The ore bodies have been mined down their dips and along their strike by inclines and drifts from the Wilfley and Kimberly tunnels which were driven from Searle Gulch (pl. 2). The rocks are cut by numerous high-angle faults that strike from about N. 10° W. to N. 50° E. Most of these have displacements of 10 feet or less. Many of the faults are mineralized and served as channels for the solutions that replaced the limestone. Movement along others occurred after mineralization, as evidenced by ore bodies offset along unmineralized fractures. The Little Chief fault, a reverse fault trending N. 55° E., with about 160 feet of vertical displacement, is exposed on the surface about 750 feet northwest of the Wilfley tunnel (see pl. 1). This fault apparently limits the northwestward distribution of ore bodies in Searle Gulch.

Ore bodies in the Wilfley-Kimberly mine are irregularly shaped masses of pyrite, pyrrhotite, sphalerite, and galena in the middle unit of the White Quail Limestone Member. The gangue is mostly a fine-grained aggregate of a brown carbonate mineral and jasperoid. The ore minerals commonly replace the limestone from its upper surface downward, forming an uneven thickness of from 4 to 9 feet of ore. In places the most intense replacement occurs as irregularly shaped sulfide bodies within the limestone, with fresh limestone below and partly altered limestone above.

ROBINSON CONSOLIDATED MINE, ELDORADO AND WILSON MINES, FELICIA GRACE MINE, AND CHAMPION (NEW YORK) MINE

INTRODUCTION

The Robinson Consolidated mine was by far the largest producer of the early mines in the Kokomo district. A discussion of the history, geology, and workings of this mine is incomplete without including also discussions of the Eldorado and Wilson mines, the Felicia Grace mine, and the Champion (New York) mine because two of the four ore bodies discovered originally on the Robinson properties were found to extend beneath adjacent claims owned by other companies and were subsequently mined by them. For example, the Robinson ore shoot 1, mined by the Robinson tunnel, was also mined through the Eldorado and later through the Wilson shafts. Ownership of the claims in this area has changed repeatedly through the years, and ores from the same deposits have been reported under various names. It seems logical, then, to consider the Robinson ore bodies as a small subdistrict with a local history of its own.

HISTORY

The original Robinson holdings (fig. 21) were staked between July 1878 and January 1879, by Charles Jones, a prospector who was outfitted by George B. Robinson, Leadville merchant and Lieutenant Governor of Colorado. High-grade ore assaying as high as 400 ounces of silver per ton was found on the claims, and during the winter of 1878 and spring of 1879 the ore was transported in wagons over poor roads to Leadville. In 1879 Robinson purchased the interests of Jones and Jack Sheppard, the original claimants, and began developing the property. The company was soon involved in litigation over the ownership of some of its claims, and Robinson was unintentionally shot and killed by one of the guards whom he had posted to protect his property from the litigants. In 1880 a new company was formed which controlled additional claims.

Shipments of ore from the Robinson, amounting to 150 tons per week, were received in Leadville beginning in July 1880, according to the Leadville Democrat of September 17, 1880. The rate of development increased to the extent that a smelter was built at Robinson in October 1880; however, the refractory nature of the Robinson ores made operation of the smelter impracticable, and it was closed in the summer of 1881. Ore shoot 1 was mined at a vigorous rate during 1881, with about 500 tons of ore per week shipped to smelters at Leadville and Argo. This ore assayed from 80 to 100 ounces of silver per ton.

Letters loaned to F. G. Wells by Jesse MacDonald, a former manager of the mine, showed smelter receipts that disclosed that from April 16, 1881, to February 18, 1882, $627,670.18 was received for ore, after haulage and smelter charges were deducted.

Dividend payments almost kept pace with ore receipts. By the end of 1881 they amounted to $575,000; however, the last dividend had to be financed by a $90,000 loan. Poor management continued to plague the property. The Robinson was under new management in 1882, and only 5,983 tons of ore, valued at $108,000, was mined. After another suit in 1883, involving mismanagement and misappropriation of funds, the mine was leased to Thomas H. Greer, who shipped about 800 tons per month for 8 months. Other lessees shipped ore fairly continuously through 1884–86.

From 1888 until 1905 the Robinson and various adjacent properties were operated by Jesse A. MacDonald. Unfortunately, much of the production during this period was contained in confidential reports. Emmons (1898, p. 4) estimated the total value of the original ore shoot at $6,000,000. What with changing ownership and desultory production from all the properties, it is not clear when the Robinson mine ceased production. It is likewise impossible to obtain an accurate estimate of the total tonnage mined or total value of the products.

In 1884 the Robinson ore body 2 was discovered in the Robinson tunnel and was observed to trend toward the Felicia Grace property (fig. 21). A shaft was sunk in 1884 on the Homestake claim, and ore was found at a depth of 85 feet. Sulfide ore with an average grade of 55 ounces of silver per ton was mined at the rate of 10 tons per day in 1884. Steady production continued until 1889, but was sporadic thereafter until 1919, when the mine was closed permanently.

The Eldorado shaft (fig. 21) was driven in 1895 to intercept the Robinson ore body 1, which was found to plunge to the northeast, beyond the Robinson property. Information on this mine is almost nonexistent.

The Robinson ore body 1 was continuous northeast of the Eldorado (fig. 21), and during 1907–8, the International Mining & Smelting Co. reopened the Wilson mine to explore the deeper projection of the ore body, east of the Eldorado workings. A mill was also constructed.

Consistent with the turbulent conditions of mining during this era of rapid growth, the ownership of the Wilson mine soon changed. The Wilson Mining Co. operated the mine during 1910–11; the King Solomon-Robinson Mining & Tunnel Co. then assumed control, operating the property from 1912 to 1916. From 1916 until 1917 the Progress Mining & Milling Co. took over the mine and remodeled the mill for flotation separation. The mine changed ownership again in 1918, and the Ready Cash Mining & Milling Co. conducted only small-scale work. After 1919 the records are blank concerning the Wilson mine. In the years 1908 and 1910–12 the Wilson was the chief producer of the Kokomo district; but production dropped off sharply thereafter, and the mine never regained its prominence.

The downdip extension of the Robinson ore shoot 2 was developed by the Champion, New York, and Ten Mile shafts. The Champion tunnel was driven to the north to mine Robinson ore shoot 1. The original operator of this property was the Champion Tunnel Mining Co., which began shipments of ore in 1888. A later operator was the Robinson Champion Mines Co. It is evident that this property changed ownership many times, but the records are incomplete in this respect. Production figures from this mine have been combined with those of other properties, so it is difficult to evaluate the mine's relative importance in the district.

PRODUCTION

Before 1902, mineral production data were compiled only by counties and only scattered references to individual mines can be found. Table 10 summarizes the available production data on the Robinson mine and its satellites.

TABLE 10.—*Recorded production of Robinson group of mines, 1880–1919*

[No production 1920–65. Leaders (----), no production; N.r., known mining but no record]

Year	Shipper	Mine	Ore (dry tons)	Gold (ounces)	Silver (ounces)	Lead (pounds)	Zinc (pounds)	Copper (pounds)
1880	Robinson Consolidated Mining Co.	Robinson	>3, 100	----	----	----	----	----
1881	do	do	23, 500	----	1, 880, 000–2, 350, 000	----	----	----
Mar. 1, 1882–Mar. 1, 1883	do	do	5, 983	----	----	----	----	----
Remainder of 1883	Thomas H. Greer	do	6, 400	----	243, 200–268, 800	----	----	----
1884	Unknown	Robinson	Unknown	----	----	----	----	----
	do	Felicia Grace.	>700	----	>38, 500	----	----	----
Feb. 31, 1885–Jan. 31, 1886	do	Robinson	5, 730	----	326, 610	----	----	----
1886–92	N.r	N.r	N.r.	N.r.	N.r.	N.r.	N.r.	N.r
1892 (July only)	Unknown	Robinson and New York.	1, 750	----	----	----	----	----
1893–98	N.r	N.r	N.r.	N.r.	N.r.	N.r.	N.r.	N.r.
1898	Unknown	Eldorado	50 per day	N.r.	N.r.	N.r.	N.r.	N.r.
1899–1902	N.r	N.r	N.r.	N.r.	N.r.	N.r.	N.r.	N.r.
1902	Robinson Consolidated Mining & Smelting Co.	Robinson	2, 817	----	20, 002	----	----	----
	Fred Crockett	Felicia Grace.	600	12. 00	10, 800	169, 412	----	----
	Unknown	New York	294	16. 00	2, 646	----	----	----
1903	Tenmile Leasing Co	do	300	16. 93	2, 800	----	----	----
1904	Unknown	do	1, 543	268. 85	27, 561	72, 476	----	----
1904–7	N.r	N.r	N.r.	N.r.	N.r.	N.r.	N.r.	N.r.
1908	International Mining Co	Wilson	315	----	----	----	83, 170	----
	do	do	2, 685	150. 00	18, 000	494, 118	----	----
1909	C. C. Warrall	Felicia Grace.	22	. 57	251	922	----	63
1910	Felicia Grace Mining Co	do	388	10. 74	6, 104	14, 306	----	----
	Wilson Mining Co	Wilson	11, 460	214. 3	51, 474	2, 023, 522	1, 505, 167	----
1911	do	do	8, 106	238. 4	47, 274	1, 524, 536	1, 374, 094	----
1912	King Solomon-Robinson Mining & Tunnel Co.	do	5, 500	172. 0	23, 862	628, 984	272, 319	789
	C. C. Warrall	Felicia Grace.	737	22. 17	9, 843	27, 283	----	46
1913	J. J. Miller	do	182	4. 49	2, 653	4, 284	----	45
1914–16	N.r	N.r	N.r.	N.r.	N.r.	N.r.	N.r.	N.r.
1917	Progress Mining & Milling Co.	Wilson	196	59. 57	2, 335	54, 314	28, 800	76
1918	Ready Cash M & M Co	do	798	102. 9	4, 604	70, 628	123, 033	----
	Unknown	Champion	44	2. 20	507	1, 602	----	----
1919	do	Wilson	21	. 40	106	1, 403	----	----
	F. S. Goodale	Felicia Grace.	302	18. 90	2, 870	12, 434	----	54

CHARACTERISTICS OF ORE BODIES

The ore bodies in the Robinson area occur in the Minturn Formation in three limestone beds known collectively as the Robinson Limestone Member. Locally, the middle and lower limestones coalesce to form a single bed; at most places, however, these two beds are separated by 17 feet of sandstone. The middle and upper limestone beds are separated by an interval of from 80 to 115 feet of sandstone. The lower limestone bed is gray to black, dolomitic, and is 10 feet thick. The middle limestone bed is the most productive of the three; it is blue-gray, almost pure calcium carbonate, and is 20 feet thick. The upper limestone bed, which is shaly in its lower half, is about 40 feet thick. In the Champion and Wilson workings this bed rests on a sill of porphyry 50 feet thick.

The four ore bodies discovered in the Robinson mine were all narrow, elongate bodies that trended from N. 50° E. to N. 60° E. and followed the dip of the beds. Ore bodies 1 and 2 replaced the upper part of the middle limestone, which was purer; apparently, the solutions entered along the intersection of fractures that offset gentle northeast-trending flexures and favorable limestone beds. Ore shoot 1, the largest and most productive, was about 130 feet wide at the surface, narrowing at depth to a minimum of 50 feet. The thickness ranged from 50 to 20 feet, and the ore shoot was continuously traceable for 2,050 feet down its plunge. Most of the middle limestone is mineralized, but in the Wilson mine (fig. 21) a thin limestone layer between the middle and top limestone beds contains a small ore shoot. Emmons (1898, p. 4) reported that a fracture lined with ore was traced from the middle limestone upward 80–100 feet to the upper limestone, where some ore was found. According to Wells (J. A. MacDonald and B. F. Rich, written commun.), oxidized ore extended downdip for 600 feet in ore body 1.

Ore shoot 2 extended from the Robinson tunnel down the dip of the middle limestone for more than 1,300 feet, where it was cut off by the Tenmile fault. Numerous faults intersected this ore body so that it was not continuous. This ore shoot was of lower grade than ore body 1; it was also narrower and unoxidized throughout.

In the Tenmile shaft on the east or hanging-wall side of the Tenmile fault, ore was found in both the upper and the middle beds of the Robinson Limestone Member. Ore in the upper bed differed from that in the middle bed in that it contained considerably more manganese (J. A. MacDonald, written commun., 1941, in files of F. G. Wells).

Very little information is available on ore body 3. According to J. A. MacDonald (written commun., 1941, in files of F. G. Wells), the ore body was a narrow veinlike replacement body along a fissure in the middle limestone bed, near its upper contact with a sandstone bed. The ore was mostly low grade, but it was fairly rich where the main fissure was cut by cross fractures.

Ore body 4 lay about 1,100 feet north of ore body 3. Here, the Robinson Limestone Member was displaced by a fault along which the northwest block was downdropped about 25 feet. A mineralized shatter zone about 1 foot wide was mined from the Robinson tunnel as well as for a few hundred feet from the surface down the dip.

The ore in ore shoot 3 was mostly low grade, averaging 22 ounces of silver per ton, but the first ore discovered is reported to have assayed 421 ounces (F. G. Wells, unpub. data). No information is available on the grade of ore in ore shoot 4.

GRADE OF ORE

The oxidized ore from ore body 1 averaged 66 2/3 ounces of silver per ton (Eng. Mining Jour., 1881, p. 394); however, assays of more than 400 ounces of silver have been reported and, according to the Engineering and Mining Journal (1881, p. 59, 92), several hundred tons of ore was shipped that assayed 80–100 ounces of silver per ton. Below the fifth level (Robinson tunnel), the tenor was lower, ranging from 30 to 57 ounces per ton.

The grade of the sulfide ore from ore body 2 may be summarized from data given by F. G. Wells (unpub. data) that were obtained from smelter returns from the New York mine for the period October 12 to December 16, 1881, for a total of 185 dry tons.

	Gold (ounces per ton)	Silver (ounces per ton)	Lead (percent	Zinc (percent)
Maximum	0. 12	190. 0	15. 2	19. 0
Minimum	Trace	35. 0	1. 0	7. 4
Average	. 025	83. 4	3. 0	9. 4

WORKINGS

None of the workings of the Robinson and its affiliated mines was open during the latest phase of this investigation. In 1949 the Robinson tunnel was opened by the American Smelting & Refining Co.; the north end was extended and the tunnel was mapped at this time.

The earliest workings were in ore body 1 and consisted of an inclined shaft that followed the plunge of the ore shoot to a point 140 feet vertically beneath the surface. Five levels were driven from this shaft. A tunnel, starting just behind the old town of Robinson, was driven along the strike of the Robinson Limestone Member to intercept the workings on the fifth level, about 800 feet from the portal. Another incline was sunk below the tunnel level following ore body No. 1 down the dip of the limestone. Levels were run out from this incline at intervals of 100 feet to mine the ore. This incline was continued downward to the 12th level, where it was joined by the East shaft. From this point the incline known as the New Incline continued down the dip for about 630 feet. At a distance of 160 feet below the collar, the East shaft was joined by the Champion tunnel that had been driven a distance of 950 feet from the southeast. The ore to the east of the bottom of the New Incline was mined from the Eldorado shaft, which penetrated ore body 1 at a depth of 565 feet. During 1907–8, the Wilson shaft was sunk to a depth of 1,200 feet. Inclines from this shaft joined the Eldorado workings, and the Robinson ore body 1 was mined farther downdip. Workings were not continued any deeper than the Wilson.

Part of ore body 2 was mined from the Robinson tunnel, but the Felicia Grace and Champion workings developed the greater part of it. The Felicia Grace workings consisted of two shafts, the Felicia Grace and the No. 2 shaft, from which networks of short tunnels were run off at a single level. The New York and Champion workings followed ore body 2 east from the Felicia Grace. From the Champion and New York shafts, the Main Incline was run and tunnels were driven at various levels. The Main Incline terminated at the Tenmile fault. Incline 2 was driven in a northeasterly direction in the faulted zone. Incline 2 is joined by level 1, leading from the Tenmile shaft, which was 1,073 feet deep. Drifts from other levels in the Tenmile shaft were driven to intercept ore in both the middle and upper limestone beds of the Robinson Member on the east side of the Tenmile fault.

Ore bodies 3 and 4 were found in the northward extension of the Robinson tunnel. No maps or records of the surface workings in these two ore bodies are available.

VICTORY–LUCKY STRIKE MINE

HISTORY AND PRODUCTION

The Victory–Lucky Strike group was the largest producer, although one of the shortest lived mines in the Kokomo district. Reliable production data were not found, but a conservative estimate of total output should be about 300,000 tons of ore.

The history of the mine begins in 1941, when A. R. Rhine and L. J. Gould completed the Lucky Strike tunnel and began shipping ore. These operators controlled the Lucky Strike until February 28, 1944, at which time the American Smelting & Refining Co. acquired the property, along with the uncompleted Cole-Peterson (Victory tunnel) to the north. The American Smelting & Refining Co. accelerated development and conducted mining on a much larger scale. The Victory tunnel was rehabilitated, and in 1945, drifts were driven for 700 feet. The following year, 10,565 feet of diamond drilling, 300 feet of shaft, and 150 feet of drifts were completed. In 1947 the combined properties became the largest producer of lead, zinc, copper, silver, and gold in Summit County and one of the five largest producers of lead and zinc in Colorado. This high rate of production was continued in 1948 and 1949. Extensive drifting and diamond drilling was done in 1948, and a new shaft, 435 feet deep, was sunk. In 1949 the Lucky Strike–Victory group was Colorado's largest producer of lead, second largest producer of zinc, and fourth largest producer of silver. The high rate of production continued until April 19, 1950, when all activity ceased—probably because of a drop in price of lead and zinc and a lack of sufficient ore reserves immediately in sight to warrant continuation of large-scale operations. The Victory–Lucky Strike group had not resumed production to 1968.

GEOLOGY, ORE BODIES, AND WORKINGS

The Victory–Lucky Strike replacement ore bodies were in the White Quail Limestone Member and consisted of sphalerite, galena, chalcopyrite, pyrite, and pyrrhotite. Sulfides were exposed at the grass roots; no oxidized blanket was present.

The workings were mapped during 1944–45 by A. H. Koschmann and in 1949 by H. T. Schassberger and D. F. Kent. From 1957 through 1965 the workings were inaccessible.

In general, the Lucky Strike–Victory workings follow the White Quail Limestone Member down its dip to the east. The Lucky Strike tunnel was the earliest workings driven in the mine. Ore was encountered in the White Quail Limestone Member and was found to extend northward along the strike of the beds to the old Washington workings. The ore was continuous for several hundred feet down the dip. Later, during 1944–45, the Victory tunnel was driven to join the Lucky Strike workings and an inclined drift was run to the east. At the 700-foot level, a drift driven to the south intersected a large ore body blocked out by drilling. The Victory shaft was later sunk to make extraction of ore easier. The southern ends of both ore bodies terminate against a prominent east-west shear zone, the Tenmile fault. Several other faults branch out from the Tenmile fault in a fan pattern striking from about N. 30° E. to about N. 70° E. Dips on these faults range from 43° to 60° NW. Movement along some of these faults has displaced the White Quail Limestone Member, and this is reflected in several sharp turns along the drifts (pl. 2).

The richer ore was found along minor folds, the axes of which were alined along the dip slope. Some of these can be seen on plate 2.

SUGGESTIONS FOR PROSPECTING AND FUTURE OF THE DISTRICT

The Kokomo-Tenmile district has been thoroughly prospected, and almost every mineralized outcrop has been investigated by pit, tunnel, or shaft. The rich oxidized ores have been virtually mined out, and it is doubtful that any undiscovered oxidized ore is present anywhere in the district. Considerable opportunities, however, exist for discovery of new sufide replacement ores, provided a program is conducted by those who have a thorough knowledge of the detailed local stratigraphy and structure and an understanding of the geologic factors that influence ore deposition in the district. In addition, any major discoveries in the district will have to come either from downfaulted segments of known ore bodies or from projections across structure of ore-bearing units; therefore, an exploration program, to be successful, must embrace sizable areas.

The area of outcrop of the Robinson Limestone Member has been thoroughly explored, but the Robinson is largely untested at depth. Holes drilled along the east flank of Elk Ridge would penetrate the Robinson at depths of probably 1,500–2,000 feet, depending on the thickness of porphyry sills and the amount of faulting. The middle part of the White Quail Limestone Member, which contains ore bodies in the Elk Ridge–East Sheep Mountain area, would be encountered stratigraphically about 1,000–1,200 feet above the Robinson.

Considerable exploration of the White Quail Limestone Member has been done in the vicinity of the Wilfley, Lucky Strike–Victory, Michigan, and Snowbank mines, along the lower southeast slope of Elk Ridge and the lower northeast slope of East Sheep Mountain. From 1944 to 1948, 42 holes, with a combined total footage of 8,370, were drilled by the U.S. Bureau of Mines to encourage development of ore bodies in the White Quail Member. Results of this drilling showed that faults and porphyry sills and dikes made a shambles of any predictions of ore body extensions, unless the geology, both underground and on the surface, was studied in detail. The fact that the two major operators of the district ceased operations in 1950 indicates that obvious major continuations of the known ore bodies were not readily apparent.

The northeast and southeast limbs of the Kokomo syncline, or that part of the syncline between Tenmile Creek and the Mosquito fault, comprising about 8 square miles, is an area that merits more attention than it has received. Ore bodies in both the White Quail and Robinson Limestone Members are cut off by the shear zone that trends north-northeast along Tenmile Creek, in the vicinity of the town of Kokomo and Robinson Flats. There is every reason to believe that the downfaulted parts of these limestones are also ore bearing and that the mineralized rock continues along strike to the southeast. A series of holes drilled by the Climax Molybdenum Co. in 1947, about 0.3–0.4 mile east of the Lucky Strike tunnel and presumably on the east side of the faulted area, showed ore in the middle part of the White Quail Limestone Member at depths between 450 and 600 feet. Thick sills of Elk Mountain Porphyry intruded the sediments on the east side of Tenmile Creek, causing a tremendous thickening of the interval between the White Quail and the surface. Five holes were drilled by the U.S. Geological Survey in Mayflower Gulch, Clinton Gulch, and Gold Hill during 1948–49, but only one penetrated the White Quail (Koschmann, 1949). In the others, the normal stratigraphic interval was greatly increased by sills, and the White Quail was not found. The Robinson also is a potential ore host rock east of Tenmile Creek. The Robinson is exposed at the Index mine in Mayflower Gulch, where it contained a small, but rich, replacement ore body. Any exploration in this area should also include consideration of the Robinson, if it is within economic depths of mining.

Another area that has been explored is the Union Mountain–Tucker Mountain–Copper Mountain area, in which the high-temperature deposits are found. The molybdenite association with garnetiferous tactite in the D and G tunnel and scattered small prospects excited interest in the possibility of an economic deposit of molybdenite in the epidote-garnet zone. The results of exploration have been generally discouraging.

The outlook for renewed activity in the Kokomo-Tenmile district is not favorable. Although it is true that considerable reserves of ore could be developed, the costs involved in rehabilitating old workings, in consolidating claims, in conducting a large-scale exploration program, and in mining deep ore bodies would have to be carefully weighed in the light of available sources of base metals elsewhere and the unpredictable fluctuations of prices over a long interval. The investment might be considerable, and no guarantees of quick returns could be assured.

REFERENCES CITED

Ahrens, L. H., 1952, Ionic radii of the elements, pt. 1 *of* The use of ionization potentials: Geochim. et Cosmochim. Acta, v. 2, no. 2, p. 155–169.

Arnold, R. G., 1962, Equilibrium relations between pyrrhotite and pyrite from 325° to 743° C: Econ. Geology, v. 57, no. 1, p. 72–90.

Ball, S. H., 1906, Pre-Cambrian rocks of the Georgetown quadrangle, Colorado: Am. Jour. Sci., 4th ser., v. 21, p. 371–389.

Barnes, H. L., 1962. Mechanisms of mineral zoning: Econ. Geology, v. 57, no. 1, p. 30–37.

Behre, C. H., Jr., 1953, Geology and ore deposits of the west slope of the Mosquito Range [Colo.]: U.S. Geol. Survey Prof. Paper 235, 176 p.

Bergendahl, M. H., 1963, Geology of the northern part of the Tenmile Range, Summit County, Colorado: U.S. Geol. Survey Bull. 1162–D, p. D1–D19.

——— 1969, Geologic map and sections of the southwest quarter of the Dillon quadrangle, Eagle and Summit Counties, Colorado: U.S. Geol. Survey Misc. Geol. Inv. Map I–563.

Boutwell, J. M., 1905, Economic geology of the Bingham mining district, Utah: U.S. Geol. Survey Prof. Paper 38, p. 71–385.

Bradley, A. J., and Jay, A. H., 1932, A method of deducing accurate values of the lattice spacing from X-ray powder photographs taken by the Debye-Scherrer method: Phys. Soc. London Proc., v. 44, p. 563–579.

Brill, K. G., Jr., 1942, Late Paleozoic stratigraphy of Gore area, Colorado: Am. Assoc. Petroleum Geologists Bull., v. 26, no. 8, p. 1375–1397.

Burbank, W. S., Lovering, T. S., Goddard, E. N., and Eckel, E. B., 1935, Geologic map of Colorado: U.S. Geol. Survey.

Burchard, H. C., 1882, Report of director of the Mint upon the production of the precious metals in the United States during the calendar year 1881: Washington, U.S. Govt. Printing Office.

——— 1883, Report of director of the Mint upon the production of the precious metals in the United States during the calendar year 1882: Washington, U.S. Govt. Printing Office.

Butler, B. S., and Vanderwilt, J. W., 1933, The Climax molybdenum deposit, Colorado, with a section on history, production, metallurgy, and development by C. W. Henderson: U.S. Geol. Survey Bull. 846–C, p. 195–237.

Cameron, E. N., 1961, Ore microscopy: New York, John Wiley & Sons, 293 p.

Corregan, R. A., and Lingane, D. F., 1883, Colorado mining directory: Denver, Colo.

Deer, W. A., Howie, R. A., and Zussman, J., 1962, Rock-forming minerals; volume 5, Non-silicates: London, Longmans, Green & Co., 371 p.

Edwards, A. B., 1954, Textures of the ore minerals and their significance [2d ed.]: Melbourne, Australasian Inst. Mining and Metallurgy, 242 p.

Emmons, S. F., 1886, Geology and mining industry of Leadville, Colorado: U.S. Geol. Survey Mon. 12, 770 p.

——— 1898, Description of the Tenmile district quadrangle [Colo.]: U.S. Geol. Survey Geol. Atlas, Folio 48, 6 p.

Engineering and Mining Journal, 1879: New York, Hill Pub. Co., v. 28.

——— 1881: New York, Hill Pub. Co., v. 32.

——— 1886: New York, Hill Pub. Co., v. 41.

Fleischer, Michael, 1955, Minor elements in some sulfide minerals *in* pt. 2 *of* Bateman, A. M., ed., Economic geology (50th anniversary volume): p. 970–1024.

Frondel, Clifford, and Bauer, L. H., 1955, Kutnahorite—a manganese dolomite, $CaMn(CO_3)_2$ [N.J.]: Am. Mineralogist, v. 40, nos. 7–8, p. 748–760.

Fyfe, W. S., Turner, F. J., and Verhoogen, John, 1958, Metamorphic reactions and metamorphic facies: Geol. Soc. America Mem. 73, 259 p.

Hamilton, W. H., and McLellan, R. R., 1955, Investigation of the Kokomo zinc deposits, Summit County, Colorado: U.S. Bur. Mines Rept. Inv. 5138, 28 p.

Harker, Alfred, 1939, Metamorphism; a study of the transformations of rock-masses, 2d ed., revised [by C. E. Tilley]: London, Methuen & Co., Ltd., 362 p.

Henderson, C. W., 1926, Mining in Colorado; a history of discovery, development, and production: U.S. Geol. Survey Prof. Paper 138, 263 p.

——— 1929, Gold, silver, copper, lead, and zinc in Colorado (mine report), p. 733–774, *in* Mineral resources of the United States, 1926, Part 1: U.S. Bur. Mines, 774 p.

——— 1943, Gold, silver, copper, lead, and zinc in Colorado, p. 317–348, *in* Minerals Yearbook, 1942: U.S. Bur. Mines, 1574 p.

Henderson, C. W., Mote, R. H., and Cushman, R. V., 1945, Gold, silver, copper, lead, and zinc in Colorado, p. 314–342, *in* Minerals Yearbook, 1943: U.S. Bur. Mines, 1626 p.

Hollister, O. J., 1867, The mines of Colorado: Springfield, Mass., S. Bowles & Co., 450 p.

Kirchhoff, Charles, Jr., 1897, Lead *in* Mineral resources of the United States, 1896; Part 5, Metallic products and coal: U.S. Geol. Survey 18th Ann. Rept., p. 237–262.

Koschmann, A. H., 1949, U.S. Geological Survey diamond drill logs, Kokomo (Tenmile) zinc-lead mining district, Colorado: U.S. Geol. Survey open-file report, 1 p., map.

——— 1960, Mineral paragenesis of Precambrian rocks in the Tenmile Range, Colorado: Geol. Soc. America Bull., v. 71, no. 9, p. 1357–1370.

Koschmann, A. H., and Bergendahl, M. H., 1960, Stratigraphy and structure of the Precambrian metamorphic rocks in the Tenmile Range, Colorado *in* Short papers in the geological sciences: U.S. Geol. Survey Prof. Paper 400–B, p. B249–B252.

Koschmann, A. H., and Wells, F. G., 1946, Preliminary report on the Kokomo mining district, Colorado: Colorado Sci. Soc. Proc., v. 15, no. 2, p. 51–112.

Kullerud, Gunnar, 1961, Two-liquid field in the Fe-S system: Carnegie Inst. Washington Yearbook 60, 1960–61, p. 174–176.

——— 1964, Review and evaluation of recent research on geologically significant sulfide-type systems: Fortschr. Mineralogie, v. 41, no. 2, p. 221–270.

Kullerud, Gunnar, and Yoder, H. S., Jr., 1959, Pyrite stability relations in the Fe-S system: Econ. Geology, v. 54, no. 4, p. 533–572.

Liddell, D. M., 1945, Handbook of nonferrous metallurgy, principles and processes, volume 2 [2d ed.]: McGraw-Hill Book Co., 721 p.

Lindgren, Waldemar, 1933, Mineral deposits, 4th ed.: McGraw-Hill Book Co., 930 p.

Lovering, T. S., and Goddard, E. N. 1950, Geology and ore deposits of the Front Range, Colorado: U.S. Geol. Survey Prof. Paper 223, 319 p.

Lovering, T. S., and Tweto, O. L., 1944, Preliminary report on geology and ore deposits of the Minturn quadrangle, Colorado: U.S. Geol. Survey Strategic Minerals Inv. Prelim. Rept. (unnumbered), 115 p.

Newhouse, W. H., 1925, Paragenesis of marcasite: Econ. Geology, v. 20, no. 1, p. 54–66.

Palache, Charles, Berman, Harry, and Frondel, Clifford, 1944, The system of mineralogy of James Dwight Dana and Edward Salisbury Dana, Yale University, 1837–1892; volume 1, Elements, sulphides, sulfosalts, oxides [7th ed., revised]: New York, John Wiley & Sons, 834 p.

——— 1951, The system of mineralogy of James Dwight Dana and Edward Salisbury Dana, Yale University, 1837–1892; volume 2, Halides, nitrates, borates, carbonates, sulfates, phosphates, arsenates, tungstates, molybdates [7th ed., revised]: New York, John Wiley & Sons, 1124 p.

Rankama, K. K., and Sahama, Th. G., 1950, Geochemistry: Chicago Univ. Press, 912 p.

Raymond, R. W., 1870, Statistics of mines and mining in the States and Territories west of the Rocky Mountains [2d rept.]: U.S. Treasury Dept., 805 p.

——— 1872, Statistics of mines and mining in the States and Territories west of the Rocky Mountains [3d rept.]: U.S. Treasury Dept., 566 p.

——— 1877, Statistics of mines and mining in the States and Territories west of the Rocky Mountains, 8th Annual Report: U.S. Treasury Dept., 519 p.

Richards, R. H., assisted by Bardwell, E. S., and Goodwin, E. G., 1909, A text book of ore dressing: McGraw-Hill Book Co., 702 p.

Schouten, Cornelis, 1962, Determination tables for ore microscopy: Amsterdam, Holland, and New York, Elsevier Pub. Co., 242 p.

Skinner, B. J., 1956, Physical properties of end-members of the garnet group: Am. Mineralogist, v. 41, nos. 5–6, p. 428–436.

Stockwell, C. H., 1927, An X-ray study of the garnet group: Am. Mineralogist, v. 12, no. 9, p. 327–344.

Tweto, O. L., 1949, Stratigraphy of the Pando area, Eagle County, Colorado: Colorado Sci. Soc. Proc., v. 15, no. 4, p. 149–235.

——— 1956, Geologic map of the Tennessee Pass area, Eagle and Lake Counties, Colorado: U.S. Geol. Survey Mineral Inv. Field Studies Map MF–34.

U.S. Bureau of Mines, 1925–31, Mineral resources of the United States [annual volumes for the years 1924–30]: Washington, U.S. Govt. Printing Office.

——— 1932–66, Minerals yearbooks of the United States [annual volumes for the years 1931–65]: Washington, U.S. Govt. Printing Office.

U.S. Department of Commerce, Weather Bureau, 1953, Climatography of the United States No. 11–5: Washington, U.S. Govt. Printing Office.

U.S. Geological Survey, 1904–24, Mineral resources of the United States [annual volumes for the years 1903–23]: Washington, U.S. Govt. Printing Office.

Wallace, S. R., Muncaster, N. K., Jonson, D. C., MacKenzie, W. B., Bookstrom, A. A., and Surface, V. E., 1968, Multiple intrusion and mineralization at Climax, Colorado *in* Ridge, J. D., ed., Ore deposits of the United States, 1933–67 (Graton-Sales volume), V. 1: Am. Inst. Mining, Metall., and Petroleum Engineers, p. 605–640.

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